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Do we need Road Lighting?

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Doctoral Thesis

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Road Lighting and Traffic Safety
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Per Ole Wanvik

Thesis submitted to the Department of Civil and Transport Engineering, Faculty of Engineering Science and Technology, the Norwegian University of Science and Technology, in partial fulfilment of the requirements for the degree of philosophiae doctor.

March, 2009

The committee for appraisal of this thesis comprised the following members:

Senior scientific officer, PhD, **Eirin Ryeng**, Department of Civil and Transport Engineering, Norwegian University of Science and Technology, (leader of the committee).

Professor, PhD, **Risto Kulmala**, VTT, Finland (first opponent).

Research engineer, PhD, **Michael Sørensen,** Institute of Transport Economics, Norway (second opponent).

Advisors during this study have been:

Professor, Dr.Ing., **Stein Johannessen**, Department of Civil and Transport Engineering, Norwegian University of Science and Technology (main advisor).

Associate Professor, Dr.Ing., **Eilif Hugo Hansen**, Department of Electric Power Engineering, Norwegian University of Science and Technology.

Preface and Acknowledgement

This PhD study was initiated by the author's participation in two previous projects at the Norwegian Public Roads Administration involving a new road lighting design guide and an energy efficiency project. These projects clearly revealed the need for more knowledge about the relationship between road lighting and road accidents during darkness. Literature studies did not give sufficient answers, and it was doubted that the benefits could compensate for the large costs related to road lighting in Norway.

The thesis is based on four studies presented in four papers. The first paper was submitted by the Norwegian jury to the Piarc Prizes 2007 Competition as the Norwegian contribution within two topics: Road safety and Sustainable Development. The second paper is unpublished. The third paper is published in Accident Analysis and Prevention and the forth paper is accepted for publication in Traffic Injury Prevention.

Many persons have contributed during the process. I would like to thank the persons at the Norwegian Public Roads Administration who have made it possible for me to carry out and finish my PhD study. I would also like to express my gratitude to the road lighting community in Norway, with Eirik Bjelland in the leading role, for encouraging me in my work and for including me in the exciting development within road lighting design and technology.

I owe many thanks to my main supervisor, professor Stein Johannessen at NTNU who has provided encouraging and constructive instructions and comments to my work. I also extend my thanks to my assistant supervisor, associate professor Eilif Hugo Hansen at NTNU and the two other members of my resource group Odd Arnesen at ENOVA and Karl Melby at Public Roads Administration. Their advices in the process and their comments to my written drafts have been of great help.

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My family and friends have also earned my gratitude. In particular I want to express my gratitude to my dear Eva for her constant support and to my children Jørgen, Hanne and Tom Anders for enduring my absorbance in the work.

Abstract

Road lighting is widely recognised as an efficient traffic safety measure. However, we know too little about the effect of road lighting on accidents in a given situation and we do not know what kind of lighting that is optimal for the situation. Society today has a demand for energy savings, locally and globally, and we should not use more energy for road lighting than is necessary. In the field of road lighting the demand for energy savings is accompanied by a fast development of techniques and equipment that give great opportunities for energy savings. The opportunity already exists to adapt the lighting to the actual road, traffic and weather situation. It is a problem, however, that we do not know what lighting quantity and quality which gives the best benefit – cost ratio. The objective of this thesis is to contribute to more knowledge about the relationship between road lighting and traffic safety and thus make a basis for benefit – cost calculations (including environmental costs).

The thesis is based on four studies about the safety effect of road lighting, reported in four papers. The first is a literature study, the second is a Norwegian before-and-after study, the third is a cross-section study of Dutch accidents and the fourth is a study of Dutch motorway accidents. The thesis also contains three appendices presenting some more details from the studies than were shown in the papers. The content of the four papers are presented and discussed as a whole in a (fairly comprehensive) introductory part consisting of 10 chapters, where conclusions about the safety effect are discussed and summarised. The thesis in addition discusses the benefit – cost ratio of road lighting, but it is not treated in any of the papers. It has been useful to discuss this matter in advance of the discussion of the future role of road lighting.

In the literature study (Paper I), the mean effect of road lighting on injury accidents during darkness was found to be -30 %. The mean effect on fatal accidents was -60 %. The mean effect on pedestrian injury accidents was -45 %, and on motorways the mean effect on injury accidents was -50 %.

In the Norwegian before-and-after study (Paper II), the estimated effect of road lighting on injury accidents during darkness was -28 %. The estimated effect was larger at high speed limits than at low speed limits. The estimated effect was smaller on roads with AADT (average daily traffic volume) > 8000 vehicles than on roads with AADT < 8000 vehicles.

In the cross-section study of accidents on all Dutch roads (Paper III), the mean effect of road lighting on injury accidents during darkness was found to be -50 %, while it was -54 % when only rural roads were considered. The effect on pedestrian, bicycle and moped accidents was larger than the effect on automobile and motorcycle accidents, and the differences were statistically significant. There was no significant difference between the safety effects for different accident types (Rear end collisions, Frontal collisions etc.) and no significant difference between the driver age groups 60 – 74 years and 30 – 39 years. The effect on fatal accidents was found to be slightly larger than the effect on injury accidents. The mean effect on twilight accidents was 2/3 of the effect during darkness.

In the study of motorway accidents (Paper IV), the effect on injury accidents during darkness was found to be -49 % on Dutch motorways, while the effect seemed to be much smaller on British and Swedish motorways.

On Dutch rural roads and Dutch motorways, the estimated effect of road lighting on accidents during darkness was smaller during adverse weather and road surface conditions than in fine weather and dry surface conditions. The differences were statistically significant. In fog, there was found no effect of road lighting during darkness. However, there were indications on a daylight safety effect during fog, possibly due to guidance from light poles.

The results from the studies described in this thesis give a basis for increasing the application of road lighting as a traffic safety measure worldwide. Cost – benefit calculations indicate that road lighting is one of the most efficient road safety measures available. However, the energy consumption related to road lighting is a problem that must be considered. The great challenge is to reduce the energy consumption as much as possible without reducing the safety benefit too much.

Future road lighting will probably be of the adaptive type, and it will be essential to know how the safety effect varies according to traffic and weather conditions and how it varies with the road lighting level and the quality of the lighting. The thesis answers some question about the safety effect during different weather conditions. There is, however, too little information about safety effect related to varying road and traffic conditions.

A more serious lack of knowledge is that we do not know how the safety effect varies according to the lighting level. It is not possible to balance the energy consumption and the safety effect as long as this relationship is not known.

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1 Introduction

Road lighting is widely applied as a safety measure in some countries, like Norway. However, the costs and the energy consumption associated with road lighting is a problem, and in Norway, the Ministry of Transport has asked the Public Roads Administration to consider energy reductions in road lighting. It is therefore essential to know the effect of road lighting on accidents. Future road lighting will, at least partly, be made adaptive. The lighting level will be adapted to the varying traffic and weather conditions for the purpose of saving energy. To consider energy reduction we therefore need to know the safety effect of road lighting during different traffic and weather conditions. We also need to know how the safety effect is affected when the lighting level is reduced or increased.

Today's knowledge about the safety effect of road lighting at different situations is quite limited. The aim of this PhD thesis has been to develop and bring forward more knowledge about such effects. I have chosen to do this in the following way:

The thesis is based on four studies about the safety effect of road lighting, reported in four papers. The first is a literature study, the second is a Norwegian before-and-after study, the third is a cross-section study of Dutch accidents and the fourth is a study of Dutch motorway accidents. The thesis also contains three appendices presenting some more details from the studies than were shown in the papers. The content of the four papers are presented and discussed as a whole in a (fairly comprehensive) introductory part consisting of 10 chapters, where conclusions about the safety effect are discussed and summarised. The thesis in addition discusses the benefit – cost ratio of road lighting, but it is not treated in any of the papers. It has been useful to discuss this matter in advance of the discussion of the future role of road lighting.

As a basis for the thesis, important elements and questions related to today's knowledge about road lighting and traffic safety are discussed in the remaining sections of Chapter 1, and gaps in this knowledge are presented.

1.1 A Battle against Road Traffic Accidents

Road traffic accidents are a growing worldwide problem and the World Health Organization discusses this problem in “World report on traffic injury prevention” (WHO, 2004). Both among children aged 5 – 14 years and among young people aged 15 – 29 years, road traffic injuries are the second-leading cause of death worldwide, following behind childhood cluster diseases among children and HIV/AIDS among young people. According to the report, the number of people killed in road traffic accidents each year is about 1.2 million, while the number of injured people is about 50 million. Without increased efforts and new initiatives, the annual numbers of killed and injured people worldwide is forecast to increase by about 65 % between 2000 and 2020. Most of the road accidents occur in developing countries and those countries also have the largest and fastest increase in road accidents. The annual costs of road accidents in low-income and middle-income countries are estimated to be about US$ 65 billion, which is more than the annual amount received by these countries in development assistance. In South-East Asia, the number of road traffic injuries is predicted to increase by a factor of 2.44 during the period from 2001 to 2021 (WHO, 2004).

According to the European Commission (EC, 2006), about 1,300,000 road accidents occur every year in Europe and more than 40,000 people are killed in those accidents. In the European White Paper on transport policy (EC, 2001), the European Commission presented the ambitious goal to reduce the number of fatalities in road traffic by 50 % within ten years. By the mid-term, road fatalities had declined by 17 % since 2001, but in some of the countries in Eastern Europe the number of fatalities had increased (EC, 2006). The Commission stated that “the road remains the least safe mode of transport” and said that “this is not acceptable and all actors must step up their efforts to improve road safety”.

The road safety work within WHO is now based on two principles. The one is to refuse to accept death and severe injuries as a consequence of traffic accidents. The other is to adapt the roads to people’s vulnerability. This is much alike the “Vision Zero” approach, which was introduced in Sweden and Norway some years ago and have since been a useful tool in the safety work.

1.2 Risk Increase during Darkness

Previous studies have shown that the accident rate is higher during darkness than during daylight. The difference is greater for pedestrians than for vehicle occupants, greater for rear-end collisions than for frontal or lateral collisions, greater for fatal accidents than for injury accidents, greater for accidents on rural roads than for accidents on urban roads, and greater during rain than during dry weather.

In Norway, about 35 % of injury accidents occur during darkness or twilight while about 20 – 25 % of vehicle kilometres travelled are within the hours of darkness or twilight. Elvik et al. (1997) concluded from their literature review that the accident risk is 1.5 – 2 times higher during darkness than during daylight.

Fatal accidents are even more overrepresented during darkness. The proportion of fatal accidents at night in 13 OECD countries was reported to range between 25 % and 59 % with average value 48.5 % (OECD, 1980). The estimated average value of vehicle kilometres travelled was 25 %. The fatal accident rate was about three times higher during the hours of darkness than during daylight, and at weekends the difference was further increased.

A study by Plainis et al. (2005) showed that the injury severity, defined as the number of fatal accidents per 100 injury accidents, was almost three times higher during night-time (not all hours were dark) on unlit roads than during daytime on the same roads. In the presence of road lighting, injury severity during night-time was reduced by around a factor of three. Equal result was found in UK and Greece.

John M. Sullivan and Michael J. Flannagan at the University of Michigan have performed several accident studies using daylight saving time (DST) transitions to produce the dark/day interval risk ratio for different kind of road traffic accidents in the USA (Sullivan and Flannagan, 1999; 2002; 2003; 2007). In their studies they found that fatal accidents not involving pedestrians increased by a factor of 1.1 during darkness while fatal accidents involving pedestrians increased by a factor of 4.6 during darkness. Moreover, they found that the risk among both adult and elderly pedestrians was nearly seven times greater in darkness than in daylight. The risk increase for children during darkness was found to be much smaller, but the authors explained that by less exposure during darkness because parents are likely to require children to be inside after dark.

The risk increase for pedestrian accidents on wet road surfaces compared with dry road surfaces was studied 40 years ago in London by Smeed (1968). He found that wet road surfaces increased the risk for pedestrian accidents by a factor of 1.4 during daylight and by a factor of 2.3 during darkness. He also found that rain increased the risk of a fatal pedestrian accidents by a factor of 3 during daylight and by a factor of 9 during darkness. Jørgensen and Rabani (1971) studied accident that occurred when pedestrians were crossing the roads in Denmark. They found that rain increased the risk of a pedestrian accident by a factor of 2.2 during daylight and by a factor of 9.6 during darkness.

A study of crash data from Kentucky, USA, compared the characteristics of crashes during daylight with crashes during darkness with no road lighting (Green et al., 2003). The study found that the following accident types were represented with a high percentage of their accidents occurring during darkness.

- Fatal accidents
- Accidents during weekend
- Accidents during snow and ice conditions
- Accidents occurring on a curve
- Collisions with fixed object
- Collisions with animal
- Collisions with parked vehicle
- Run off the road accidents
- Accidents involving alcohol, drugs, speed and sleepiness

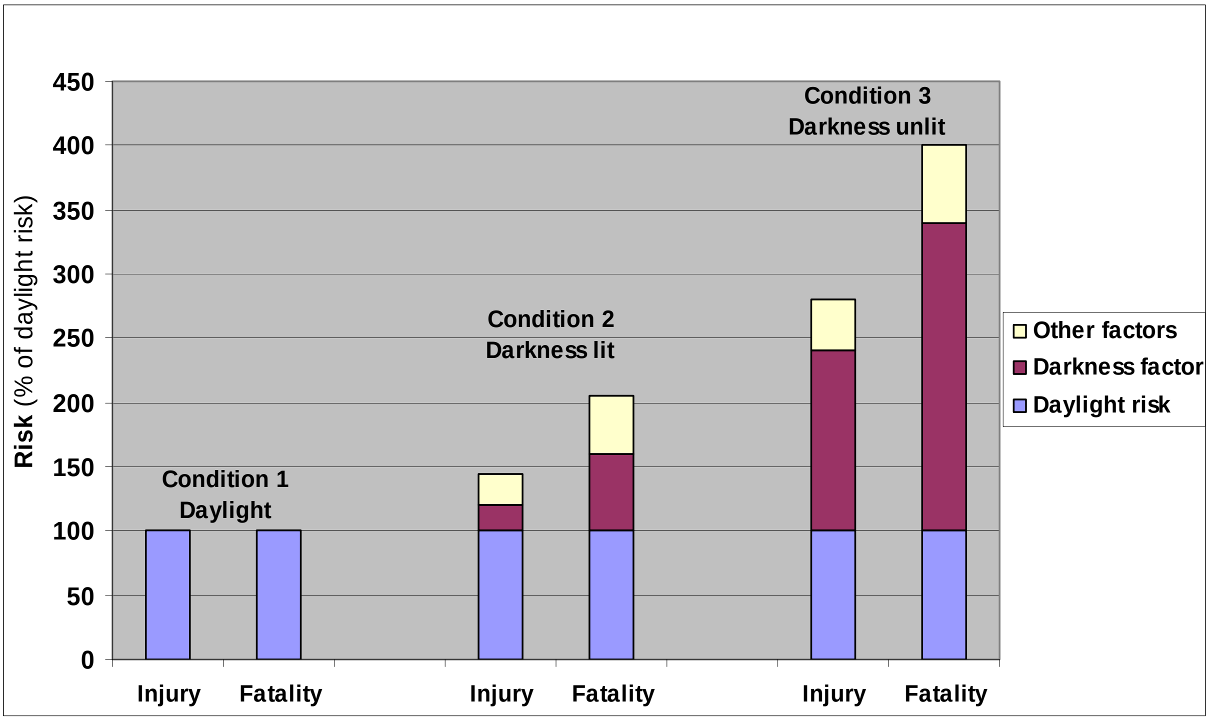
The following accident types were represented with a low percentage during darkness:

- Rear end collisions
- Collisions at intersections

Not all the risk increase during the hours of darkness is related to visibility. Some is due to more presence of animals, wet road surfaces, rain, snow, fog etc. Fatigued or intoxicated drivers, young and inexperienced drivers, high speed, drunken pedestrians etc. are factors that tend to increase the accident risk in night-time traffic. Analyses by Clarke et al. (2006) showed that a large number of night-time accidents were associated with risk-taking behaviours of young drivers. Crettenden at al. (1994) adjusted accident frequency for distance travelled during daytime and night-time and for driver age/experience, and they found that night-time driving was particularly risky for young and inexperienced drivers. Clark et al. (2002) found that loss of control on bends in darkness was a particular problem for the 17 – 19 year age group of drivers, and they related the problems not only to lack of skill, but also to “failure of attitude”. However, it is known that a large part of road injuries are attributed to human perceptual error. It is also known that our visual performance is reduced during darkness at low luminance. Owens and Sivak (1996) found that degraded visibility in low illumination is associated primarily with collisions involving pedestrians and cyclists, while alcohol plays a larger role in other accidents during darkness.

The risk increases during darkness relative to daylight risk is illustrated in Figure 1, in principle. Daylight risk is set to 100 %. Darkness risk is shown for injury accidents (left bar) and fatal accidents (right bar), on lit roads (in the middle) and unlit roads (to the right). The figure also illustrates how the risk increase is partly due to the darkness itself and partly due to other factors associated with night-time traffic.

Figure 1: Illustration of risk increase during darkness on lit roads and unlit roads, in principle.



In most studies of the accident risk associated with darkness, other factors than darkness and degraded visibility have influenced the results largely. However, the method used by Sullivan and Flannagan, studying accidents at the transition to and from daylight saving time, is probably an exception. The method does to a large degree exclude other risk increasing factors that are associated with night-time driving.

An intention in this PhD project is to estimate the accident reducing effect of road lighting as the ratio between the risk in darkness on lit roads and the risk in darkness on unlit roads while other factors than darkness are eliminated or kept constant.

1.3 Road Lighting as an Accident Countermeasure

The purpose of road lighting is to permit the drivers to manoeuvre safely and efficiently by improving the visibility of the road, the immediate environment, pedestrians, cyclists, other vehicles, and other objects or hazards. The visibility of an object depends on a combination of the following factors:

- The contrast between the object and its immediate background
- The luminance of the background
- The angular size of the object in the view of the observer
- The duration of the observation

A road lighting system incorporates the photometric properties of many elements, like the light sources, the luminaires, the objects to be seen, the road surface, the surroundings, and the road lighting geometry. These properties influence the visibility of the objects to be seen and are important factors in road lighting design. However, visibility criteria are not used in road lighting design today. The current road lighting design concept, “The luminance concept”, have criteria for average road surface luminance, luminance uniformity and glare limitations. The idea is to make dark objects on the road visible in contrast against the background of a light road surface. It is not the light from the luminaires incident upon the road surface that is considered but the reflected light from the road surface as seen by the eye of the driver.

The use of road lighting in rural areas varies from country to country depending on how much road safety is pushed and how effective road lighting is considered to be as a road safety measure. In some countries, like Germany and Sweden, road lighting is not commonly used on rural motorways, while in other countries, like Holland and Belgium, most of the motorways are lit. In Norway all motorways are lit.

In general, countries that have the lowest accident rates, like Norway, Sweden, Great Britain and Holland, have relied much on road lighting as a safety measure. In developing and emerging countries, where the accident rate may be as much as 35 times higher (WHO, 2004), road lighting is not yet commonly used even on roads with dense traffic and a mixture of pedestrians, bicycles and all kinds of vehicles.

Many studies, mainly in the 1960s and 1970s, proved that road lighting was an effective safety measure against road accidents during darkness, on motorways as well as on other roads. 62 road lighting and accident studies from 15 countries were analysed in Publication 93 from the International Commission on Illumination (CIE, 1992a), and some 85 % of the results showed road lighting to be beneficial. One third of these studies had statistically significant results and showed accident reductions between 13 % and 75 %. It was concluded that the average reduction in accidents was at least 30 %, and it was recommended that this value was used if results from local studies were not available.

Later studies have to a large extent confirmed this result, as described in Paper I. In a meta-analysis Elvik (1995) evaluated the safety effect of road lighting based on 38 earlier studies. The following results were found:

Table 1: Effect of road lighting found in a Meta analysis by Elvik (1995)

Accident group	Effect	95 % conf.int.
Fatal accidents	-64 %	-74, -50
Injury accidents	-28 %	-32, -25
Property damage only	-17 %	-21, -13

The accident reduction due to road lighting is seen despite that drivers have been found to increase their speed and reduce their concentration during darkness when the road is lit (Assum et al., 1999).

Few studies have examined the relationship between lighting level and accidents, but the common opinion has been that the effect on accidents increases when the road lighting level is increased within the area between 0.5 cd/m^2 and 2.0 cd/m^2. This belief is based partly on some of the accident studies reported in CIE Publication 93, partly on visibility studies, and partly on knowledge about the nature of human vision. When the average road surface luminance is increased, the visual system will be adapted to a higher lighting level, the sensitivity to low contrasts will be increased, and the sensitivity to glare will be reduced. For older drivers this is more important than for younger, because both contrast sensitivity and glare recovery performance is impaired with increasing age. It is also known that images are processed more slowly by the human vision system from the retina to the brain at low luminance compared to higher luminance. Thus the visual reaction times in traffic situations are longer during low luminances (Plainis and Murray, 2002). In Finland, Eloholma et al. (2006) found that the performance of visual tasks during light levels usually found in night-time traffic (mesopic light levels) decreased with decreasing luminance level. It is therefore reasonable to conclude that road safety is increased when the road lighting level is increased.

Another type of measure that is commonly used to improve the visibility in night-time traffic is delineating measures. Table 2 shows estimated mean effect of such measures, as presented in the Norwegian handbook of road safety measures (Elvik et al., 1997). The different measures may be used separately or in combination, and the table shows that a combination of measures may give the best safety effect. Road lighting is not included in Table 2, but it is reasonable to conclude that the effect of road lighting also depends on how it is combined with other visibility measures.

Table 2: Effect of delineating measures on injury accidents, as presented in the Norwegian handbook of road safety measures (Elvik et al, 1997)

Measure	Effect
Edge lines:	-3 %
Centre line:	-1 %
Lane lines:	-18 %
Reflecting delineators:	+ 5 %[1]
Edge lines + centre line:	-24 %
Edge lines + centre line + reflecting delineators:	-45 %

[1] Effect on injury accidents during darkness.

Light emitting diodes (LED) mounted on the road surface or on posts are used as delineators in some countries, and the use of LED guide lights is described as an alternative or additional measure in Norwegian and Swedish road lighting recommendations. The effect on accidents is so far unknown, but there may probably be a safety effect of LED guide lights either alone or in combination with road lighting.

Light road surfaces are in some countries considered as a safety measure improving the visibility in night-time traffic. It is known as a fact that dark surfaces absorbs much of the incoming light and the luminance is low unless the illumination from the road lighting is at a very high level. It is therefore obvious that dark road surfaces are less energy economic than light surfaces on lit roads. However, no studies are found that confirm a safety effect of light road surfaces compared to dark surfaces. A study by Amundsen (1983) showed no safety effect of light road surfaces, neither in darkness on lit or unlit roads nor in daylight.

The problem of glare from reflected light on wet road surfaces is well known but it is not much considered in road lighting design or road surface design. The luminance uniformity on wet surfaces is considered in road lighting design in some countries, using the lighting classes for wet surface. However, the glare from reflected light on wet road surfaces is not regarded in today road surface photometry (reference to the international symposium on road surface photometric characteristics in Turin 9 – 10 July 2008). Loss of visibility due to glare is probably a considerable road safety problem especially in areas where the road surface is wet during large parts of the dark hours.

1.4 Visual Tasks in Night-time Traffic

CIE Publication 100 (CIE, 1992a) deals with visual tasks in night-time traffic and reports on knowledge and experience concerning the effect of road lighting on visual tasks.

In this publication as well as in other publications driving tasks are regarded as consisting of three groups of behavioural tasks: positional tasks, situational tasks and navigational tasks.

Positional tasks are: maintenance of the desired lateral position and correct heading with respect to the road ahead, including the maintenance of correct speed.

Positional information is obtained from detection and recognition of visual changes in road elements and surroundings while the vehicle is in movement. In night-time driving, insufficient illumination limits the use of peripheral vision and visual information must be provided mainly by road elements as lane lines, curbs, shoulders, edge lines, delineators, guard rails, light poles etc.

Some authors have considered the driver's visibility requirements for road delineation. Allen et al. (1977) in his study found that drivers were looking at a point three or four seconds ahead of their present position. Godthelp and Riemersma (1982) found that a minimum of four seconds preview time was needed for safe control through curves. If the speed is 80 km/h, the travel distance during four seconds is 89 m.

Field studies carried out on a test road, "Virginia Smart Road", in the USA show that the detection distance for road markings during darkness depends on several factors (Gibbons, 2006). Some of the results are presented below because they may be of importance when the safety effect of road lighting is discussed. The car used is a sedan and the headlamps are standard halogen lamps aimed using the standard SAE alignment method.

- The detection distance in rain varied by road marking material from 25 metres for "Paint with Standard Beads" to 63 metres for "Wet Retro Tape".
- Rain reduced the mean detection distance on worn asphalt surface by 58 %, from 88 metres to 37 metres.
- Glare reduced the mean detection distance on worn asphalt in rain by 23 % from 37 metres to 29 metres. (All types of marking material showed reduced detection distance due to glare).
- Road lighting increased the mean detection distance in rain by 3 % on worn asphalt surface and by 17 % on worn concrete surface. The low mean effect of road lighting is due to a 12 % reduction of the detection distance for "Wet Retro Tape" while the detection distance increased by 84 % for "Paint with Standard Beads"
- Road lighting increased the mean detection distance on dry surface by 22 %.

For long-range guidance, post-mounted reflecting delineators give useful support for the drivers' positional tasks during darkness (Good and Baxter, 1985; Triggs and Fildes, 1986;

Kallberg, 1993; Schumann, 2000). However, a study in Finland (Kallberg, 1993) showed an increase in speed and an increase in accidents rates on roads with post –mounted delineators.

Pilot projects in Sweden show that post-mounted light emitting diodes (LED) are more visible during fog and snow than reflective delineators. A study in Japan (Hagiwara et al., 2006) also showed that LED delineators were particularly effective under poor visibility conditions during night-time.

Situational tasks are: avoidance of objects or hazards and execution of course changes and speed control relative to other vehicles. Situational tasks require visual information about relative positions and relative velocity associated with other vehicles, traffic control devices, pedestrians, hazards and changes in roadway alignment. Visual information about wet road surface and other factors influencing the braking or manoeuvring ability is also needed. The road users need not only to see but also to rapidly comprehend the visual information to make the right decisions and actions.

The minimum required visible distance for situational tasks is the sum of reaction distance and breaking distance. The reaction distance is the distance the vehicle travels from the moment an object or hazard is detected to the moment of brake application. Based on a field study, Olson and Sivak (1986) suggested 2.5 seconds to be used for design purpose. The braking distance is the distance required to reach the desired speed from the moment the brakes have first been applied.

Helmers and Rumar (1973) measured sight distances while driving with dipped lights on wet and dry road surfaces, with and without glare from opposing headlights, on unlit roads with different road surface texture. The size of the obstacle used was 0.4 x 0.4 m. When the object reflectance was 7 %, the sight distance varied between 37 m and 115 m, and the following results were found:

- The sight distance was greatly reduced by glare from oncoming vehicles, especially on wet road surfaces.
- With no oncoming vehicles, the sight distance was significantly longer on wet surfaces than on dry surfaces. It was longer on smooth surfaces than on rough surfaces, and it was especially longe (115 m) when the surface was dark, smooth and wet.

- With oncoming vehicles, the sight distance was shorter on wet surfaces than on dry surfaces. It was especially short (37 m) on medium dark, smooth and wet surfaces.

- On light and rough surfaces the sight distance varied little (55 – 77 m) with varying situations. On dark and smooth surfaces the sight distance varied much more (40 – 115 m).

Sullivan et al. (2007) found that young drivers detected objects at longer distances (89 m) than older drivers (48 m) on an unlit dark road. All drivers detected the large targets (size of pedestrians and deer) at longer distances (68 m and 88 m) than the small targets (42 m).

Road lighting is the main safety measure for the improvement of situational information during darkness. Road lighting will sometimes illuminate the scene and make the whole situation more visible and comprehensible. However, the currant principle of road lighting design is not to light up a scene, but rather to make a negative contrast between a dark object and a light background (CIE, 2008). The main quality parameter is the average road surface luminance, and the intention is to make a light road surface as a background for dark objects and make the objects visible by luminance contrast. The contrasts in a traffic scene depend on the luminance of different objects and backgrounds, and as the luminance varies while vehicles and other objects are in movement, the contrasts tend to be shifting and quite unpredictable. Pedestrians wear cloths with different reflection properties and vehicles have different colours. The road surface is often reflecting light from different light sources, and the reflection is some times glaring and may reduce visual performance. In dense traffic, when the road is full of vehicles, the road surface is hardly visible. In many situations the principle of contrast between a dark objects and a light road surface, the “luminance concept”, seems to be rather unsuitable or irrelevant. That is why the International Commission of Illumination, CIE, is working on the development of visibility concepts for road lighting design in the technical committee CIE TC-4-36 (CIE, 2007b).

Navigational tasks are: route selection and route following. For navigational tasks the information from guide signing systems is important. Road lighting may be beneficial for the visibility of signs, but interior lighting or external spot light are less expensive alternatives for illumination of signs. Additional information for navigational tasks may be obtained by road lighting if junctions, ramps and surroundings are well illuminated.

1.5 Critical Visual Elements in Night-time Traffic

A few studies give information about which elements automobile drivers consider as most critical and what kind of visual information they consider as most necessary for safe driving during the hours of darkness. In a study by Walton (1975) eight drivers answered a questionnaire after driving a route consisting of both motorways and other roads. In a study by Walraven (1980) nine drivers drove a car along a 112 km route, consisting of different kind of rural roads. In a study by Padmos (1981) 1200 drivers were interviewed about their experiences in driving in rural areas. In a study by Gallagher and Lerner (1983) drivers were asked to scale the difficulties of driving under different conditions on two-way roads shown in a series of photographs. In a study by Padmos (1988) eight drivers drove 32 times along 243 km of motorway.

Some main conclusions from the studies are summarized below.

- Positional information was considered to be the most critical and necessary information. In too many cases the drivers attended to positional tasks at the sacrifice of situational and navigational tasks. The most frequently reported critical visual elements were in the category "course of the road and other geometrical road characteristics". Worn and faded lane lines and absence of edge lines some times made problems.
- Obstacles on the road were never mentioned as a visual problem.
- Seeing other cars was rarely mentioned as a visual problem. Some exceptions were related to defective car lighting.
- Seeing cyclists and pedestrians was somewhat more frequently mentioned as a visual problem.
- Glare from the headlights of oncoming vehicles was often mentioned as a visual problem.
- Visual problems increased as traffic volume and speed increased, mainly due to glare from opposing headlights.

- Visual problems occurred more frequently on unlit local roads than on lit main roads.
- On motorways, very few problems were mentioned; either the road was lit or unlit.
- For night-time near-accidents on motorways only 5 % of the subjects thought that (better) road lighting could have prevented the near-accident.
- For night-time near-accidents on other roads 27 % thought that (better) road lighting could have prevented the near-accident.
- Delineation provided by road markings, curbs, and other features were considered as very valuable for the drivers when the road was low in brightness.
- On wet road surfaces, the number of visual problems per km was a factor of four higher than on dry surfaces. Road lighting decreased the frequency of problems with a factor of two.
- Road lighting seemed to decrease glare problems and problems of confusion due to lights from other vehicles and from the surroundings.
- Road lighting seemed to slightly decrease problems with seeing geometrical road characteristics. However, high quality reflecting road markings and delineators seemed to be more efficient.
- Road lighting seemed to be of minor importance for the visibility of obstacles and other road users on motorways.

The conclusions above, supplemented with conclusions from the visibility studies in Virginia (Section 1.4), are compressed in Table 3:

Table 3: Visual problems during darkness

Task group	Visual problem	Ranking of problem
Positional tasks	Worn or missing lane and edge boundaries	High
	Missing road lighting	Medium/Low
	Wet road surface	High
	Impact of glare	High
Situational tasks	Low visibility of objects/hazards on the road	Low
	Low visibility of other vehicles	Low
	Estimation of speed or position of vehicles is difficult	Medium
	Low visibility of pedestrians and cyclists	High/Medium
	Impact of rain	High
	Impact of glare	High
Navigational tasks	Low visibility of road signs	Low

1.6 The "Dark Side" of Road Lighting

Road lighting has a cost side that is commonly represented by investments, energy costs and maintenance costs. Electrical power is in short supply and energy costs are growing and have become a considerable problem for many communities. As remedial action some local governments have switched off the road lighting for some hours in the middle of the night, while others have switched off every second lamp for a period. Those measures have not been successful because of negative effects on general security, welfare and road safety.

A more serious problem, however, is the global environmental problem. Global warming, widely believed to be caused by the emission of greenhouse gases such as CO_2, is now forcing the international community to make agreements about limitation of CO_2 emission. The energy consumption related to the construction, the electric power supply and the maintenance of road lighting installations is part of this global problem. Environmental costs are not yet fully included in the road lighting costs but they may be in the future.

There are also other environmental concerns related to road lighting:

- "Light trespass" affects the human "biological clock" and the living conditions of a range of organisms
- "Sky glove" means loss of the naturally dark star-filled sky and it may also disturb astronomical observations

The International Dark-Sky Association (IDA) is working worldwide with these problems. They argue that road lighting causes 35 – 50 % of atmospheric light pollution, and their "Outdoor Lighting Code Handbook" (IDA, 2000/2002) shows how the problem may be reduced. Organisations working with the problems of light trespass and sky glove are not necessarily aiming at energy reduction. However, less spilled light also means less spilled energy.

Norway has a high share of lit roads and a higher lighting level than most other countries. One reason for this is the belief in road lighting as a major factor contributing to road safety during the dark hours. Another reason is low energy costs through many decades. Norway has probably nearly one million road lighting luminaires, which is about one road lighting luminaire per 5 inhabitants. The energy consumption to road lighting in Norway is about 200 kWh per inhabitant per year (ENOVA, 2004) and the energy cost of road lighting is about 25 Euros per inhabitant per year.

Whether or not the Norwegian extent of road lighting and level of energy consumption for road lighting is the right level for Norway or other countries in the future depends on several factors. It depends on the future benefits and the future costs of road lighting, on the priority of road safety, and on the availability of funds. The priority of road safety is for politicians to decide. However, estimation of benefits, costs and benefit to cost ratios is a professional task. The development of technical solutions for energy efficient and cost efficient road lighting installations is also of professional character but should be promoted by the demand from society and politicians.

If environmental costs are fully included in the total costs, energy efficient installations will be favoured. Luminaires powered by individual solar or wind power sources or connected to a common renewable power source for a group of luminaires will also be favoured, and the development of equipment less harmful to the environment will be urged.

Nevertheless, to optimize the use of road lighting as safety measure we need to know the expected effect of road lighting on accidents during the prevailing conditions. We also need to know the expected effect of different kinds of road lighting (different level of luminance, uniformity of luminance, size of glare, colour temperature of the light, spectral power distribution of the light, etc). When road lighting is switched off or dimmed without foreseeing the consequences, the accident risk may be raised to an unacceptable high level.

1.7 New Technology – A Way to Success?

Road lighting equipment is now available that makes it easy to control the lighting level and adapt it to the prevailing conditions. The lighting level may be adapted continuously or in intervals according to shifting weather and road surface conditions, traffic flow and ambient light.

The revised publication from the International Commission on Illumination (CIE) Publication 115 (CIE, 2008) and some national road lighting guides give recommendations for reduced lighting level during certain conditions, though the consequences on the accident risk are unknown. If the consequences were known, the choice of lighting level could be reduced to a matter of benefit versus costs. The choice between a static not dimmable lighting installation, a two step dimmable installation with conventional ballasts, or a step-less dynamic lighting installation with electronic ballasts and two way communication devices could also be a matter of a benefit versus costs. There may be a potential for energy savings by the control of the lighting level, and there may be a potential for efficiency in maintenance by the application of a two way communication system. However, the potential benefit depends on the availability of skilled local personnel for operation and maintenance. At the same time there may be a problem of reduced effect on accidents when the lighting level is reduced. To adapt the road lighting to an appropriate level, we have to know what is the appropriate lighting level during the prevailing conditions (fine weather, rain, fog, snowing, dry road surfaces, wet surfaces, snow covered surfaces, dense traffic, low traffic, and so on). Until now this is not known even to experts.

Other light sources than traditional high pressure sodium is coming into the market. Metal halide with white light is in some areas replacing yellow light sources, and light emitting diodes (LED) are predicted to become a common light source in road lighting in the near future. White light sources have in some experiments showed to improve the visibility of objects significantly, and the benefit of white light seems to be particularly beneficial in road lighting when objects are in movement in a peripheral position and the average luminance is low. This may often be the situation on future urban roads where pedestrians must be detected in low level road lighting.

1.8 Gaps in Knowledge – Questions to be answered

An ever returning question that needs to be answered is: What is the effect of the road lighting on accidents during possible future situations?

It has been generally accepted that road lighting reduces accidents during darkness by about 30 %. However, there has not been satisfactory evidence based on research to support this claim. Studies of the safety effect of modern road lighting during current road and traffic conditions are difficult to find. Most of the studies are from the USA or Great Britain some 30 – 40 years ago when the quality of the road lighting was poorer and the headlights of the vehicles were poorer. Hardly any studies show how the effect of road lighting varies with different conditions and hardly any studies show how the effect varies with the quality of the road lighting.

There may be several reasons for the lack of recent studies within those subjects:

- Prioritizing of road lighting as safety measure is rarely based on estimation of the safety effect or on benefit – cost calculations.
- The results from the old studies were convincing once, and the old knowledge is still regarded as the truth.
- Before-and-after studies are difficult to conduct. They depend on information about road lighting and other safety measures related to accident records, and such information is limited or does not exist
- Controlled cross-section studies are difficult to conduct. They depend on information about accidents and traffic volumes related to road lighting, and such information usually does not exist.

The need for more updated and detailed information has increased through the last years because of high energy costs, awareness of global warming and the availability of adaptive lighting systems. It is therefore time for more research about road lighting and its effect on accidents.

Many questions need to be asked and answered. Some are listed below.

1. What is the mean expected effect of modern road lighting in today traffic situations? Can we trust the results from earlier studies? (CIE, 1992a; Elvik et al., 1997)

2. How and why does the effect differ for fatal accidents, serious accidents, slight accidents and “Property Damage Only” (PDO) accidents? Can we trust the results from earlier studies? (CIE, 1992a; Elvik et al., 1997)

3. How and why does the effect vary from country to country (depending on geography, climate, demography, traffic situation, economic development, etc.)?

4. How and why does the effect vary with the climatic conditions (weather conditions, road surface conditions, sky light, etc)?

5. How and why does the effect vary with the traffic situation (type of accidents, type of road users, type of vehicles, traffic volumes, etc.)?

6. How and why does the effect vary with the photometric characteristics of the road surface (reflectance, specularity, etc)?

7. How is the effect during dusk and dawn compared with the effect in darkness? (When should road lighting be turned on and turned off?)

8. How and why does the effect vary with the quality of the road lighting (average horizontal luminance level, luminance uniformity, average vertical luminance, luminance contrasts, colour contrasts, light colour, heights of light poles, distance between light poles, etc). If it varies, what are the critical quality parameters and what is best quality?

9. Is the effect different for old drivers compared with young drivers? If so, do old drivers have special needs that should be considered in road lighting design?

10. How is the effect when road lighting is combined with delineating measures?

11. How is the effect of road lighting affected by new vehicle technology (adaptive headlamps, screen warnings, distance control and lateral control devices, etc.)?

2 Study Objectives

It is not possible within the limits of this PhD project to elaborate on all the questions raised in Section 1.7. The availability of data also makes limits for the studies. The study has three objectives, and hypotheses are determined for each of the subjects, as described in Section 2.1 to Section 2.3. The delimitation of the study is explained in Section 2.4.

The three objectives are:

1. To estimate the mean effect of modern road lighting on accidents during darkness.

2. To examine how the effects of road lighting vary according to different parameters, such as type of road, type of accidents, weather conditions and road surface conditions.

3. To evaluate the need for road lighting on motorways in the future.

The three objectives are commented on further below. In total ten hypotheses are presented. Hypotheses 1 – 9 are further analysed and discussed in Chapters 3 – 5 and conclusions related to these hypotheses are summarised in Chapter 6. Hypothesis 10 is analysed and discussed in Chapter 8, and a conclusion is made at the end of Chapter 8.

2.1 The First Objective

The first objective of this study is to estimate the mean effect of modern road lighting on accidents during darkness. Road lighting appears to be an effective measure against serious road accidents problems, but the effect on accidents needs to be documented through new studies. As shown in Paper I, most previous studies are more than 20 years old and use accidents that are even further back in time. Their relevance to current traffic and modern road lighting are questionable.

The author made a preliminary before-and-after study in 2004 on the effect of road lighting on 35 road sections in Southern Norway (Wanvik, 2004). The study showed no effect of road lighting on accidents. This emphasized the need for a more comprehensive and better controlled study. The costs of road lighting installations are large and need to be justified by well documented effects on accidents.

Some hypotheses are determined for the studies:

Hypothesis 1: Modern road lighting reduces the number of injury accidents during darkness by about 30 %.

It seems likely that the effect of road lighting is much the same today as it has been for decades. No reasons for a change in effect by time seem obvious. Road lighting quality has been improved through the years, but so has also automobile headlamps. The low quality in most of the earlier studies may however have led to an overestimation of the effect. This is discussed in Section 3.

Hypothesis 2: The effect of road lighting is significantly larger on fatal accidents than on injury accidents and significantly smaller on "Property Damage Only" (PDO) accidents than on injury accidents.

The statement above is acknowledged by earlier studies (Table 1). If it is true, one explanation may be that road lighting increases the time from detection of a hazard to the crash is a fact, and hence the time for speed reduction and reduction of consequences is increased

2.2 The Second Objective

The second objective is to examine how the effects of road lighting vary according to different parameters, such as type of road, type of accidents, weather conditions and road surface conditions. Knowledge about this is essential for two purposes. One purpose is benefit - cost calculations, which must be based on the known accident reducing effects relative to specific conditions. The other purpose is adaptation of the lighting level to varying conditions, which can only be performed wisely if the safety effect is known for different traffic and weather conditions at different lighting levels.

Hypothesis 3: The safety effect of road lighting is the same on all types of roads (urban roads, rural roads and motorways).

This is the conclusion from the meta-analysis by Elvik (1995).

Hypothesis 4: The effect of road lighting is larger for pedestrian accidents than for other accidents.

It is known from earlier studies that road lighting reduces pedestrian accident more than other accidents (CIE, 1992a; Elvik et al., 1997). This seems reasonable because pedestrians wear no light sources and rarely wear reflecting material. The visibility of dark cloths is very low when the background is dark.

Hypothesis 5: The safety effect of road lighting is larger for single vehicle accidents than for accidents involving more than one vehicle.

Seeing other cars was rarely mentioned in interview studies as a visual problem (Section 1.4). The most frequently mentioned visual problem were those related to positional tasks. It is also probable that road lighting is more effective in reducing accidents due to low vision of road elements or dark objects on the road than it is in seeing other vehicles. Other vehicles are normally made visible by their headlamps and rear lamps.

Hypothesis 6: The effect of road lighting is independent of weather conditions.

Several studies have shown that the accident risk increases during rain, snow, fog and on snow or ice covered surfaces. Based on all available studies, Elvik et al. (1997) concluded that the accident risk is increased by 30 % on wet road surfaces, by 50 % on slushy roads and by 150 % on snow or ice covered roads. However, earlier studies give no information about different effects of road lighting during different weather conditions and it seems not to be any obvious reason for the effect to vary according to weather conditions.

Hypothesis 7: The effect of road lighting on accidents is increasing with increasing speed level.

It seems probable that the effect of road lighting increases with increasing speed because the required visibility distance increases while most delineating measures come to short as the speed increases.

Hypothesis 8: The effect of road lighting on accidents is smaller at high traffic volumes than at low traffic volumes.

It seems probable that the effect of road lighting decreases with increasing traffic density. One reason is that other vehicles contribute to positional information through their rear lamps and to situational information by illuminating the road, the roadsides and objects on or along the road. Another reason is that only a small part of the road surface is visible when the road is filled up with vehicles, and the road surface luminance provided by road lighting is less relevant.

Hypothesis 9: The effect of road lighting on accidents is larger for older drivers than for younger drivers.

It is well known that the visual capacity decreases with age. The transmission of the ocular media decreases, the scattering in the ocular media increases, the receptor density in the retina decreases, and the adaptation to shifting luminance is slower. It is also well known that older people need more time for reactions and decisions. It is therefore reasonable to believe that older drivers need more light than younger drivers for visual tasks during the dark hours. The effect of road lighting on accidents involving older drivers should therefore be larger than the effect on other accidents, unless the difference in effect is eliminated by a higher representation of older drivers during darkness when the roads are lit.

2.3 The Third Objective

The third objective is to evaluate the need for road lighting on motorways in the future. Efforts are done to reduce the need for road lighting on motorways by the use of guide lights, mainly for the purpose of saving energy. In the Netherlands the lighting level is reduced to 20 % during good driving conditions, while it is 100 % during heavy traffic, during precipitation, and in case of accidents or work on the road. The 20 % lighting level is by the Dutch authorities considered as guide light. In Sweden, LED guide lights are used as an alternative to road lighting on four-lane motorways. In pilot projects road lighting is replaced by LED delineators.

The accident situation on motorways in the future may be forecast with and without road lighting, based on the knowledge about the present situation and the expected development within motorway safety and motorway lighting. Even a benefit – cost analysis related to the installation of road lighting may be conducted. It is, however, difficult to estimate the effect on accidents of guide lights because relevant accident studies are not found.

Hypothesis 10: Road lighting on motorways may be replaced by more energy efficient visibility measures without reducing the road safety.

It is reasonable to believe that guide lights may provide sufficient information for positional tasks on motorways during all conditions. It also seems probable that the visibility of other vehicles during most conditions is provided by rear lights. The visibility of obstacles is not reported to be a problem.

2.4 What is not treated as a Study Objective

One important question is most relevant in modern road lighting: What is the relationship between the lighting level and the effect of the road lighting on accidents? The knowledge of this relationship is essential for the utilisation of a two-step or a step-less dimmable lighting installation, for the purpose of saving energy and for the purpose of optimising the benefit-cost ratio. If we do not know the effect on accidents of reducing or raising the luminance level, it is not possible to find useful principles of dimming. Even if some road lighting standards such as CIE Publication 115 give recommendations for dimming, the effect of dimming on accidents is unknown and the result may be an unexpected increase in accidents. This question is not elaborated in the thesis. Data is not available for statistical studies of accidents related to lighting level, and no field studies are carried out as part of the thesis.

Neither are technical questions related to power supply, dimming systems, luminaries, light sources etc. treated in the thesis. These questions are treated in another ongoing PhD study at the Norwegian University of Science and Technology by Pål Johannes Larsen.

3 Study Methods

Four studies of the effect of road lighting on accidents are carried out as part of this thesis. The aim of the studies is to verify the hypotheses that were determined in Section 2.1 to Section 2.3 and thereby to fill some gaps in knowledge. The first study is a literature review. This study is the basis for the identification of gaps in knowledge within the field of road lighting and road safety. The second study is a before-and-after study in Norway. The intention of this study is to test the validity of earlier study results on today’s traffic on Norwegian main roads. The third study is a cross-section study of Dutch accidents. This study is carried out because of the availability of a large amount of Dutch accident data, the geographical and climatic uniformity of Dutch roads, and the top five position of Dutch road safety. The fourth study is a cross-section study of motorway accidents, mainly in the Netherlands but also in Sweden and Great Britain. This study is conducted to study in detail some of the findings in the third study, regarding visibility related safety problems on motorways. Additional data from Sweden and Great Britain are used to compare the safety effect of motorway lighting in the Netherlands with the safety effect of motorway lighting in other countries that are also positioned among the top five regarding road safety.

This chapter gives a short review of the content of the four papers and focuses on the study methods used. The results are presented and discussed in Chapter 4.

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3.1 The Literature Review (Paper I)

The literature review is carried out by the use of free search engines as Google and licensed information systems as Science Direct and Engineering Village 2. Information is also sought in lighting journals and in all kinds of written information from the International Commission on Illumination (CIE). The quarterly published “CIE News” for the last years is reviewed for news about road lighting and the effect on accidents. The lists of content from lighting journals and the reports from CIE meetings are especially studied.

In addition to the literature study, knowledge about earlier and present studies is obtained from the PhD candidate’s participation in international activities, such as:

- World conferences:

    - The 6th Right Light conference in Shanghai 2005
    - The 26th session of the CIE in Beijing 2007

- CIE technical committee TC4-44, working on the revision of Publication 115: Recommendations for the Lighting of Roads for Motor and Pedestrian Traffic. The candidate participated as member of the committee in meetings in Oslo, Athens and Washington in 2006 and Eindhoven, Oslo and Beijing in 2007, along with some of the most experienced road lighting experts in Europe, like Axel Stockmar and Pentti Hautala.

- Meetings with road lighting experts and researchers in the USA:

    - Carl Andersen at the Federal Highway Administration, Turner-Fairbank Highway Research Centre, who is also CIE reporter on “Road lighting and accident”
    - Paul Lutkevich, who is author of the Canadian Guide for the Design of Roadway Lighting
    - Ronald Gibbons, leader of research related to “The smart road” at Virginia Tech Transportation Institute
    - Mark Rae, John Bullough, and Yukio Akashi at Lighting Research Centre, Rensselaer Polytechnic Institute

Some of these experts have read a draft version of Paper I and some have contributed through discussions to confirm that relevant studies and conclusions are included in the paper.

The paper was referred to by CIE reporter on “Road lighting and accidents”, Carl Andersen, at the CIE Division 4 meeting in Beijing July 2007 as a most important document within the subject, and he recommended it to be used as basic document in technical committee works within CIE.

Paper I was finished in April 2006, but more recent literature reviews have not revealed any new studies of relevance for the conclusions.

3.2 The Before-and-After Study in Norway (Paper II)

A before-and-after study may be considered as the most reliable method for studying the effect of road lighting on accidents during darkness, provided that the numbers of accidents are large enough and that the effect of confounding factors is controlled.

Earlier before-and-after-studies of the effect of road lighting most often include a simple comparison of accidents before and after the installation without any control of other factors. In a meta-analysis by Elvik (1995) he concluded that 20 out of 29 before-and-after studies about the effect of road lighting were of low quality. Only three of the studies were considered to be of high quality. This may have created bias in the results. Research has shown that for most of the road safety works, the effect of other contributing factors has been of the same order as the real safety effect (Hauer and Persaud, 1983). If this is true also for road lighting installations, the effect of road lighting on accidents is overestimated in many of the earlier studies, and the conclusions from the literature study may be wrong.

A main objective of this Norwegian before-and-after study is to conduct a study that consider more adequately potentially confounding factors than most previous studies of the safety effect of road lighting.

The sample consists of 125 road sections with a total length of 247 km, and 1185 accidents are included. The safety effect of road lighting is estimated in terms of an odds ratio, where the odds of having an accident during darkness after the installation of road lighting is divided by the odds of having an accident during darkness before the installation of road lighting.

This is explained by the following example:

Number of accidents in hours of darkness before:	188
Number of accidents in daylight before:	375
Number of accidents in hours of darkness after:	155
Number of accidents in daylight after:	467

$$\text{Estimate of effect} = \frac{\left(\frac{155}{467}\right)}{\left(\frac{188}{375}\right)} = 0.662 = 34\ \%\ \text{accident reduction}$$

The odds ratios are converted to percentage changes in the number of accidents for ease of understanding. In this example, the effect is a 34 % reduction of the number of accidents.

Uncertainty is estimated by taking the log of the odds ratio, and 95 % confidence intervals are estimated. This is explained in Paper II, Section 2.2.

The effect of long-term trends, in particular trends regarding the distribution of accidents between daylight and darkness, is controlled by the use of a comparison group consisting of all other Norwegian main roads than the 125 study sections. In that case, the estimate of effect is the ratio of odds ratio. The results of the control, presented in Paper II, Chapter 3, show that long term trends have only a small influence on the estimates. The estimated overall safety effect of road lighting is not influenced.

The effect of “Regression to the mean” (RTM) is explained as follows: Accident counts vary by time and can be high or low in a given period due to random fluctuations. A randomly high or low accident count in one period will then tend to normalize in the next period. This is called “Regression to the mean”. If road lighting is installed at a road section because of a relatively high darkness accident rate it is likely that the accident rate will decrease after the installation of road lighting, due partly to the road lighting and partly to the RTM effect. A simple before-and-after comparison of accidents may then lead to biased conclusions. Road lighting may appear to be more effective than it actually is.

The effect of RTM is evaluated by employing the Empirical Bayes method. A normal number of darkness accidents is predicted by means of a multivariate accident prediction model for each kind of road section that has a certain set of values on the independent variables or background variables. However, a road section may differ from other apparently equal sections in other ways than by the independent variables. The expected number of accidents on a section is therefore estimated as a weighted sum of the normal number of accidents and the recorded number of accidents on the section. The method for this is described by Ragnøy, Christensen and Elvik (2002). The difference between the recorded number of accidents and the expected number of accidents show the expected RTM effect.

Expected numbers of injury accidents during darkness in the before period are evaluated for each of the 125 road sections, and mean values for the 125 sections are calculated for recorded numbers and expected numbers of injury accidents during darkness per road section per year. The results are shown in Table 4 below.

Table 4: Recorded and expected number of injury accidents in the before period

Mean number of injury accidents in darkness per section and year in the before period	
Recorded	Expected
0.1065	0.0975

In the before period, the recorded number is 9 % higher than the expected number. The estimated RTM effect is therefore 9 %.This effect must be controlled for in the estimation of the effect of road lighting on the 125 road section.

This rather small RTM effect indicates that high accident counts during darkness for some years are not widely used as a criterion for the installation of road lighting as safety treatment in Norway. The Norwegian Public Roads Administration confirms that high traffic volume is the main criterion for installation of road lighting even on existing roads. Some times the feeling of insecurity and demands from the road users are also considered and used as criterion.

Poor statistical validity due to small samples is a large problem in a before-and-after study of the safety effect of road lighting in Norway. The number of accidents is particularly low in some accident groups (e.g. pedestrian accidents or accidents in snow). This problem will persist as long as the year of installation of road lighting is not registered in the data bank or in any other register. As long as this information may be found only by chance, it is very difficult to select road sections that meet the criteria for the study. It is essential for road lighting studies in the future that the year of installation is registered.

3.3 The Cross-Section Study of Dutch Accidents (Paper III)

Besides the before-and-after study, another common method of studying the safety effect of road lighting is the cross-section study.

This study estimates the safety effect of road lighting on accidents during darkness on Dutch roads, using data from en interactive database containing 763,000 injury accidents and 3.3 million property damage accidents covering the period 1987 – 2006. Two estimators of effect are used, and the results are obtained by means of a combined effects model.

The first estimator is the odds ratio, defined as follows:

$$\text{Odds ratio} = \frac{\left(\dfrac{\text{Number of accidents in darkness on lit roads}}{\text{Number of accidents in daylight on lit roads}}\right)}{\left(\dfrac{\text{Number of accidents in darkness on unlit roads}}{\text{Number of accidents in daylight on unlit roads}}\right)}$$

As an example, an odds ratio of 0.7 means that the darkness to daylight accident ratio is 30 % smaller on lit roads than on unlit roads.

This odds ratio is based on the number of accidents only. It does not refer to any data regarding the distribution of traffic between daylight and darkness. This distribution may differ between lit and unlit roads, which could bias the odds ratio. In this study, the odds ratio is estimated for each hour of the day separately, in order to minimise the potential for bias. For the reason of statistical validity only hours that have at least 15 accidents in each of the four groups forming the odds ratio are used for analysis. This leaves only hour 7 (6:00 – 6:59), hour 8, and hours 18 – 22 for analysis. All other hours of the day are omitted.

Estimates referring to different hours have been combined by applying the log odds technique, which is described in Paper III, Section 2.3.

The second estimator of the safety effect used in the study is the ratio of odds ratios. It is based on a method developed by Johansson (2007) for assessing the accident risk associated with darkness. His idea is that by studying how the number of accidents in a specific hour of the day changes throughout the year, it is possible to eliminate most of the effects of confounding variables. Certain hours, such as the hours 8 and 18 when we are talking about The Netherlands, are in darkness part of the year but have full daylight in another part of the year. If the darkness contributes to more accidents, one would expect these hours to have more accidents in the part of the year when there is darkness than when there is daylight. An hour that has daylight the whole year is used as a comparison, to control seasonal variations in the number of accidents. An odds ratio is estimated, indicating the change in risk associated with darkness. In the study of Dutch accidents, similar estimates are made for lit and unlit roads, and a ratio of odds ratios is formed to estimate the effect of road lighting.

The method is further described and illustrated by figures in Appendix B. The figures show the “Johansson Method” of assessing the risk increase due to darkness by studying how the number of accidents in specific hours of the day changes throughout the year. A relative accident increase is seen during “the dark months of the year” (November – January) in the hours 8 and 18 compared to the control hours. One diagram shows the change in the accident risk associated with darkness on lit roads. Another diagram shows the change in the accident risk on unlit roads. An odds ratio is estimated for lit roads, based on the change of risk, and a corresponding odds ratio is estimated for unlit roads. The ratio of these odds ratios is the estimate of the effect of road lighting.

A log odds technique is applied to combine estimates of odds ratios and estimates of ratios of odds ratios, as explained in Paper III, Section 2.3.

A cross-section study is useful for estimation of the effect of road lighting only when information is available about road lighting related to accident data. The Netherlands is one of a few countries where this information is available. The Netherlands is also suited for such a study because of small geographic, topographic and climatic variations. The weather situation and the natural light situation should therefore be quite equal on lit roads and unlit roads.

In a cross-section study, the accident sample is large, except for some accident types or special weather conditions. Uncertainty due to small numbers of accidents is therefore not a great problem, as it is in a before-and-after study. Two of the most important confounding factors in a before-and-after study are also eliminated in a cross-section study: the effect of RTM and long-term trends in the number of accidents. On the other hand, there are other potential sources of error. One is the risk of endogeneity bias that may arise from a tendency to introduce road lighting as a safety measure on roads that have a higher-than-average proportion of accidents in darkness. As explained in Paper III, Section 4, this is unlikely to be the case in the Netherlands. Another possible source of error is that the distribution of traffic throughout the day may be systematically different on lit roads and unlit roads. This problem is minimised by the estimation of odds ratio for each hour of the day separately. Validity problems may also arise because of different road characteristics, driver characteristics, traffic conditions and weather conditions on lit roads and unlit roads. This is discussed in Paper III, Section 4, and it is concluded that such variables do not influence the results significantly. A lot of validity problems are avoided when night-time traffic is not included in the calculations.

A bias may also arise if accidents involving light poles are not controlled for. Such accidents occur on lit roads during all light conditions, and they do not affect the darkness/daylight ratio largely. However, the number of accidents involving light poles during daylight may be of an order that decreases the safety effect of road lighting significantly.

3.4 The Cross-Section Study of Motorway Accidents (Paper IV)

In this study, the effect of road lighting on motorway accidents is studied in detail. One purpose of the study is to contribute to the verification of three of the hypothesis in Section 2.2:

> Hypothesis 3: The safety effect of road lighting is the same on all types of roads (urban roads, rural roads and motorways).
>
> Hypothesis 5: The safety effect of road lighting is larger for single vehicle accidents than for accidents involving more than one vehicle.
>
> Hypothesis 6: The effect of road lighting is independent of weather conditions.

Another purpose is to evaluate the future benefit of road lighting, which includes a discussion of Hypothesis 10 in Section 2.3.

> Hypothesis 10: Road lighting on motorways may be replaced by more energy efficient visibility measures without reducing the road safety.

In this study, the odds ratio as defined in Section 3.3 is used as estimator of the effect of motorway lighting, and the main source of data is the same Dutch database as was used in the study of all Dutch roads. This database contains information about 23,600 injury accidents and 153,100 property damage accidents on Dutch motorways with speed limit 120 km/h in the period 1987 - 2006. In addition, British and Swedish accident data are used for comparison.

However, when only injury accidents are used to form the odds ratio and the odds ratio is estimated for one hour at the time, there is a problem of too small accidents samples on Dutch motorways. To counter this problem, four versions of odds ratio are applied. The versions differ in terms of the hours and accidents included, as shown below:

Version A: All hours, injury accidents

Version B: All hours, property damage and injury accidents

Version C: One hour at the time, injury accidents

Version D: One hour at the time, property damage and injury accidents

In Version A and Version B, the odds ratio is estimated for all hours of the day at the same time instead of separate estimates for one hour at the time (as in Version C and Version D). This increases the number of accidents serving as the basis for estimates, but it weakens the control of confounding factors. The most important potentially confounding factor is systematic differences between lit roads and unlit roads with respect to the distribution of traffic throughout the day.

In Version B and Version D, property damage accidents are included to increase the accident sample. This, however, may complicate the interpretation of study findings, because earlier studies have found that the effect of road lighting is smaller for property damage accidents than for injury accidents.

Version C (one hour at the time, injury accidents) is regarded as the best. It is used to estimate the effect of road lighting for large groups of accidents. Version D (one hour at the time, property damage and injury accidents) is applied for smaller groups of accidents (e.g. accidents in rain), where the number of injury accidents is too small to apply Version C. The problem of smaller effect on injury accidents is taken care of by adjusting the estimates by means of a factor that is deduced from a comparison between the results from Version C and the results from Version D in the largest groups of accidents.

Version A (all hours, injury accidents) is used for accident groups where the number of injury and property damage accidents is too small for Version D (e.g. all accident types in fog). The estimates are adjusted by applying a factor that is deduced by a comparison between the results from Version C and results from Version A in the largest groups of accidents. Version

A is also used to estimate the effect of road lighting on motorway accidents based on the Swedish and British data. The purpose is to roughly compare the estimated effects in Holland with effects estimated for other countries that are at equally high traffic safety level.

Version B (all hours, property damage and injury accidents) is used for accident groups where the number of injury and property damage accidents is too small for other methods.

The estimates of odds ratios for Version A to Version D are finally combined by applying the log odds technique, as explained under “Data and methods” in Paper IV.

4 Study Results

This chapter summarizes the results in the four studies: The literature study, the before-and after study in Norway, the cross section study of Dutch accidents and the cross-section study of motorway accidents.

The estimated effect of road lighting on accidents during darkness are presented for all roads in Section 4.1, for urban roads in Section 4.2, for rural roads during different conditions (weather and road surface conditions, category of road user, and accident type) in Section 4.3, and for motorways during different conditions in Section 4.4. More detailed results are presented in Paper I to Paper IV, appended to the thesis.

Section 4.5 shows some results regarding risk increase due to darkness on lit roads and unlit roads, found as a by-product in the study of accidents on rural Dutch roads when the ratio of odds ratio is used as estimator of effect.

4.1 Overall Effect of Road Lighting

The first study objective is to estimate the mean effect of modern road lighting on accidents during darkness. Three studies contribute with estimates and 95 % confidence intervals: the literature review, the before and after study in Norway and the cross-section study based on Dutch accident statistics.

Table 5: Estimated mean overall effect of road lighting during darkness

Accident group	Estimated mean effect (and 95 % confidence interval)		
	Literature review[2]	Before-and-after study in Norway	Cross-section study of Dutch accidents
Injury accidents in darkness	-30 % (-32 %, -25 %)	-28 % (-42 %, -8 %)[3]	-50 % (-53 %, -47 %)[4]
Fatal accidents in darkness	-60 % (-74 %, -50 %)	-53 % (-83 %, +32 %)[5]	-49 % (-57 %, -39 %)[6]
Injury accidents in twilight			-31 % (-36 %, -26 %)[6]

[2] The 95 % confidence intervals are from the meta analysis by Elvik (1995).
[3] Controlled for RTM
[4] Combined estimate of Odds Ratio and Ratio of Odds Ratio is used as estimator
[5] Not controlled for RTM
[6] Odds Ratio is used as estimator

In the before-and-after study in Norway, the effect of RTM is accounted for in the estimated effect on injury accidents but it is not accounted for in the estimated effect on fatal accidents. The influence of daylight collisions with light poles is not accounted for in the results, because it is quite small.

The overall effect of road lighting on injury accidents during darkness is larger in the cross-section study of Dutch accidents (-50 %) than in the literature review (-30 %) and in the before-and-after study in Norway (-28 %). The difference between the Dutch result and the other results is statistically significant. No reasons seem obvious for the large difference, and possible explanations are discussed in Chapter 5.

The effect of road lighting on fatal accidents during darkness is smaller in the Dutch study (-49 %) than in the literature (-60 %) and in the before-and-after study in Norway (-53 %). However, the estimate of the effect on fatal Dutch accidents is not comparable with the estimate of the effect on Dutch injury accidents. The odds ratio is applied as estimator for fatal accidents, while the combined estimate of odds ratio and ratios of odds ratio is applied as estimator for injury accidents. If only the odds ratio was applied as estimator for injury accidents, the estimated effect would be -46 % (se Table 2 in Paper III), which is slightly smaller than the effect on fatal accidents (-49 %). This means that the estimated effect on fatal accidents is slightly larger than the estimated effect on injury accidents in the Netherlands, while in earlier studies the effect on fatal accidents is about twice as large as the effect on injury accidents. No obvious reason is found for this disproportion.

During twilight, the estimated effect of road lighting on Dutch injury accidents is 2/3 of the effect during darkness, and the difference is statistically significant. The conclusion is that road lighting is an effective safety measure even during twilight conditions.

4.2 Effect of Road Lighting in Urban Areas

In the study of Dutch accidents, the effect of road lighting on injury accidents during darkness is much smaller in urban areas (-13 %) than in rural areas (-54 %). The difference is statistically significant, but the validity is doubted because only a small part of urban Dutch roads are unlit, and road and traffic characteristics are therefore probably quite different on unlit urban roads compared to most lit roads.

In the Norwegian before-and-after study the effect of road lighting on injury accidents during darkness is smallest (-15 %) when the speed limit is 40 – 50 km/h, larger (-20 %) at speed limits 60 – 70 km/h and largest (-49 %) at speed limit 80 – 90 km/h. The differences are not statistically significant.

In CIE Publication 93 (CIE,1992) ten studies on urban roads showed effects on injury accidents ranging from -9 % to -75 % with mean effect -29 %, while four studies on rural roads showed effects ranging from -13 % to -75 % with mean effect -36 %.

In a meta-analysis by Elvik (1995), the effect of road lighting on injury accidents was larger on urban roads (-32 %) than on rural roads (-20 %). Elvik (2004) updated the meta-analysis as part of an ongoing development of a Highway Safety Manual in the USA. In this work he has concluded about road lighting that “there is little variation in effects between various types of traffic environment (rural, urban, freeways)”.

Considering the total results no conclusions can be made about the general effect of road lighting on urban roads. However, it may be concluded from previous studies that the effect of road lighting on pedestrian accidents in urban areas is larger than the effect of all accidents in urban areas.

4.3 Effect of Road Lighting during Varying Conditions on Rural Roads

Table 6 shows estimated effect of road lighting on injury accidents during darkness on rural roads based on the cross-section study of Dutch accidents. Neither the literature review nor the study of Norwegian accidents gives any useful contribution to estimates of the effect in rural areas separately. Effects on accident on rural motorways are treated in Section 4.4.

Table 6: Estimated mean effect of road lighting on injury accidents in darkness during different conditions on rural Dutch roads

Conditions		Effect	95 % conf.
All		-54 %	-56 %, -52 %
Weather conditions	Fine weather	-54 %	-56 %, -52 %
	Rainy weather	-45 %	-53 %, -37 %
	Foggy conditions	0 %	-15 %, +18 %
	Snowy weather	-26 %	-40 %, +8 %
Road surface conditions	Dry road surface	-56 %	-59 %, -54 %
	Wet road surface	-46 %	-50 %, -43 %
	Snow / ice covered	-22 %	-31 %, -11 %
Road user	Pedestrian	-70 %	-77 %, -61 %
	Bicycle	-60 %	-65 %, -54 %
	Moped	-61 %	-64 %, -56 %
	MC	-26 %	-42 %, -5 %
	Automobile	-50 %	-52 %, -47 %
Accident type	Hit fixed object	-54 %	-58 %, -49 %
	Frontal collisions	-50 %	-55 %, -43 %
	Flank collisions	-46 %	-51 %, -41 %
	Hit animal	-57 %	-63 %, -50 %
	Rear end collisions	-51 %	-54 %, -46 %

The mean effect of road lighting on rural Dutch roads is a 54 % reduction in injury accident during darkness. The accident reduction is larger on rural Dutch roads (54 %) than on all Dutch roads (50 %).

This cross-section study is useful for the estimation of the effects of road lighting during different conditions because the number of accidents is large enough for grouping. Compared to earlier studies, the estimated safety effects are larger in the Dutch study than in most of the earlier studies, and this may indicate that the effects of some unknown reasons are overestimated. Possible reasons for this are further discussed in Chapter 5. However, even if the effects were systematically overestimated in the study of Dutch accidents, it would probably not largely influence the differences between estimates during different conditions.

No studies are found in the literature regarding effect of road lighting during different conditions. Only the before-and-after study in Norway (Paper II) gives some information about this, but the study includes urban roads and the results are not quite representative for rural roads. Another problem with the Norwegian study is the small accident sample, which makes the results quite uncertain when it comes to accident groups related to different conditions.

Table 6 shows that the effect of road lighting is smaller during rain (-45 %) than during fine weather (-54 %) and smaller on wet road surfaces (-46 %) than on dry road surfaces (-56 %). The effect during snowy conditions (-26 %) is smaller than the effect during rain (-45 %) and the effect on snow or ice covered road surfaces (-22 %) is smaller than the effect on wet surfaces (-46 %). Most of the differences are statistically significant. During foggy conditions there is found no effect of road lighting; however, there are found some indications of accident reduction during foggy conditions in daylight that may be due to guidance from light poles. This is commented in Paper III.

Table 6 also shows other interesting results. The estimated effect of road lighting is larger for pedestrian accidents (-70 %), bicycle accidents (-60 %) and moped accidents (-61 %) than for automobile accidents (-50 %). The effect on motorcycle accidents (-26 %), however, is lower than the effect on automobile accidents. The differences are statistically significant.

When looking at the different accident types (frontal collisions etc.), there is little variation in the effect of road lighting on accidents during darkness. However, if accidents during daylight are included, the effect of road lighting on accident during 24 hours is probably reduced for the accident type “Hit fixed objects” due to collisions with light poles.

4.4 Effect of Road Lighting on Motorway Accidents

The literature review (Paper I) shows that the mean effect of motorway lighting on injury accidents during darkness is about -50 %, and the results from several studies are quite consistent. In the before-and-after study in Norway the effect on motorway accidents is -31 %, but the number of accidents is small and the validity is low.

The results from the study of Dutch motorway accidents are presented in Table 7 below, and a more detailed description of the process of combining the estimates obtained by Version A to Version D can be seen in Paper IV.

The estimated mean effect of road lighting on all injury accidents during darkness is -49 % and the 95 % confidence interval is narrow [-50 %, -48 %].

The effect during rain (-32 %) and during snowy conditions (-33 %) is smaller than the effect during fine weather (-54 %). Likewise the effect on wet road surfaces (-36 %) and on snow or ice covered surfaces is smaller than the effect on dry road surfaces (-56 %). The differences are statistically significant.

During foggy conditions there is found no overall effect of road lighting (-1 %) during darkness. For “Rear end collision” there is even found a small accident increase (+10 %). This accident increase may be due to higher speed on lit roads than on unlit roads during fog. However, it may also be due to an underestimation of the effect.

Table 7: Estimated mean effect of road lighting on injury accidents in darkness during different conditions on rural Dutch motorways

Climatic conditions	Accident type[7]	Combined effects	
		Mean	95 % conf.
All	Single vehicle acc.	-55 %	-56 %, -53 %
	Rear end collision	-44 %	-45 %, -41 %
	Others	-54 %	-56 %, -52 %
	All	**-49 %**	-50 %, -48 %
Fine weather	Single vehicle acc.	-59 %	-60 %, -57 %
	Rear end collision	-50 %	-52 %, -48 %
	Others	-58 %	-60 %, -56 %
	All	**-54 %**	-55 %, -53 %
Rain	Single vehicle acc.	-47 %	-50 %, -43 %
	Rear end collision	-23 %	-29 %, -16 %
	Others	-37 %	-43 %, -30 %
	All	**-32 %**	-35 %, -29 %
Fog	Single vehicle acc.	-32 %	-47 %, -13 %
	Rear end collision	10 %	-12 %, +38 %
	Others	-24 %	-46 %, -7 %
	All	**-1 %**	-14 %, +14 %
Snowing	Single vehicle acc.	-50 %	-56 %, -43 %
	Rear end collision	-5 %	-31 %, +31 %
	Others	-16 %	-39 %, +15 %
	All	**-33 %**	-40 %, -25 %
Dry road surface	Single vehicle acc.	-58 %	-59 %, -56 %
	Rear end collision	-53 %	-56 %, - 51 %
	Others	-60 %	-62 %, -58 %
	All	**-56 %**	-57 %, -55 %
Wet road surface	Single vehicle acc.	-50 %	-52 %, -48 %
	Rear end collision	-25 %	-29 %, -21 %
	Others	-41 %	-46 %, -37 %
	All	**-36 %**	-38 %, -34 %
Snow or ice covered road surface	Single vehicle acc.	-50 %	-55 %, -45 %
	Rear end collision	-14 %	-35 %, +13 %
	Others	-16 %	-37 %, +11 %
	All	**-33 %**	-39 %, -26 %

The estimated effect of road lighting is larger for “Single vehicle accident” (-55 %) than for “Rear end collisions” (-44 %) during all weather conditions. The difference is especially large during adverse weather. For rear end collisions the effect is especially small during rain (-23 %), during snow (-5 %), during fog (+10 %), on wet road surfaces (-25 %) and on snow covered road surfaces (-14 %).

[7] The accident type “Single vehicle accident” includes the accident type “Hit fixed object” which in the Dutch accident statistics means accident where a vehicle hits a fixed object outside the road

The estimated effects on Dutch motorways are much in line with the effects found on all Dutch accidents in Section 4.3. However, the differences between effects during fine weather and effects during adverse weather conditions are larger on motorways than on other roads.

The effects of road lighting on Swedish and British motorway accidents are only roughly estimated. The results are presented in Paper IV, and they show that the effect of motorway lighting is significantly smaller in Sweden and Great Britain than in the Netherlands. For motorways as well as for the entire road network, the safety effect of road lighting is larger in the Netherlands than in other western countries. The reasons for this are not obvious and the subject is thoroughly discussed in Chapter 5.

On Swedish motorways no effect of road lighting is found on accidents during snowing, and on Swedish and British motorways there is found almost no effect of road lighting on snow or ice covered road surfaces. As a whole, the results from Swedish and British motorways confirm the results from Dutch motorways with respect to the differences of the safety effect during the changing weather and road surface conditions.

4.5 Risk Increase due to Darkness on Lit and Unlit Rural Dutch Roads

In the study of Dutch injury accidents (Paper III), the accident risk increase due to darkness is estimated for lit and unlit rural Dutch roads. These results are some kind of by-product when the ratio of odds ratio is used as estimator of the effect of road lighting. Nevertheless, the results contribute to make a better picture of the role of road lighting is an accident countermeasure. If looking at figure 1 in Section 1.2, the estimated risk increase found in the study of Dutch accidents represents the darkness factor. Other risk factors associated with night-time driving are more or less excluded.

The main results are listed below (results for several other accident groups are found in Paper III, Table 5):

1. The average accident risk increase due to darkness is 17 % [11 %, 22 %] on lit rural roads and 145 % [124 %, 167 %] on unlit rural roads.

2. The average accident risk increase due to darkness in rain is 53 % [36 %, 73 %] on lit rural roads and 192 % [128 %, 275 %] on unlit rural roads.

3. For pedestrian accidents the average accident risk increase due to darkness is 141 % [76 %, 230 %] on lit rural roads and 361 % [165 %, 700 %] on unlit rural roads.

The results in this study are much in line with the results from earlier studies mentioned in Section 1.2. However, earlier studies like the studies by Sullivan and Flannagan (1999; 2002; 2003; 2007) did not estimate risks for lit roads and unlit roads separately.

5 Discussion

The results from the four studies largely confirm that the “old knowledge” about the effect of road lighting on accidents during darkness is still valid in modern road traffic. However, there are some unexpected results in the studies and some possible validity problems that must be discussed.

5.1 Is the Effect of Road Lighting really that large in the Netherlands?

The estimated effects of road lighting found in the studies of Dutch accidents (Chapter 4) are much larger than the mean effects found in the Norwegian before-and after study and in other studies. It is therefore necessary to discuss some possible reasons for this. At least five hypotheses may be considered:

1. Dutch road lighting is more effective than road lighting in most other western countries.

   This is not an unreasonable assumption, considering the fact that the Dutch have possessed a dominating role within international road lighting organisations like CIE through many years. Both road authorities and road lighting companies like Philips have participated a great deal in research and development. The safety effect of road lighting has been focused on for many years within CIE Division 4, Lighting for Signalling and Transport. It is therefore likely that the quality of Dutch road lighting is good and that this causes the safety effect to be good. It is also a fact that the road lighting level has been lower in the US standards than in the European standards. This may have led to lower effect on accidents in the USA than in Europe. A large part of earlier studies are from the USA and this may have contributed to lower mean effect in earlier studies.

   The large difference between the effects found on Dutch motorways and the effects found on Swedish and British motorways may partly be explained by different road lighting quality, but it is not likely that this explains the whole difference.

2. The results from the before-and-after study in Norway are uncertain and the real effect is larger.

   The results are uncertain but it is not likely that the true mean effect in Norway is as large as the mean effect found in the Dutch study.

3. The result from the literature study is based on old studies and the effect is larger today.

   This may be true, but it is also likely that the effect found in earlier studies is overestimated due to lack of control for the RTM effect.

4. The effect in the Netherlands is overestimated due to bias in the accident data.

   Accidents during daylight on unlit roads or accident during darkness on lit roads could be underreported. Bias could also arise if accidents on unlit roads and accidents on lit roads were unequally classified according to daylight and darkness, possibly influenced by the lit road lighting installation. None of these explanations are likely to be essential.

5. The effect in the Netherlands is overestimated due to methodological errors.

   This may be true. Some possible sources of error are discussed below.

One possible source of error in the study of Dutch accidents is the lack of control for accidents involving light poles during daylight. If collisions with light poles increase the total number of daylight accidents on lit roads, the estimated effect of road lighting on darkness accidents will be too high. Accident data for Dutch roads show that light poles are hit in 2.2 % of daylight accidents on lit roads. In 1.5 % of the accidents light poles are hit without any involvement of other vehicles, while in 0.7 % of the accidents light poles are hit in a frontal or lateral or rear end collision. In all these accidents, however, the vehicle was out of control before the light pole was hit. If the light poles were not there, the vehicle would in most cases have hit another object, or something else would have happened that lead to some degree of injury. In some cases no persons would have been injured in the absence of the light poles. There may also be cases where light poles are hit without causing any injury. Some light poles are yielding and will gently stop a car and perhaps prevent a more serious accident from happening. Summing up, the increase in daylight accidents due to light poles is probably not more than 1 % and hence has little influence on the calculated effect of road lighting on accidents during darkness. Moreover, the error made by not considering collisions with light poles is probably of the same order in other studies of the effect of road lighting as in this study.

Another possible source of error in the results may be that road and traffic conditions (others than road lighting) are different on lit roads and unlit roads, causing a smaller share of darkness accidents on lit roads than on unlit roads. Dutch road authorities have informed the author that the main criterion for prioritising road lighting is traffic volume. It is therefore likely that lit roads in general have higher traffic volumes and probably also higher standard than unlit roads. Based on this, a supposition may be that a higher standard leads to a lower share of accidents during darkness. Higher quality of road markings and delineators on high traffic roads may be a factor that supports the hypothesis. However, the problem of glare from oncoming vehicles is larger on high traffic roads than on low traffic roads, and this rather important factor weigh against the supposition. Another possible explanation that may support the hypothesis is that a higher maintenance standard on high traffic roads causes a lower darkness/daylight accident ratio. However, the low effects of road lighting that are found during snow and on snow or ice covered surface indicate that it is not true. All in all it seems not probable that a higher standard on lit roads compared to unlit roads contributes to the large estimated effect of road lighting in the study of Dutch accidents.

The main conclusion from the discussion in this section is that there is found no indication of large methodological errors. The only reason that is found for the effect of road lighting to be particularly large in the Netherlands is that the quality of road lighting might be particularly high in this country

5.2 Does the Safety Effect of Motorway Lighting really vary that much Between Countries?

Another quite similar subject to discuss is the large safety effect of road lighting found on Dutch motorways compared with the much smaller effect found on Swedish and British motorways. A look for Dutch extremities or particularities related to road or traffic conditions on motorways may possibly give some useful information.

The information in Table 8 is found in the report from the Sunflower project, a comparative study of the development of road safety in Sweden, Great Britain, and the Netherlands (Koornstra et al., 2002). Dutch extremities are not seen in these data. On the contrary, there is a lot of similarity between Great Britain and the Netherlands, and the Netherlands is positioned between Sweden and Great Britain both in average traffic density and in fatality rate on motorways. No cause is found in Table 8 for the safety effect of road lighting to be larger in the Netherlands than in Great Britain and Sweden.

Table 8: Some motorway related data from Sweden, Great Britain and the Netherlands, from the Sunflower report (Koornstra et al., 2002)

Data for motorways 2000	Sweden	Great Britain	The Netherlands
Length	1,510 km	3,465 km	2,275 km
Fatalities	24	189	116
Vehicle kilometres, in billon	9.6	94.1	51.2
Average AADT	17,418 vehicles	67,252 vehicles	61,617 vehicles
Fatality rate per vehicle km	2.50	2.01	2.27
Speed limit	110 km/h	112.6 km/h	120 km/h
Average actual speed	115 km/h	113 km/h	114 km/h

Some other information about accidents related to light conditions on motorways in the Netherlands, Great Britain, Sweden and Norway are shown in table 9.

Table 9: Distribution of motorway injury accidents over light condition in some countries

Country	Lit roads			Unlit roads		
	Daylight	Twilight	Darkness	Daylight	Twilight	Darkness
The Netherlands	70 %	6 %	24 %	51 %	7 %	42 %
Great Britain[8]	74 %	-	26 %	66 %	-	34 %
Sweden	60 %	8 %	33 %	51 %	9 %	40 %
Norway	64 %	6 %	30 %	-	-	-

In the Netherlands, the share of accidents in darkness is especially low on lit motorways and especially high on unlit motorways, compared with the other countries. The difference between lit and unlit roads is larger in the Netherlands than in Great Britain and Sweden. This

[8] Twilight is not used for classification of light condition in Great Britain. Darkness is defined as the time period from half an hour after sunset to half an hour before sunrise. Twilight conditions in fine weather are typically classified as darkness, and twilight conditions in cloudy weather are typically classified as daylight.

causes the larger estimated effect of road lighting in the Netherlands than in Great Britain and Sweden. All motorways are lit in Norway, and on lit motorways Norway and Sweden have a larger share of accidents in darkness than have the Netherlands and Great Britain, probably due to geographic and climatic conditions (dark, wet, slippery winter conditions, partly in rush hours).

When comparing motorway accidents in the neighbouring countries Norway and Sweden, where the climatic conditions and other conditions are not very different, the main conclusion is:

> The share of accidents occurring during darkness is significantly larger on unlit Swedish motorways than on lit Swedish and Norwegian motorways. This indicates that road lighting effectively reduces accidents during darkness.

However, no reason is found in Table 9 for a larger safety effect of motorway lighting in the Netherlands than in Great Britain and Sweden.

Table 10 shows the percentage distribution of Swedish, British and Dutch motorway accidents over climatic conditions and light conditions. Again, the British and Dutch data are very much alike, except for some more accidents on snow or ice covered surfaces in the Netherlands.

Table 10: Percentage distribution of Swedish, British and Dutch motorway accidents over climatic conditions and light conditions

Climatic conditions	Sweden				Great Britain				The Netherlands			
	Daylight		Darkness		Daylight		Darkness		Daylight		Darkness	
	Lit	Unlit	Lit	Unlit	Lit	Unlit	Lit	Unlit	Lit	Unlit	Lit	Unlit
All	100	100	100	100	100	100	100	100	100	100	100	100
Fine	80	74	59	63					82	78	76	76
Rain	12	13	17	13					15	15	20	17
Fog	1	2	6	6					2	4	2	3
Snow	6	9	17	16					1	2	2	4
Dry surface	57	53	28	34	72	72	53	53	71	69	52	56
Wet	27	26	41	32	27	27	45	44	27	28	43	38
Snow/ice	15	20	31	34	1	1	2	3	2	3	4	6

A relatively large share of accidents during rain in darkness on lit roads is found on Swedish motorways as well as on Dutch motorways. This subject is further discussed in Section 5.3.

Swedish motorways also have a large share of accidents in snow and on snow covered surfaces compared with Dutch and British motorways. If it is true that the safety effect of road lighting is small during these conditions (found in the studies), this may partly explain why the effect of road lighting is smaller on Swedish motorways than on Dutch motorways. However it does not explain why the effect is smaller on British motorways.

Beside these differences in climatic conditions, no other “extremity” is seen in the Dutch data in this section that may have caused the large safety effect of road lighting. The most likely conclusion is that the safety effect of road lighting really is larger in the Netherlands than in Sweden and Great Britain. Earlier studies showed about the same effect of motorway lighting (about -50 %) as was found in the Dutch study (-49 %). This may indicate that the Dutch effect is “normal”, and the Swedish and the British effects are unusually small. Future studies are needed for more certain conclusions about the effect of motorway lighting.

5.3 Is the Effects during Adverse Weather really that low?

Estimates of safety effect of road lighting on rural Dutch roads (Table 6), on Dutch motorways (Table 7), on Swedish motorways (Paper IV, Table 8) and on British motorways (Paper IV, Table 9) are lower during rain and snow and fog, than during fine weather and lower on wet and snow or ice covered road surfaces than on dry surfaces. Two questions must be discussed:

1. Are the low estimates during rain and on wet surfaces caused by some confounding factors?

   The answer is: probably not. No such factors are found through the discussion in Section 5.1 and Section 5.2. The effects found on Dutch motorways indicate that the phenomenon is not only related to a comparison between small unlit roads and larger lit roads. Moreover, the effects found on Swedish and British motorways confirm that it is not related to Dutch accidents only. The large share of accidents in rain and on wet road surfaces during darkness on lit roads, shown in Table 10, explains the small effects of road lighting in rain and on wet surfaces. Obviously road lighting is an insufficient visibility measure during darkness in rain and on wet road surfaces.

2. Are the lower safety effects in rain and on wet road surfaces reasonable and explainable?

   The answer is yes. Though road lighting generally improves the visibility and makes most driving tasks easier in darkness during all kind of weather conditions, some visibility problems are less effectively reduced by road lighting in rain and on wet road surfaces. One such problem is the visibility of pedestrians. Wet road surfaces tend to provide less uniform luminance (as seen in the picture on the front page of the thesis). Some areas are very bright and glaring, while other areas are very dark. Areas are very bright where the light from oncoming vehicles, road lighting luminaires or other light sources are reflected from a mirroring road surface into the eyes of the driver. Disability glare is known to reduce contrasts and make object less visible. The very dark areas are problematic because they provide a low contrast as background for dark pedestrians. Another problem is that direct or reflected light from vehicle headlights, luminaries or other light sources is scattered when passing through a wet or dirty windscreen and by this the vision may be badly impaired.

6 Conclusions

Based on the study results presented in Chapter 4 and the discussion in Chapter 5, the conclusions about the effect of road lighting are summarised in this chapter. The summary includes the conclusions related to 9 of the 10 hypotheses presented in Chapter 2. Hypothesis 10 is discussed in Chapter 10 and a conclusion is made at the end of the chapter.

1. The mean effect of modern road lighting on today's traffic is about 30 % reduction in injury accidents during darkness. The study of Dutch accidents indicates that the effect may be larger if the road lighting installation is well designed.

   The estimated mean effect of road lighting during darkness on all Dutch roads is a 50 % reduction in injury accidents. No other reason is found for the large effect in the Netherlands than high quality of the road lighting. However, the large difference between the effect found on Dutch roads (-50 %) and the mean effect found in the literature (-30 %) and on Norwegian roads (-28 %) give reason to suspect that the Dutch effect is too large.

   Hypothesis 1 "*Modern* r*oad lighting reduces the number of injury accidents during darkness by about 30 %*" is verified.

   This conclusion strengthens the belief on road lighting as an effective safety measure.

2. The effect of road lighting is larger for fatal accidents than for injury accidents and smaller for property damage accidents than for injury accidents. However the differences seem to be smaller than is known from earlier studies. In the study of Dutch accidents, the estimated effect of road lighting is only slightly larger for fatal accidents than for injury accidents and slightly smaller for property damage accidents than for injury accidents.

   Hypothesis 2 "*The effect of road lighting is larger for fatal accidents than for injury accidents and smaller for Property Damage Only (PDO) accidents than for injury accidents*" is not fully supported by the Dutch results.

3. On Dutch roads the effect of road lighting during twilight is found to be 2/3 of the effect during darkness.

This indicates that road lighting should not be switched off too early in the morning when people are on their way to school or work.

4. The effect of road lighting on motorways seems to vary very much from country to country. The estimated effect on injury accidents during darkness is -49 % on Dutch motorways. This is in good accordance with earlier studies, e.g. the study by Bruneau (2001). However, estimates of effects on Swedish and British motorways are much smaller (Estimated effect based on odds ratio Version A is -30 % for Swedish motorways, -31 % for British motorways, and -58 % for Dutch motorways).

   In earlier studies (Paper I), the mean effect of road lighting during darkness is larger on motorways (50 %) than on all roads (-30 %). In The Netherlands, however, the estimated effect of road lighting on injury accidents during darkness is slightly smaller on motorways (-49 %) than on all rural roads (-54 %). The effect of road lighting in Dutch urban areas is uncertain, but it is probably smaller than in rural areas because the estimated effect is smaller on all Dutch roads (-50 %) than on Dutch rural roads (-54 %).

   Hypothesis 3 "*The safety effect of road lighting is the same for all types of roads*" is not fully verified.

   More studies are needed to see how the effect of road lighting varies from country to country and why it varies.

5. The safety effect of road lighting is larger for pedestrian accidents than for other accidents.

   In earlier studies the effect on injury accidents during darkness was about -45 % for pedestrian accidents and about -30 % for all accidents. In the study of Dutch accidents the estimated effect on injury accidents during darkness is -70 % for pedestrian accidents in rural areas and -54 % for all accidents in rural areas.

   The main reason for the large effect on pedestrian accidents is probably that the visibility of pedestrians is low during darkness on unlit roads. The contrast between a dark pedestrian and a dark background is low.

Hypothesis 4 "*The effect of road lighting is larger for pedestrian accidents than for other accidents*" is verified.

6. On Dutch motorways, the estimated effect of road lighting is larger for single vehicle accidents (-55 %) than for rear end collisions (-44 %). The effect on rear end collisions is especially low during adverse weather conditions. However, collisions with light poles represent a considerable problem during daylight and twilight as well as during darkness. Such accidents tend to increase the total number of accidents and to reduce the effect of road lighting, especially the effect on single vehicle accidents.

   The results support hypothesis 5: "*The safety effect of road lighting is larger for single vehicle accidents than for accidents involving more than one vehicle*" as long as collisions with light poles do not reduce the effect on single vehicle accidents too much.

7. Road lighting is less effective as a safety measure during adverse weather (when the risk is highest) than during fine weather.

   In the study of accidents on Dutch rural roads the estimated effect on injury accidents during darkness is smaller in rain (-45 %) and snow (-26 %) and fog (0 %) than in fine weather (-54 %) and smaller on wet road surfaces (-46 %) and on snow or ice covered surfaces (-22 %) than on dry surfaces (-56 %)

   In the study of Dutch motorway accidents the tendency is the same. The estimated effect on injury accidents during darkness is smaller in rain (-32 %) and snow (-33 %) than in fine weather (-54 %) and smaller on wet road surfaces (-36 %) and on snow or ice covered surfaces (-33 %) than on dry surfaces (-56 %). The estimated effect is especially small for rear end collisions during adverse weather conditions.

   The main reason for the reduced effect during adverse weather conditions is probably problems related to reflected light from the road surface and scattered light from wet and dirty windscreens.

   Hypothesis 6 "*The effect of road lighting is independent of weather conditions*" is falsified.

The low effect of road lighting during adverse weather is a problem that must be considered. How may the problem be reduced? How should the problem be treated in adaptive road lighting systems?

8. During fog no safety effect is found during darkness neither on all Dutch roads (0 %) nor on Dutch motorways (-1 %). However, there are indications on a daylight safety effect during foggy conditions due to guidance from light poles. If this is the case, the darkness safety effect of road lighting during fog is also underestimated because of the influence of daylight accidents on the odds ratio. Nevertheless, the influence of road lighting on safety during fog seems to be small.

   The small effect of road lighting during fog, found in the Dutch study, is natural. During dense fog, the visibility distance is limited by the fog and not by the light level. Road lighting only increases the short range road surface luminance and makes the road look brighter without increasing the long range visibility.

9. The Norwegian before and after study as well as the study of Dutch accidents indicate that the effect of road lighting is larger at high speed limits than at low speed limits.

   Hypothesis 7 "*The effect of road lighting on accidents is increasing with increasing speed level*" is supported, but the results are uncertain.

10. The Norwegian before-and-after study indicates that the effect of road lighting is smaller when the traffic volume (AADT) is higher than 8000 vehicles than when the traffic volume is lower than 8000 vehicles. The study of Dutch accidents gives no information about traffic volumes.

    As explained in Section 2.2 it seems probable that the need for road lighting becomes smaller when the traffic density is increasing, because the vehicles illuminate the road and roadsides and any objects on and near the road. Moreover, the contribution from a road lighting installation becomes smaller when the traffic load increases.

    Hypothesis 8 "*The effect of road lighting on accidents is smaller at high traffic volumes than at low traffic volumes*" is supported.

Further studies are needed to verify the hypothesis. The knowledge about this is essential in adaptive road lighting.

11. The estimated effect of road lighting on accidents during darkness on Dutch rural roads is the same for older drivers as for all drivers. However, the result may be influenced by low exposure during darkness on unlit roads.

    Hypothesis 9 "*The effect of road lighting on accidents during darkness is larger for older drivers than for younger drivers*" is not verified.

12. Collisions with light poles are a considerable safety problem on some lit roads, especially on motorways. The safety effect of road lighting may to some extent be reduced by the increased number of accidents caused by light poles.

7 Benefit – Cost Ratio of Road Lighting

Cost – effectiveness and benefit – cost ratio of road lighting are not treated in the four papers. However, it may be useful to discuss this matter before the discussion of the future role of road lighting in Chapter 8.

When the effect of road lighting on accidents is known, a cost-effectiveness analysis may be performed. The cost – effectiveness analysis estimates the ratio between the number of accidents prevented and the cost of a road lighting installation, including investment and operation/maintenance costs. No monetary valuation of benefits is required and such analysis may be useful for

- ranking of road lighting projects
- ranking of road lighting investments relative to other kinds of safety measures

However, some problems may arise when comparing projects or measures where the severity of prevented accidents is unequal or when the duration of the investments is unequal. Problems will also arise when other benefits than accident reduction are considerable and are unequally affected. In such cases, a benefit – cost analysis is more useful. When benefit – cost analyses are used for ranking of road lighting projects and ranking of road lighting against other safety measures, the problems mentioned above are solved by performing a monetary comparison.

Benefit – cost analysis estimates the ratio between the benefits to society, stated in monetary terms, and the total costs. Such analyses are useful for:

- assessment of the profitability of certain road lighting investments (certain lighting system and certain equipments)
- assessment of the lowest average annual daily traffic volume (AADT) where road lighting investments are profitable

A benefit – cost analysis is conceptually a more complicated method than a cost-effectiveness analysis, but a simplified version may be nearly as easy to perform as a cost – effectiveness analysis.

The use of benefit – cost calculations for road lighting installations is further discussed below, and motorway lighting is used in an example.

7.1 Benefit

The main purpose and main benefit of road lighting is accident reduction, at least in rural areas. This benefit may be expressed in monetary value as the product of two factors

1. the expected future accident costs during darkness without road lighting

2. the estimated effect of road lighting on accident costs

The expected future accident costs during darkness without road lighting depend on the expected number of accidents, the distribution of accidents related to the degree of injury, and the society's valuation of accident reduction.

Unfortunately, there is no common international standardised method of valuation of accidents or reduction of accidents, and the value of reduced accidents varies from country to country if such a valuation is assessed at all. In a report on barriers against the use of efficiency assessments Elvik and Veistein (2005) show how countries in Southern and Central Europe have strong institutional barriers against the use of efficiency assessments and lack the tools for using such methods, while countries in Northern Europe have the main barrier in the implementation phase due to political opportunism and conflicts of interest.

In Norway, benefit – cost assessments are commonly used for large road investments and they are increasingly used for smaller road safety investments. The value of avoiding accidents is assessed as the total of society's costs and personal loss of welfare. When all non reported accidents and all material damages are included, the accident cost per reported injury accident in Norwegian road traffic is 500,000 Euros in 2007. The costs consist of material costs (22 %), medical treatment costs (4 %), administrative costs (10 %), loss of production (16 %), and loss of welfare (49 %) based on individual willingness to pay to reduce risk. Mean accident costs are assessed for individual injuries, where the cost of a fatality (3.72 mill €) is 33 times higher than the cost of a slight injury (112,000 €). Mean accident costs are also assessed for different accident types at different speed limits, and mean accident costs are assessed per million vehicles per kilometre for different types of roads and per million approaching vehicle for different types of junctions.

Other types of benefit from road lighting are

- better comfort and feeling of safety for all road users during the dark hours
- increased mobility due to improved feeling of safety
- reduced crime risk during darkness
- increased driver speed during darkness (gives the advantage of reduced travel time and the disadvantage of increased emission of CO_2 and noise)

A study by Assum et al. (1999) showed that the average speed during darkness increased by 5 % on straight road sections and 0.7 % on the curved parts of the roads due to road lighting. According to the Power Model by Nilsson (2004), later evaluated by Elvik et al.(2004), a 5 % increase in speed should lead to a 7.6 % increase in injury accidents and a 19.2 % increase in fatal accidents. But obviously this risk increase due to higher speed is outweighed by the accident reducing effect of road lighting. If the speed on straight sections increases due to road lighting, the travel-time-costs are reduced. However, on high speed roads an increased speed also leads to the disadvantage of increased fuel consumption, increased emission of CO_2 and increased noise.

Until now, reduced accident costs are the only benefit of road lighting that is normally included in calculations. Increased comfort, feeling of safety and reduced crime risk are not easy to calculate in monetary value, and those factors are normally not included in benefit-to-cost calculations. Neither is benefit or disadvantage of increased speed usually included in the calculations, but some times it is included as part of the travel costs. Global environmental consequences of road traffic are not much considered until now but it will probably be included in future benefit – cost calculations.

The studies presented in the four papers show estimated accident reduction due to road lighting during different conditions. However, in benefit – cost calculations the benefit must be transformed from per cent accident reduction into monetary value depending on both currency and valuation of avoided accidents. In an example presented below, benefit – cost calculation of a road lighting installation is carried out for a typical Norwegian four-lane motorway with a speed limit of 100 km/h. Euro is used as currency and the official Norwegian valuation of road accidents is used for the estimation of benefit.

<u>Example</u> (supposed to describe a typical Norwegian motorway situation):

AADT = 20,000 vehicles. The accident rate through the last ten years has been 0.07 injury accidents per million vehicles per km. 64 % of the injury accidents occurred during daylight, 6 % occurred during twilight and 30 % occurred during darkness.

The annual number of accidents per km road section has been:
$N = 0.07 \times 20{,}000 \times 365 \times 10^{-6} = 0.50$.

The annual number of accidents per km during twilight has been:
$N_{twilight} = 0.50 \times 0.06 = 0.03$.

The annual number of accidents per km during darkness has been:
$N_{darkness} = 0.50 \times 0.30 = 0.15$.

On lit Norwegian motorways 1996 – 2005, "Run off the road" accidents represented 53 % of twilight accidents and 55 % of darkness accidents. "Rear and collisions" represented 23 % of twilight accidents and 22 % of darkness accidents. Other accidents represented 24 % of twilight accidents and 23 % of darkness accidents. Using the same percentage distribution of accidents in the example as is shown above for all lit Norwegian motorways, the annual number of accidents in the example (1 km motorway with speed limit 100 km/h and AADT = 20,000 vehicles) is:

Number of "Run off the road" accidents during twilight:	0.03 x 0.53 = 0.0159
Number of Rear end collisions" during twilight:	0.03 x 0.23 = 0.0069
Number of other accidents during twilight:	0.03 x 0.24 = 0.0072
Number of "Run off the road" accidents during darkness:	0.15 x 0.55 = 0.0825
Number of "Rear end collisions" during darkness:	0.15 x 0.22 = 0.0330
<u>Number of other accident types during darkness:</u>	<u>0.15 x 0.23 = 0.0345</u>
Total number of accidents during twilight and darkness:	0.1800

However, the accident rate is expected to be lower on modern lit Norwegian motorways in the near future than it has been on a typical Norwegian motorway through the last ten years. “Run off the road” accidents are to a large degree reduced due to “forgiving” roadsides, installations and constructions. Nearly no frontal collisions will occur because of guard rails in the median. Nearly no pedestrians will be injured during darkness or twilight because the drivers will use reflective vests when leaving the car on a motorway. Nearly no accidents involving animals will occur because of continuous fences. Rear end collisions will be reduced when automobiles are equipped with distance control, but this is not supposed to be commonly used in the near future. Based on this expected development and on the safety effects assessed in the effect catalogue for the topical safety measures, the author anticipates the following risk reductions in twilight and darkness on future Norwegian motorways compared to Norwegian motorways through the last ten years:

“Run off the road” accidents:	40 % risk reduction
Rear end accidents:	No risk reduction
Other accidents:	30 % risk reduction

Based on this, the estimated annual numbers of injury accidents per km during twilight and darkness conditions on a lit Norwegian motorway with AADT = 20,000 vehicles and speed limit 100 km/h in the near future are:

Number of “Run off the road” accidents during twilight:	0.60 x 0.0159 = 0.0095
Number of “Rear end collisions” during twilight:	1.00 x 0.0069 = 0.0069
Number of other accidents during twilight:	0.70 x 0.0072 = 0.0050
Number of “Run off the road” accidents during darkness:	0.60 x 0.0825 = 0.0495
Number of “Rear end collisions” during darkness:	1.00 x 0.0330 = 0.0330
Number of other accident during darkness:	0.70 x 0.0345 = 0.0242
Total number of accidents in twilight and darkness:	0.1281

The benefit of road lighting is the difference between accident costs on an unlit road and accident costs on a lit road. Calculations of benefit are shown in Table 11. The following estimated effects of road lighting on Dutch motorway accidents, reported in Paper IV, are applied for calculations:

"Run off the road" accidents during darkness:	55 % accident reduction
Rear end collisions during darkness	44 % accident reduction
Other accidents during darkness:	54 % accident reduction

The effect of road lighting on Dutch accidents during twilight is found to be 2/3 of the effect during darkness (Paper III). The following accident reduction during twilight is therefore applied for calculations in Table 11.

"Run off the road" accidents during twilight:	37 % accident reduction
Rear end collisions during twilight:	29 % accident reduction
Other accidents during twilight:	36 % accident reduction

Experienced accident costs on Norwegian motorways with speed limit 100 km/h are (NPRA, 2007):

400,000 € per "run off the road" accident

580,000 € per "rear end collision"

690,000 € per other accident (rough estimate)

In Table 11 the estimated number of annual accidents on 1 km of a modern Norwegian motorway with AADT = 20000 vehicles is multiplied with the experienced costs per accident. To ease the understanding of the calculations in the table, the calculations for "Run of the road" accidents during twilight is explained in detail: On lit motorways, the annual number of accidents is 0.0095 and the accident cost is 400,000 € per accident. The accident costs related to "Run of the road" accidents is: 0.0095 x 400,000 € = 3,800 €. Because the number of "Run off the road" accident during twilight is 37 % lower when the motorway is lit than it is when the motorway is unlit, the annual number of accidents on the unlit motorway is 0.0095/(1-0.37) = 0.0151. The accident costs related to "Run of the road" accidents in twilight is 0.0151 x 400,000 € = 6,040 € when the motorway is unlit.

Table 11: Example: calculation of reduced annual accident costs by road lighting on 1 km of a Norwegian motorway with AADT = 20,000 vehicles

Accident type	Unlit motorway		Lit motorway		Difference unlit - lit	
	Number of acc.	Accident cost (€)	Number of acc.	Accident. cost (€)	Number of acc.	Accident cost (€)
Run off the road, twilight	0.0151	6,040	0.0095	3,800	0.0056	2,232
Rear end coll., twilight	0.0097	5,637	0.0069	4,002	0.0033	1,635
Other accidents, twilight	0.0078	5,391	0.0050	3,450	0.0024	1,941
Run off the road, darkness	0.1100	44,000	0.0495	19,800	0.0605	24,200
Rear end coll., darkness	0.0589	34,179	0.0330	19,140	0,0259	15,039
Other accidents, darkness	0.0526	36,300	0.0242	16,698	0.0284	19,602
All	0.2541	131,545	0.1281	66,890	0.1260	64,656

The calculations show that road lighting in this example reduces the annual accident costs on 1 km of a motorway by 64,656 €.

7.2 Cost

Three kinds of road lighting installation are relevant in today road lighting, when dimming is considered, and the annual costs attached to the lighting installation depend on which type is chosen. Table 12 show some typical costs related to the three types of installation, based on information from the Norwegian Public Roads Administration.

The first type is a static, no dimmable installation. It is the traditional kind of road lighting where the lighting level is constant and the light can only be switched on and off.

The second type is a two-step installation where the lighting level can be switched between 100 % and 50 %. With traditional light sources, the energy consumption is reduced from 100 % to about 70 % when the lighting level is reduced from 100 % to 50 %. The investment costs are only slightly higher for a two-step dimmable installation fitted with electromagnetic ballast. The technology is simple and reliable.

The third type is a step-less dimmable installation. The lighting level can be fully controlled even separately for each lamp, and the light can be adapted according to the need. The ballast is electronic and a communication unit can be fitted to each lamp, allowing two-way communication between the lamp and the operator. Information about the lamp conditions is easily available. The investment costs are high, but the potential for energy savings and reduction in maintenance costs is large. As in a two-step installation, the reduction in lighting level is larger than the power reduction (not so much when LED is used as light source).

Table 12: Typical annual road lighting costs on 1 km of a Norwegian motorway

Equivalent annual costs (€/km/year)	Not dimmable	Two-step dim.	Step-less dim.
Investments, luminairs and electronics	1,300	1,500	2,250
Investments, columns, cables etc	4,600	4,600	4,600
Operation and maintenance	2,200	2,300	1,900
Energy	7,000	5,900	5,200
Annual cost	15,100	14,300	13,950
Tax cost (20 % of annual cost)[9]	3,020	2,860	2,790
Annual LCC	18,120	17,160	16,740

The length of the examination period is 25 years, the interest is 4.5 %, life length of luminaires and electronics is 15 years and life length of columns and cables is 25 years. It is assumed that the road lighting is placed in the median of the motorway with a distance of 50 m between the columns. Each column carries two 250W luminaries. Electronic ballast is not available in 250W luminaires today, but it is assumed that it will be in the future at the same prise as for 150W. It is assumed that the electrical power cost will be 0.125 €/kWh.

Costs of damaged columns when hit by cars are not included in the calculations. Experiences show that approximately one hit column must be replaced per km per year if the columns are not protected by a guard rail. The cost would be about 2,500 €/km/year.

[9] 20 % tax cost is commonly used in Norway to represent the society's cost related to public in- and outgoing payment.

7.3 Benefit – Cost Ratio

Using benefit values (= reduced accident costs) from Section 7.1 and annual road lighting costs including tax costs from Section 7.2, the benefit – cost ratio of a not dimmable road lighting installation on a future motorway with AADT = 20,000 vehicles is

B/C = 64,656 € / 18,120 € = 3.6

Net benefit – cost

(B – C)/C = (64,656 – 18,120) / 18,120 = 2.6

The calculations are quite rough, but they indicate that road lighting is a profitable safety measure even on the lowest traffic loaded modern Norwegian motorways where the AADT is only 12,000 vehicles. (If accidents and traffic volume are equally reduced, the benefit/cost will be B/C = 3.6 * 12000/20000 = 2.2).

For a two-step dimmable installation the costs are reduced because of the lower energy consumption, and for a step-less dimmable installation the energy consumption and the total costs are further reduced. For dimmable installations, however, the benefit from avoided accident may also be reduced when the light level is dimmed. This estimated reduction in avoided accidents can not be assessed, and benefit – cost ratios are therefore not assessed for dimmable installations.

If one hit column has to be replaced per km per year, the benefit – cost ratio is still 3.4, and road lighting is still profitable.

In an example in CIE Publication No. 115 (CIE, 2007) the calculations show that road lighting is profitable on motorways when AADT is 17,600 vehicles or more. The calculations are based on the assumption that accidents during darkness are reduced by 20 %. If the accident reduction was 50 %, the calculations would have shown that road lighting was profitable when AADT exceeded 6300 vehicles.

In Swedish calculations carried out as support for the work on the new Swedish road lighting standard, road lighting show to be profitable on motorways when AADT is 11,000 vehicles or more (SRA, 2003). The calculations are based on the assumption that accidents during darkness are reduced by 30 %. If the accident reduction was 50 %, the calculations would have shown that road lighting was profitable when AADT exceeded 6600 vehicles.

The three examples indicate that the benefit of road lighting outweighs the costs even on motorways with the lowest traffic ((AADT = 12,000 vehicles).

On modern two-lane roads with two-way traffic, the accident rate is at least two or three times higher than on modern four-lane motorways. On those roads, the benefit of road lighting will in most cases be at least twice as high as on a modern four-lane motorway when the AADT is equal, and the road lighting costs will be smaller on the two-lane road than on the four-lane road. A road lighting installation on a two-lane road will therefore in most cases be profitable at 30 % of the traffic volume where road lighting is profitable on a four lane motorway.

In a Norwegian effect-catalogue for road traffic safety measures (Erke and Elvik, 2006), road lighting is calculated to be beneficial at AADT as low as1600 vehicles. The calculation is based on a 25 % accident reduction during darkness, giving a benefit of 95,000 €/km, and on a total cost of 90,000 €/km, both in net present value.

8 Discussion of the Future Role of Road Lighting

The studies concerning the safety effect of road lighting leaves no doubt about the need for more road lighting installations, especially on roads where pedestrians are in conflict with vehicles. The majority of road traffic fatalities occur in developing countries and they also have the fastest increase in numbers of fatalities and numbers of cars. In the future, road lighting should therefore be commonly applied in urban areas even in developing countries. On rural roads, the future role of road lighting depends on the future benefits and costs associated with road lighting.

The studies included in this thesis indicate that the safety effect of road lighting during darkness may be even larger than the 30 % accident reduction that is commonly applied by experts today. According to the Norwegian effect catalogue (Erke and Elvik, 2006), the benefit exceeds the costs (B/C > 0) at AADT > 1600 vehicles and net benefit – cost is larger than one ((B-C)/C > 1) at AADT > 3000 vehicles even when the calculation is based on 25 % accident reduction during darkness. Calculations also indicate that road lighting is beneficial on all motorways (Chapter 7).

It is obviously a huge potential for avoidance of future accidents in road traffic by the installation of high quality road lighting. However, there is one serious conflicting factor that must be considered: the demands for energy savings and reduction in the CO_2 emission. In the future, the environmental costs must therefore be fully included in the benefit – cost calculations.

Other factors will also influence the benefit – cost situation of road lighting in the future. The development of safer roads and safer vehicles will lead to a reduction in the accident rate and the benefit of road lighting will be reduced. New Norwegian motorways are already designed by new safety principles in accordance with the “vision zero”, the vision of a future road system without fatal or lifelong injuries. The road and its close surroundings, including ditches, slopes, fences, light poles and other constructions will be designed and constructed to avoid serious consequences when a road user makes a mistake. On motorways, frontal collisions will be prevented by safety barriers or a sufficiently large distance between vehicles travelling in opposite directions, and collisions with light poles in the central reserve will be prevented by the barriers. Fences along the roadsides will prevent animals from crossing the road and cause accidents. Even main roads with only two lanes will be equipped with a barrier between the lanes, which has recently become a standard in Norway. Vehicles will be constructed to better absorb collision energy. Vehicles will also be equipped with electronic devices that give warnings to the driver or control the vehicle if a critical situation arises. These safety measures will reduce the accident risk on future roads, and the benefit of road lighting will be reduced.

Some of the new safety measures will reduce accidents during darkness more than accidents during daylight. Vehicle headlights will be improved, and vehicles will be equipped with devices that detect animals, pedestrians and objects ahead, make them visible to the driver, or give warnings to the driver. Mandatory use of a reflective vest when leaving the car will prevent pedestrian accidents. These safety measures will reduce the accident rate in darkness and the effect of road lighting will be reduced.

The development of road lighting will also affect the benefit – cost ratio of future road lighting. Road lighting equipment and systems will be improved, and the use of dynamic lighting with electronic ballast will make way for a reduction in energy consumption, emission of green house gases and light pollution. Two-way communication systems will also make maintenance more efficient, and the safety effect should be better when road lighting is adapted to traffic and weather conditions.

New light sources will be more efficient, and the benefit (road safety) may be increased or the cost (energy cost) may be reduced. White light with a wide spectral power distribution and a high content of blue light has proved to give better visual performance than yellow light. The white light from metal halide lamps or other white light sources are beneficial compared to the yellow light of high pressure sodium (HPS) lamps when the luminance is low, and particularly in peripheral vision when the target is moving (Eloholma, 2005). Other light sources may be more effective yet if the spectral power distribution is optimised with respect to the spectral sensibility of the human eye. LED (light emitting diodes) may be such a light source.

Some experts within road lighting believe that LED within a few years will replace HPS as the main light source in new road lighting installations. If this is true, we will get a light source that is more easily adaptable to the situation than the existing road lighting sources. LEDs may be switched off and lit again with no delay time for cooling down and warming up, and it is dimmable within a wider range than the existing sources.

Several factors influence the benefit – cost ratio of future road lighting. Our challenge is to make the most out of the potential for increasing the safety effect and reducing the total costs including the environmental costs.

To increase the safety effect we need to know how the light level, uniformity, colour etc affects the road safety during different traffic and weather conditions.

To reduce the total costs we need a road lighting installation that is suited to produce the light quantity and quality we want at different situations with as low total costs as possible.

There is obviously one large obstacle to progress within this field: We know very little about the relationship between the level or quality of road lighting and the effect on accidents. We do not know how much light and what kind of light we need during different conditions, and we do not know the consequences on the accidents by dimming the light. As long as this remains unknown, we are not able to optimise the lighting level and we are not able to fully utilise the potential for energy savings.

Assuming that the problem above is solved, at least partly, lighting installations with advanced technology such as electronic ballasts, two-way communication and step-less dimming of each fixture will have the potential to reduce the life cycle costs more than a simple two-step dimming system. However, uncertainty about the durability of advanced technology may be a problem. It may be less useful than expected because of unforeseen technical problems and unforeseen demand for human resources to follow up the systems. Advanced technology may also be replaced by more efficient installations in the future, e.g. by LED luminaires, and the installation will be less beneficial if the life length is shortened.

More knowledge about light level and accidents, more experience with dimming installations and more experience with LED as light sours in road lighting may hopefully reduce some of the uncertainties within a short time, and it will be easier to make reliable benefit – cost calculations and to choose the most beneficial road lighting installation.

Anyway, road lighting is among the most cost-efficient infrastructural safety measures available today, and the uncertainties mentioned above will not prevent the application of this safety measure. Simple, well known techniques are safe and cheap and will be applied for a long time, particularly in low cost countries. Advanced technological solutions are more interesting in western countries, and western road authorities will probably cooperate with manufacturers of road lighting equipment and other partners in the development of more effective road lighting installations. The MOVE project (Eloholma and Halonen, 2005) and the E-street project (E-street, 2006) are examples of consortium projects for the development of energy efficient street lighting. The European Commission is also working on energy savings in street lighting, and a new proposal is announced for 2008.

Concerning motorway lighting, at least two factors work against a common application of road lighting on future motorways, in spite of the large safety effect found in the study of Dutch accidents and some other studies. One factor is that alternative measures to some degree may reduce accidents during darkness on motorways with far less energy consumption than road lighting. LED guide lights are such a measure. The effect on accidents is unknown, but pilot projects and field studies may prove an accident reducing effect. In the longer term, advanced vehicle technology will also contribute to reduce the accident rate during darkness and thus reduce the need for road lighting. The other factor that may work against a common use of road lighting on motorways is tradition. As shown in Paper IV, Table 1, the use of road lighting on motorways varies from country to country. Some countries, like Germany, Sweden and the USA, have little tradition for road lighting on rural motorways, and when the society demands energy savings, road lighting on motorways will probably be considered as a step in the wrong direction. The future role of road lighting is therefore more uncertain on rural motorways than on other kind of roads.

Regarding Hypotheses 10 *"Road lighting on motorways may be replaced by more energy efficient visibility measures without reducing the road safety"* it is not supported by studies. The effect of road lighting on motorway accidents is found to be large while the effect of alternative measures is uncertain. Road safety will therefore probably be reduced if road lighting is replaced by alternative measures. However, the demand for energy savings will probably make alternatives to motorway lighting interesting even if they are less effective as a safety measure. Anyway, further development of effective alternatives and more studies of the effect on accidents are necessary.

9 The Need for Further Research

The need for further research within road lighting and traffic safety is related to the lack of essential knowledge for an optimal use of road lighting as a safety measure. Some lack of knowledge is documented in the thesis, and the discussion of the future role of road lighting show that some gaps in our knowledge need to be filled through further research.

Most basic is the information from earlier studies and studies within this thesis about the mean effect of road lighting on accidents. The effects found on rural Dutch roads are much larger than the effects found in earlier studies. Further studies are therefore needed to validate the Dutch results. On Dutch motorways, the mean effect is the same as the mean effect found in earlier studies. However, the effect seems to be smaller in Great Britain and Sweden. Further studies are therefore needed for estimation of effects of motorway lighting in different countries. The studies of Dutch accidents indicate that modern road lighting have the potential of reducing accidents during darkness by 50 %, but it can not be concluded that such a large effect is commonly achievable in other countries.

The study of Dutch accidents also shows how the effect on accidents varies according to varying weather and road surface conditions. This is a valuable contribution to existing knowledge, but more knowledge is needed about this subject, especially in relation to adaptive road lighting systems.

The problem of high accident risk during darkness in rain and on wet road surfaces, which is concurrent with small effects of road lighting during these conditions, must be studied in field studies and pilot projects. The reflecting and draining properties of road surfaces must be studied with the intention to reduce the visual problems during darkness in rain and on wet road surfaces. Unequal distribution of luminance on wet surfaces, mirrored reflection of light from vehicle headlights and other light sources, scattered light from wet or dirty windscreens, etc. are problems that cause accidents, but the problems may be reduced by technical solutions if it is paid more attention to them.

One particularly important question regarding the effect of road lighting on accidents remains to be answered: How does the effect vary with varying light conditions? Previous studies give little information about this, and the studies within this thesis give no such information. To be able to optimise the light from a road lighting installation we need to know how the effect on accidents varies with varying average luminance. Information about the relationship between the road safety and the luminance uniformity, the colour temperature and other road lighting characteristics may also be useful for the optimal design and adaptation of the road lighting to the actual conditions.

The international road lighting community should take a responsibility for this research concerning lighting characteristics and road accidents. Research programs could be organised within CIE with several participating countries. In this way the samples of accidents could be large enough, and the studies could perhaps explain the variations in the safety effect between countries like these found on Dutch, British and Swedish motorways. To prepare for such a study, road authorities should immediately start to make records of road lighting level and quality related to accident statistics.

Field studies are needed for some purposes:

The studies of Dutch accidents show that the effect of road lighting is smallest during adverse weather conditions, when the accident risk is highest. Field studies are needed to evaluate the optimal road lighting design for such weather conditions.

Field studies are also needed to optimise the road lighting design at pedestrian crossings. Poor visibility and low attention may lead to serious accidents on sites where pedestrians are encouraged by the authorities to cross the street. New concepts based on positive contrasts should be closely studied.

Peripheral vision is important in urban areas for detection of pedestrians or animals intending to cross the road or detection of a vehicle coming out from a side road. Resent studies in Finland and USA have shown that the spectral power distribution of the light source is essential for peripheral vision, and further studies should be carried out about this to improve the safety effect of road lighting in urban areas.

The safety effect of combining road lighting with other measures should also be studied. LED guide lights on motorways are such a measure. Light road surfaces are another example. Such measures may reduce the need for road lighting or reduce the needed light level. The combined effect may be beneficial and may lead to a further reduction in accidents or to lower energy costs.

The benefit – cost ratio of road lighting may also be increased by technical improvements. More efficient light sources and luminaires and improved systems for adaptive lighting will make road lighting more beneficial, and a lot of research is needed for the development of better solutions. Most of this research will take place at road lighting companies. However, better founded results may be gained when research is organised as a consortium project with several kinds of partners acting together. The NumeLite project (Crab et al., 2005) is an example of this.

A trend that must be regarded, when considering energy savings in road lighting, is that the group of older drivers is increasing. It is well known that older drivers have great problems with the vision in night-time traffic. Research is needed to study how the road lighting can ensure mobility and safety for older drivers.

In Europe and in most other parts of the world, the level and uniformity of road surface luminance is the main dimensioning parameter in road lighting, as described in CIE Publication 115 (1995). In North America, illumination can be chosen as an alternative parameter to luminance, and a third concept called "Small Target Visibility" (STV) was introduced in the North American standard in 2000. The evolution of visibility criteria like STV came as a consequence of studies that found a closer correlation between target contrast and visibility than between luminance level and visibility (Janoff, 1988). Janoff also claimed that there existed a valid statistical relationship between visibility and visual performance and safety in night-time driving. It is also a common understanding among road lighting experts that a further developed visibility concept may lead to lower energy consumption in road lighting than the luminance concept. The CIE (2007b) technical committee TC4-36 "Visibility Design for Roadway Lighting" is now working on the subject, and may be in the long term some kind of visibility concept may become a useful tool in road lighting design.

Finally there is a need for a continuous literature review and updating of the "state of the art" regarding the research subjects mentioned above, and this work should naturally be organised by CIE.

10 Concluding Remarks

The results from the studies and the discussion in the thesis may have some influence on the future application of road lighting and on future research within road lighting.

Road lighting should be more widely used as a safety measure in Norway and especially in other countries where roads with greater traffic volumes are still unlit. The thesis demonstrates that the general effect of road lighting is at least as large today as has been previously known. Though the estimated effect on Dutch accidents might be overestimated, the mean effect of road lighting is probably more than 30 % reduction in injury accidents during darkness on rural roads and motorways. Road lighting seems to be an effective traffic safety measure on all kinds of roads, and it is rather easy to accomplish.

However, the energy consumption related to road lighting is a problem that must be more considered. The great challenge is to reduce the energy consumption as much as possible without reducing the safety benefit too much. The efficiency of light sources and fixtures must be improved, and it is obvious that future road lighting must be of the adaptive type. This makes it even more essential than before to know how the safety effect of road lighting varies according to the road, traffic and climatic conditions and how it varies with the road lighting level. The thesis answers some questions related to this.

The thesis confirms that the accident reducing effect of road lighting is especially large for pedestrians. The effect seems to be even larger than has been known from earlier studies. The thesis further shows that the risk of bicycle and moped accidents are largely reduced by road lighting. Road lighting should therefore be a mandatory safety measure on roads with mixed traffic and a large share of vulnerable road users.

On the other side, the thesis clearly shows that the effect of road lighting is reduced during adverse weather conditions, when the accident risk is especially high and visibility improvements are really needed. During these conditions the effect of road lighting must be increased by more knowledge, better solutions, and more actions to reduce the problems caused by uneven reflections and glare from wet road surfaces and by scattered light through wet or dirty windscreens, etc. Road surfaces with good reflecting and draining properties seem to be essential for good visibility and road safety during darkness. Other visibility measures like special markings and guide lights must also be considered for safety improvements during rain, snow and fog.

The thesis does not answer all important questions related to the safety effect of road lighting. Some problems are identified that needs to be studied further and some serious gaps in knowledge are identified that need to be closed. The most serious lack of knowledge is that we do not know how the safety effect varies according to the lighting level. It is not possible to balance the energy consumption and the safety effect as long as this relationship is unknown. There is an urgent need for research on this subject, and CIE should take the responsibility to organise a multinational research project.

On motorways, alternative or additional measures to road lighting must be considered for the purpose of energy savings. Motorway lighting seems to effectively reduce single vehicle accidents in darkness during most weather conditions, but collisions with light poles may some times reduce the effect a great deal. Rear end collisions are also effectively reduced in fine weather, but the effect of the road lighting is much lower during rain and snow and on wet road surfaces. In fog, there seems to be nearly no effect of road lighting on motorways. Guide lights may therefore probably be an effective and energy saving alternative on low traffic motorways. On dense traffic motorways, where rear end collisions and accidents involving other vehicles represent a larger safety problem, guide lights may be used as an additional measure to road lighting. More knowledge about this must be gained through pilot projects.

The safety effect of road lighting seems to be significantly smaller on British and Swedish motorways than on Dutch motorways. Further studies are needed for estimation of the effect of road lighting on motorway accidents in different countries.

Through more knowledge about the safety effects of road lighting and further development of energy efficient technical solutions road lighting will become a progressively more efficient safety measure, optimally adapted to the prevailing conditions in a combination with other visibility measures.

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Paper I

Road lighting and traffic safety. State of knowledge and recommendations for further research

Submitted to the Piarc Prize 2007 Competition as the Norwegian contribution related to the prize within Road Safety or alternatively to the prize within Sustainable Development.

Road lighting and traffic safety. State of knowledge and recommendations for further research

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Abstract

Studies have shown that the accident rate is nearly twice as high in darkness as in daylight. The fatal accident rate is three times as high in darkness as in daylight. It is believed that this is partly due to visibility problems, and road lighting is therefore used as accident countermeasure.

Road lighting is considered to be among the most efficient traffic safety measures available. However, the energy consumption in road lighting is a problem, and energy savings must be considered. Energy can be saved by changing to more efficient equipment, especially by using dynamic lighting systems. New technology and equipment make it possible to adapt the lighting according to road, traffic and weather situations at any time and place. The lighting level can be reduced to the minimum of what is required to ensure good traffic safety.

A problem is, however, that we do not know what lighting quantity and quality that is needed to ensure good traffic safety at the actual situation. Lighting standards do not fully answer the question. Firstly, they are given for a static situation with fixed road lighting under static traffic, road and environmental conditions. Secondly, they are mainly based on consensus and not so much on accident research. We know very little about what kind of lighting that has the best effect on accidents in a given situations.

We need to know more about the relationship between road lighting and traffic safety. The author of this paper intends to contribute to that by stating today's knowledge, identifying gaps in the knowledge and pointing at areas where more research is needed.

From a literature review the today knowledge on the effect of road lighting on accidents is summarized. The mean accident reducing effect in darkness is found to be 30 % for all injury

accidents, 60 % for all fatal accidents, 45 % for pedestrian accidents, 35 % for injury accidents at rural junctions, and 50 % for injury accidents on motorways. There is found no significant correlation between lighting level or other quality parameters and accident rate. However, there are indications that raised road luminance level reduces the accident risk for pedestrians, especially at pedestrian crossings.

Most of the accident studies are conducted in USA and UK from 1960 to 1990, and their relevance to today's traffic may be questioned. Another overall objection to former studies is that they are badly controlled for other contributory factors. The known effects of road lighting are mainly based on before-and-after studies. Most of them are insufficiently controlled for the effect of regression to the mean, effects independent of road lighting, spillover effects, migration effects, time trends in accidents and traffic volume changes. The most severe lack of control is to ignore the effect of regression to the mean, and it is likely that the effect on accidents is overestimated in most studies.

Considering the huge amount of road traffic accident data worldwide, it is remarkable how little research is found concerning the correlations between road lighting parameters and accidents. Therefore, recommendations and quality criteria for road lighting, in general, are questionable.

In North America, "Small Target Visibility" (STV) was introduced in 2000 as an alternative to road surface luminance as design parameter and quality measure for road lighting. This was based on research on visibility and driving task performance, indicating a closer relationship between accidents and visibility than between accidents and road surface luminance. However, the STV method seems to lack relevance for visual tasks in a critical traffic situation. The method needs to be refined, and efforts should be concentrated on those visual tasks that are known to be critical in night-time accidents. It is a great challenge to develop a visibility concept that is relevant for critical driving tasks and accident risk at complex and shifting road traffic conditions, keeping in mind that the concept should be a user-friendly tool for lighting designers.

After 50 years of work, time has come to introduce a new photometry based on the works in the MOVE project and in other research projects. This will bring new values for lamp lumens, followed by new design criteria and measure methods for road lighting. This will make designers more able to choose suitable light sources and light levels, and it will promote the development of more efficient lighting products. In this way a new photometry will make way for better road safety and energy efficiency.

It may be just the right time to bring principles for road lighting some large steps forward after decades of rather small steps. The brake-through in development of a new photometry, the development of new light sources, the focus on the driver's visual tasks, the demand for visibility measures in road traffic, the new equipment that allows full control of lighting level according to the situation, are elements that must be combined in new systems for road lighting. This will make it possible to obtain more benefits from road lighting at lower costs and lower energy consumption. Thus road lighting will increasingly become a more useful measure against road accidents in darkness.

However, the steps forward depend very much on the efforts of research within some important fields.

- The relationship between lighting and accidents must be thoroughly investigated. Thousands of kilometres of roads were equipped with modern road lighting through the 1990s, and detailed information is available from injuries and fatalities before and after installation of lighting. Detailed information is also available on road characteristics and lighting characteristics. It is high time that some researchers grasp the opportunity to study in detail the relationship between road lighting and accidents.

- Peripheral vision must be studied in real traffic situations. This may be of great importance for detection of pedestrians at the road side, vehicles coming from a side road, or animals crossing the road. New photometric models must include the spectral efficiency in peripheral vision when performing visual tasks in real traffic.

- The critical visual tasks related to accidents must be recognized and the processes of scanning, perception, recognition and manoeuvring must be analysed.

- Visibility criteria have to be developed, where factors important for visibility in critical situations must be considered.

- Research is needed to develop better light sources, light fixtures, and dynamic light control systems.

- Research is needed to evaluate alternatives or supplements to road lighting, such as lighter road surfaces, better road markings and the use of LED for guidance. Such measures may reduce the need for road lighting or reduce the needed light level.

- A trend that must be regarded, when considering energy saving in road lighting, is that the group of old drivers is increasing. It is well known that old drivers have great vision problems in night-time traffic, and research is needed to find how road lighting can ensure mobility and safety for old drivers.

1 Introduction

Road lighting is considered to be among the most efficient traffic safety measures available. At the same time society today has a demand for energy savings, locally and globally. In the field of road lighting the demand for energy savings is accompanied by a fast development of techniques and equipment that give great opportunities for energy savings. The opportunity already exists to adapt the lighting to the actual road, traffic and weather situation at any time and place, but until now only a few communities has seized this opportunity. This may be due to uncertainty about new technical solutions, but the main problem seems to be uncertainty about what lighting quantity and quality that is needed to ensure good traffic safety in an actual situation. Lighting standards do not fully answer the question. Firstly, they are given for a static situation with fixed road lighting under static traffic, road and environmental conditions. Secondly, they are mainly based on consensus and not so much on accident research. In fact we do not quite know what kind of lighting that is best suited for the different situations. We obviously need to know more about the relationship between road lighting and traffic safety. Hopefully this paper will contribute to that by stating today’s knowledge, identifying gaps in the knowledge and pointing at areas where more research is needed.

2 The Problem of Night-time Accidents

Several publications from reliable sources state that night-time accidents are disproportionately high in number and severity compared to daytime accidents.

The International Commission on Illumination (CIE, 1992) referred to statistics from 13 OECD countries at about 1980. As a median, 48.5 % of fatal road accidents occurred during the hours of darkness while about 25 % of travelled kilometres were in the same period. This means that the fatal accident rate (fatal accidents/km) was 2.8 times higher in darkness than in daylight.

Elvik et al. (1997) found from their literature review that the accident rate was 1.5 to 2 times as high in darkness as in daylight.

A conclusion, considering this and other reports (Plainis et al.,1997; Hasson and Lutkevich, 2002; Opiela et al., 2003, NHTSA, 2003), is that the fatal accident rate is about three times as high in darkness as in daylight and the injury accident rate is about 1.5 times higher in darkness than in daylight.

A comprehensive study by the Danish Public Roads Administration (Jensen, 1998) showed that the accident rate for pedestrians was 2.7 times higher in darkness than in daylight on urban roads. On rural roads the factor was 7.4.

Accident studies also show that some other types of accidents are overrepresented in night time, such as single-vehicle accidents, accidents with animals involved and accidents in wet and slippery road conditions (Sørensen, 1980).

3 Effect of Road Lighting on Accidents

Decreased visibility is not the only explanation for the increased accident risk in the hours of darkness, but it is an important factor.

Several reports and proceedings have presented some kind of review on current knowledge and experience within the field of road lighting and traffic safety (CIE, 1992; Elvik et al., 1997; van Bommel, 1999).

Some analyses, as the meta-analysis, intend to find the average effect of road lighting on accidents, in general. However, to decide when and how road lighting is a suited countermeasure against accidents, we need more detailed information about the relationship between accidents and road lighting.

3.1 Injury Accidents in General

CIE (1992) presented 23 before and after studies on the effect of installation or upgrading of lighting. The average effect was a 30 % reduction in night-time injury accidents. One study showed an increase in accidents. Among the 23 studies 15 were from Europe, five from USA, and the rest from Australia and Japan.

A Norwegian meta-analysis (Elvik, 1995) of 38 studies evaluated the safety effect of installation of road lighting. The effect on night-time injury accidents was a 28 % reduction (weighted mean) and the 95 % confidence interval was 25 to 32 %. Most of the studies were from USA and Great Britain. One study was from the 1990s, eight were from the 1980s and the other 29 were from 1978 and back to 1948. Elvik found that “studies performed in different decades have yielded similar results” and that “there is no indication that the safety effects of road lighting have diminished over time”.

In a before and after study in Finland, Mäkelä and Kärki (2004) studied the effect of road lighting established in the 1990s on 236 road sections. The overall effect of lighting the roads was 17 % reduction in injury accidents in a 24-hour period. The effect on night time accidents was calculated to be a 51 % reduction.

The conclusion, based on today knowledge, is that the installation of road lighting reduces injury accidents in darkness by 30 %.

3.2 Fatal Accidents

Three before-and-after studies in the CIE (1992) accident report specified the effect on fatal night-time accidents. The effect was a 49 %, 75 % and 53 % reduction, respectively, and the average effect was a 59 % reduction after lighting was installed. The studies were from England and USA, published in 1964, 1969 and 1972.

The meta-analysis by Elvik (1995) included seven studies of fatal accidents, published from 1948 to 1977. The analysis showed a 64 % reduction in fatal night-time accidents as a mean effect. The 95 % confidence interval was 50 % to 74 %.

The best estimate, based on all studies, seems to be a 60 % reduction in fatal night-time accidents. However, the studies are few and old.

3.3 Pedestrian Accidents

In Israel, Katz and Polus (1978) found that pedestrian accidents in darkness were reduced by 43 % after road lighting was installed on 99 road sections.

Two studies from the USA in the 1980s showed that the number of pedestrian accidents in darkness was reduced by 35 % and 43 %, respectively, after the installation of road lighting. (Zeeger and Zeeger, 1988).

A study from the USA (Huang et al., 1993) showed that the installation of road lighting reduced the number of pedestrian accidents in darkness by 43 %.

Elvik (1995) concluded from the meta-analysis that night-time pedestrian accidents were reduced by 50 % after lighting was installed on former unlit roads. The analysis was based on eleven studies, published in the years 1955 to 1982.

In Denmark (Jensen, 1998), installing road lighting was estimated to reduce pedestrian night-time accidents by 45 % on roads where the speed limit exceeded 50 km/h. The reduction was only 12 % on roads with a speed limit up to 50 km/h.

The results from all these studies are consistent, and they indicate that road lighting reduces night-time pedestrian accidents by about 45 %.

3.4 Accidents at Junctions

A lot of research is done on the safety impact of lighting at isolated rural junctions.

Lipinski and Wortman (1976) reported from a survey study at rural highway junctions in Illinois that illumination resulted in a 45 % reduction in night-time accident rate. No statistical tests were carried out.

CIE (1992) Publication 93 included only two before-and-after studies on effect of lighting at rural junctions. A Finnish study (Salminen, 1978) showed an increase in injury accidents, while a U.S. study (Walker and Roberts, 1976) found a 44 % reduction in night-time injury accidents after lighting was installed. The last one had statistical significance. However, the accident reduction was found at channelised 4-legged junctions only. For unchannelised junctions and 3-legged junctions, they found no statistical change in accident rate.

Elvik (1995) found that the effect of lighting was greater at junctions than at other locations. Assuming that the accidents severity was equal at junctions and in other accidents, we can calculate from de accident data that the reduction in night-time injury accidents at junctions was about 35 %. The effect on accidents at junctions was about twice as high as on accidents between junctions.

A study on 12 rural junctions in Minnesota (Preston and Schoenecker, 1999) reported a reduction in night-time accidents of 25 % to 40 % when road lighting was installed, while a before-and-after study on nine junctions in Kentucky (Green et al., 2003) showed a 45 % reduction.

Iowa State University evaluated the effect of road lighting on night-time accidents at rural junctions in Minnesota (Isebrands et al., 2004). This work included a literature review, a comparative analysis on 3622 rural stop-controlled junctions on trunk highways, and a before and after analysis at 34 rural junctions. They found that previous published research reported a 25 % to 50 % reduction in night-time to total accident rate due to the installation of junction lighting. Previous studies also reported a reduction in severity. The comparative analysis showed that the expected night to total accident ratio for unlit junctions was 7 % higher than at lit junctions, holding all other variables constant. The result was statistically significant. The before and after analyses showed a 35 % reduction in night-time accident rate (p=0.1), while daytime accident rate increased 30 %. Accident severity decreased at night-time and increased at daytime.

The studies measured different units, but as an average they indicated a 40 % reduction in accidents at rural junctions after the installation of lighting. The studies also indicated that the effect on night-time accidents is twice as high at junctions as in sections between junctions.

3.5 Accidents on Motorways

Box (1971; 1972) used data from 21,000 accidents on 28 lighted and seven unlighted urban or suburban motorway sections in North America. The sections ranged from four-lane to ten-lane widths. The study indicated that illumination reduced night-time accidents by an average of 40 %.

In Germany, Lamm et al., (1985) analyzed 1,900 accidents reported from 1972 to 1981 on eight km of a four-lane motorway. The route was divided into three sections. Two sections were lighted, while the third was used as a control. One section showed no change in the night to day ratio of accidents as a result of lighting, while the second section showed a ratio reduction of 17 %. The ratio for the unlit control section increased 38 %.

CIE (1992) reported three before and after studies that identified the effect of installation of lighting on motorways. The results were consistent, with a 57 % reduction in night-time accidents. However, the studies had small sample sizes and were published back in 1972 and 1973.

In Minnesota, Griffith (1994) compared the safety of 88 km of continuously lighted urban motorways and 57 km of urban motorways with junction lighting only. He found that illumination of unlighted sections between lighted junctions could theoretically reduce night accidents on motorways by 16 %.

A Canadian study by Bruneau (2001) used a database of 22,740 accidents on 770 km of motorways in Quebec. Continuous lighting was found to reduce the night-time accident rate by 33 % (p=.001) compared with junction lighting alone, and by 49 % (p=.05) compared with dark motorways.

These studies indicate that illumination can reduce accidents on motorways by about 50 %. The effect of lighting seems to be larger at junctions than at the sections between.

3.6 Specific Kinds of Accidents

In Finland, Mäkelä and Kärki (2004) found that the 24-hour accident reduction due to road lighting was 17 % for pedestrian and bicycle accidents, 8 % for single vehicle accidents, 3 % for accidents with animals involved, and 14 % for other accidents. If assuming that the effect on night-time accidents is 3 times as high as the effect on 24-hour accidents (as the authors estimated for all injury accidents), then the night-time accident reduction can be calculated to be 51 % for pedestrian accidents, 24 % for single vehicle accidents, 9 % for accidents with animals involved, and 42 % for other accidents.

3.7 Driver, Road or Weather Conditions

No studies are found that relate the accident reducing effect of road lighting to driver characteristics or road or weather conditions, though it is well known that such factors may greatly influence vision and visibility.

3.8 Lighting Quality

A study by Box (1972) showed that 1 cd/m^2 was optimal luminance on main roads. Both decreased and increased luminance had a negative influence on accidents. The result was based on 3000 night-time accidents and 4000 daytime accidents.

Another study by Box (1976) showed that switching off one third of the lamps on an urban major route increased the night-time accidents with 36 %.

In Göteborg, the street lighting was improved during the years 1975 – 1978. The conclusion from a study by Danielsson (1987) was that those improvements had no effect on accidents. From this study and a literature review of earlier studies in Denmark and England, Danielsson concluded that installation of street lighting has a good effect on accidents, but the additional effect of increasing the luminance level is small.

The relationship between average road surface luminance and night accidents was discussed in CIE Publication 93 (1992). It was referred to an English study (Scott, 1980) where a strong relationship was found. In the range 0.5 cd/m^2 to 2.0 cd/m^2 it was estimated that an increase of 1 cd/m^2 led to 35 % decrease in accidents. It was also referred to an Australian study (Fisher, 1977) were a similar effect was found. Road lighting was upgraded from a before level of about 0.1 cd/m^2 – 0.7 cd/m^2 to a level of about 0.9 cd/m^2 – 1.9 cd/m^2. The result was a 29 % reduction in injury accidents. Pedestrian accidents were reduced by 57 %. The changes were significant. Two other studies, by Janoff et al. (1978) and by Box (1971), were referred. They showed an opposite effect, but it was argued that this might be due to other parameters acting simultaneously. Finally, CIE found indications on a linear relationship with 2.5 % accident reduction for a 10 % increase in road lighting level in the middle of the range.

Elvik et al. (1997) found from a literature review that a doubling of the luminance reduced the night-time injury accidents about 5 % (not statistical significant). When the luminance was increased 2 to 5 times, the number of night-time accidents was reduced about 10 %. When the luminance was reduced 50 %, night-time injury accidents increased about 20 %. The before luminance level was not considered.

In Canada, the Oregon Department of Transportation conducted a before- and-after study on the change in accident risk as illumination was reduced at various junctions and highway sections (Yin, 2005). It was found an increase in accidents varying between 7 % and 22 % ($p=0.05$). Lighting levels are unknown.

An experiment with reduced lighting was conducted in southern Finland (Sshirikoff et al., 2001). When the luminance was reduced from 1.5 cd/m^2 to 0.75 cd/m^2, the accident rate increased 13 %.

Keck (2001) however, analyzed earlier studies and found no correlation between average luminance and accident rates.

The installation of floodlights at 63 zebra crossings in Perth, Australia, resulted in a 62 % reduction in the number of pedestrian accidents in darkness, while no effect was found on accidents in daylight or on other accidents (Zeeger and Zeeger, 1988).

CIE Publication 93 (1992) included four studies that gave separate effects on pedestrian accidents on road sections where the lighting was improved. As an average, it was found a 42 % reduction in night-time pedestrian accidents, varying from 16 % to 57 %. The CIE-report also analysed the effect of improved lighting at pedestrian crossings. The average of eight results was a 54 % reduction in night-time pedestrian accidents, varying from 32 % to 74 %.

The conclusion from these studies is that there is no proof of a correlation between average road luminance and accident rate. However, there are strong indications that the pedestrian accident risk is reduced when the level of luminance is increased.

No studies are found that relate accidents to other lighting characteristics, such as luminance uniformity, luminance contrast, glare from fixed road lighting, or glare from headlights.

3.9 Discussion and Conclusions

Though road accident counts are a direct measure of traffic safety, it seems that accident studies never played an important role in describing the quality parameters of road lighting. Considering the huge amount of road traffic accident data worldwide, it is remarkable how little research is published concerning correlations between photometric parameters and accidents, especially from the last 20 years. It seems that road lighting recommendations to a great extent are based on knowledge, experiences and consensus among experts in international lighting communities. Therefore, recommendations and quality criteria for road lighting, in general, may be questionable.

The effects of road lighting on accidents, found in this review of literature, are as follows:

Type of accident	Mean effect	95 % confidence interval (from Elvik, 1995)	Number of studies	Consistence
All injury accidents	30 %	25 - 32	> 40	Good
All fatal accidents	60 %	50 - 74	10	Good
Pedestrian accidents	45 %		15	Good
Injury accidents at rural intersections	35 %			Not good
Injury accidents on motorways	50 %		7	Good

Some studies indicate that the effect of lighting is higher at junctions than at sections between junctions. Little is found about other types of accident, but there are some indications that single vehicle accidents and accidents involving animals are less affected by road lighting than other types of accidents.

There is found no significant correlation between lighting level or other quality parameters and accident rate. The findings in the NumeLiTe project (Crabb et al., 2005) support this conclusion, as a reduction in luminance level from 1.0 cd/m^2 to 0.5 cd/m^2 did not affect the measured visibility of objects. However, there are indications that raised road luminance level reduces the accident risk for pedestrians, especially at pedestrian crossings.

Most of the accident studies are conducted in USA and UK from 1960 to 1990, and their relevance to today's traffic may be questioned. Though Elvik did not find any indication that the safety effect had changed over time, it is obvious that a lot has changed the last decades, like the quality of both road lighting and car headlights.

Another overall objection to former studies is that they are badly controlled for other contributory factors. The known effects of road lighting are mainly based on before-and-after studies. Most of them used daylight accidents as a control, a few used control sections, and a few used accident data in the whole study area as control. Nevertheless, the studies in general are insufficiently controlled for the effect of regression to the mean, effects independent of road lighting, spillover effects, migration effects, time trends in accidents and traffic volume changes. The most severe lack of control is to ignore the effect of regression to the mean, and it is likely that lighting investments some times are based on unusually high accident counts. Research by Hauer and Persaud (1983), shows that the effect of regression to the mean may be of the same order as the real safety effect of the accident countermeasure. This problem is typically not accounted for in previous studies. Another common error in before-and-after studies is to compare accident rates at different traffic volumes. According to Pendleton (1996), the accident rate is expected to be lower at higher traffic volumes. The traffic volume has generally increased through the years, and the road lighting installations may increase the share of the traffic occuring in the hours of darkness. These problems are not much accounted for in previous studies, and therefore the effect of road lighting, presented in the studies, may be overestimated to some extent.

It is therefore a need for newer and better controlled studies. The most serious lack of knowledge however, is that we do not know how the accident reducing effect varies according to lighting quantity and quality, type of road, type of accident, weather conditions, road surface conditions, amount of traffic or the type of vehicles involved. It is serious that standards and criteria for road lighting are not in a larger degree based on accident studies. Designers and public authorities need more facts about the safety effects to be able to design the most effective lighting systems, to make cost-benefit calculations and to decide whether or not new or improved road lighting is the right kind of safety measure. This kind of knowledge has become even more important today than before, as technology today gives greater opportunity to regulate the road lighting and adjust it to a given situation.

4 Influence of Lighting Design Criteria on Safety

In Europe and in most other parts of the world, the level and uniformity of road surface luminance is the main dimensioning parameter in road lighting, as described in CIE Publication 115 (1995). In North America, illumination can be chosen as an alternative parameter to luminance, and a third concept called "Small Target Visibility" (STV) was introduced in the latest North American standard (ANSI/IESNA RP-8-00, 2000). The development of visibility criteria has come as a consequence of studies that found a closer correlation between target contrast and visibility than between luminance level and visibility (Janoff, 1988). Janoff also claimed that there existed a valid statistical relationship between visibility and visual performance and safety in night-time driving. Even in the European road lighting community, there has been a growing interest in visibility methods for road lighting design. The STV method was described and discussed in CIE Publication 115 (1995), but it was not adapted as a recommended method. The committee wanted to await more information and experience from North America and other users before they could make recommendations on using the method. Keck (2001) evaluated former studies and stated that there was no statistical significant correlation neither between average luminance and accident rate nor between STV and accident rate.

The STV method is a method for computer calculations of visibility, and the calculated STV value is a measure of the driver's ability to see and recognize small objects. Partly based on studies on visibility and driver performance, it was assumed that increased target visibility resulted in improved nighttime driver performance and increased safety. However, it is the same problem with STV as with other design criteria, that it is not related to accident studies.

The STV method is not much used, and it is not even recommended as standard practice in the draft for a new Roadway Lighting Design Guide (AASHTO, 2005). It says that "the benefit of the method has not been adequately demonstrated". The STV method seems to lack relevance for visual tasks in a critical traffic situation. The method needs to be refined, and efforts should be concentrated on those visual tasks that are known to be critical at night-time accidents. Probably should the dimensioning targets be larger and placed closer to the observer in a more peripheral view. Glare from headlights should be better incorporated in the model, as glare is proved to cause serious visibility problems in night-time traffic (Raynham, 2004).

The visibility of targets in a static situation may be quite different from the visibility in heavy traffic with moving observer, moving target, shifting background, reflected light from oncoming vehicles changing with varying pavement reflectance, change in amount of off-road lighting, etc. It is therefore a great challenge to develop a visibility concept that is relevant for critical driving tasks at complex and shifting road traffic conditions, keeping in mind that the concept should be a user-friendly tool for lighting designers.

5 Influence of a New Mesopic Photometry

The current system of photometry is based on the human eye's specific characteristics for daylight (photopic) vision. The $V(\lambda)$ eye sensitivity curve for photopic conditions was adopted by CIE in 1924 and is still used for measuring lamp lumens and surface luminance at all levels. Dimensioning methods, standards, acceptance criteria and measuring instruments for lighting are based on daylight vision, although it is known that this gives wrong results at lower light levels. This mislead the users of the system to choose light sources and systems for road lighting that are not the most effective in reducing accidents and saving energy. It is well known that the eye's visual response gradually changes when the light level is reduced from daylight (photopic) conditions to night-time (scotopic) conditions. The eye's sensitivity to long-waved yellow light is reduced while the response to short-waved bluish light is increased. This has been known for the last hundred years as "the Purkinje shift". During the last decades research has shown that changes in visual performance in road traffic under different spectral conditions may be even greater than explained by the Purkinje shift.

Road lighting is in the mesopic region of human vision that lies in the middle between the photopic region and scotopic region. CIE has for a long time realised that the current photometric system produces inadequate values for road lighting situations, and efforts have been done through the last seven decades to establish standardized mesopic response functions for the eye. In 2005 it might have come to a breakthrough in this work. A European research consortium, MOVE, proposed a performance based model for mesopic photometry (Eloholma and Halonen, 2005), and at the CIE Expert Symposium in May 2005 it was recognised that the work was sufficiently advanced to form a basis for a practical system of mesopic photometry (Shanda and Goodman, 2005). It was agreed that the model should bee refined with the aim of having a trial system ready by June 2006 for field-testing. The CIE

Division Director pronounced that “the potential implications for road safety and improved energy efficiency alone make this a major break through for the CIE”.

Research within MOVE (Eloholma, 2005), and research during the last ten years mainly at Lighting Research Center, USA, state that metal halide (MH) lamps produce more visibility in mesopic conditions than high pressure sodium (HPS) lamps with the same photopic lumen output. The researchers give different answers to how much better a MH lamp is in producing visibility, varying from no better to several times better at luminance 1 cd/m^2. This obviously depends on the test conditions and what kind of visual task was performed. However, it is a common conclusion that MH lamps become more favourable as the light level decreases and as the object is placed further off from the axis of vision. An object in movement does also favour MH lamps. Using the proposed MOVE-model for mesopic photometry, Eloholma (2005) found that MH lamps gave a 38 % higher mesopic weighted luminance compared to a conventional HPS lamp at photopic luminance 0.5 cd/m^2. The European consortium project NumeLiTe (Grabb et al., 2005), however, found no such benefit from MH lamps.

After 50 years of work, time has come to introduce a mesopic photometry based on the works in the MOVE project. An international accepted system for mesopic photometry will bring new values for lamp lumens, followed by new design criteria and measure methods for road lighting. This will make designers more able to choose suitable light sources and light levels, and it will promote the development of more efficient lighting products. In this way a mesopic photometry will make way for better road safety and energy efficiency.

6 Recommendations for Further Research

It may be just the right time to bring principles for road lighting some large steps forward after decades of rather small steps. The brake-through in development of mesopic photometry, the development of new light sources, the focus on the driver’s visual tasks, the demand for visibility measures in road traffic, the new equipment that allows full control of lighting level according to the situation, are elements that must be combined in new systems for road lighting. This will make it possible to obtain more benefits from road lighting at lower costs and lower energy consumption. Thus road lighting will increasingly become a more useful measure against road accidents in darkness.

However, the steps forward depend very much on the efforts of research within some important fields.

- The relationship between lighting and accidents must be thoroughly investigated. Thousands of kilometres of roads were equipped with modern road lighting through the 1990s, and detailed information is available from injuries and fatalities before and after installation of lighting. Detailed information is also available on road characteristics and lighting characteristics. It is high time that some researchers grasp the opportunity to study in detail the relationship between road lighting and accidents.

- Peripheral vision must be studied in real traffic situations. This may be of great importance for detection of pedestrians at the road side, vehicles coming from a side road, or animals crossing the road. New mesopic models must include the spectral efficiency in peripheral vision when performing visual tasks in real traffic.

- The critical visual tasks related to accidents must be recognized, and the processes of scanning, perception, recognition and manoeuvring must be analysed.

- Visibility criteria have to be developed, where factors important for visibility in critical situations must be considered.

- Research is needed to develop better light sources, light fixtures, and dynamic light control systems.

- Research is needed to evaluate alternatives or supplements to road lighting, such as lighter road surfaces, better road markings and the use of LED for guidance. Such measures may reduce the need for road lighting or reduce the needed lighting level.

- A trend that must be regarded, when considering energy saving in road lighting, is that the group of old drivers is increasing. It is well known that old drivers have great vision problems in night-time traffic, and research is needed to find how road lighting can ensure mobility and safety for old drivers.

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Paper II

Effects of road lighting on accidents: a before-and-after study in Norway

Unpublished

Effects of road lighting on accidents: a before-and-after study in Norway

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Abstract

Objective: To estimate the safety effect of modern road lighting on accidents in general and during different conditions and to control for potentially confounding factors. Most of the earlier studies are based on accidents that occurred on North American and British roads more than 30 years ago and many of the studies did not control for confounding factors. **Method:** This paper presents a before-and-after study of the effects of road lighting on accidents on 125 road sections in Norway with a total length of 274 km. The study controlled for regression-to-the-mean and long-term trends. **Results:** The number of injury accidents in darkness was reduced by 28 %. Fatal accidents in darkness were reduced by 53 % (not controlled for the effect of regression-to-the-mean). Road lighting was found to be more effective for older drivers than for other drivers, more effective in fine weather than during precipitation, more effective in the afternoon and evening than later at night and in the morning, more effective during winter and summer than in autumn, more effective on roads with high speed limit than on roads with low speed limit, and more effective on roads with low traffic volumes than on roads with high traffic volumes. **Conclusions:** The study gives evidence on a general safety effect of modern road lighting. The estimated mean effect on injury accidents is equal to the mean effect found in earlier studies. This confirms that road lighting is still an effective road safety measure.

Key words: road lighting, before-and-after study, evaluation, Norway

1 Introduction

The effects on accidents of providing road lighting have been studied extensively. Elvik and Vaa (2004), in the Handbook of Road Safety Measures, have summarised evidence from 38 studies that evaluated the effects of providing lighting on previously unlit roads. The best summary estimates of effect, based on a meta-analysis of the studies, were a 64 % reduction of fatal accidents in darkness, a 28 % reduction of injury accidents, and a 17 % reduction of property damage only accidents.

Elvik (2004) updated the meta-analyses presented by Elvik and Vaa (2004) as part of the ongoing development of a Highway Safety Manual in the United States. The update added new studies and included an assessment of study quality, based on criteria proposed for the Highway Safety Manual by Ezra Hauer. A study was rated as good if it controlled adequately for potentially confounding factors. The most common design in studies evaluating the effects of road lighting was a simple before-and-after study, using accidents in daytime as a comparison group. This study design will not control for long-term trends with respect to the distribution of accidents between day and night, nor will it control for regression-to-the-mean attributable to an abnormally high number of accidents in darkness in the before period. Most studies that have evaluated the effects of road lighting were therefore rated as poor. It should also be regarded that most of the studies were from the USA and Great Britain and were based on accidents that occurred more than 30 years ago.

Future road lighting systems are likely to be adaptive, i.e. it will be possible to vary the intensity of lighting depending on the need for it. To apply adaptive lighting in a way that does not greatly reduce the safety benefits associated with lighting, knowledge is needed about variation in the effects of road lighting with respect to various environmental characteristics and types of accident. Little is known about this from earlier studies. Elvik (2004) found that the effects of road lighting were almost the same in rural areas, urban areas and on freeways.

The before-and-after study presented in this paper has two main objectives. The first is to conduct a study that controls more adequately for confounding factors than most previous studies of the effects of road lighting. The second objective is to examine how the effects of road lighting vary according to type of accident as well as several background variables, such as type of road, traffic volume, weather conditions, age of road users, etc.

2 Method

2.1 Sample Selection

Employees of the Public Roads Administration in each of its 30 districts, covering the national road network in Norway, were asked to identify road sections according to three criteria:

1. Road lighting had been installed or improved on the road section in the period 1991 – 2000.

2. No other measures had been carried out on or near the section that could have influenced the number of accidents significantly in the study period (i.e. the year of installation of road lighting, the last five years before the installation, and the first five years after the installation).

3. The length of the selected road section had to be at least 1000 metres.

Each district was asked to select as many lighting installations as possible and at least one from each of the following road types, if present in the district:

1. Four lane motorways

2. Rural main roads without pedestrians and cyclists

3. Rural main roads with pedestrians and cyclists

4. Urban main roads with pedestrians and cyclists

The first and third criterion was not completely satisfied in the selection of study sections. The final sample consisted of 125 road sections with a total length of 274 km.

In addition to the data provided by the districts of the Public Roads Administration, large amounts of data were downloaded from the national road data bank. These data provide information on background characteristics of the road, including type of road and speed limit. The road data bank also contains a register for accidents, providing detailed information about each injury accident. The data provided by the districts and the data obtained from the road data bank were merged by using county, road number, section number and kilometre location reference as matching variables.

2.2 Estimate of Safety Effect

The effect of road lighting on safety was estimated in terms of the odds ratio. A numerical example shows the estimate of effect:

Number of accidents in hours of darkness before:	188
Number of accidents in daylight before:	375
Number of accidents in hours of darkness after:	155
Number of accidents in daylight after:	467

$$\text{Estimate of effect} \quad \frac{\left(\frac{155}{467}\right)}{\left(\frac{188}{375}\right)} = 0.662 = 34\ \%\ \text{accident reduction}$$

Darkness or daylight is a coded variable in the accident record. Odds ratios were converted to percentage changes in the number of accidents for ease of understanding. In this example, the effect was a 34 % reduction of the number of accidents (presented as – 34% in the subsequent tables).

Uncertainty was estimated by taking the log of the odds ratio. The variance of the logarithm of the odds ratio is:

$$v_i = \frac{1}{A} + \frac{1}{B} + \frac{1}{C} + \frac{1}{D}$$

A, B, C, and D are the four numbers that enter the calculation of the estimate of effect. A comparison group was used to control for long-term trends. In that case, the estimate of effect is the ratio of odds ratios. Its variance is estimated the same way as for the odds ratio, but there are now eight numbers that enter the calculation.

The standard error of each estimate of effect equals the square root of the variance. 95% confidence intervals were estimated by adding or subtracting 1.96 times the standard error of the estimate of effect.

2.3 Controlling for Regression-to-the-mean (RTM)

To control for regression-to-the-mean, an accident prediction model was fitted to the data. The model relied on data for all national roads for the period 1986-2005. The model predicted the number of accidents in darkness as a function of traffic volume (AADT), type of road (motorway or other), speed limit (km/h), changes in speed limit in 2001 and 2002, number of lanes, number of junctions per kilometre of road and whether the road was designated as a main road (yes/no). Negative binomial regression was applied to develop the accident prediction model. The model was similar to models developed by Ragnøy, Christensen and Elvik (2002).

Based on model predictions, the empirical Bayes method (Hauer 1997) was applied to obtain estimates of the expected number of accidents for each of the 125 road sections included in the study. These estimates were compared to the recorded number of accidents in the before-period.

The mean annual expected number of accidents in darkness for the 125 road sections was 0.0975. The mean recorded number was 0.1065. Thus, the mean recorded number was 9 % higher than the mean expected number. The sample included both road sections that had a lower recorded than expected number of accidents and road sections that had a higher recorded than expected number of accidents.

The recorded number of accidents was very close to the expected number of accidents. While a small bias may be present in the data, it is at most 9 %. The effect of the regression-to-the-mean (RTM) is at most 9 %.

The RTM effect is not estimated for fatal accidents or subgroups of accidents and the effect of RTM is therefore not controlled for in estimation of the effect of road lighting on fatal accidents or subgroups of accidents.

The finding that regression-to-the-mean is small is not surprising. It is well known at the Norwegian Public Roads Administration that road lighting is mainly implemented on the basis of a high traffic volume (AADT) and not so often on the basis of a high number of accidents in darkness or a high darkness to daylight accident ratio.

2.4 Controlling for Long Term Trends

To control for long term trends in accidents, in particular trends regarding the distribution of accidents between daylight and darkness, a comparison group is needed. All main road sections in Norway except the 125 study sections were used as comparison group. There was, however, a problem related to the fact that road lighting had been installed at different times. One way of dealing with this problem was to use the mean time of installation of road lighting as the virtual time of installation for the comparison group. If trends are not linear, however, this could introduce a bias. The virtual times of installation for the comparison group were therefore allocated randomly. The 125 study road sections were placed in groups according to the year of installation of road lighting. The distribution of all accidents between these groups was then determined, disregarding whether they occurred before or after road lighting was installed. In this way, the percentage of accidents on the sections where lighting was installed in 1990, in 1991, etc, was obtained. To obtain the same distribution of the accidents in the comparison group according to the virtual year of installation, the year of each comparison accident was allocated by random draws where the probability of for example 1991 was the percentage of road sections where lighting had been installed in 1991. Accidents in the comparison group were then defined as before or after in the same way as the accidents on the treated sections, using periods of five years before and five years after the year of virtual installation. The change in the darkness/daylight ratio of accidents from the before period to the after period was then calculated.

When subgroups of accidents were analysed, the same procedure was carried out for the subgroup. The distribution of accidents in the subgroup by installation year for the study sections was used to randomly allocate the virtual year of installation for the accidents in the comparison group.

2.5 Controlling for a Potential Effect of Road Lighting on Accidents in Daylight

Estimates of effect based on the odds ratio or on the ratio of odds ratios rely on the assumption that road lighting has no effect on accidents in daylight. If this assumption is incorrect, estimates of effect can be biased.

Road lighting could influence accidents in daytime, since lighting poles represent a new hazard. Moreover, road lighting may influence speed, which would also be expected to influence accident occurrence both in daylight and in darkness. One Norwegian study (Sakshaug 1986) found that road lighting was associated with a reduction in speed; another Norwegian study (Assum et. al. 1999) found the opposite.

If road lighting is associated with an increase in accidents in daylight, the odds ratio estimator will overstate the true effect of road lighting. Conversely, if road lighting is associated with a reduction in accidents in daylight, the odds ratio estimator will understate the true effect on safety. In the present study, like in all previous studies, the assumption has been made that there is no net effect of road lighting on accidents in daylight.

3 Results

The results of the study are shown in Tables 1 and 2. Table 1 shows estimates of effect stated in terms of the odds ratio, i.e. not controlling for long-term trends. Table 2 shows corresponding estimates of effect based on the ratio of odds ratios, i.e. controlling for long term trends.

Table 1: Accidents before and after the installation of road lighting on 125 road sections, and the safety effect of road lighting (not controlled for RTM and general trends).

Type of accident	Number of accidents last five years before			Number of accidents first five years after			Effect of road lighting not controlled for general trends
	Dark	Day	Dark/day ratio	Dark	Day	Dark/day ratio	
Injury accident	188	375	0.50	155	467	0.33	-34 %
Fatal accident	14	29	0.48	8	31	0.26	-47 %
Motorway 4 lanes, 90 – 100 km/h	15	23	0.65	13	29	0.45	-31 %
2 lanes, 80 – 90 km/h	72	98	0.73	46	123	0.37	-49 %
2 lanes, 60 – 70 km/h	57	137	0.42	52	157	0.33	-20 %
2 lanes, 40 – 50 km/h	15	32	0.47	12	30	0.40	-15 %
2 lanes, 80 km/h, ADT > 8 000 vehicles	38	50	0.76	32	71	0.45	-41 %
2 lanes, 80 km/h, ADT < 8 000 vehicles	33	48	0.69	14	52	0.27	-61 %
Frontal collision	36	98	0.37	28	94	0.30	-19 %
Run off the road accident	59	81	0.73	69	130	0.53	-27 %
Hitting object in carriageway	4	5	0.80	2	7	0.29	-64 %
Rear end collision	32	120	0.27	19	169	0.11	-58 %
Angle collision	15	33	0.45	9	39	0.23	-49 %
Collision with pedestrian	19	15	1.27	12	11	1.09	-14 %
Collision with animal	18	4	4.50	8	6	1.33	-70 %
Only drivers age <40	124	204	0.61	123	205	0.60	-1 %
Only drivers age >65	24	81	0.30	9	99	0.09	-69 %
Heavy vehicle involved	32	96	0.33	18	117	0.15	-54 %
Only light cars involved	213	446	0.48	194	536	0.36	-24 %
MC or moped involved	13	52	0.25	8	49	0.16	-35 %
Fine weather	118	317	0.37	94	384	0.25	-34 %
Rain or snow	51	55	0.93	51	74	0.69	-26 %
Dry road surface	63	263	0.24	58	309	0.19	-22 %
Wet surface	51	55	0.93	43	92	0.47	-50 %
Snow/ice covered surface	67	48	1.40	49	59	0.83	-41 %
Winter, Jan., Feb., March	71	68	1.04	52	80	0.65	-38 %
Late autumn, Oct., Nov.	44	40	1.10	41	38	1.08	-2 %
Summer, May, June, July	10	144	0.07	8	179	0.04	-36 %
Night, 0 – 6 o'clock	47	10	4.70	42	13	3.23	-31 %
Morning, 6 – 9	10	37	0.27	13	44	0.30	+9 %
Afternoon, 15 – 18	33	100	0.33	19	127	0.15	-55 %
Evening, 18 – 24	91	54	1.69	78	62	1.26	-25 %

Table 2: Effect of road lighting on accidents in darkness on 125 road sections, controlled for trends in accidents

Type of accident	Effect of road lighting not controlled for trends in accidents	Effect of road lighting controlled for trends in accidents	95 % confidence interval
Injury accident	-34 %	-34 %	-49 %, -15 %
Fatal accident	-47 %	-53 %	-83 %, +32 %
Motorway 4 lanes, 90 – 100 km/h	-31 %	Not controlled	Not calc.
2 lanes, 80 – 90 km/h	-49 %	Not controlled	Not calc.
2 lanes, 60 – 70 km/h	-20 %	Not controlled	Not calc.
2 lanes, 40 – 50 km/h	-15 %	Not controlled	Not calc.
2 lanes, 80 km/h, ADT > 8 000 vehicles	-41 %	Not controlled	Not calc.
2 lanes, 80 km/h, ADT < 8 000 vehicles	-61 %	Not controlled	Not calc.
Frontal collision	-19 %	-20 %	-55 %, +43 %
Run off the road accident	-27 %	-27 %	-54 %, +14 %
Hitting object in carriageway	-64 %	-67 %	-96 %, +166 %
Rear end collision	-58 %	-62 %	-80 %, -28 %
Angle collision	-49 %	-49 %	-81 %, +32 %
Collision with pedestrian	-14 %	-18 %	-72 %,+140 %
Collision with animal	-70 %	-73 %	-94 %, +27 %
Only drivers age <40	-1 %	Not controlled	Not calc.
Only drivers age >65	-69 %	Not controlled	Not calc.
Heavy vehicle involved	-54 %	Not controlled	Not calc.
Only light cars involved	-24 %	Not controlled	Not calc.
MC or moped involved	-35 %	Not controlled	Not calc.
Fine weather	-34 %	-35 %	-53 %, -11 %
Rain or snow	-26 %	-20 %	-53 %, +36 %
Dry road surface	-22 %	-26 %	-50 %, +11 %
Wet surface	-50 %	-47 %	-69 %, -10 %
Snow/ice covered surface	-41 %	-42 %	-66 %, -1 %
Winter, Jan., Feb., March	-38 %	-38 %	-62 %, +1 %
Late autumn, Oct., Nov.	-2 %	-2 %	-47 %, +83 %
Summer, May, June, July	-36 %	-42 %	-78 %, +52 %
Night, 0 – 6 o'clock	-31 %	-17 %	-68 %, +111 %
Morning, 6 – 9	+9 %	+2 %	-60 %, +161 %
Afternoon, 15 – 18	-55 %	-56 %	-76 %, -17 %
Evening, 18 – 24	-25 %	-20 %	-50 %, +30 %

For some of the subgroups, control for long-term trends was not performed as it was unlikely to make much of difference for the estimate of effect, but would add to the statistical uncertainty of the estimates. Long-term trends in accidents do not appear to influence the results very much, given the statistical uncertainty in each of the subgroups. The same can be said for the effect of RTM which is only estimated for all injury accidents and not for the subgroups.

Despite the fact that the confidence intervals are wide, the estimated effects of road lighting are very consistent with the findings of previous studies, except in some of the subgroups.

When controlled for the effect of RTM, the effect of road lighting on injury accidents in darkness is (−28 %). This is consistent with previous studies. The same applies to the effect on fatal accidents (−53 %), though it is not controlled for the effect of RTM. The number of accidents in darkness is reduced in all sub groups, except for one. For some groups the reduction is significant, but for other groups it is not, as can be seen from the confidence intervals. The only group that shows an increase in accidents is “Morning, 6 – 9 am”.

The safety effect on motorways is smaller in this study (−31 %) than in former studies from the United States (−50 %). For pedestrian accidents, the safety effect in this study (−18 %) is much smaller than in earlier studies (−45 %). For motorway accidents and pedestrian accidents, however, the results are uncertain because of a low accident count.

The safety effect on 2-lane roads with speed limits 80 – 90 km/h (−49 %) is larger than the effect on 4-lane motorways with speed limits 90 – 100 km/h (−31 %). The safety effect on 2-lane roads is greater when the speed limit is high than when the speed limit is low, and the effect is smaller when traffic volume is high than when it is low. The differences are not significant but they indicate that the influence of speed limit and traffic volume on the effect of road lighting should be subject to future studies.

When comparing different types of accident, the estimated effect on accidents in darkness varies from −73 % for “collision with animal” to −18 % for “collision with pedestrian”. The confidence intervals are wide, except for “rear end collision” and the differences in the safety effect between the groups are not significant. More comprehensive studies are needed to improve knowledge about the safety effect of road lighting with respect to different types of accident.

For drivers under 40 years of age, no safety effect of road lighting is found at all, while the effect for drivers over 65 years is large (−69 %). The safety effect for accidents involving heavy vehicles is greater (−54 %) than the safety effect for accidents involving only light vehicles (−24 %).

The safety effect is smaller during precipitation (−20 %) than during fair weather conditions (−35 %). The effect is smaller in the rainy autumn months (−2 %) than in the other seasons.

On a wet pavement, however, the safety effect is larger than on a dry surface. This seems to be a contradiction. The safety effect also varies by the time of day. The effect is larger in the afternoon (−56 %), smaller in the evening (−20 %), and smallest in the night (−17 %). In the morning, no effect at all is found (−2 %). The differences are not significant.

4 Discussion and conclusions

One of the objectives of this paper was to control more fully for potentially confounding factors than most previous studies of road lighting have done. In particular, the study aimed to control for regression-to-the-mean and long-term trends in accidents. It turned out that neither of these potentially confounding factors actually did confound study results to a great extent. Regression-to-the-mean is at most 9 %. If the recorded number of accidents in darkness in the before period is adjusted down by 9 %, the estimated effect of road lighting on all injury accidents in darkness becomes 28 %, versus 34 % when regression-to-the-mean is not controlled for. Controlling for long-term trends had no effect on the estimate of effect for all injury accidents, leaving it unchanged at 34 %.

The main findings of the study are consistent with those of previous studies. It is therefore likely that the effects attributed to road lighting are indeed caused by this measure and not by something else. The quality of the road lighting on the sections included in this study is generally good and in good accordance with European and Norwegian standard. The light source is High Pressure Sodium. Average road surface luminance is between 1.0 cd/m^2 and 2.0 cd/m^2, and average luminance, uniformity and glare are related to road and traffic characteristics. Because of this, and because of the limited amount of data, it is not possible in this study to find a relationship between the safety effect of road lighting and the quality of the lighting. A difference in quality of the road lighting may give other results, but this we do not know, neither from earlier studies nor from this study.

The following conclusions can be drawn:

- The estimated effect of road lighting on injury accidents in darkness is −34 % (95 % confidence interval is −49 % to −15 %). This confirms that the mean result from earlier studies (−28 %) is still valid for modern road lighting on Norwegian main roads.

- The estimated effect of road lighting on fatal accidents in darkness is −53 %. This confirms the mean result from earlier studies (−60 %). However, the confidence interval is wide (−83 %, +32 %).
- For all accident groups, except for accidents in the morning, there is a reduction in accidents in darkness due to road lighting. The reduction is significant for some of the groups.
- The estimated safety effect is smaller during precipitation (−20 %) than during fair weather conditions (−35 %). Further studies are recommended, because this subject is relevant for future road lighting systems that may be adaptive to different weather conditions.
- The results show no safety effect of road lighting on accidents in darkness in the humid autumn months (−2 %). The calculated safety effect is greater during the winter season (−38 %) and during the summer (−42 %). However, the differences are not significant.
- During a 24 hour day, the safety effect is largest in the afternoon (−56 %) smaller in the evening (−20 %) and in the night (−17 %), and smallest in the morning (2 % increase). The differences are not significant.
- For drivers under 40 years of age, no safety effect of road lighting is found at all, while the effect for drivers over 65 years is large (-69 %).
- The safety effect for accidents involving heavy vehicles is greater (−54 %) than the safety effect for accidents involving only light vehicles (−24 %).

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Paper III

Effect of road lighting: an analysis based on Dutch accident statistics 1987 – 2006

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Effects of road lighting: An analysis based on Dutch accident statistics 1987–2006

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ABSTRACT

This study estimates the safety effect of road lighting on accidents in darkness on Dutch roads, using data from an interactive database containing 763,000 injury accidents and 3.3 million property damage accidents covering the period 1987–2006. Two estimators of effect are used, and the results are combined by applying techniques of meta-analysis. Injury accidents are reduced by 50%. This effect is larger than the effects found in most of the earlier studies. The effect on fatal accidents is slightly larger than the effect on injury accidents. The effect during twilight is about 2/3 of the effect in darkness. The effect of road lighting is significantly smaller during adverse weather and road surface conditions than during fine conditions. The effects on pedestrian, bicycle and moped accidents are significantly larger than the effects on automobile and motorcycle accidents. The risk of injury accidents was found to increase in darkness. The average increase in risk was estimated to 17% on lit rural roads and 145% on unlit rural roads. The average increase in risk during rainy conditions is about 50% on lit rural roads and about 190% on unlit rural roads. The average increase in risk with respect to pedestrian accidents is about 140% on lit rural roads and about 360% on unlit rural roads.

1. Introduction

The effects on accidents of providing or improving road lighting have been studied extensively. Some studies deal with the effect on injury accidents on urban roads (Tanner and Christie, 1955; Tanner, 1958; Transportforskningskommissionen, 1965; Christie, 1966; Tennessee Valley Authority, 1969; Walthert et al., 1970; Fisher, 1971; Box, 1972a, 1976; Cornwell and Mackay, 1972; Sabey and Johnson, 1973; Fisher, 1977; Jørgensen, 1980; Scott, 1980; Box, 1989), some deal with the effect on injury accidents on rural roads (Transportforskningskommissionen, 1965; Christie, 1966; Walthert et al., 1970; Box, 1972a; Cornwell and Mackay, 1972; Sabey and Johnson, 1973; Mäkelä and Kärki, 2004), some deal with the effect on motorway accidents (Billon and Parsons, 1962; Christie, 1962, 1966; Walthert et al., 1970; Box, 1971, 1972b; Cornwell and Mackay, 1972; Nishimori, 1973; Andersen, 1977; Ketvirtis, 1977; Hilton, 1979; Lamm et al., 1985; De Clercq, 1985; Cobb, 1987; Griffith, 1994; Bruneau et al., 2001), some deal with the effect on pedestrian accidents (Jørgensen and Rabini, 1971; Pegrum, 1972; Polus and Katz, 1978; Zegeer and Zegeer, 1988; Huang et al., 1993; Jensen, 1998), and some deal with the effect on accidents at junctions (Onser, 1973; Lipinski and Wortman, 1976; Walker and Roberts, 1976; Salminen, 1978; Brude and Larsson, 1981, 1985; Schwab et al., 1982; Preston and Sshoenecker, 1999; Green et al., 2003; Isebrands et al., 2004).

The International Commission on Illumination analysed 62 studies from 15 countries about the effect of road lighting (CIE, 1992) on accidents. The average effect of installation of road lighting based on 23 before-and-after studies was 30% reduction in night-time injury accidents. Only one study showed an increase in accidents. The effect on pedestrian accidents was larger than the effect on all accidents.

Elvik and Vaa (2004), in the Handbook of Road Safety Measures, have summarised evidence from 38 studies that evaluated the effects of providing lighting on previously unlit roads. The best summary estimates of effect, based on a meta-analysis of the studies, were a 64% reduction of fatal accidents in darkness, a 28% reduction of injury accidents, and a 17% reduction of property damage only accidents. Elvik and Vaa also summarised evidence from 26 studies that evaluated the effects of upgrading existing lighting. Improving the quality of lighting was found to reduce the number of accidents in darkness; the more so, the greater the improvement. However, a precise description of the measures taken to improve lighting was not given. It is therefore difficult to develop practical guidelines based on the information given by Elvik and Vaa. Finally, Elvik and Vaa summarised evidence from eight studies that evaluated the effects of reducing road lighting to save energy. These studies

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found that reducing lighting was associated with an increase of the number of accidents in darkness.

Elvik (2004) updated the meta-analyses presented by Elvik and Vaa (2004) as part of the ongoing development of a Highway Safety Manual in the United States. The update added new studies and included an assessment of study quality, based on criteria proposed for the Highway Safety Manual by Ezra Hauer. A study was rated as good if it controlled adequately for potentially confounding factors. The most common design in studies evaluating the effects of road lighting is a simple before-and-after study, using accidents in daytime as a comparison group. This study design will not control for long-term trends with respect to the distribution of accidents between day and night, nor will it control for regression-to-the-mean attributable to an abnormally high number of accidents in darkness in the before period. Most studies that have evaluated the effects of road lighting were therefore rated as poor.

While it seems clear that road lighting in most cases reduces the number of accidents in darkness, less is known about variation in the effect of road lighting with respect to the quality of lighting and various background characteristics. Elvik (2004) found that the effects of road lighting were almost the same in rural areas, urban areas and on freeways. Future road lighting systems are likely to be adaptive, i.e. it will be possible to vary the intensity of lighting depending on the need for it. To apply adaptive lighting in a way that does not greatly reduce the safety benefits associated with lighting, more needs to be known about variation in the effects of road lighting with respect to various environmental characteristics and types of accident (not all types of accident are equally likely to occur at any time of the day).

A controlled before-and-after study comprising 125 Norwegian main road sections found a 34% reduction in the number of injury accidents and a 53% reduction in the number of fatalities during darkness (Wanvik, submitted for publication). The results of this study confirmed the results of earlier studies. However, the results were uncertain, due to a small number of accidents. The total number of injury accidents (sum before-and-after) was 1185.

In principle, the effects of road lighting can be evaluated by means of a cross-section study design, preferably employing data for an extensive road system in order to increase the size of the accident sample. A good example is the study made by Griffith (1994). A comparison of safety on lit and unlit roads eliminates two of the most important confounding factors in before-and-after studies: regression-to-the-mean and long-term trends in the number of accidents. On the other hand, there is a risk of endogeneity bias (Kim and Washington, 2006). This bias is, in a sense, a mirror image of the bias attributable to regression-to-the-mean. It arises because sites tend to be selected for treatment because they have a particular safety problem, e.g. an abnormally high proportion of accidents in darkness. Installing lighting may reduce that proportion, but not always to the level found on unlit roads. Thus, when lit and unlit roads are compared in a cross-section study, the lit roads may have a higher proportion of accidents in darkness than the unlit roads, which erroneously suggests an adverse effect of road lighting. A very instructive example of endogeneity bias and how it can be controlled for by statistical techniques is given by Kim and Washington (2006).

The present study relies on aggregate data that do not allow for the use of econometric techniques to control for endogeneity bias. The potential for this bias has been minimised by using a large sample of roads and data for a long period of time. It is unlikely that all lit roads in a large sample will have a higher-than-average proportion of accidents in darkness. Also, by using data that refer to a long period of time, random fluctuations are greatly reduced and the recorded number of accidents will more accurately reflect the long-term expected number.

The study in this paper is based on the information available in an interactive Internet database (SWOV, 2007) containing 762,835 injury accidents and 3,271,343 property damage accidents in Dutch road traffic during the period 1987–2006. Selections of accidents are easily made by defining the content of a range of variables related to the road characteristics, traffic and road user characteristics, weather conditions, etc. By also defining “light conditions” and “street lighting”, accidents can be sorted by daylight and darkness conditions on lit roads and unlit roads, respectively, with respect to the selected set of background variables. The distribution of accidents by daylight conditions on lit and unlit roads was compared in order to evaluate the effects of road lighting on Dutch roads.

2. Methods of analysis

2.1. The odds ratio estimator of effect

Two estimators of effect have been applied in this study. The first is the odds ratio, defined as follows:

$$\text{Odds ratio} = \frac{\text{Number of accidents in darkness on lit roads/number of accidents in daylight on lit roads}}{\text{Number of accidents in darkness on unlit roads/number of accidents in daylight on unlit roads}}$$

The odds ratio is based on the number of accidents only. It does not refer to any data regarding to the distribution of traffic between daylight and darkness. This distribution may differ between lit and unlit roads, and this could bias the odds ratio. In order to minimise the potential for bias, the odds ratio has been estimated for each hour of the day separately. Only hours that have at least 15 accidents in each of the four groups used to estimate the odds ratio were included. This leaves only hours 7, 8, and 18–22 for analysis. All other hours of the day are omitted. In this way night-time hours, when fatigue, alcohol and speeding are frequent causes of accidents, are excluded.

The idea of confining the analysis to certain hours for the purpose of controlling for confounding factors that tend to be associated with darkness, such as fatigue or drinking and driving, has previously been suggested by Sullivan and Flannagan (2002) and Johansson (2007). By doing the analysis hour-by-hour, the effects of potential differences between lit and unlit roads with respect to the distribution of traffic are also minimised. Estimates referring to different hours have been combined by applying the log odds technique, see Section 2.3.

2.2. The ratio of odds ratios estimator of effect

The second estimator of effect used in the study is the ratio of odds ratios. This estimator is based on a method for assessing the risk associated with darkness, developed by Johansson (2007). The idea is that by studying how the number of accidents in a specific hour of the day changes throughout the year, it is to a large extent possible to eliminate the effects of confounding variables when estimating the change in accident risk associated with darkness. Certain hours, such as hours 8 (07:00–07:59) and 18 (17:00–17:59) are dark part of the year, but have full daylight in another part of the year. If darkness contributes to more accidents, one would expect these hours to have more accidents in the part of the year when there is darkness than in the part of the year when there is daylight. An hour that has daylight the whole year is used as a comparison group, to control for seasonal variations in the number of accidents.

Table 1
Effect of road lighting on fatal accidents in darkness according to odds ratio estimator of effect.

Hour of the day	Daylight ac.		Darkness ac.		Effect of lighting
	Lit	Unlit	Lit	Unlit	
H7	136	53	205	132	−39%
H8	341	104	193	107	−45%
H18	884	188	196	87	−52%
H19	523	101	303	170	−66%
H20	414	85	343	158	−55%
H21	297	82	299	143	−42%
H22	115	43	351	177	−26%
Weighted mean					−49%
95% confidence interval					−57%, −39%

An odds ratio is estimated, indicating the change in risk associated with darkness. Similar estimates are made for lit and unlit roads and a ratio of the odds ratios is formed to estimate the effect of road lighting.

The method is not useful for estimating the effect of road lighting during hours of twilight, because no hours of the day have only twilight through a whole month.

2.3. The log odds technique for combining odds ratios and ratios of odds ratios

Combining the results from two analysis based on two different methods using the same sample of data usually strengthen the validity of the results. A log odds technique was therefore applied to combine estimates of odds ratios and ratios of odds ratios. The log odds method of analysis takes the logarithm of the odds ratio as the estimate of effect. Combining logarithms of odds ratios yields an unbiased estimate of the weighted mean effect based on a set of estimates of effect. Each estimate of effect is assigned a statistical weight which is inversely proportional to its variance. For a general description of the technique, see Shadish and Haddock (1994). Its application to road safety evaluation studies is explained by Elvik and Vaa (2004).

3. Results

3.1. General effects of road lighting on all roads

Estimates of effect based on the odds ratio are shown in Table 1 for fatal accidents and Table 2 for injury accidents. The effects are found to be slightly greater for fatal accidents than for injury accidents.

Applying the ratio of odds ratios estimator of effect, it was not possible to estimate the effect on fatal accidents because of too small accident counts. The effect on injury accidents was estimated to 55% reduction of accidents in darkness (95% confidence interval from −59% to −50%).

Table 2
Effect of road lighting on injury accidents in darkness according to odds ratio estimator of effect.

Hour of the day	Daylight ac.		Darkness ac.		Effect of lighting
	Lit	Unlit	Lit	Unlit	
H7	3496	410	5004	1202	−51%
H8	16484	1554	7512	1548	−54%
H18	47285	2964	8469	1040	−49%
H19	25764	1802	12418	1623	−47%
H20	20039	1375	14663	1762	−43%
H21	12489	1051	12278	1703	−40%
H22	4847	462	11997	1827	−39%
Weighted mean					−46%
95% confidence interval					−50%, −42%

Table 3
Effect of road lighting on injury accidents in twilight according to odds ratio estimator of effect.

Hour of the day	Daylight ac.		Twilight ac.		Effect of lighting
	Lit	Unlit	Lit	Unlit	
H6	494	90	677	164	−25%
H7	3496	410	1333	283	−45%
H8	16484	1554	4982	683	−31%
H9	38523	2420	6523	672	−39%
H17	63098	3891	3474	273	−22%
H18	47285	2964	7200	688	−34%
H19	25772	1802	2330	241	−32%
H20	19962	1375	1498	126	−18%
H21	12645	1051	1706	188	−25%
H22	4947	462	2265	282	−25%
Weighted mean					−31%
95% confidence interval					−36%, −26%

Combining estimates based on the two estimators, the weighted mean effect is a reduction of injury accidents in darkness of 50% (−53%, −47%).

Table 3 shows estimates of effect for accidents in twilight, applying the odds ratio estimator. Effects are somewhat smaller than in darkness, but still clearly statistically significant (based on 95% confidence intervals).

3.2. Effects of road lighting in urban areas

Road lighting was found to reduce injury accidents in darkness by 13% in urban areas (−29%, +6%). Nearly all urban Dutch roads are lit, and only 1% of the accidents on urban roads occur on unlit roads. Road and traffic characteristics are therefore probably quite different on unlit urban roads compared to most lit urban roads. A comparison may therefore be like comparing apples and oranges, and calculations of the safety effect may produce wrong answers. The rest of this paper will therefore focus on effects in rural areas.

3.3. Effects of road lighting in rural areas

Table 4 shows results estimates employing the odds ratio estimator of effect for different weather and road surface conditions, different road user groups and different accident types. The effect is calculated hour-by-hour, but only the weighted mean result is shown in the table. The table also gives information about which hours are included in the calculation and the uncertainty in the weighted effect.

Table 4 shows some significant differences (based on the 95% confidence intervals) of the effect of road lighting on injury accidents:

- The effect in rain (−44%) and fog (−26%) and snow (−26%) is significantly smaller than the effect in fair weather (−56%).
- The effect when the road surface is wet (−46%) is significantly smaller than when the surface is dry (−56%) and the effect for snow or ice covered surfaces (−22%) is even significantly smaller than the effect for a wet road surface.
- The effect for pedestrian accidents (−72%) and moped accidents (−60%) is significantly larger than the effect for automobile accidents (−50%) and motorcycle accidents (−25%).

There is no significant difference between the safety effects for different accident types (hit fixed objects, frontal collisions, etc.) and there is no difference between the driver age groups 60–74 years and 30–39 years.

Table 4
Effect of road lighting on injury accidents in different situations on rural roads according to odds ratio estimator of effect.

Accident group	Hours included in calculation	Effect	
		Mean	95% conf. int.
All	H7, H8, H18–H22	−54%	−56%, −52%
Fair weather	H7, H8, H18–H22	−56%	−58%, −53%
Rain	H7, H8, H18–H22	−44%	−53%, −34%
Fog[a]	H7, H8, H18	−26%	−46%, +1%
Snow[a]	H8, H18–H20	−26%	−40%, +8%
Dry surface	H7, H8, H18–H22	−56%	−59%, −53%
Wet surface	H7, H8, H18–H22	−46%	−50%, −42%
Snow/ice covered[a]	H7–H9, H18, H19	−22%	−31%, −11%
Pedestrian	H18–H21	−72%	−79%, −63%
Bicycles	H8, H18–H22	−58%	−64%, −51%
Moped	H7, H8, H18–H22	−60%	−65%, −56%
MC	H7, H8, H18–H22	−25%	−44%, −1%
Automobile	H7, H8, H18–H22	−50%	−53%, −48%
Driver age 30–39	H7, H8, H18–H22	−53%	−57%, −49%
Driver age 60–74	H7, H8, H18–H22	−53%	−60%, −45%
Hit fixed object	H7, H8, H18–H22	−55%	−59%, −50%
Frontal collision	H7, H8, H18–H22	−50%	−56%, −43%
Flank collision	H7, H8, H18–H22	−46%	−51%, −40%
Hit animal[a]	H7, H8, H19–H22	−58%	−66%, −48%
Rear end coll.	H7, H8, H18–H22	−48%	−53%, −44%
Speed limit 120	H7, H8, H18–H22	−49%	−54%, −43%

[a] Property damage accidents are included.

Table 5 shows results using the ratio of odds ratios as estimator of effect for some of the same groups as in Table 4. The table also gives additional information concerning the increase in risk of accidents during the hours of darkness on lit roads and unlit roads. The 95% confidence interval for all estimates is also included. The estimated effects in Table 5 are not significantly different from the effects presented in Table 4. The confidence intervals are larger in Table 5 than in Table 4, except for accidents during foggy conditions.

In Table 6, mean results have been estimated by combining estimates based on the odds ratio estimator of effect and estimates based on the ratio of odds ratios estimator of effect. In general, the pattern in the findings is similar to that reported in Tables 4 and 5.

4. Discussion

This paper has estimated the effects of road lighting by comparing the distribution of accidents by daylight conditions on lit and unlit roads in the Netherlands. Using a cross-section design is not common in studies evaluating the effects of road lighting. Most previous studies have employed a before-and-after design (Elvik, 1995, 2004). While a cross-section design is less likely than a before-and-after design to suffer from bias due to regression-to-the-mean and long-term trends, there are other potential sources of error. Two of the most important are systematic differences between lit and unlit roads with respect to the distribution of traffic throughout the day and endogeneity bias, arising from a tendency to introduce road lighting on roads that have a higher-than-average proportion of accidents in darkness.

Both these potential sources of error can be expected to lead to lower estimates of the effects of road lighting than the estimates of effect obtained in before-and-after studies. More specifically, if the proportion of traffic in darkness is higher on lit roads than on unlit roads, this would, all else being equal, increase the number of accidents in darkness. Likewise, if the true proportion of accidents in darkness is higher on lit roads than on unlit roads, the effect attributed to road lighting will be reduced.

The study, however, found comparatively large effects of road lighting – in fact larger than those found in most before-and-after studies. This suggests that the sources of bias mentioned above may in fact not have biased this study very much.

Table 6
Estimated mean effect of road lighting on injury accidents in darkness on rural roads based on both estimators of effect.

Accident group	Estimated effect	
	Mean	95% conf. int.
All injury accidents	−54%	−56%, −52%
Fair weather	−54%	−56%, −52%
Rain	−45%	−53%, −37%
Fog	0%	−15%, +18%
Dry surface	−56%	−59%, −54%
Wet surface	−46%	−50%, −43%
Pedestrian	−70%	−77%, −61%
Bicycles	−60%	−65%, −54%
Moped	−61%	−64%, −56%
MC	−26%	−42%, −5%
Automobile	−50%	−52%, −47%
Hit fixed object	−54%	−58%, −49%
Frontal collision	−50%	−55%, −43%
Flank collision	−46%	−51%, −41%
Hit animal	−57%	−63%, −50%
Rear end collisions	−51%	−54%, −46%
Speed limit 120 km/h	−49%	−53%, −43%

Table 5
Estimated risk increase in darkness and effect of road lighting in different situations on rural roads according to ratio of odds ratios estimator of effect.

Accident group	Risk increase on lit roads		Risk increase on unlit roads		Effect	
	Estim.	95% conf. int.	Estim.	95% conf. int.	Estim.	95% conf. int.
All	17%	11%, 22%	145%	124%, 167%	−52%	−57%, −47%
Fair weather	11%	6%, 17%	116%	90%, 138%	−49%	−54%, −43%
Rain	53%	36%, 73%	192%	128%, 275%	−48%	−60%, −31%
Fog[a]	25%	12%, 40%	12%	−5%, 35%	+12%	−8%, +36%
Dry surface	4%	−2%, 11%	135%	106%, 168%	−56%	−62%, −49%
Wet surface	23%	13%, 33%	132%	95%, 176%	−47%	−56%, −36%
Pedestrian	141%	76%, 230%	361%	165%, 700%	−54%	−78%, −7%
Bicycles	81%	61%, 105%	429%	303%, 596%	−66%	−75%, −54%
Moped	48%	30%, 68%	287%	179%, 435%	−62%	−73%, −46%
MC	70%	40%, 107%	131%	49%, 260%	−27%	−55%, +19%
Automobile	−1%	−7%, 5%	88%	69%, 110%	−47%	−54%, −40%
Hit fixed object	−29%	−37%, −19%	44%	20%, 73%	−51%	−60%, −38%
Frontal collision	28%	14%, 43%	144%	92%, 210%	−48%	−60%, −32%
Flank collision	37%	26%, 49%	160%	109%, 223%	−47%	−58%, −33%
Hit animal[a]	109%	79%, 145%	381%	300%, 479%	−57%	−66%, −45%
Rear end coll.	26%	15%, 39%	267%	193%, 358%	−66%	−73%, −56%
120 km/h	0%	−15%, 18%	86%	48%, 132%	−46%	−59%, −29%

[a] Property damage accidents are included.

Using the odds ratio estimator of effect, the question is whether different traffic volume distributions by months on lit and unlit roads still influence the results, because accidents in darkness occur in other months than accidents in daylight. However, estimating the safety effect month-by-month shows no other result than estimating these effects for all months put together. Even when the effects are estimated for each hour in each month separately, the results are the same. This suggests that potentially different distributions of traffic volume by months on lit and unlit roads do not confound study results.

Using the ratio of odds ratios estimator of effect, two factors may disturb the results. One factor is that the effects are estimated for hours H8 and H18 only. According to the odds ratio estimator of effect those two hours often show a larger safety effect than other hours, and the mean effects using the ratio of odds ratios will therefore probably be overestimated. The other factor influencing the safety effect according to the ratio of odds ratios is that some of the accidents in November and January occur during twilight and even during daylight conditions in the selected hours H8 + H18. Because of this, the effects will be underestimated. The two factors affect the results in opposite directions, and one may hope that their net effect is neutral.

Information from Dutch road authorities states that the traffic volumes are generally higher on lit roads than on unlit roads. This could influence the ratio between the number of accidents during periods of darkness and the number of accidents during daylight and the estimate of safety effect. According to a Norwegian before-and-after study the Dark/Day accident ratio was higher and the safety effect of road lighting was smaller on roads with daily traffic volumes above 8000 vehicles per day than on roads with lower traffic volumes. One might expect the effects of road lighting to be smaller on roads with a high traffic volume than on roads with a small traffic volume, because car headlights and taillights illuminate the road and provide optical guidance to other drivers.

This suggests that it is unlikely that higher traffic volumes on lit roads in Holland has led to a lower Dark/Day accident ratio on lit roads than on unlit roads. Hence, it is not probable that this factor contributes to an overestimate of the safety effect of road lighting.

For accidents in the two groups “snow” and “snow or ice covered surface”, the ratio of odds ratios could not be used because there are no such accidents in the summer months. For those groups of accidents, the mean safety effect and uncertainty is estimated by the odds ratio alone, as shown in Table 4. A potential problem with respect to these accidents is that winter maintenance probably is better on high priority lit roads than on unlit roads. This may lead to a lower Dark/Day accident ratio on lit roads compared to unlit roads and to an overestimation of the safety effect of road lighting. The estimated safety effect for precipitation with snow (−26%) and for snow or ice covered road surfaces (−22%) may therefore be too high.

For accidents in fog, the estimated effect of road lighting is low according to the odds ratio estimator of effect (−26%). Using the ratio of odds ratios the calculations even show an accident increase (+12%) due to road lighting. A particular phenomenon was discovered for accidents in fog when the ratio between number of accidents on lit roads and number of accidents on unlit roads (Lit/Unlit ratio) was analysed (not shown in tables). The Lit/Unlit ratio during daylight is significantly smaller during foggy conditions (1.87) than for all weather conditions (4.70). This may indicate that road lighting reduces daylight accidents in fog due to improved guidance from the light poles. If that is the case, the safety effect during darkness is underestimated, because both estimators of effect are based on the assumption that daylight risk is equal on lit and unlit roads. This safety effect of the road lighting during conditions of fog should therefore be the subject of further studies.

5. Conclusions

The main conclusions from the research reported in this paper can be summarised as follows:

1. For all the Dutch roads the mean effect of road lighting on injury accidents during the hours of darkness is −50% [−53%, −47%]. This is a much larger effect than has been found in earlier studies.
2. The effect of road lighting on fatal accidents during darkness is slightly larger than the effect on injury accidents.
3. The effect of road lighting during the hours of twilight is about 2/3 of the calculated safety effect during the hours of darkness. (Compare Tables 3 and 2)
4. The effect of road lighting on accidents during darkness is significantly smaller in urban areas than in rural areas.
5. The estimated effect of road lighting on injury accidents during darkness on rural roads is −54% [−56%, −52%]. This is a very large safety effect compared to the effects found in earlier studies.
6. The safety effect of road lighting is significantly smaller during adverse weather and road surface conditions than during fair weather and dry surface conditions.
7. The safety effects of road lighting on pedestrian, bicycle and moped accidents are significantly larger than the effects on automobile and motorcycle accidents.
8. The safety effect of road lighting during foggy conditions may be underestimated. There are indications of a daylight safety effect possibly due to guidance from light poles. If this is the case, the safety effect of road lighting during the hours of darkness is also underestimated.
9. The effect of road lighting on injury accidents during precipitation with snow is −26% [−40%, +8%] and the effect on snow or ice covered road surface is −22% [−31%, −11%].
10. The risk of injury accidents is found to increase in darkness. The average increase in risk is 17% on lit rural roads and 145% on unlit rural roads (seen in Table 5).
11. The average increase in risk during rainy conditions is 53% on lit rural roads and 192% on unlit rural roads (seen in Table 5).
12. The average increase in risk with respect to pedestrian accidents is 141% on lit rural roads and 361% on unlit rural roads (seen in Table 5).

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Paper IV

Road lighting and motorway accidents

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Effects of road lighting on motorways

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ABSTRACT

Objectives: The study has three objectives. The first is to investigate how the effect of road lighting on motorway accidents varies with different weather and road surface conditions. The second is to evaluate the future benefit of road lighting as safety measure on motorways. The third is to evaluate the need for further research in the field of motorway lighting. **Method:** This paper presents a cross-section study of the effects of road lighting on motorways mainly in the Netherlands. The main source of data is a Dutch database of accidents covering the period 1987-2006, but British and Swedish data are also used. **Results:** The effect of road lighting on motorways is found to be greater in the Netherlands than in Great Britain or Sweden. Reasons for this are not known. Effects are found to vary according to background characteristics and are smaller during precipitation than during fine weather and smaller on wet road surfaces than on dry surfaces. No effect of road lighting is found during fog. Collision with light poles constitutes a large part of accidents on lit motorways and reduces the safety effect of road lighting. **Conclusions:** The effect of road lighting on injury accidents during darkness is found to be very high (-49 %) on Dutch motorways. However the effect seems to vary much between countries. Collisions with light poles reduce the effect of road lighting. Road lighting will probably be an effective safety measures on motorways for many years. In the long term, however, the benefit of road lighting will probably be reduced along with the implementation of new vehicle and road technology

Modern technology permits a continuous adaptation of luminance levels so as to optimise the effect of road lighting on safety, while at the same time minimising energy consumption. However, more detailed knowledge concerning the effects of road lighting at different lighting levels is needed in order to use this technology effectively.

Alternative or additional measures like LED guide lights and light road surfaces also need to be evaluated.

Key words: road lighting, road safety, evaluation study, motorways, light poles, adaptive lighting.

INTRODUCTION

The need for road lighting on motorways is a subject that needs to be studied and discussed for several reasons. In the first place, warrants, criteria, and practice for using road lighting on motorways vary considerably between countries. Table 1 shows the guidelines applied in some countries. While motorways in Norway are illuminated at a high level regardless of traffic volume, most other countries, like Sweden, Denmark, Germany, Great Britain and the Netherlands, do not illuminate motorways at the traffic volumes that are typical in Norway. In the United States and Canada, the luminance level on motorways, if illuminated at all, is lower than in Europe and lower than the levels recommended by the International Commission on illumination (CIE).

Table 1: Required or recommended lighting level on motorways in some countries or parts of the world

	AADT = 12 –35000 veh.	AADT = 35 - 70 000 veh.	AADT > 70 000 vehicles
CIE (global)	When lighting: 1 - 2 cd/m^2 (Depending on traffic volume and complexity)		
CEN (European)	When lighting: 0.5 – 1.5 cd/m^2 when AADT < 25 000 0.75 – 2 cd/m^2 when AADT > 25 000		
Norway before 2008	2 cd/m^2		
Norway from 2008	1 cd/m^2 , may be dimmed to 0.5 cd/m^2		
Sweden 1994	No lighting	When lighting: 1.0 – 2.0 cd/m2	
Sweden, 2004	No lighting	0.5 - 0.75 cd/m^2	1.0 - 1.5 cd/m^2
Denmark	Normally no lighting. When lighting, 1 cd/m^2		
Netherlands, 1977	No lighting	When lighting: 1 – 2 cd/m^2	
Netherlands, 2006	No lighting	Switching between 0.2 cd/m^2 and 1.0 cd/m^2	
Germany	When lighting: 1 cd/m^2		
Great Britain	When lighting: 1.5 – 2.0 cd/m^2		
USA	No lighting	When lighting, 0.4 – 1.0 cd/m^2 Normally only in urban areas	
Canada	Point score warrants. When lighting, 0.6 cd/m^2.		

Secondary, the energy consumption associated with road lighting is at the focus of interest at the international level because of the contribution to global warming and at the local level because of high energy costs. In Norway, the Department of Transport has asked the Public Roads Administration to consider the energy consumption in road lighting, and in a new road lighting standard issued in 2008 (NPRA, 2008) the required average luminance level on motorways is reduced from 2 cd/m^2 to 1 cd/m^2.

In the third place, technology is available today that makes it easy to dim the fixtures individually according to traffic and weather conditions. A Norwegian study (Augdal, 2007) shows that the luminance level increases by factor 4 or 5 when the surface is covered with snow, and design luminance level is obtained when the light flux is dimmed to 20 % level. Some new international and national standards encourage dimming systems for road lighting on motorways (CIE, 2007; NPRA, 2008; VV, 2004). The New Norwegian standards require that dimming from 1 cd/m^2 to 0.5 cd/m^2 is considered in low traffic periods.

Fourthly, alternatives to road lighting on motorways are introduced for the purpose of saving energy when accident problems are small. In the Netherlands a new concept has been introduced for motorway lighting, where the average luminance level is dimmed to 0.2 cd/m^2 when driving conditions are good. Road lighting is then used as guide light for the drivers, and the intention is not to illuminate the road surface. Road authorities do not know the safety effect but estimate the accident risk to be low (Rijkswaterstaat, 2006). In Sweden, Light Emitting Diodes (LED) is introduced as guide light in the median of motorways as an alternative to road lighting. Energy consumption is low and collisions with light poles are avoided. The safety effect is not known, and the number of accidents is yet too small for a before-and-after study.

In the fifth place, driving on motorways is likely to become safer in the future. Motorways and cars will be designed to prevent fatalities or serious injuries, and cars will be equipped with warning or control systems. The accident rate will be reduced and hence the benefit of road lighting will be reduced. The accident rate in darkness will probably be reduced more than the accident rate in daylight because of new head light systems and systems for detection and warning for animals and pedestrians ahead. Thus, the need for road lighting will be reduced. For these reasons we need to know how different kinds of road lighting systems affect the accident rate on motorways during different conditions.

A literature study shows that the mean overall effect of road lighting on motorway accidents found in earlier studies was about 50 % reduction in injury accidents. This conclusion is based on the following studies:

Box (1971; 1972) used data from 21,000 accidents on 28 lighted and seven unlighted urban or suburban motorway sections in North America. The sections ranged from four-lane to ten-lane widths. The study indicated that illumination reduced night-time accidents by an average of 40 %.

In Germany, Lamm et al., (1985) analyzed 1,900 accidents reported from 1972 to 1981 on eight km of a four-lane motorway. The route was divided into three sections. Two sections were lighted, while the third was used as a control. One section showed no change in the night to day ratio of accidents as a result of lighting, while the second section showed a ratio reduction of 17 %. The ratio for the unlit control section increased 38 %.

CIE (1992) reported three before and after studies that identified the effect of installation of lighting on motorways. The results were consistent, with a 57 % reduction in night-time accidents. However, the studies had small sample sizes and were published back in 1972 and 1973.

In Minnesota, Griffith (1994) compared the safety of 88 km of continuously lighted urban motorways and 57 km of urban motorways with junction lighting only. He found that illumination of unlighted sections between lighted junctions could theoretically reduce night accidents on motorways by 16 %.

Probably the most comprehensive study (Bruneau ,2001) used a database of 22,740 accidents on 770 km of motorways in Quebec. Continuous lighting was found to reduce the night-time accident rate by 33 % (p=.001) compared with junction lighting alone, and by 49 % (p=.05) compared with dark motorways.

In a before-and after study (Wanvik, 2007) the effect on injury accidents on Norwegian motorways 1986 – 2005 was estimated to 31 % reduction of injury accidents during darkness. However, the number of accidents was small, and statistical uncertainty was large.

In a study of Dutch accidents, Wanvik (2008) estimated the effect of road lighting on motorways to be a 49 % reduction of accidents during darkness while the overall effect on all Dutch rural roads was a 54 % reduction of accidents during darkness.

These studies give no valid information on how the effect of road lighting varies according to type of accident, weather conditions or road surface conditions. However, the study by Wanvik (2008) on Dutch accidents produced some findings that deserve more careful investigation:

1. The effect of road lighting on accidents during darkness was smaller during rain than during fine weather.
2. The effect was smaller yet during snowing than during rain.
3. During fog, there was no effect of road lighting.
4. The effect was smaller on wet road surfaces than on dry road surfaces.
5. The effect on snow or ice covered surfaces was smaller yet.

No studies show how the effect of road lighting is related to lighting level and other quality parameters.

STUDY OBJECTIVES

The study reported in this paper has three objectives. The first objective is to investigate how the effect of road lighting on motorway accidents varies with different weather and road surface conditions. Collisions with light poles must be taken into consideration.

The second objective is to evaluate the future benefit of road lighting as safety measure on motorways. The main questions posed are: Is road lighting a suitable measure to prevent motorway accidents attributable to darkness in the future? Are other alternative or additional measures needed?

The third objective is to evaluate the need for further research in the field of motorway lighting. The questions asked are: What knowledge is needed for the development of effective future road lighting systems? How can this knowledge be obtained?

DATA AND METHODS

Data sources

The main source of data used to evaluate the effects of road lighting on motorways is a large Dutch database, accessible online at the website of the SWOV Institute for Road Safety Research (SWOV 2007). This database contains detailed and easily available information about 23,600 injury accidents and 153,100 property damage accidents between 1987 and 2006 on motorways with a speed limit of 120 km/h. Effects of road lighting on motorways are also evaluated by means of less extensive accident data from British motorways provided by Department of Transport in England, accident data from Swedish motorways provided by the Swedish Road Administration, and data from Norwegian motorways provided by the Norwegian Public Roads Administration.

Estimates of effect

To estimate the effect of road lighting on accidents, an odds ratio is applied as estimator of effect. The odds ratio is defined as follows:

$$\text{Odds ratio} = \frac{\left(\dfrac{\text{Number of accidents in darkness on lit roads}}{\text{Number of accidents in daylight on lit roads}}\right)}{\left(\dfrac{\text{Number of accidents in darkness on unlit roads}}{\text{Number of accidents in daylight on unlit roads}}\right)}$$

This odds ratio is based on the number of accidents only. It does not refer to any data regarding to the distribution of traffic between daylight and darkness. To control for potential differences between lit and unlit roads with respect to the distribution of traffic by hour of the day, the odds ratio is estimated for each hour of the day separately. Accidents in daylight and accidents in darkness are taken from the same hour of the day. Only hours that have at least 15 accidents in each of the four groups forming the odds ratio are used. This leaves only hour 7 (06:00 – 06.59), hour 8, and each of the hours 18 – 22 for analysis. All other hours of the day are omitted. Estimates referring to different hours have been combined by applying the log odds technique, commonly applied in meta-analyses.

However, there is a problem of small accidents samples when only accidents on motorways are studied. To counter this problem, four versions of the odds ratio are applied. The versions differ in terms of the hours and accidents included, as shown below:

Version A: All hours, injury accidents

Version B: All hours, property damage and injury accidents

Version C: One hour at the time, injury accidents

Version D: One hour at the time, property damage and injury accidents

In Version A and Version B, the odds ratio is estimated for all hours of the day at the same time instead of separate estimates for one hour at the time (as in Version C and Version D). This increases the number of accidents serving as the basis for estimates, but it weakens the control of confounding factors. The most important potentially confounding factor is systematic differences between lit road and unlit roads with respect to the distribution of traffic throughout the day.

In Version B and Version D, property damage accidents are included to increase the accident sample. This, however, may complicate the interpretation of study findings, because earlier studies have found that the affect of road lighting is smaller for property damage accidents than for injury accidents.

Version C (One hour at the time, only injury accidents) is regarded as the best. It is used to estimate the effect of road lighting for large groups of accidents. Version D (One hour at the time, property damage and injury accidents) is applied for smaller groups of accidents (e.g. accidents during rain), where the number of injury accidents is too small to apply Version C. The problem of smaller effect on injury accidents is taken care of by adjusting the estimates by means of a factor that is deduced from a comparison between the results from Version C and the results from Version D in the largest groups of accidents.

Version A (All hours, only injury accidents) is used for accident groups where the number of injury and property damage accidents is too small for Version D (e.g. all accident types during foggy conditions). The estimates are adjusted by applying a factor that is deduced by a comparison between the results from Version C and Version A in the largest groups of accidents.

Version B (All hours, property damage and injury accidents) is used for accident groups where the number of injury and property damage accidents is too small for other methods.

The effect of road lighting on motorway accidents is also estimated by means of Version A of the odds ratio for Swedish and British data. The purpose is to roughly compare the estimated effects in the Netherlands with effects estimated for other countries that are at an equally high traffic safety level.

The log odds technique was applied to combine estimates of odds ratios. This technique takes the logarithm of the odds ratio as the estimate of effect. Combining logarithms of odds ratios yields an unbiased estimate of the weighted mean effect based on a set of estimates of effect. Each estimate of effect is assigned a statistical weight which is inversely proportional to its variance. For a general description of the technique, see Shadish and Hafddock (1994). Its application to road safety evaluation studies is explained by Elvik and Vaa (2004).

The second aim of the study is to evaluate the future benefit of road lighting as a safety measure on motorways. Because the benefit of lighting is a product of future accidents without road lighting and the future effect of road lighting, the evaluation is based on knowledge about past accidents on dark motorways and past effects of road lighting together with expectations about future motorway safety and future motorway lighting. Past accidents and effects of road lighting are estimated in this paper, and future expectations about motorway safety and the need for road lighting are discussed in Chapter 6.

RESULTS

Dutch motorways

The effects of road lighting on Dutch motorways with a speed limit of 120 km/h according to the four versions of the odds ratio are shown in Table 2 – Table 5. In the Dutch statistics, the accident type “Hit fixed object” includes accidents where a vehicle hits an object after running off the road, as well as accidents where a vehicle hits an object on the road. This is not common. Commonly the first category is included in the accident type “Single vehicle accident”, while the latter constitutes the accident type “Hit fixed object”. The first category normally contains a lot more accidents than the latter. Therefore, in this study, the two Dutch accident types “Hit fixed object” and “Single vehicle accident” are merged into one group labelled “Single vehicle accident”.

Table 2: Effect on injury accidents in darkness on Dutch motorways 1987 - 2006, Version A – All day, injury accidents

Climatic conditions	Accident type	Daylight acc.		Darkness acc.		Effect	
		Lit	Unlit	Lit	Unlit	Estim.	95 % conf. int.
Fine weather	Single vehicle acc.	3335	1866	1229	1491	-54 %	-58 %, -49 %
	Rear end collision	3366	1261	827	860	-64 %	-68 %, -60 %
	Others	1274	465	403	496	-70 %	-75 %, -65 %
	All	7975	3592	2459	2847	-61 %	-64 %, -58 %
Rain	Single vehicle acc.	703	403	378	362	-40 %	-50 %, -28 %
	Rear end collision	551	226	273	176	-36 %	-50 %, -19 %
	Others	208	83	85	102	-67 %	-77 %, -51 %
	All	1462	712	736	640	-44 %	-51 %, -36 %
Fog	Single vehicle acc.	29	27	32	43	-31 %	-65 %, +39 %
	Rear end collision	97	133	30	44	-7 %	-45 %, +59 %
	Others	32	20	14	16	-45 %	-78 %, +36 %
	All	158	180	76	103	-16 %	-42 %, +21 %
Snowing	Single vehicle acc.	79	51	45	93	-69 %	-81 %, -48 %
	Rear end collision	36	21	13	16	-53 %	-81 %, +18 %
	Others	30	18	10	23	-74 %	-90 %, -33 %
	All	145	90	68	132	-68 %	-78 %, -53 %
All	Single vehicle acc.	4185	2382	1704	2021	-52 %	-56 %. -48 %
	Rear end collision	4065	1651	1152	1109	-58 %	-62 %, -53 %
	Others	1551	591	514	649	-70 %	-74 %, -65 %
	All	9801	4624	3370	3779	-58 %	-60 %, -55 %
Dry road surface	Single vehicle acc.	2872	1644	909	1097	-53 %	-57 %, -47 %
	Rear end collision	2907	1111	563	639	-66 %	-71 %, -62 %
	Others	1136	411	282	365	-72 %	-77 %, -66 %
	All	6915	3166	1754	2101	-62 %	-65 %, -59 %
Wet road surface	Single vehicle acc.	1156	635	687	735	-49 %	-55 %, -41 %
	Rear end collision	1113	511	565	439	-41 %	-50 %, -30 %
	Others	377	155	203	236	-65 %	-73 %, -54 %
	All	2646	1301	1455	1410	-49 %	-54 %, -44 %
Snow or ice covered road surface	Single vehicle acc.	112	85	90	174	-61 %	-73 %, -43 %
	Rear end collision	26	20	23	24	-26 %	-67 %, +67 %
	Others	29	20	27	44	-58 %	-80 %, -11 %
	All	167	125	140	242	-57 %	-68 %, -41 %

Table 3: Effect on injury accidents in darkness on Dutch motorways 1987 - 2006, Version B – All day, property damage and injury accidents

Climatic conditions	Accident type	Daylight acc.		Darkness acc..		Effect	
		Lit	Unlit	Lit	Unlit	Mean	95 % conf. int.
Fine weather	Single vehicle acc.	19770	9482	7451	7268	-51 %	-53 %, -49 %
	Rear end collision	25109	8301	5279	3632	-52 %	-54 %, -50 %
	Others	15384	5165	4220	4958	-71 %	-73 %, -70 %
	All	60263	22948	16950	15858	-59 %	-60 %, -58 %
Rain	Single vehicle acc.	5789	3229	2967	2581	-36 %	-40 %, -31 %
	Rear end collision	4768	1740	1805	903	-27 %	-34 %, -20 %
	Others	1986	804	935	838	-55 %	-60 %, -49 %
	All	12543	5773	5707	4322	-39 %	-42 %, -36 %
Fog	Single vehicle acc.	241	179	243	219	-18 %	-37 %, +8 %
	Rear end collision	551	548	166	161	+3 %	-20 %, +31 %
	Others	148	105	93	129	-49 %	-65 %, -26%
	All	940	832	502	509	-13 %	-25 %, +2%
Snowing	Single vehicle acc.	883	811	767	1112	-37 %	-45 %, -28 %
	Rear end collision	227	170	115	89	-3 %	-31 %, +36 %
	Others	164	113	121	133	-37 %	-56 %, -12 %
	All	1274	1094	1003	1334	-35 %	-42 %, -28 %
All	Single vehicle acc.	27191	14806	11668	11537	-45 %	-47 %, -43 %
	Rear end collision	30827	10814	7462	4831	-46 %	-48 %, -43 %
	Others	17990	6297	5469	6182	-69 %	-70 %, -68 %
	All	76008	31917	24599	22550	-54 %	-55 %, -53 %
Dry road surface	Single vehicle acc.	16157	7981	4941	4914	-50 %	-53 %, -48 %
	Rear end collision	21263	7113	3394	2545	-55 %	-58 %, -53 %
	Others	13957	4620	3289	4003	-73 %	-74 %, -71 %
	All	51377	19714	11624	11462	-61 %	-62 %, -60 %
Wet road surface	Single vehicle acc.	9279	4787	5250	4492	-40 %	-43 %, -36 %
	Rear end collision	9091	3497	3841	2071	-29 %	-33 %, -24 %
	Others	3713	1471	1934	1870	-59 %	-62 %, -55 %
	All	22083	9755	11025	8433	-42 %	-44 %, -40 %
Snow or ice covered road surface	Single vehicle acc.	1147	1013	1283	1837	-38 %	-45 %, -31 %
	Rear end collision	199	163	168	171	-20 %	-40 %, +8 %
	Others	171	127	171	213	-40 %	-56 %, -19 %
	All	1517	1303	1622	2221	-37 %	-43 %, -31 %

Table 4: Effect on injury accidents in darkness on Dutch motorways 1987 - 2006, Version C – One hour at the time, injury accidents

Climatic conditions	Accident type	Hours included in calculations	Effect	
			Mean	95 % conf. int.
Fine weather	Single vehicle acc.	H7, H8, H18 – H22	-57 %	-65 %, -48 %
	Rear end collision	H7, H8, H18 – H21	-51 %	-60 %, -40 %
	Others	H8, H18 – H20	-60 %	-72 %, -42 %
	All	H7, H8, H18 – H22	-53 %	-59 %, -47 %
Rain	All	H8, H18 – H21	-19 %	-37 %, +5 %
All	Single vehicle acc.	H7, H8, H18 – H22	-55 %	-61 %, -47 %
	Rear end collision	H7, H8, H18 – H21	-44 %	-52 % - 33 %
	Others	H7, H8, H18 – H21	-54 %	-65 %, -40 %
	All	H7, H8, H18 – H22	-49 %	-54 %, -43 %
Dry road surface	Single vehicle acc.	H7, H19 – H22	-57 %	-67 %, -45 %
	Rear end collision	H7, H8, H18 – H21	-55 %	-64 %, -43 %
	Others	H19 – H20	-62 %	-79 %, -32 %
	All	H7, H8, H18 – H22	-55 %	-61 %, -49 %
Wet road surface	Single vehicle acc.	H7, H8, H19 – H21	-41 %	-57 %, -20 %
	Rear end	H8, H18, H19	-20 %	-50 %, +28 %
	All	H7, H8, H18 – H22	-32 %	-43 %, -19 %

Table 5: Effect on injury accidents in darkness on Dutch motorways 1987 - 2006, Version D – One hour at the time, property damage and injury accidents

Climatic conditions	Accident type	Hours included in calculations	Effect	
			Mean	95 % conf. int
Fine weather	Single vehicle acc.	H7, H8, H18 – H22	-47 %	-52 %, -42 %
	Rear end collision	H7, H8, H18 – H22	-44 %	-49 %, -38 %
	Others	H7, H8, H18 – H22	-52 %	-62 %, -40 %
	All	H7, H8, H18 – H22	-46 %	-52 %, -39 %
Rain	Single vehicle acc.	H7, H8, H18 – H22	-37 %	-47 %, -26 %
	Rear end collision	H8, H18 – H21	-15 %	-28 %, 0 %
	Others	H8, H18 – H21	-39 %	-52 %, -22 %
	All	H7, H8, H18 – H22	-25 %	-33 %, -16 %
Fog	All	H7, H8	+40 %	-25 %, +162 %
Snowing	All	H8, H18, H19	-48 %	-69 %, -12 %
All	Single vehicle acc.	H7, H8, H18 – H22	-46 %	-52 %, -40 %
	Rear end collision	H7, H8, H18 – H22	-38 %	-44 %, -31 %
	Others	H7, H8, H18 – H22	-51 %	-60 %, -40 %
	All	H7, H8, H18 – H22	-42 %	-48 %, -36 %
Dry road surface	Single vehicle acc.	H7, H8, H18 – H22	-42 %	-49 %, -33 %
	Rear end collision	H7, H8, H18 – H22	-46 %	-53 %, -38 %
	Others	H7, H8, H18 – H22	-57 %	-61 %, -52 %
	All	H7, H8, H18 – H22	-45 %	-53 %, -37 %
Wet road surface	Single vehicle acc.	H7, H8, H18 – H22	-37 %	-46 %, -26 %
	Rear end collision	H7, H8, H18 – H22	-22 %	-32 %, -9 %
	Others	H7, H8, H18 – H22	-44 %	-55 %, -30 %
	All	H7, H8, H18 – H22	-29 %	-37 %, -19 %
Snow or ice	All	H8, H18, H19	-48 %	-69 %, -12 %

When the effect of road lighting is estimated by means of Version A of the odds ratio, the effect during rain or fog is significantly smaller than the effect during fine weather or snowing. The effect on wet road surfaces is significantly smaller than the effect on dry surfaces. During fine weather or on dry road surfaces, the effect on single vehicle accidents is significantly smaller than the effect on other types of accident.

When the effect of road lighting is estimated by means of Version B of the odds ratio, the effect during rain or fog or snowing is significantly smaller than the effect during fine weather. The effect on wet road surfaces or on snow or ice covered road surfaces is significantly smaller than the effect on dry road surfaces. During fine weather or on dry road surfaces, the effect on single vehicle accidents and the effect on rear end collisions are significantly smaller than the effect on other types of accident.

When effects of road lighting are estimated according to Version C or Version D of the odds ratio, the effect during rain or on wet surfaces is significantly smaller than the effect during fine weather or on dry road surfaces.

The results obtained by the four versions of the odds ratio have been combined by applying a fixed effects model of analysis. However, before combining estimates of effect, the estimates obtained by Version A, Version B and Version D need to be adjusted for the following reasons: Effects estimated by Version A and Version B are overestimated because of different traffic volume distributions between hours of the day on lit roads and unlit roads. Estimates obtained by Version B and Version D include property damage accidents and the effects are therefore slightly too small to be representative of injury accidents. Only the effects estimated according to Version C can be applied without correction.

Correction factors, shown in Table 6, are estimated by dividing estimates of effect according to Version A, Version B and Version D by the estimates of effect according to Version C. This is only done for the climatic condition group denoted as “All” because this group represents all accidents and the number of accidents is large enough even in Version C to obtain unbiased correction factors.

Table 6: Correction factors for effects in Version A, Version B and Version D

Climatic conditions	Accident type	Correction factor		
		A	B	D
All	Single vehicle acc.	1.06	1.21	1.18
	Rear end collision	0.75	0.96	1.10
	Others	0.66	0.68	1.08
	All	0.82	0.90	1.13

The same set of correction factors is applied for every group of climatic condition and the corrected effects in all groups are presented in Table 7. The correction factors may not be equally well suited for every climatic condition, but it would be too complicated to evaluate different factors for different climatic conditions, and it is not essential for the results. A fixed effects model was used to combine the effect from the four methods, and the results are presented in Table 7.

Table 7: Effect on injury accidents during darkness on Dutch motorways 1987 –2006, combining the results from Version A, Version B, Version C and Version D

Climatic conditions	Accident type	Corrected effects				Combined effects	
		A	B	C	D	Mean	95 % conf.
Fine weather	Single vehicle acc.	-56 %	-59 %	-57 %	-55 %	-59 %	-60 %, -57 %
	Rear end collision	-52 %	-50 %	-51 %	-49 %	-50 %	-52 %, -48 %
	Others	-55 %	-58 %	-60 %	-56 %	-58 %	-60 %, -56 %
	All	-53 %	-55 %	-53 %	-52 %	-54 %	-55 %, -53 %
Rain	Single vehicle acc.	-43 %	-47 %		-47 %	-47 %	-50 %, -43 %
	Rear end collision	-15 %	-24 %		-23 %	-23 %	-29 %, -16 %
	Others	-50 %	-33 %		-43 %	-37 %	-43 %, -30 %
	All	-32 %	-32 %	-19 %	-34 %	-32 %	-35 %, -29 %
Fog	Single vehicle acc.	-34 %	-32 %			-32 %	-47 %, -13 %
	Rear end collision	25 %	7 %			10 %	-12 %, +38 %
	Others	-17 %	-25 %			-24 %	-46 %, -7 %
	All	2 %	-3 %		24 %	-1 %	-14 %, +14 %
Snowing	Single vehicle acc.	-70 %	-48 %			-50 %	-56 %, -43 %
	Rear end collision	-37 %	1 %			-5 %	-31 %, +31 %
	Others	-61 %	-8 %			-16 %	-39 %, +15 %
	All	-61 %	-28 %		-54 %	-33 %	-40 %, -25 %
All	Single vehicle acc.	-55 %	-55 %	-55 %	-55 %	-55 %	-56 %, -53 %
	Rear end collision	-44 %	-44 %	-44 %	-44 %	-44 %	-45 %, -41 %
	Others	-54 %	-54 %	-54 %	-54 %	-54 %	-56 %, -52 %
	All	-49 %	-49 %	-49 %	-49 %	-49 %	-50 %, -48 %
Dry road surface	Single vehicle acc.	-55 %	-59 %	-57 %	-50 %	-58 %	-59 %, -56 %
	Rear end collision	-55 %	-53 %	-55 %	-51 %	-53 %	-56 %, - 51 %
	Others	-58 %	-60 %	-62 %	-59 %	-60 %	-62 %, -58 %
	All	-54 %	-57 %	-55 %	-52 %	-56 %	-57 %, -55 %
Wet road surface	Single vehicle acc.	-51 %	-50 %	-41 %	-47 %	-50 %	-52 %, -48 %
	Rear end collision	-21 %	-26 %	-18 %	-29 %	-25 %	-29 %, -21 %
	Others	-47 %	-40 %		-48 %	-41 %	-46 %, -37 %
	All	-38 %	-36 %	-32 %	-37 %	-36 %	-38 %, -34 %
Snow or ice covered road surface	Single vehicle acc.	-63 %	-49 %			-50 %	-55 %, -45 %
	Rear end collision	-1 %	-16 %			-14 %	-35 %, +13 %
	Others	-36 %	-12 %			-16 %	-37 %, +11 %
	All	-48 %	-30 %		-54 %	-33 %	-39 %, -26 %

Table 7 shows that the overall effect of road lighting during darkness on Dutch motorways is 49 % reduction in injury accidents. The overall effect during rain (-32 %) and during snowing (-33 %) is significantly smaller than the overall effect during fine weather (-54 %). Likewise the overall effect on wet road surfaces (-36 %) and on snow or ice covered surfaces (-33 %) is significantly smaller than the overall effect on dry road surfaces (-56 %). The effect on rear end collisions is significantly smaller than the effect on single vehicle accidents regardless of climatic conditions. The effect on rear end collisions during rain is only -23 % [-29 %, -16 %] while the effect on run off the road accidents during fine weather is -59 % [-60 %, -57 %]

During foggy conditions there is no overall effect of road lighting (-1 %), and for rear end collisions during fog there is even a small accident increase (+10 %). However, the results for foggy conditions are uncertain. The effect on rear end collisions is also small during snowing (-5 %) and on snow covered road surfaces (-14 %), but these results are highly uncertain.

Swedish and British motorways

The effects of road lighting on accidents on Swedish and British motorways have been estimated according to Version A of the odds ratio, and the results are shown in Table 8 and Table 9. For British motorways, the overall effect of road lighting is also estimated according to Version C of the odds ratio, and the results are shown in Table 10.

Table 8: Effect on injury accidents in darkness on Swedish motorways (110 km/h) 2003 – 2006, estimated according to Version A

Weather and road surface conditions	Daylight acc.		Darkness acc.		Effect	95 % conf. interval
	Lit	Unlit	Lit	Unlit		
Fine weather	347	658	140	431	-38 %	-51 %, -22 %
Raining	50	115	39	90	0 %	-40 %, +65 %
Snowing	28	84	41	113	+9 %	-38 %, +90 %
All	433	885	236	685	-30 %	-42 %, -15 %
Dry road surface	248	473	66	230	-45 %	-60 %, -25 %
Wet surface	116	227	97	217	-13 %	-37 %, +21 %
Snow/ice covered	64	179	72	234	-14 %	-42 %, +27 %

Table 9: Effect on injury accidents on British motorways 2001 – 2004, estimated according to Version A

Road surface condition	Daylight acc.		Darkness acc.		Effect	95 % conf. interval
	Lit	Unlit	Lit	Unlit		
Dry road surface	10646	6790	2767	2663	-34 %	-38 %, -30 %
Wet surface	4038	2613	2434	2194	-28 %	-33 %, -23 %
Snow/ice covered	110	133	123	151	-2 %	-30 %, +39 %
All	14849	9552	5338	5012	-31 %	-35 %, -28 %

Table 10: Effect on injury accidents in darkness on British motorways 2001 - 2004, estimated according to Version C

Hour of the day	Daylight ac.		Darkness ac.		Effect of lighting
	Lit	Unlit	Lit	Unlit	
H7	340	222	207	217	-38 %
H8	930	634	152	148	-30 %
H18	1060	643	606	454	-19 %
H19	601	389	645	439	-5 %
H20	356	213	442	385	-31 %
H21	172	130	411	372	-16 %
H22	48	36	400	358	-16 %
Weighted mean					-19 %
95 % confidence interval					-27 %, -11 %

The first conclusion to be drawn from the tables above is that the effect of motorway lighting is significantly smaller in Sweden and Great Britain than in the Netherlands. Moreover, the tables show that the effect of road lighting on injury accidents on Swedish motorways is smaller during rain than during fine weather, and on Swedish and British motorways the effect is smaller on wet road surfaces than on dry road surfaces. On Swedish motorways no effect on accidents of road lighting is found on accidents during snowing, and on Swedish and British motorways there is almost no effect of road lighting for snow or ice covered road surfaces. As a whole, the results from Swedish and British motorways confirm the results from Dutch motorways with respect to the differences of the safety effect during changing weather and road surface conditions.

DISCUSSION OF THE INFLUENCE OF COLLISIONS WITH LIGHT POLES

When the effect of road lighting on accidents is estimated by the odds ratio, it is assumed that road lighting does not affect accidents during daylight. Accident statistics, however, show that light poles are involved in 3.3 % of daylight accidents and 5.3 % of darkness accidents on Dutch motorways with speed limit 120 km/h. This is shown in Table 11 below. The total number of collisions with light poles during the period 1987 – 2006 is 536. The table also show accidents involving light poles on Norwegian motorways during the period 1996 – 2005.

Table 11: Numbers of injury accidents involving light poles and share of accidents involving light poles on lit Dutch motorways 1987 – 2006 and lit Norwegian motorways 1996 – 2005

Country, road type, condition	Daylight		Dusk/dawn		Darkness		All	
	Number	%	Number	%	Number	%	Number	%
The Netherlands, 120 km/h	320	3.3	27	3.4	179	5.3	536	3.8
The Netherlands, 120 km/h, single vehicle	288	6.9	26	8.0	152	8.9	466	7.5
Norway, 90 – 100 km/h	36	10.3	4	12.5	15	11.4	55	10.2
Norway, 90 – 100 km/h, single vehicle accidents	33	24.8	4	25.0	14	19.1	51	23.0

Collisions with light poles obviously influence the estimated effect of road lighting. Firstly, the odds ratio is influenced by collisions with light poles during darkness and daylight. Secondly the real effect of road lighting is probably reduced because of collisions with light poles during daylight, twilight and darkness.

If all collisions with light poles were deleted, the estimated effect of road lighting calculated by Version A would be increased from -58 % to -59 %. The combined effect based on Version A – Version D would be increased from -49 % to -50 %. The number of accidents during darkness on lit roads during the years 1987 – 2006 would be reduced from 3771 to 3600 when the 171 collisions with light poles were deleted. The effect of road lighting on accidents during darkness on lit roads would have reduce the number of accidents during darkness during the years 1987 – 2006 from 7200 to 3600 (50 % reduction). In fact, the number of collisions with light poles on Dutch motorways during this period is 536. If all these accidents are additional accidents due to light poles, the road lighting has only reduced the number of accidents by 3600 - 536 = 3064. (The calculation is rough because the effect of road lighting during twilight is not included). Hence the reduction is not 50 % but 43 %.

However, not all collisions with light poles would have been avoided if the light poles were not there. A vehicle that hits a light pole is already out of control, and if the light poles were not there, some other kind of accident might have occurred. A vehicle might have crossed the central reserve and hit an oncoming vehicle or a vehicle might have hit a rock or a fence outside the road instead of hitting a light pole. On some Norwegian motorway sections, where yielding light poles are placed in the central reverse, about one light pole is hit per km per year while only one tenth of the cases are reported as injury accidents. Vehicles are often stopped by light poles with no personal injury. This is probably also the case on Dutch motorways. The conclusion is that the influence on the odds ratio of accidents involving light poles is small and may be ignored.

However, the additional number of injury accidents due to light poles in daylight, twilight and darkness may be of an order that must be regarded. These accidents counteract the positive effect of road lighting to some extent that varies with the conditions. On Norwegian motorways, where collisions with light poles during daylight, twilight and darkness constitute more than 10 % of injury accidents (Table 11), the collisions with light poles may neutralize a large part of the safety effect of the road lighting. A 10 % accident increase during daylight neutralizes roughly a 25 % accident reductions during darkness because the number of accidents during daylight is in general two or three times higher than the number of accident during darkness.

The influence of collisions with light poles is naturally larger on single vehicle accidents than on other accidents, and the effect of road lighting on single vehicle accidents may be very much reduced because of such collisions.

On future motorways the light poles may be protected by guard rails to more effectively prevent injury accidents. Ideally, accidents involving light poles should be avoided and the effect of road lighting should not be reduced by this kind of accidents.

ROAD LIGHTING IN THE FUTURE

Based on the results of this study it is obvious that road lighting will be an important safety measure on motorways for many years. The effect of modern motorway lighting may be as much as 50 % reduction in injury accident, but the effect seems to vary a lot from country to country. Even if the effect is a 25 % accident reduction, motorway lighting is a cost effective safety measure on high traffic motorways. In an example in a draft version of a revised CIE Publication No. 115 (CIE, 2008) the calculations show that road lighting is profitable on motorways when AADT is 17,600 vehicles or more. The calculations are based on the assumption that accidents during darkness are reduced by 20 %. In Swedish calculations carried out as support for the work on the new Swedish road lighting standard, road lighting show to be profitable on motorways when AADT is 11,000 vehicles or more (SRA, 2003). The calculations are based on the assumption that accidents during darkness are reduced by 30 %.

Cost-benefit analyses like these can be applied to determine marginal volumes at which benefits are equal to costs of a new road lighting installation. However, additional considerations regarding environmental effects will also be essential and environmental costs will probably be included in cost-benefit analyses.

The future situation concerning motorway safety and motorway lighting will be different from the past situation in many ways: Future motorways and vehicles will be safer, and the accident rate will be reduced during daylight and darkness, with or without road lighting. Motorways in Norway and other countries will be designed according to new safety principles based on “Vision Zero”, the vision of a road system without fatal or lifelong injuries. The road and its near surroundings, including ditches, slopes, fences, light poles and other constructions will be designed and constructed to prevent serious consequences when a road user makes a mistake. A safety barrier or a sufficiently large distance between vehicles travelling in opposite directions will prevent frontal collisions, and fences along the roadsides will prevent animals from crossing the road and cause accidents. Vehicles will be constructed to better absorb collision energy. Vehicles will also be equipped with electronic devices that give warnings to the driver or control the vehicle if a critical situation arises. These safety measures will reduce the accident rate on future motorways, and the benefit of road lighting will be reduced by time.

Some of the new safety measures will probably reduce accidents during darkness more than accidents during daylight. Vehicle headlights will be improved, and vehicles will be equipped with devices that detect animals, pedestrians and objects ahead, make them visible to the driver, or give warnings to the driver. Mandatory use of a reflective vest when leaving the car will prevent pedestrian accidents on motorways. These safety measures will reduce the accident rate in darkness and the effect of road lighting will be reduced by time.

Road lighting equipment and systems will be improved, and the use of dynamic lighting with electronic ballast will make way for a reduction in energy consumption, emission of green house gases and light pollution. Two-way communication systems will also make maintenance more efficient, and the safety effect will be better when road lighting is adapted to traffic and weather conditions. However, more knowledge about the relationship between the road lighting level and the effect on accidents is needed in order to use this technology effectively.

Because of the demand for energy savings, alternative measures to road lighting must be explored. LED guide lights, retro reflective edge lines and lane lines, reflecting delineators, and light road surfaces may be alternatives to motorway lighting because a combination of such measures may reduce the need for road lighting on low traffic motorways. These measures are presumed to especially reduce the risk of single vehicle accidents. Single vehicle accidents represent about half of all accidents on motorways, and though road lighting may have a good effect on single vehicle accidents, it is known (see the previous chapter) that road lighting installations have caused many collisions with light poles on motorways. On Dutch lit motorways 7.5 % of single vehicle accidents involved light poles, and on Norwegian lit motorways 23 % of single vehicle accidents involved light poles, as shown in Table 11. The alternative measures mentioned above do not increase risk by adding to the number of fixed objects like light poles.

LED guide lights, light road surface etc, may also be useful as supplements to adaptive road lighting installations on future motorways. Such measures may reduce the need for energy to the road lighting and, during fog and snow the guide lights may give an additional safety effect. When motorways are provided with road lighting it is also necessary to put up guard rails to prevent collisions with the light poles (or unprotected light poles must at least be of the yielding type).

NEEDS FOR FURTHER RESEARCH

Current knowledge and study results give only some indications about possible future benefits of road lighting. More research and pilot projects are needed in the search for improvements in the use of road lighting and alternative or additional measures.

Though the statistical precision of the results in the present study is high, the results may be affected by confounding factors that are not controlled for. The best way to control for confounding factors is to conduct a large scale before-and-after study in cooperation between several countries, with as large an accident sample as possible. Such a study could in principle also indicate how and why the effect on accidents varies from country to country, and it could maybe explain the great difference that was found between effects on Dutch, British and Swedish motorways in the present study.

A very important subject that needs to be studied, is the relationship between average luminance level (and other quality parameters) and motorway accidents. Today we do not really know the consequences on road safety of reducing or increasing the lighting level. Field studies of visibility during different weather conditions at different lighting levels would be useful. However, international cooperation is also needed for accident studies related to lighting level.

The effect of road lighting on accidents during snowy and foggy conditions and on snow covered surfaces should be studied more in detail in a study based on a large number of accidents. In the present study, these accident groups contained few accidents.

It is also a need for studies of the effect of LED guide lights and the effect of road surfaces with better photometric properties. Such measures are probably favourable, but it remains to be shown by appropriate evaluation studies.

CONCLUSIONS

The conclusions about the effect of motorway lighting on darkness accidents are:

1. The estimated effect on Dutch motorways is -49 % [-50 %, -48 %].

2. The estimated effect is significantly larger in the Netherlands than in Great Britain and Sweden. The reason for this is not known.

3. The estimated effect is significantly smaller during rainy conditions (-32 %) and snowy conditions (-33 %) than during fine weather (-54 %).

4. The estimated effect is significantly smaller on wet road surfaces (-36 %) and on snow or ice covered surfaces (-33 %) than on dry surfaces (-56 %).

5. Road lighting seems not to be effective during fog.

6. The estimated effect is larger on single vehicle accidents than on rear end collisions. However, the effect on single vehicle accidents is probably to some extent offset by collisions with light poles.

7. Collisions with light poles represent 3.3 % of injury accidents during daylight and 5.3 % of injury accidents during darkness on lit Dutch motorways. On lit Norwegian motorways collisions with light poles represent 10.2 % of injury accidents during daylight and 11.4 % of injury accidents during darkness.

Conclusions about future motorway lighting and the need for more research:

8. Road lighting will probably be an effective safety measures on motorways for many years. In the long term, however, the benefit of road lighting will probably be reduced along with the implementation of new vehicle and road technology.

9. It is essential that vehicles running of the road are taken care of in a safe way before they hit a light pole or another vehicle or object.

10. Future motorway lighting will be of the adaptive type for the purpose of energy savings.

11. The relationship between lighting level and accident risk is unknown and should be studied in an international cooperation. In adaptive road lighting it is essential to know how a reduction or increase in lighting level affects the accident risk.

12. LED guide lights may be an alternative to road lighting on low traffic motorways in order to reduce the energy consumption. However, the effect on accidents needs to be evaluated.

13. LED guide lights and light surfaces may also be beneficial in combination with road lighting in order to optimize energy consumption and safety effect. Pilot projects are needed.

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Appendix A

Accidents on Norwegian Main Roads 1986 - 2005

Table A1: Accidents related to light conditions and degree of injury

	Degree of injury	Day-light	Twi-light	Dark lit	Dark unlit	Darkness/ daylight accident ratio	Share of accidents in darkness or twilight
All injury accidents	All injury	61290	5534	13764	9647	0,38	**0,32**
	Serious	8249	860	1896	1792	0,45	**0,36**
	Fatal	2357	256	552	664	0,52	**0,38**

Table A1 shows that accidents during darkness or twilight are more serious than accidents during daylight.

Table A2: Accidents related to light conditions and type of road

	Degree of injury	Day-light	Twi-light	Dark lit	Dark unlit	Darkness/ daylight accident ratio	Share of accidents in darkness or twilight
4 lanes roads 90–100 km/h	All	242	19	120	14	0,55	0,39
4 lanes roads 80 km/h and less	All	1521	88	587	10	0,39	0,31
	Fatal	23	0	11	1		
2 lanes roads 80–90 km/h	All	9877	947	994	3043	0,41	0,34
	Fatal	594	59	67	228		
2-lane roads 60–70 km/h	All	9002	734	2153	1144	0,37	0,31
	Fatal	356	32	110	72		
2-lane roads 40–50 km/h	All	5270	356	1799	173	0,37	0,31
	Fatal	71	13	54	7		
2-lane roads 80 km/h, AADT > 8 000 vehicles	All	1223	109	402	220	0,51	0,37
	Fatal	93	12	26	26		
2-lane roads 80 km/h, AADT < 8 000 vehicles	All	8093	781	527	2646	0,39	0,33
	Fatal	446	44	38	186		

Table A2 shows that 2-lane roads with speed limit 80 km/h and AADT > 8000 vehicles have a higher share of their accidents in darkness or twilight than the other types of 2-lane roads.

Table A3: Accidents related to light conditions and type of accidents

	Degree of injury	Day-light	Twi-light	Dark lit	Dark unlit	Darkness/ daylight accident ratio	Share of accidents in darkness or twilight
Frontal collision	All	8830	979	1732	2128	0,44	0,35
	Fatal	1006	93	166	270		
Vehicle leaving the road	All	15946	2037	3546	4897	0,53	0,40
	Fatal	634	85	165	233		
Hitting object in carriageway	All	638	76	306	128	0,68	0,44
	Fatal	16	2	11	6		
Chain or rear collision	All	19116	984	2958	799	0,20	0,20
	Fatal	138	11	27	20		
Angle collision	All	9042	673	2555	375	0,32	0,28
	Fatal	234	13	30	6		
Collision with pedestrian	All	4068	454	2032	542	0,63	0,43
	Fatal	223	42	145	99		
Collision with animal	All	409	167	88	550	1,56	0,66
	Fatal	7	7	4	17		

Table A3 shows that the following accident groups are overrepresented in darkness or twilight: “Collision with animal”, “Collision with pedestrian”, “Hitting object in carriageway”, “Vehicle leaving the road”, and “Frontal collision”. Chain or rare collisions are underrepresented in darkness/twilight.

Table A4: Accidents related to light conditions and weather conditions

	Degree of injury	Day-light	Twi-light	Dark lit	Dark unlit	Darkness/ daylight accident ratio	Share of accidents in darkness or twilight
Fine weather	All	49787	3595	8708	6036	0,30	0,27
	Fatal	1950	181	370	431		
Rain or snow	All	9780	1536	4040	2672	0,69	0,46
	Fatal	364	65	137	165		
Fog or mist	All	266	151	250	259	1,91	0,71
	Fatal	15	7	13	24		
Dry road surface	All	37415	1988	4657	2669	0,20	0,20
	Fatal	1496	109	229	232		
Wet surface	All	12117	1510	4883	2016	0,57	0,41
	Fatal	434	68	212	161		
Snow or ice covered surface	All	9757	1823	3577	4467	0,82	0,50
	Fatal	390	73	93	251		

Table A4 shows that the following accident groups are overrepresented in darkness/twilight: “Fog or mist”, “Rain or snow”, “Snow or ice covered surface” and “Wet surface”. The groups “Fine weather” and “Dry road surface” are underrepresented in darkness/twilight.

Table A5: Accidents related to light conditions and type of vehicles

	Degree of injury	Day-light	Twi-light	Dark lit	Dark unlit	Darkness/ daylight accident ratio	Share of accidents in darkness or twilight
Moped or MC involved	All	8343	499	1292	483	0,21	0,21
Cyclist involved	All	4107	169	511	126	0,16	0,16
Heavy vehicle involved	All	9349	614	1304	1214	0,27	0,25
Only light cars involved	All	52710	4911	12512	8544	0,40	0,32

Table A5 shows that mopeds, MCs, cycles and heavy vehicles have a smaller share of their accidents during darkness or twilight than light cars

Table A6: Accidents related to light conditions and gender and age of drivers

	Degree of injury	Day-light	Twi-light	Dark lit	Dark unlit	Darkness/ daylight accident ratio	Share of accidents in darkness or twilight
Only male drivers	All	34061	3403	8267	6815	0,44	0,34
Only female drivers	All	8561	803	1590	1445	0,35	0,30
Only drivers age less than 50 years	All	24731	2896	7189	5783	0,52	0,38
Only drivers age more than 50 years	All	10872	607	1558	793	0,22	0,21

Table A6 shows that female drivers have a smaller part of their accidents during darkness or twilight than male drivers. Drivers over 50 years have a smaller part of their accidents during darkness/twilight than younger drivers.

Appendix B

Illustration of the Ratio of Odds Ratios Estimator

Illustration of the Ratio of Odds Ratios Estimator

This appendix shows by illustrating figures how the ratio of odds ratios estimator is used to estimate the effect of road lighting on Dutch accidents (used in Paper III). This estimator is based on a method developed by Johansson (2007). Johansson estimated the change in risk associated with darkness by using an odds ratio as estimator.

The odds ratio estimator of risk increase in darkness (the Johansson method)

The number of accidents that occurred within the hours 8 (07:00 – 07:59) and 18 (17:00 – 17:59) is observed month by month throughout the year. In Holland, those hours have darkness during November – January and daylight during the period April – August. During the other months, H8 and H18 have some twilight, some darkness and some daylight, and those months are not considered in the method of risk assessment.

The number of accidents is also observed month by month for two other hours, H10 and H16. Those two hours are chosen as comparison group because they have only daylight through the whole year and they are as close as possible to the studied hours H8 and H18.

Figure B1 show accidents month by month on all lit Dutch roads in H8+H18 and in H10-H16 throughout the year. Figure B2 shows accidents on unlit roads in a similar way.

Figure B1: Injury accidents on lit Dutch roads in H8+H18 and H10+H16

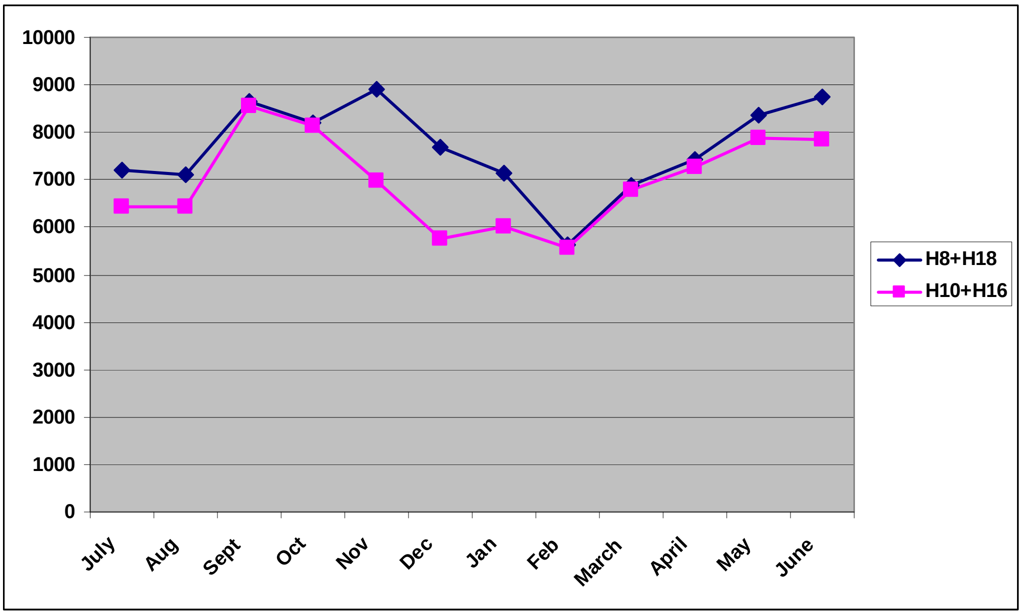
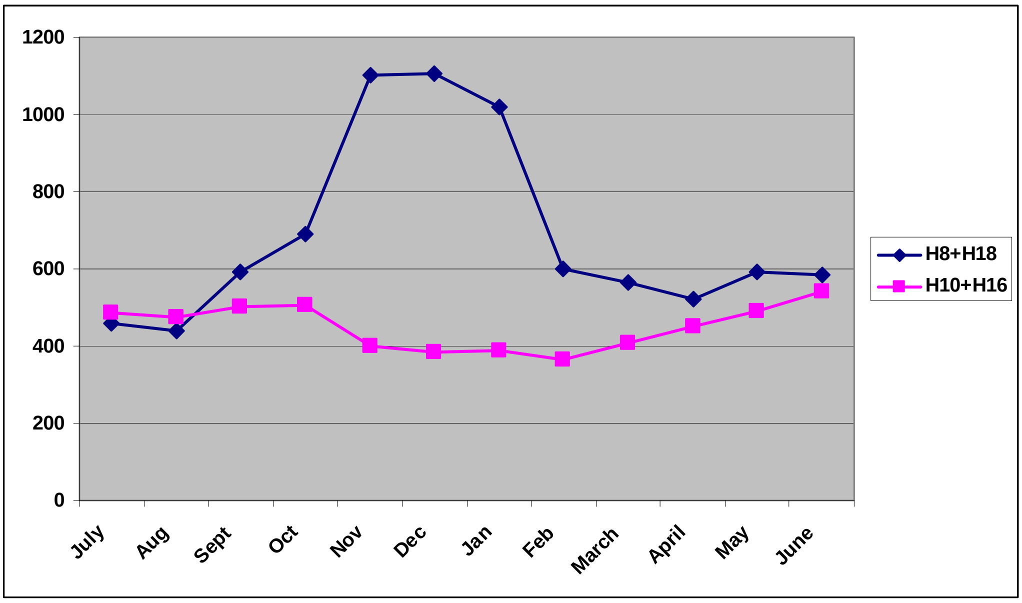


Figure B2: Injury accidents on unlit Dutch roads in H8+H18 and H10+H16



The number of accidents in hours H8+H18 are compared the number of in hours H10+H16 for two periods. One period is November – January, when H8 and H18 have darkness. The other period is April – August, when H8 and h18 have daylight. An odds ratio is estimated as shown below, indicating the change in risk associated with darkness.

$$\text{Odds ratio} = \frac{\dfrac{\text{Number of accidents in H8+H18 in November - January}}{\text{Number of accidents in H10+H16 in November – January}}}{\dfrac{\text{Number of accidents in H8+H18 in April – August}}{\text{Number of accidents in H10+H16 in April – August}}}$$

Calculations show that the odds ratio on lit roads is 1.17 and the odds ratio on unlit roads is 2.59. This means that the risk in darkness increases by 17 % on lit roads and by 159 % on unlit roads.

The ratio of odds ratios estimator of effect of road lighting

The ratio of odds ratios is used as estimator of the effect of road lighting on accidents. For all Dutch accidents, shown in Figure B1 and Figure B2, the ratio of odds ratios is: 1.17/2.59 = 0.45. This means that estimated accident reduction is 55 %.

The same method used on other accident groups

The ratio of odds ratios was used to estimate the effect of road lighting for several groups of injury accidents on rural Dutch road. Those estimates are presented in Paper III, but figures used to illustrate the odds ratios, indicating the accident increase in darkness, are not included in Paper III. Those figures are presented below.

Figure B3 and Figure B4 show all injury accidents on Dutch rural roads.

Figure B5 and Figure B6 show injury accidents in fair weather on Dutch rural roads.

Figure B7 and Figure B8 show injury accidents during rain on Dutch rural roads.

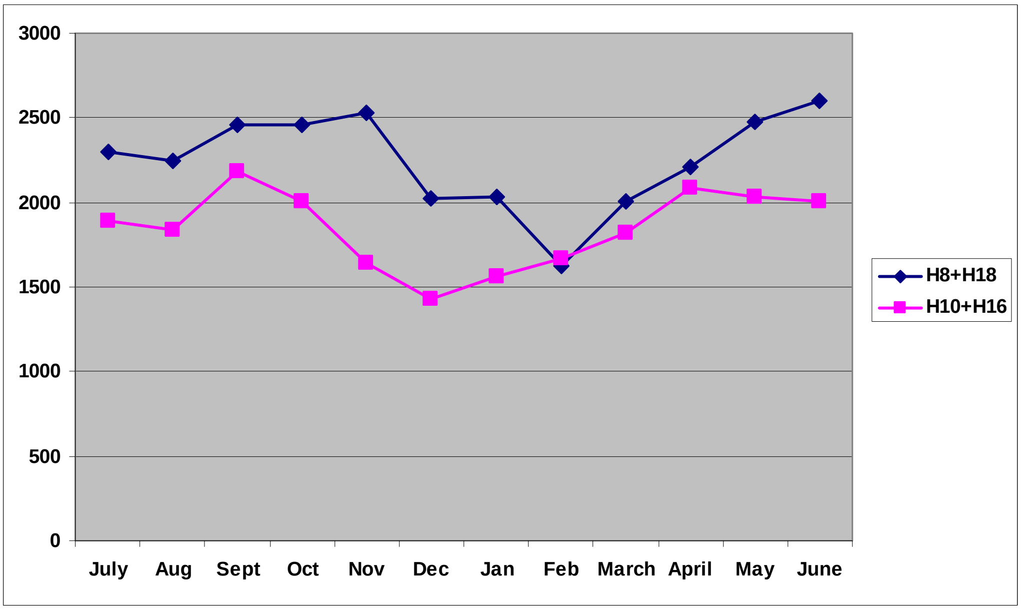
Figure B9 and Figure B10 show injury and material damage accidents in fog on Dutch rural roads.

Figure B11 and Figure B12 show injury accidents on dry road surface on Dutch rural roads.

Figure B13 and Figure B14 show pedestrian injury accidents on Dutch rural roads.

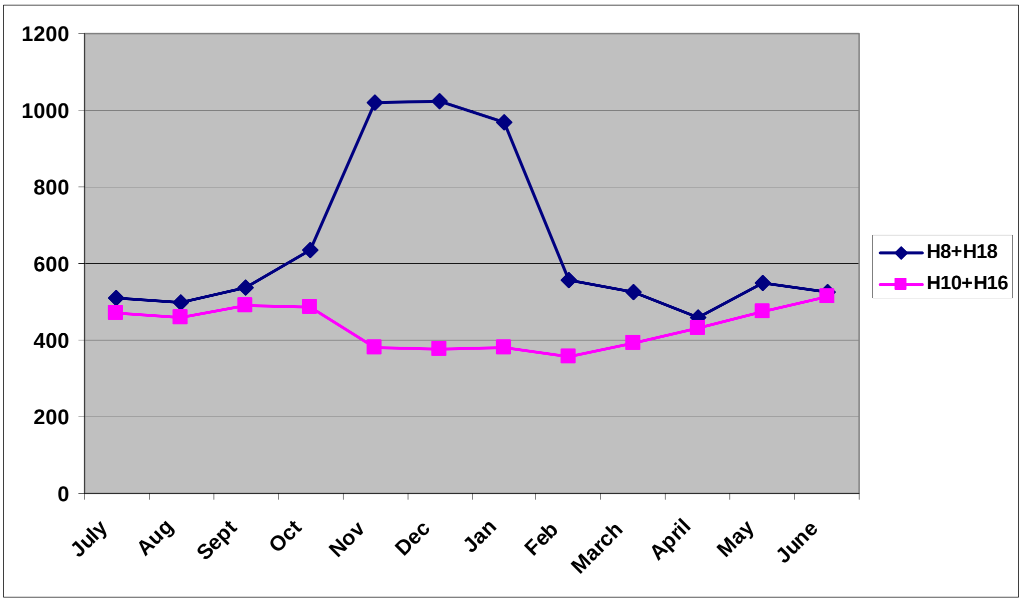
Figure B15 and Figure B16 show bicycle injury accidents on Dutch rural roads.

Figure B3: Injury accidents in H8+H18 and H10+H16 on lit Dutch rural roads



The estimated risk increase for injury accidents during hours of darkness on lit rural roads in H8+H18 is 17 %.

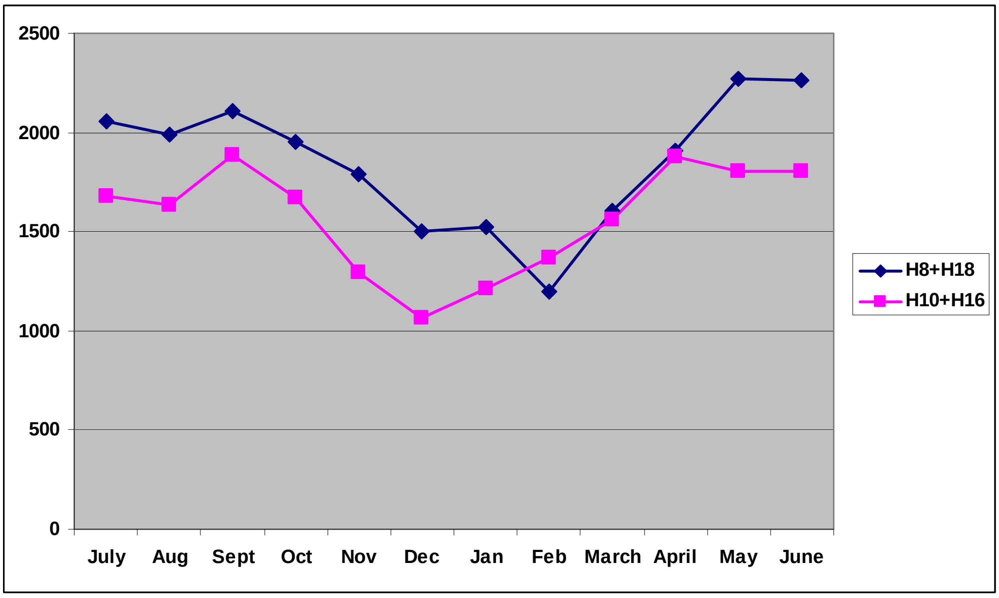
Figure B4: Injury accidents in H8+H18 and H10+H16 on unlit Dutch rural roads



The estimated risk increase for injury accidents during hours of darkness on unlit rural roads in H8+H18 is 145 %.

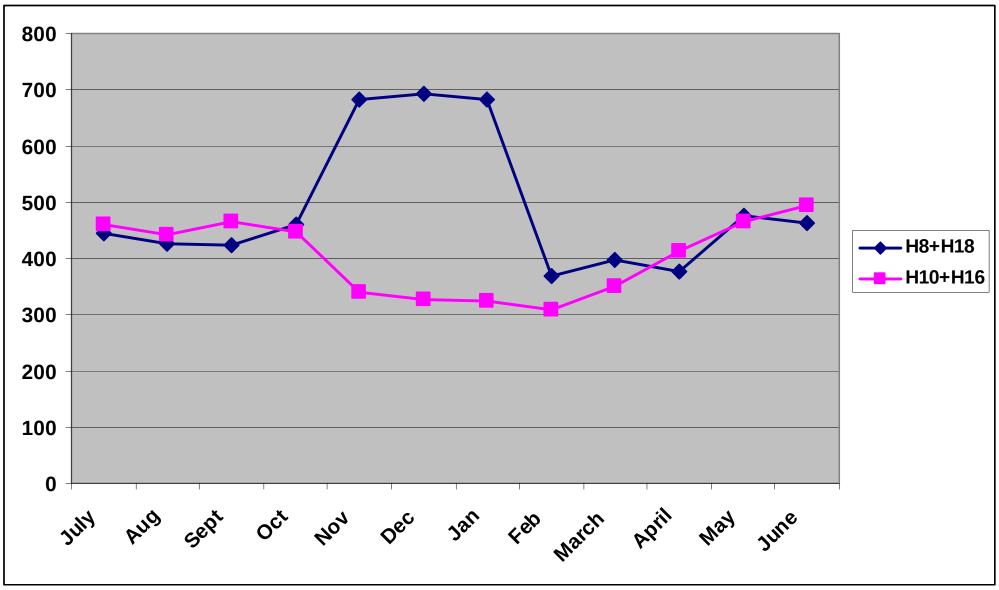
The estimated effect of road lighting on injury accidents is -52 %.

Figure B5: Injury accidents in fair weather on lit Dutch rural roads in H8+H18 and H10+H16



The estimated accident risk increase during darkness in fair weather on lit roads in H8+H18 is 11 %.

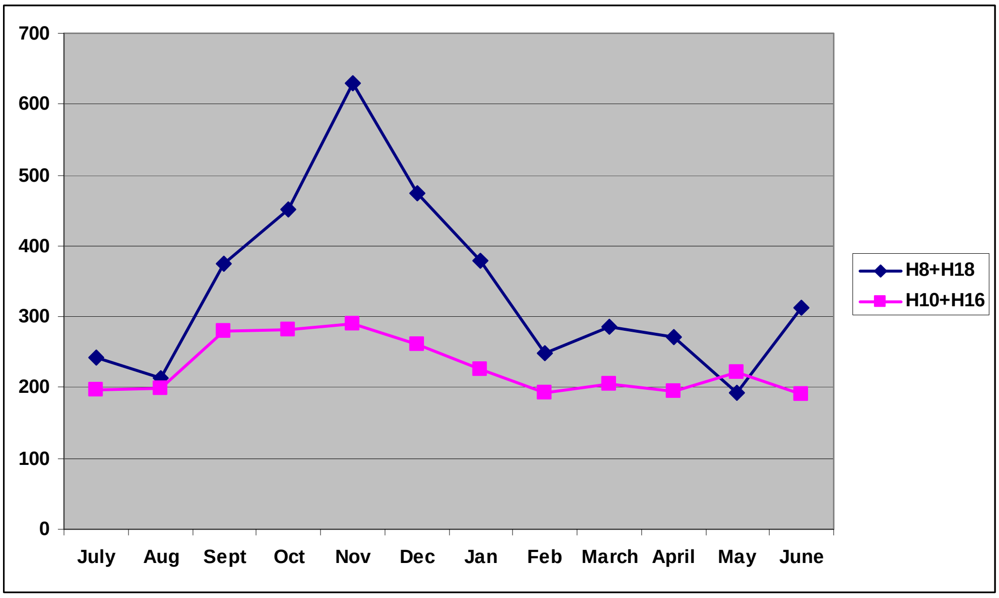
Figure B6: Injury accidents in fair weather on unlit Dutch rural roads in H8+H18 and H10+H16



The estimated accident risk increase during darkness in fair weather on unlit roads in H8+H18 is 116 %.

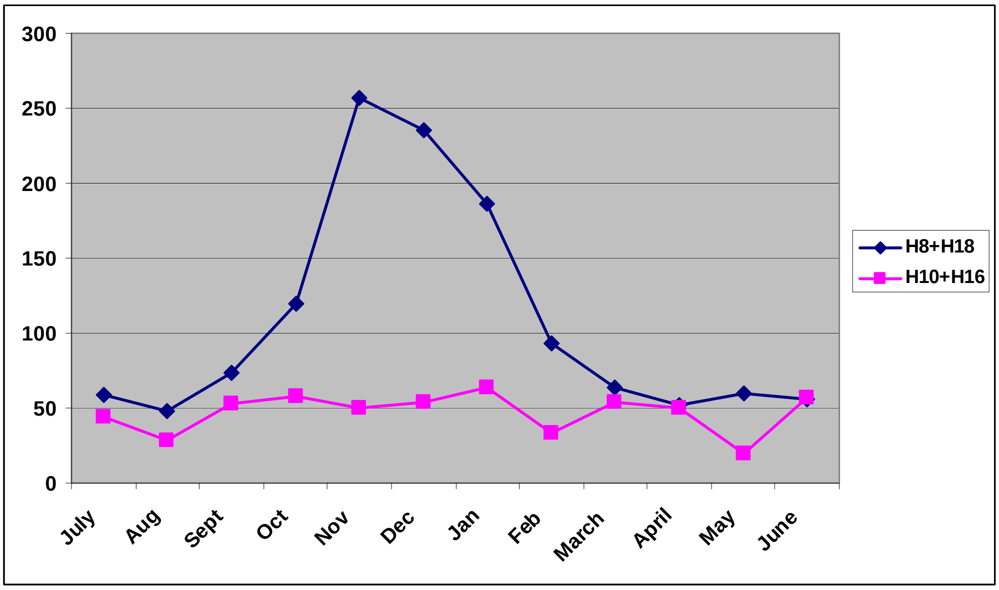
The effect of road lighting on accidents in fair weather is -49 %.

Figure B7: Injury accidents during rain on lit Dutch rural roads in H8+H18 and H10+H16



The estimated risk increase during darkness in rain on lit roads in H8+H18 is 53 %.

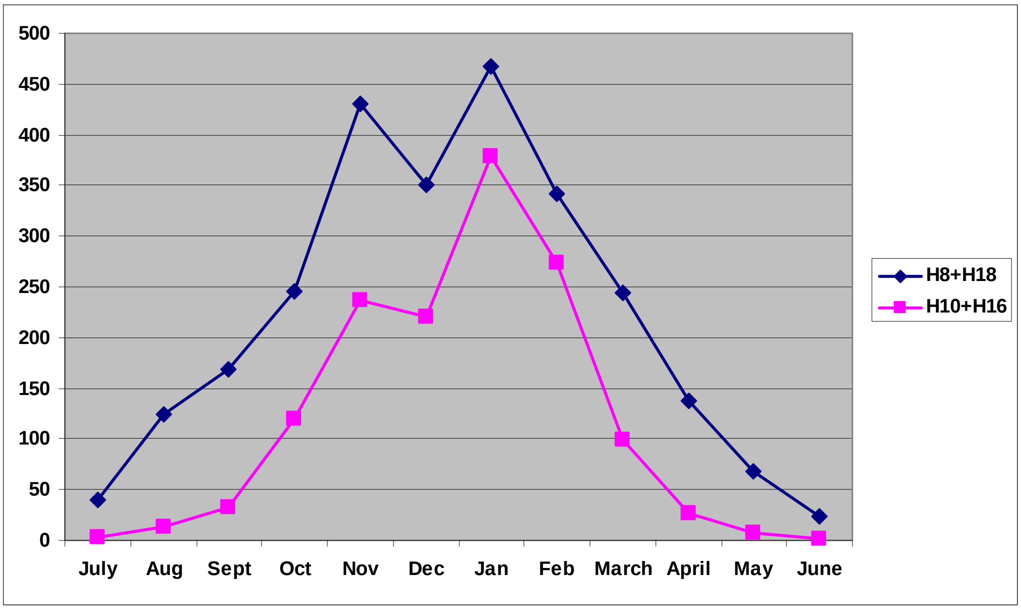
Figure B8: Injury accidents during rain on unlit Dutch rural roads in H8+H18 and H10+H16



The estimated risk increase during darkness in rain on unlit roads in H8+H18 is 192 %.

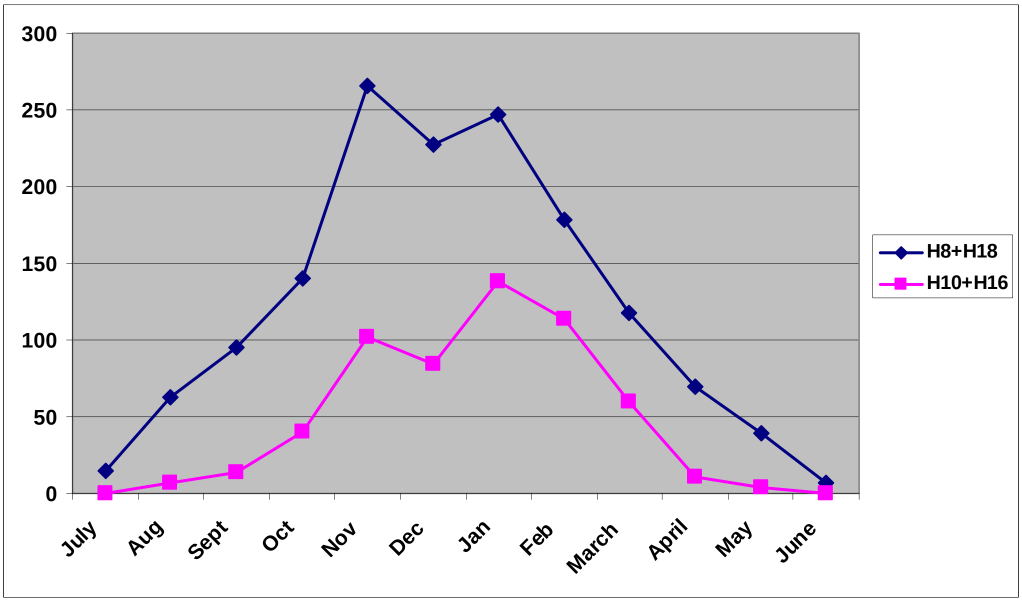
The estimated effect of road lighting on accidents during rain is -48 %.

Figure B9: Injury and material damage accidents during fog on lit Dutch rural roads in H8+H18 and H10+H16



The estimated risk increase during darkness in fog on lit roads in H8+H18 is 25 % when material damage accidents are included.

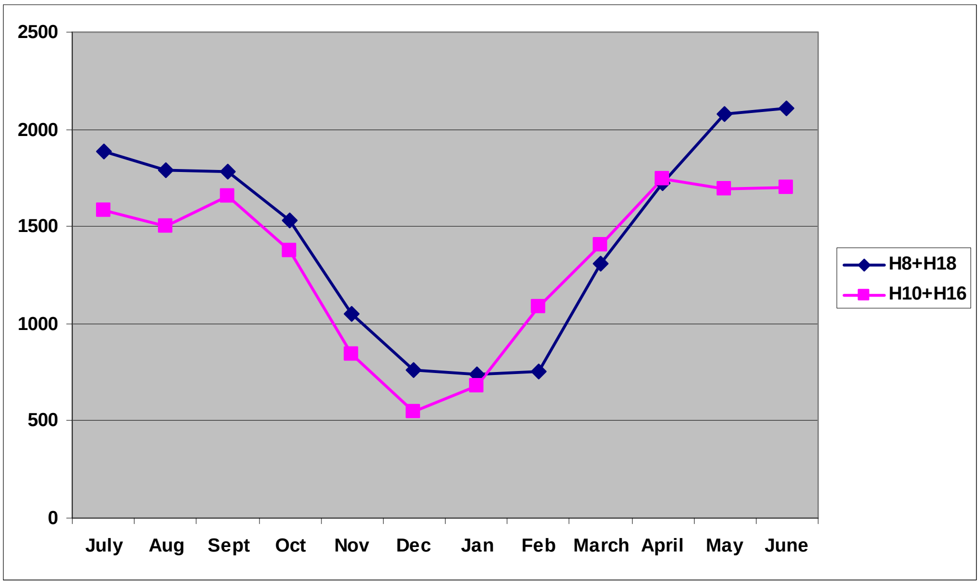
Figure B10: Injury and material damage accidents in fog on unlit Dutch rural roads in H8+H18 and H10+H16



The estimated risk increase during darkness in fog on unlit roads in H8+H18 is 12 % when material damage accidents are included.

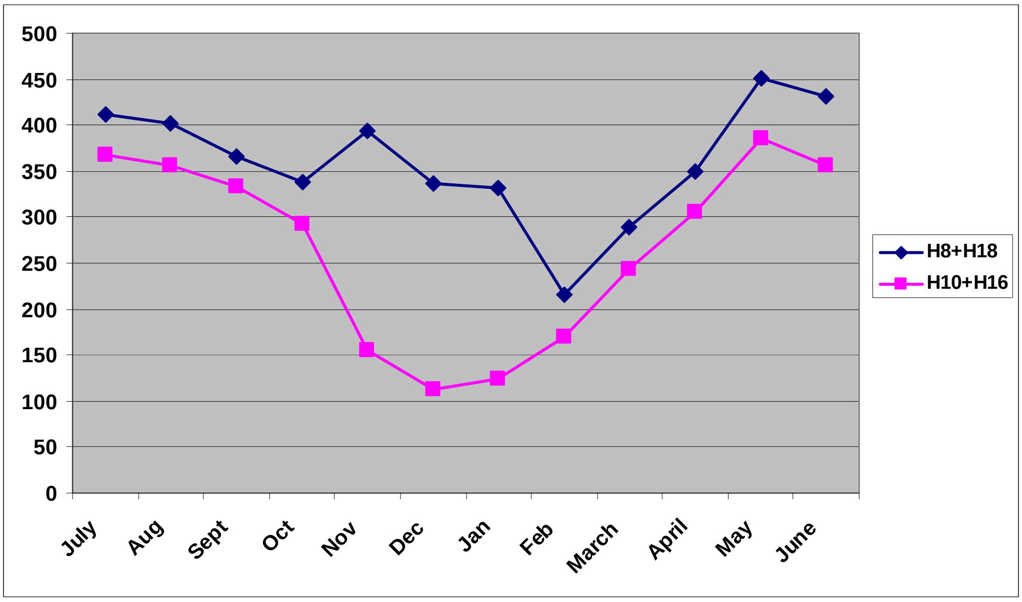
The estimated effect of road lighting in fog is 12 % accident increase when material damage accidents are included.

Figure B11: Injury accidents on dry surface and lit Dutch rural roads in H8+H18 and H10+H16



The estimated accident risk increase during darkness and dry road surfaces on lit roads in H8+H18 is 4 %.

Figure B12: Injury accidents on dry surface and unlit Dutch rural roads in H8+H18 and H10+H16

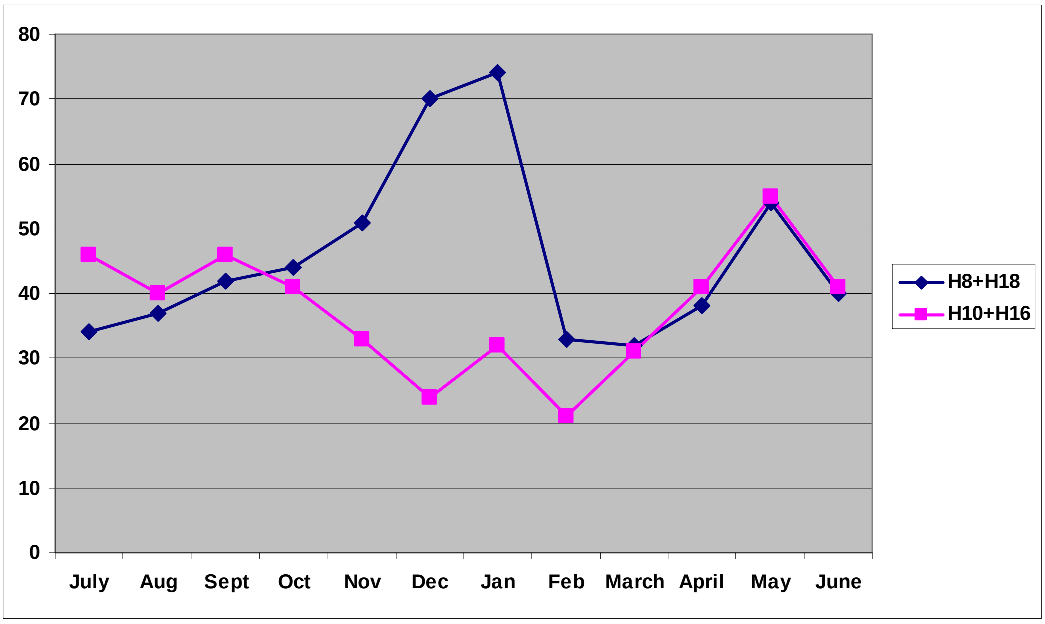


The estimated accident risk increase during darkness and dry road surfaces on unlit roads in H8+H18 is 135 %.

The estimated effect of road lighting on injury accidents on dry road surfaces is -56 %.

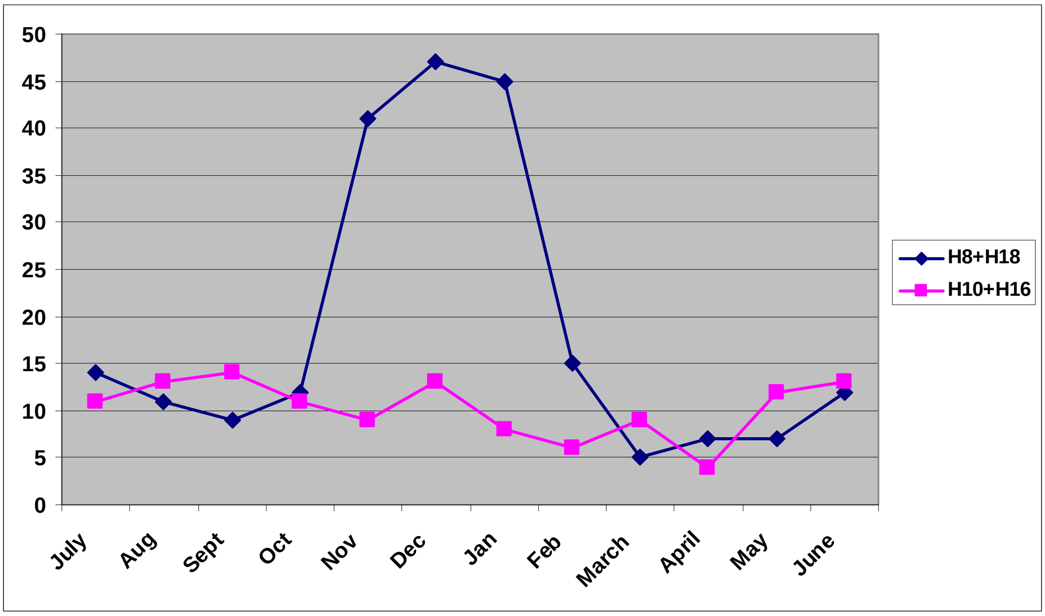
The figures also show that there are few accidents on dry road surfaces during the winter. The reason is that the surfaces often are wet or covered with snow or ice during the winter months.

Figure B13: Pedestrian injury accidents on lit Dutch rural roads in H8+H18 and H10+H16



For pedestrian accidents, the estimated accident risk increase during hours of darkness on lit roads in H8+H18 is 141 %.

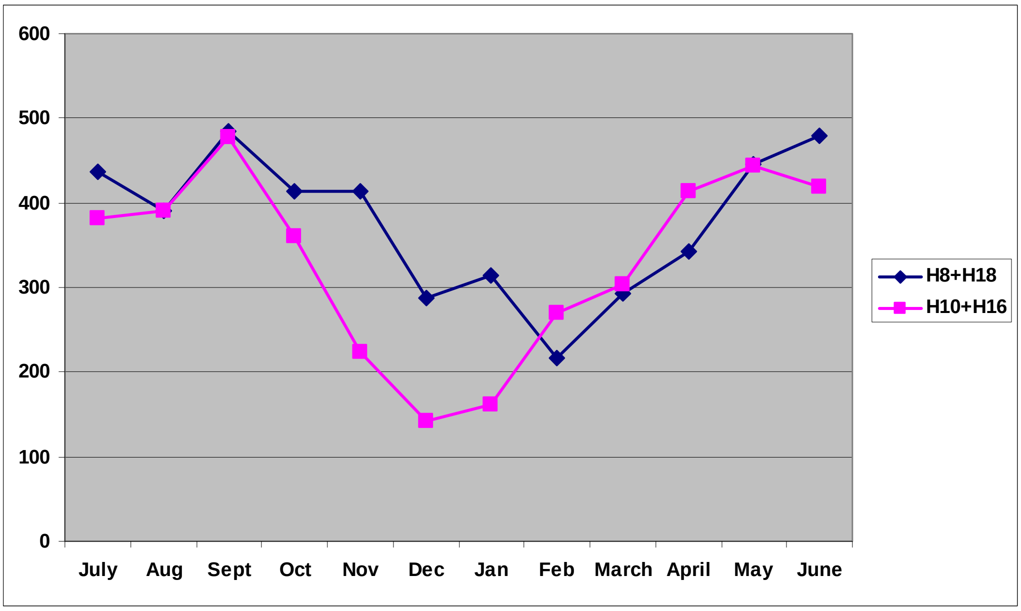
Figure B14: Pedestrian injury accidents on unlit Dutch rural roads in H8+H18 and H10+H16



For pedestrian accidents, the estimated risk increase during hours of darkness on unlit roads in H8+H18 is 361 %.

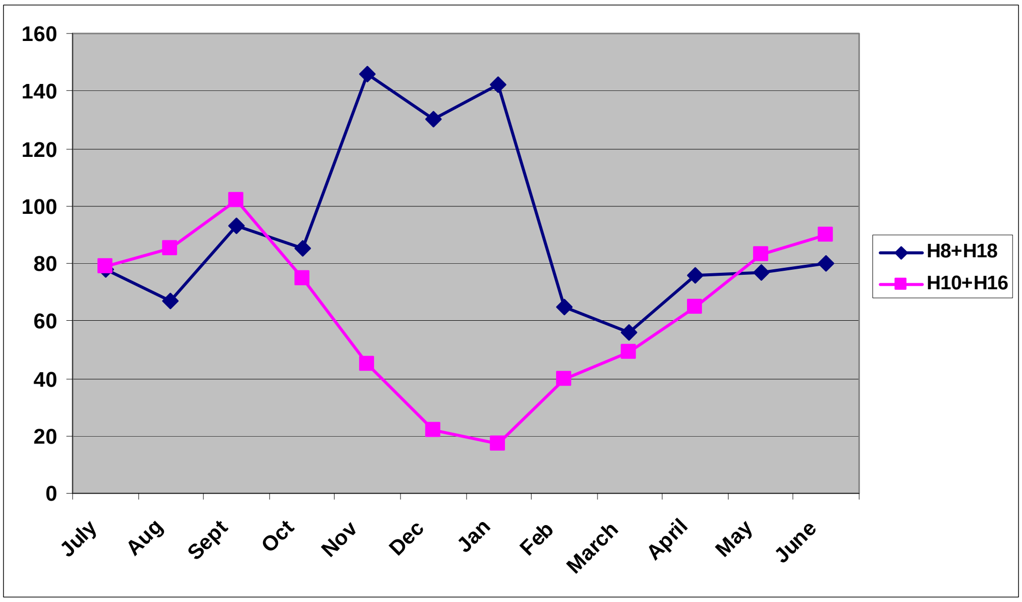
The estimated effect of road lighting on pedestrian accidents is -48 %.

Figure B15: Bicycle injury accidents on lit Dutch rural roads in H8+H18 and H10+H16



For bicycle accidents, the estimated risk increase during darkness on lit roads in H8+H18 is 81 %.

Figure B16: Bicycle injury accidents on unlit roads in H8+H18 and H10+H16



For bicycle accidents, the estimated risk increase during darkness on unlit roads in H8+H18 is 429 %.

The estimated effect of road lighting on bicycle accidents is -66 %.

Appendix C

Accidents on Dutch Roads 1987 – 2006

Table C1: Injured persons on Dutch roads 1987 - 2006

Accident type/ condition	Daylight		Darkness		Darkness/Daylight	
	Lit	Unlit	Lit	Unlit	Lit	Unlit
All accidents	587605	43245	167170	31725	0.28	0.73
Built-up areas	412886	4021	117311	1531	0,28	0,38
Outside built-up	174280	39209	48830	30182	0,28	0,77
Fine weather	512509	36133	126864	24274	0,25	0,67
Raining	66123	5008	33607	4965	0,51	0,99
Fog	2684	1051	2395	1302	0,89	1,24
Snowing	2709	532	1715	574	0,63	1,08
Dry road surface	444495	30926	90472	17706	0,20	0,57
Wet or damp	133085	10466	69896	11791	0,53	1,13
Snow/ice covered	4786	1016	4207	1554	0,88	1,53
Fine. Snow/ice	2655	483	2326	791	0,88	1,64
Fine. Wet	63982	4826	34273	5966	0,54	1,24
Rain. Wet	65171	4790	32732	4623	0,50	0,97
Snowing. Wet	1107	128	499	111	0,45	0,87
Snowing. Snow/ice	1567	376	1181	456	0,75	1,21
Pedestrian acc.	43315	1166	11599	1462	0,27	1,25
Single vehicle	34273	6350	10376	5477	0,30	0,86
Frontal collision	100441	7484	26808	4228	0,27	0,56
Rear-end coll.	95621	7638	20119	4088	0,21	0,54
Animal accidents	1587	404	648	756	0,41	1,87
Straight road	242992	26823	66365	21143	0,27	0,79
Straight Separated	2790	554	945	439	0,34	0,79
Bend	39848	8795	18158	8233	0,46	0,94
Crossroad 3 arms	120577	3032	29246	1139	0,24	0,38
Crossroad 4 arms	173782	3919	49234	747	0,28	0,19
Light cars	199879	24502	83572	22001	0,42	0,90
Lorry involved	3698	756	671	366	0,18	0,48
Cyclist involved	157147	5983	25372	1814	0,16	0,30
Age >74	25786	1301	2391	286	0,09	0,22
Age 60 - 74	54494	3707	7436	1231	0,14	0,33
Age 30 - 39	90401	8131	29204	6064	0,32	0,75
Male driver	368676	31141	124059	25786	0,34	0,83
Female driver	215474	11901	41196	5766	0,19	0,48
Sunday	55452	6253	29075	6631	0.52	1.06
Tuesday	92335	6014	19892	3396	0.22	0.57
Friday	100588	6665	28538	5191	0.28	0.78
Saturday	80074	6928	27347	5774	0.34	0.83
120 km/h	13245	6427	4730	5627	0,36	0,88
100 km/h	17533	3093	6429	2372	0,37	0,77
80 km/t	116708	26783	29298	19737	0,25	0,74
70 km/h	16592	442	6744	266	0,41	0,60
60 km/h	4233	678	1171	410	0,28	0,60
50 km/h	385526	4091	108785	1670	0,28	0,41
120 km/h. Fine	10649	4960	3418	4205	0,32	0,85
120 km/h. Raining	1981	954	997	939	0,50	0,98
120 km/h. Fog	322	326	171	224	0,53	0,69
120 km/h Snowing	207	120	101	175	0,49	1,46
120 km/h. Dry	9254	4402	2471	3133	0,27	0,71
120 km/h. Wet	3659	1823	1995	2109	0,55	1,16
120 km/h Snow/ice	240	157	246	348	1,03	2,22
120 km/h Fatigue	604	449	336	475	0,56	1,06
120 km/h Alcohol	420	238	827	975	1,97	4,10
120 km/h Speeding	205	103	128	137	0,62	1,33

Table C1 shows in the right columns the darkness/daylight accident ratio on lit roads and unlit roads respectively. This ratio is the odds of having an accident in darkness and it is used for estimation of the effect of road lighting in paper III. Ratios that are more than twice as high as the average are coloured read and ratios that are less than half as high as the average are coloured green.

Table C2: Percentage of injuries on Dutch rural roads 1987 – 2006, distributed over weather conditions, road user groups and accident types

Accident type/ condition	Daylight		Darkness	
	Lit	Unlit	Lit	Unlit
All injury accidents	100	100	100	100
Fine weather	86 %	84 %	76 %	77 %
Rain	12 %	12 %	19 %	15 %
Fog	0.9 %	2.2 %	2.7 %	4.1 %
Snow	0.7 %	1.3 %	1.5 %	1.9 %
Dry road surface	73 %	71 %	52 %	56 %
Wet road surface	25 %	24 %	43 %	37 %
Snow/ice covered	1.2 %	2.6 %	3.9 %	5.1 %
Pedestrian	2.1 %	2.4 %	3.0 %	4.9 %
Bicycles	17 %	15 %	6.9 %	6.6 %
Moped	14 %	9.1 %	11 %	9.4 %
MC	9.5 %	9.6 %	4.4 %	2.8 %
Automobile	58 %	64 %	75 %	76 %
Driver age 60 - 74	9.0 %	7.7 %	4.3 %	3.2 %
Hit fixed object	14 %	23 %	32 %	37 %
Frontal collision	16 %	14 %	12 %	9.8 %
Flank collision	32 %	20 %	20 %	9.3 %
Hit animal	0.4 %	1.1 %	0.9 %	2.8 %
Rear end collision	24 %	17 %	18 %	12 %
Single vehicle	8.7 %	17 %	9.6 %	19 %

Table C2 shows that the share of accidents in fog or snow or on snow or ice covered road surface is smaller on lit road than on unlit roads, especially during daylight. If we suppose that weather conditions are equal on lit roads and unlit roads, which seems to be a reasonable assumption for the geographically small area of the Netherlands, there are at least two possible explanations for the differences mentioned above: One possible explanation is that the share of traffic volume in fog or in snow or on snow or ice cowered surfaces is smaller on lit roads than on unlit roads. The other possible explanation is that the accident risk during these conditions is smaller on lit roads than on unlit roads even during daylight. Both explanations seem reasonable. The table also shows that the share of accidents in rain and on wet road surfaces is the same on lit roads as on unlit roads during daylight, while the share of accidents during these conditions is larger on lit roads than on unlit roads during darkness. This indicates that the share of traffic volume in rain or on wet road surfaces is the same on lit roads as on unlit roads. The high share of accidents during these conditions in darkness on lit roads is probably due to the smaller effect of road lighting during these conditions than during fine weather. The table shows that driving in darkness is very risky during rain and on wet road surfaces even on lit roads.

Table C3: Injury accidents on Dutch motorways 1987 – 2006
distributed over accident types and light conditions

Accident type	Lit roads			Unlit roads		
	Daylight	Twilight	Darkness	Daylight	Twilight	Darkness
Rear end collision	41 %	42 %	34 %	36 %	38 %	29 %
Frontal collision	3 %	4 %	2 %	2 %	1 %	2 %
Flank collision	9 %	8 %	7 %	6 %	6 %	6 %
Hit fixed object	27 %	29 %	35 %	27 %	30 %	33 %
Hit loose object	1 %	1 %	1 %	1 %	1 %	1 %
Hit pedestrian	1 %	1 %	1 %	1 %	0 %	2 %
Hit parked vehicle	2 %	1 %	2 %	2 %	1 %	2 %
Hit animal	0 %	1 %	1 %	1 %	1 %	2 %
Single vehicle acc.	16 %	13 %	16 %	24 %	20 %	20 %
Unknown	1 %	2 %	1 %	2 %	2 %	1 %
All types	100 %	100 %	100 %	100 %	100 %	100 %
Hit light pole	3 %	3 %	5 %	0 %	0 %	0 %

Table C3 shows that three accident types are dominating in daylight as well as in twilight and darkness and on lit motorways as well as on unlit motorways. “Rear end collision”, “Hit fixed object”, and “Single vehicle accident” represent more than 80 % of all injury accidents on Dutch motorways.

“Rear end collision” is the largest accident type. However, the problem is typically related to traffic density and “Rear end collision” represents a larger part of daylight accidents on lit roads (41 %) than of darkness accidents on unlit roads (29 %).

Accidents within the two groups “Hit fixed object” (occurring when a vehicle runs off the road) and “Single vehicle accident” (mainly occurring when a vehicle runs off the road) represent 51 % of darkness accidents on lit motorways and 53 % of darkness accident on unlit motorways. A light pole is hit in 3 % of daylight accidents and in 5 % of darkness accidents on lit motorways.

Beside the three main accident types, “Hit pedestrian” has also been a darkness problem on unlit Dutch motorways 1987 – 2006 because 28 out of 39 hit pedestrians are killed.