# Street lighting and road safety on motorways

*A study into the relationship between the level of street lighting and road accidents on motorways outside the built up area in the Netherlands during the period 1989 to 1991, inclusive*

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A.A. Vis
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SWOV Institute for Road Safety Research, The Netherlands

SWOV Institute for Road Safety Research
P.O. Box 170
2260 AD Leidschendam
The Netherlands
Telephone 31703209323
Telefax 31703201261

# Summary


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One of the functions of street lighting is to encourage the safer and more rapid transit of traffic travelling at night. It is now broadly accepted that street lighting indeed assists in reducing the number of night-time accidents and that the associated level of luminance of street lighting plays a role. However, these assumptions still need to be confirmed through a specific relationship study.

This report relates to the study of the cited relationship with respect to motorways outside the built up area. The principal policy queries to which this series of studies is intended to offer a reply are as follows: Under which conditions and on which roads is the installation of street lighting useful, above which level of luminance is no further improvement in road safety likely and what is the most effective level of luminance?

The study was therefore confined to accidents registered on through (main) carriageways and only utilised existing databases available within a relatively short time period. Part of the essential data were obtained from the routinely revised files. Supplementary data on road and traffic characteristics were collected by means of interviews with road authorities and other organisations responsible for the maintenance of street lighting. Calculation of luminance values was carried out with the aid of the computer programme RWSLICHT version 2.0.

The data for approximately 2000 kilometres of Dutch motorways were reviewed. 80% proved to be unlit and approx. 15% lit. For the remaining 5%, approx., this was not determined during the review, due to time pressure and the ensuing need to prioritise areas of study.
The study utilised all accident data (i.e. both injury accidents and accidents with material damage only) from the period 1989 to 1991 inclusive, selected on the basis of through main carriageways on motorways outside the built up area. The day/night distribution of accidents was based on the data provided by the Royal Dutch Meteorological Institute, KNMI.

The 'rough' analysis file was realised by joining the (combined) road characteristics, lighting characteristics and accident database based on the linking key, road number and hectometre indication. After deletion of non-relevant cases, this analysis file consisted of almost 28,000 accidents. Approximately 25,000 of these could be categorised either under the night or under the day period.

The collected data and results respectively were then entered into a research matrix, composed on the one hand of a number of traffic intensity categories and on the other of a number of luminance categories. Per matrix cell, the night and day risks, as well as the night/day risk ratios were calculated for both lit and unlit road sections.

Based on the (interpretation of) these variables and the previously reviewed data, the following (principal) conclusions could be summarised:

- Roughly one fifth of the Dutch motorways is provided with street lighting.
- A relatively large proportion of night-time accidents occurs on unlit road sections.
- The night-time mobility (kilometre travelled) on both lit and unlit road sections on average amounts to one quarter of the total daily intensity on an annual basis; viewed on a monthly basis, this night/day traffic intensity ratio varies markedly, however, thereby casting doubt on the previously assumed constant value of one quarter of the daily intensity as a basis for night-time mobility.
- The risk experienced on Dutch motorways tends to be greater at night than during the daytime, both on lit and unlit road sections.
- The night/day risk ratios for lit road sections are generally lower, particularly at relatively high luminance levels.
- An interaction between traffic intensity and luminance level with re-spect to (night-time) risk is likely, although the pattern indicated by the calculated risks and the resultant night/day risk ratios offers only an indication, with no means of correcting the effect of the luminance level on the basis of traffic intensity (in relation to the number of lanes).
- Road sections with street lighting tend to be 'less safe' in the daytime than unlit sections; they demonstrate both a greater traffic risk, expressed in terms of the number of accidents per kilometre travelled, as well as a greater number of accidents per kilometre of road length, at least insofar they belong to the same intensity category. It could be deduced from this information that, in practice, it is particularly those road sections which are relatively unsafe that are provided with street lighting (the recommended installation criteria agree more or less with this inference).

- Unexpectedly, a comparison between road sections with 2x2 and 2x3 lanes did not offer any indication that this difference in lane distribution for lit road sections within the traffic intensity category of 45,000 to 80,000 vehicles/day had led to considerable differences in night-time and daytime risks or in the derived night/day risk ratios.
- The final conclusion that can be made is that most trends point towards the positive effect of street lighting. However, the nature and scope of the available data do not allow a reliable and accurate quantitative relationship to be established between the level of street lighting and road safety.
- The report closes with a number of suggestions for further study; in the first place to include intersections, sliproads and roundabouts etc. which were not previously considered and in the second place, to perform more detailed study, taking into account aspects such as traffic intensity per lane, saturation level of road sections studied, driving direction, period of the day (e.g. peak time), type of accident, severity of injury, actual night-time mobility and homogeneity of road sections.

# Résumé

**Eclairage et sécurité routière sur les autoroutes**

L'auteur présente une série d'études destinées à apporter une réponse aux questions suivantes: dans quelles conditions et sur quelles routes est-il utile d'installer un éclairage, au-delà de quel degré de luminance n'y-t-il plus d'amélioration de la sécurité à attendre et quel est le degré de luminance le plus efficace?

On a analysé les données d'accidents et de caractéristiques de l'infrastructure pour plus de 2000 km d'autoroutes aux Pays-Bas. 80% étaient dépourvus d'éclairage et environ 15% en étaient pourvus. Pour les 5% restants, le temps avait manqué pour le déterminer. On a utilisé toutes les données d'accidents (c'est à dire avec dommages corporels ou simples dommages matériels), de la période 1989 à 1991 inclus, survenus sur la chaussée principale d'autoroutes. La répartition nuit/jour des accidents s'est effectuée en fonction des données fournis par l'organisme officiel de météorologie.

Les principaux résultats peuvent être résumés de la manière suivante
- Un cinquième environ des autoroutes néerlandaises est éclairé.
- Une proportion relativement importante des accidents qui surviennent la nuit arrivent sur des tronçons non éclairés.
- La mobilité nocturne (kilomètres parcourus) aussi bien sur les tronçons éclairés que non éclairés correspond en moyenne (calculée sur un an) au quart de son intensité diurne; si l'on calcule mois par mois, ce ratio varie sensiblement ce qui jette un doute sur la constance de la valeur un quart généralement adoptée pour l'estimation de la mobilité nocturne.
- Le risque auquel on s'expose sur les autoroutes néerlandaises tend à être plus important la nuit que le jour, sur les sections éclairées comme sur celles qui ne le sont pas. Mais le rapport est généralement plus faible sur les tronçons éclairés, en particulier lorsque le niveau de luminance est assez élevé.
- De jour les tronçons éclairés tendent à être moins sûrs, à la fois en termes du nombre d'accidents par kilomètre parcouru ainsi que du plus grand nombre d'accidents par kilomètre de voie, du moins dans la mesure ou ils appartiennent à la même catégorie d'intensité de trafic. On peut déduire de ce qui précède que ce sont les tronçons les plus dangereux qui sont en priorité équipés en éclairage (les critères d'installation corroborent plus ou moins cette hypothèse).
- La conclusion qu'on peut en définitive tirer est que la plupart des tendances vont dans le sens d'un effet positif de l'éclairage des voies. Mais la nature et la portée des données disponibles ne permettent pas d'établir une relation quantitative fiable et précise entre le niveau d'éclairage et la sécurité routière.

# Street lighting and road safety on motorways

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A.A. Vis
SWOV Institute for Road Safety Research, The Netherlands

## 1. Introduction

A number of functional aspects can be distinguished for street lighting. Traditionally - and particularly in urban areas - street lighting was intended to combat criminality and promote public safety and quality of life. In addition, street lighting now fulfils an increasingly important role for the safe and rapid flow of traffic while also contributing to driving comfort. The study described in this congress contribution focuses particularly on the role which street lighting plays in the field of road safety.

In the current organisation of our society, the transport of goods and the mobility of people represent important (economic) factors. In both cases, these are still bringing increasing pressure to bear. It should be taken into account, particularly in the Netherlands, that the resultant need to expand the road network is associated with restrictions. This can mean that on many routes, but particularly on motorways, night-time traffic will continue to increase. It is known that the number of road accidents that occur during conditions of darkness is relatively great with respect to the situation in the daytime. This can be attributed in part to the nature and composition of night-time traffic and the more frequent presence of relatively unfavourable conditions. Also, it is likely that the condition of darkness itself represents a risk-enhancing factor.

It is generally assumed that road safety will improve under most circumstances if roads are lit at night. It is likely that the quality of such street lighting - or, put another way, the lighting level or luminance level - plays a role in this regard. To date, relatively little evidence was available to support either assumption, however. Confirmation could be obtained by performing a direct relationship study. The studies performed to dante have been relatively few in number and, also as a result of the methodological objections associated with most of these studies, could not offer a clear and reliable quantitative relationship between lighting level and road safety.

However, in addition to positive aspects, street lighting is also associated with negative aspects based on considerations other than road safety. In addition to the installation and maintenance costs, energy consumption represents a considerable cost item and, as a result, street lighting imposes a burden on the environment. The installation and coverage of street lighting therefore demands an assessment of the costs and benefits. While the costs can be calculated relatively simply, the 'benefits' are not as simple to determine.

In the Netherlands, the Transportation and Traffic Research Division DVK of the Ministry of Public Works therefore took the initiative some years ago to conduct a study into the relationship between the level of street lighting and road hazard, as expressed through the

indicator 'accidents'. The principal (policy) questions to which this study attempted to find an answer were as follows:

- Under which circumstances and on which roads would the installation of street lighting be considered useful (taking into account whether the advantages compare reasonably favourably with the investment and exploitation costs involved).
- Beyond which luminance level can no further (measurable) improvement of road safety be anticipated.
- Which lighting level should be regarded as the most effective, in view of the circumstances.

The study planned at the time comprised three parts: The first part related to a study of secondary roads outside the built up area (Schreuder 1990), the second part focused on motorways outside the built up area (Vis, 1993) and the yet to be performed third part will focus on roads inside the built up area. This contribution describes the second part of the study, which was carried out by the Institute for Road Safety Research SWOV in 1992 and 1993.

## 2. Results and interpretation of preliminary study and preconditions at commencement of the second phase

The primary question which needs to be answered is whether, and to what degree, street lighting contributes towards improving road safety; secondly, what is the influence of the luminance level in that regard. According to a large number of experts in the field of street lighting, the answer to the primary question should have been sufficiently affirmative on the basis of previously conducted study (including CIE publications 1986 and 1990; OECD, 1992; Schreuder, 1983, 1988 and 1990). Deliberations and results based on theoretical study supported this view: Street lighting benefits the visual performance of road users. It is also likely that by improving such street lighting - in general, that is to say, by increasing the luminance level - visual performances can be enhanced, the driving task can be alleviated and comfort can be improved, thereby reducing accident involvement. The 'proof' of this latter assumption can only be shown, however, through a direct relationship study in the form of an accident analysis. The scarcity of studies of this nature performed to date - also due to limited scope, inadequate representative value and methodological objections - have not resulted in a clear, unequivocal causal and quantitative relationship (Schreuder, 1983 and 1989).

The first phase of the three-part study described in the introduction (examining the relationship between the level of street lighting and road safety) is an explorative study based on a representative, random sample of road sections selected from non-motorways outside the built up area (BGC/SWOV, 1990). Apart from obtaining an insight into the previously cited relationship, this monograph was designed to investigate whether the methodology as developed and applied would be suitable for application with the performance of the two subsequent phases of the proposed integrated research plan. In this first phase, characteristics of street lighting were related to accident characteristics, while a (limited) number of relevant road characteristics were applied as parameters.

Both with respect to the results and the conclusions based thereon with regard to the relationship studied, and with respect to the opinions offered concerning the methodology as

developed and applied, some considerations are in order. In the first place, it should be viewed as a considerable restriction that, due to the nature of the available data, it proved to be impossible to associate night-time road accidents directly with actual night-time traffic performances. Since the latter information was generally not available for most road sections studied, the (average) daily traffic density was used as an alternative comparison, where the hypothesis that the night-time share in overall daily traffic can be set at one quarter was taken as point of departure for all road sections. At the time, this hypothesis could not be assessed in practice due to the limitations of the available data. The suspicion that the given point of departure would not be appropriate under all circumstances even proved to be justified (in retrospect). In addition, there were strong indications that there were further interactions between the various traffic and road characteristics and between the presence of street lighting and its effect on road safety. The luminance level, for example, proved to (be able to) explain only a limited proportion of the variance in risk found. A second basic hypothesis assumed that any changes in the accident pattern following the introduction (and putting into operation!) of street lighting would mainly be experienced during conditions of darkness, and hence be expressed in the developments seen with night-time accidents. This hypothesis also - albeit unexpectedly - remained unsubstantiated: after some time, the risk during hours of darkness proved to remain about the same on road sections where street lighting was installed, while the risk in the daytime proved to have increased. With some reservation it was finally concluded that although there was question of a relationship between luminance level and road hazard at night, this still did not explain the variance in night-time risks. Apparently, there are still other explanatory aspects which play a role. It is likely - with further confirmation based on information supplied by the various road authorities - that street lighting is not installed along entirely randomly selected road sections. In general, road authorities consider aspects such as an increase in night-time traffic intensity, the noted relative road hazard based on registered accidents, the relatively poor visibility and environmental conditions, the special composition of night-time traffic or other risk-enhancing factors.
In retrospect, it was confirmed that the first phase of the three-part project still left a number of questions unanswered. In any case, the results and conclusions proved unable to provide a complete answer to the policy questions posed at the time, such as under which circumstances and on which road sections is installation of street lighting useful, above which luminance level is there no further measurable improvement in road safety (or decline in the number of accidents, respectively) to be anticipated and at what level is there question of optimal efficiency. It is certain that the relationships to be studied are complex in nature. The hypotheses applied in the first phase will have to be reviewed in detail and, if necessary, reviewed for application in the subsequent phase of the study. With the further optimisation of the research methodology in the following phases of the project, the comparability of the monograph results should also be taken into account.

An important complicating factor which played a role during all phases of the study is the indirect nature of the relationship between street lighting and road safety. Street lighting improves the visual conditions and, as a result, also the visual performances on the whole. In many cases, this alleviates the driving task, therefore allowing behaviour in traffic to be influenced and perhaps reduce road hazard. The causal dependence in this case is not precisely known, difficult to determine, study or predict. A driving task which demands little effort can, for example, lead to a reduced attention level or cause the driver to increase speed. If indeed - as some assume - risk compensation occurs (e.g by increasing driving speed), then this should be taken into account with the interpretation of the study results. Also, another effect of installing street lighting may be a change in route selection and

changes in the intensity and composition of (also night-time) traffic flows. Such side effects cannot be entirely ignored with the interpretation of effects either.

As shown with the inventory taken during the executive phase, another complicating factor of an entirely different nature which cannot be ignored is represented by the very limited incidence of comparable lit and unlit road sections and the poor homogeneity with respect to both road and traffic characteristics and the nature and design of the street lighting in place. It is anticipated that this homogeneity will be greater with the performance of the second phase, viz. the study of motorways outside the built up area.

Finally, a number of restrictions and simplifications with respect to the original setup of this second phase which were chosen on the basis of budgetary considerations should not be ignored, because they not only affect the setup of the study but also influence the conclusions to be anticipated and the possible recommendations. It should first be mentioned that the study remained confined to only those road sections which form part of the through carriageways. As a result, a means of obtaining insight into the effect on slip roads, on and off ramps and bends is lost, while it can be assumed that street lighting can be particularly effective for both road safety and driving comfort precisely at those locations where the driving task demands extra attention, due to the numerous actions to be performed. In addition, upon commencement of the second phase, the precondition was set that an inventory of the necessary road, traffic and accident characteristics would only take place on the basis of existing and immediately available databases. This decision again led to restrictions on the results, as will be dealt with during the description of the study realisation.

## 3. Setup of the second phase of the study

The study performed considered street lighting to be the independent variable, while the number of road accidents was treated as the dependent variable. Road and traffic characteristics which, also based on the results of previous study, could influence the relationship to be investigated between the (level of) street lighting and road safety, are regarded as parameters. The restrictions and simplifications in setup and execution introduced in consultation with the contract giver for budgetary considerations have led to only traffic intensity (hence allowing calculation of traffic performance per road section) and the number of lanes per carriageway to be included amongst the traffic and road characteristics surveyed. At the time of the study, the Netherlands had about 2000 km of motorway. In principle, the entire motorway network was surveyed and further distinguished on the basis of lit and unlit road sections. Both categories were further subdivided into a number of intensity categories and, if the survey gave cause to do so, into several categories based on the number of lanes per carriageway. For the road sections with street lighting, the nature of lighting (including luminance and distribution) was surveyed and, depending on the results, distinguished into several relevant luminance categories. The objective is to arrive at groups of road sections which were as homogenous as possible with respect to intensity, number of lanes per carriageway and luminance level. The road sections not provided with street lighting were subdivided in a similar fashion and served as a comparison with the lit sections (viz. functional lighting). In contrast with the study in the first phase, the actual traffic performances (based on the annual daily average) were used as a basis for both daytime and night-time conditions. If possible, the hypothesis assumed during the first phase, viz. that the majority of road sections were subject to a constant day/night distribu-

tion of traffic, was further assessed. The daytime and night-time traffic performances were calculated per road section (category) and period on the basis of the product of the (average) daily weekday intensity on an annual basis and the road length in kilometres. The risks were calculated on the basis of the quotient of the number of accidents and the traffic performance and expressed in terms of the number of accidents per million vehicle kilometres. The degree of road hazard was expressed per road section in terms of the number of accidents per kilometre of road length. The basis for the study design is a matrix in which the number of cells is on the one hand determined by the number of luminance categories and on the other by the number of intensity categories. In relation to the number of accidents per year to be analysed, the study period 1989 to 1991 inclusive was used as a basis. Also with a view towards the available number of accidents, both injury accidents (including fatal accidents) and accidents involving material damage only were included in the analysis.

## 4. Practical phase of the study

The principle of only using existing and more or less immediately accessible databases for the inventory has influenced the practical phase of the study. From a research perspective, there is a need for data about road and traffic characteristics, road accidents and the street lighting installation for the entire motorway network during the period 1989 to 1991. The previously cited principle implies that, as a rule, not all these required data were available or comprehensive, representative or available in the required format. There is generally no question of 'custom made' data, and often various (sub) databases had to be linked up on the basis of a further to be determined and shared 'key'. The revision of various databases is sometimes associated with loss of information, dated files introduce uncertainties concerning the actual situation and the control of externally provided (sub)databases proved to be only marginally possible within the framework of the study.

The way in which the database that was ultimately used for analysis was arrived at is best illustrated on the basis of Figure 1. Based on a link key, consisting of the national trunk road number and the hectometric value, 6 separate databases with various characteristic combinations were integrated to form the operating database to which the analyses were applied. Road traffic and light characteristics were filed in databases 1, 2 3 and 4. These databases were in part realised independently, thereby allowing a measure of control. Database 5 includes the accident data. Database 6 is a specific file in which detailed characteristics of street lighting have been processed per road section (and per hectometre). To date, such data had not been centrally collected and registered in the Netherlands. For this reason, they were specifically collected by the SWOV for the purposes of this study on the basis of interviews with road traffic authorities and/or contractors, who were responsible for installation and maintenance of the lighting during the study period. By investing considerable time and effort and in a laborious manner, the necessary data on lighting installations were collected for approximately 400 km of motorway. On the basis of data derived from this survey, a computer programme was used to calculate the luminance levels.
All databases used for the linkup were revised beforehand to exclude non-relevant data. The subdivision of accidents according to 'day' and 'night' was carried out on the basis of astronomical data provided by the Royal Meteorological Institute KNMI in De Bilt (the Netherlands), whereby summer and winter time was also taken into account. The operational database ultimately realised by linking up the subdirectories contained 27,724 accidents: 177 fatal, 3,046 injury accidents and 24,501 accidents involving material damage

only, which occurred during the period 1989 to 1991 across a total of 1963.5 km of motorway in the Netherlands.

## 5. Results of the study

The results can be broadly subdivided into four categories:

- General characteristics concerning the motorways involved in the study, general characteristics of accidents that occurred on these motorways and a frequency distribution of the luminance levels for the street lights found on these roads.

- The relationship between the presence and luminance level of street lighting and the risk (expressed in terms of the number of accident per million vehicle kilometres).

- The relationship between the presence and luminance level of street lighting and road safety (expressed in terms of the number of accidents per kilometre of road length).

- The possible interactions between traffic intensity and the luminance level of street lighting with respect to risk and the extent of road hazard.

### *5.1. Characteristics of motorways included in the study, accidents analysed and street lighting installations surveyed*

- Of the approximately 2,000 kms of motorway in the Netherlands, 80% is not equipped with street lighting. About 15% is equipped with street lighting, while for the remaining 5% it was not possible to establish whether street lighting was present or not, for various reasons.

- 80% of the approximately 2,000 km of motorway in the Netherlands has 2x2 lanes. For unlit road sections, this figure is 90%, for the 400 km equipped with street lighting this is 50%. In other words: road sections with a lane construction of 2x2 are only lit in 13% of cases, in combinations totalling 5 lanes this figure has risen to 46% and in combinations of 2x3 lanes it is approximately 70%, while roads with over 6 lanes in total are virtually all lit. This already serves to indicate that street lighting is not installed at random, but is generally found on busier road sections. It was also shown that with respect to lane composition, lit and unlit road sections in general are not entirely comparable. This fact should not be ignored with the analysis and interpretation of the results.

- Further investigation of the traffic intensity distribution over the 2000 kms of motorway demonstrates that there is question of a broad distribution, both with respect to road section, period of time and season.
However, there is also a striking difference in this respect between lit and unlit road sections. The average daily weekday intensity on an annual basis amounts to about 48,000 motor vehicles/24 hours for the overall number of kilometres of motorway in the Netherlands. For the lit road sections, this approximately 75,000, for unlit road sections about 35,000. Below an intensity of about 40,000 street lighting hardly seems to be installed, while at an intensity of 80,000 or higher, the Dutch motorways are virtually always provided with street lighting. These results also support the supposition that there is a rela-

tionship between traffic intensity and the installation of street lighting, and also with regard to this point, it appears that lit and unlit roads can hardly be compared, if at all.

• When considering the already completed first phase (study of random non-motorways outside the built up area), the hypothesis applied there is that for all road sections, a constant proportion of 0.25 of the overall daily traffic could be regarded night-time traffic, as already discussed. At the time, it was shown that, due to circumstances, assessment of this hypothesis was impossible. During the performance of the second phase - the motorways study -counting data of approximately 80 counting points, distributed over the motorway network, became available. Based on these counting points, daily counts were carried out for the entire year according to day type and hour. On an average annual basis, it was shown that for all counting points the night share was virtually constant at approximately 0.25 of the daily total. From this result, one would conclude that the previously applied hypothesis represented a acceptable point of departure. However, further investigation - e.g. on a monthly basis - indicated that the night/day ratio varied markedly on a monthly average basis. Figure 2 shows the transition of this ratio over the months of the year on the basis of one counting point. Between January /December and June, a factor 12 difference is noted. All counting points show a comparable pattern: for all points, the transition from night/day ratio falls roughly within the hatched area (see Figure 2). It is not entirely unlikely that the accident pattern also varies over the months of the year. If this proves to be the case to a significant degree, then the constant night/day ratio applied on an annual basis should be further differentiated, e.g. according to the month. Due to the restricting preconditions, it was no longer possible to apply this correction in the second phase of the current study, but this could be considered as a follow-up activity. The discussion below considers this point further.

• Of the almost 28,000 analysed accidents, 57% occurred on unlit roads and 32% occurred on roads equipped with street lighting (the remaining 12% could not be allocated either category due to incomplete data). Under daytime conditions, 55% of accidents occurred on roads not equipped with street lighting, as against 33% on roads where lighting was provided. For night-time conditions, these percentages were 61% and 29%, respectively. The night/day accident ratio for road sections not equipped with street lighting is 0.33, as against 0.28 for road sections with street lighting.

• Due to the nature and quality of data, no detailed statements were possible about aspects such as the nature of the accident locations, weather and road surface conditions and (average) severity of injury. What can be noted on the basis of the accident analysis is that approximately 2% of accidents that occurred on lit road sections were at the site of a bend, as against 5% on road sections without street lighting. There did not seem to be a clear relationship between the presence of a wet road surface and street lighting. Both on unlit and lit road sections, the share fluctuated at around 30%. Based on data provided by the Meteorological Institute, it is known that the road surface is only considered to be wet for a very short proportion of the overall time. Finally, the share of injury accidents (including fatal accidents) was somewhat greater at some 13% on unlit roads than the 10% figure (approximately) for lit road sections. Perhaps this offers some indication that the average severity of road accidents is somewhat greater on unlit road sections.

• Based on the frequency distribution of the luminance values calculated with the aid of the computer programme, it appears that the luminance level of street lighting is certainly not homogenous for each road section. Figure 3 offers an impression of this distribution of

luminance values (comment: road sections that were very short and had an extreme luminance value, e.g. at the point of a service station or restaurant - were not included in the analysis).

*5.2. The relationship between the presence and luminance level of street lighting and the road hazard*

From the standpoint of the road user, it is relevant to have an insight into how 'hazardous' participation in traffic is under certain conditions. It is common practice to express this road hazard in terms of the number of accidents related to the traffic performance carried out, e.g. in the number of accidents per million vehicle kilometres covered. Figures 4 and 5 offer an indication of the cited risk during daylight conditions and darkness for lit and unlit motorways in the Netherlands, respectively, set against traffic intensity. In both cases and with all intensities, the risk during conditions of darkness appear greater than for daytime conditions. The night/day difference is clearly greater for road sections without street lighting: in other words, the relative increase in risk during night-time conditions with respect to the daytime proves to be greater for unlit road sections. Both during the daytime and at night, the risk shows a rising trend as the traffic intensity increases. It is striking to note that the risk on road sections provided with street lighting is also greater in the daytime than on roads without street lighting. The latter is another indication that road hazard is an (implicitly) applied criterium for the installation of street lighting. Figure 6 offers an indication for the relationship between risk and luminance level (one of the quality aspects of street lighting). The higher luminance values seem to go hand in hand with the higher risks. Apparently, better street lighting tends to be installed on relatively hazardous road sections.

*5.3. The relationship between presence and level of street lighting and the scope of road hazard*

For road traffic authorities, it makes sense to gain an impression of the 'road hazard' associated with the road section for which they are responsible. In particular, when weighing up costs and benefits and during the subsequent decisionmaking process for the installation of street lighting, it may be important for the road authority to know what the effect would be with respect to the number of accidents in the road section in question if street lighting were introduced. Figures 7 and 8 therefore show the number of accidents per kilometre of road length both for the situation during the daytime and during the night-time, and for road sections with and without street lighting, per traffic intensity category. All daytime values are greater than the concomitant values during conditions of darkness. In itself this is logical as a result of the far greater traffic intensity during the day. For most intensity categories, the number of accidents per kilometre road length on roads with street lighting is greater in the daytime. Again, this confirms the assumption that the relative road hazard is one of the installation criteria for street lighting. During conditions of darkness, the number of accidents per kilometre of road length on lit and unlit roads sections is approximate the same. Assuming that the night/day relationship for the volume of traffic on both categories of road sections does not differ markedly either, this would indicate that the number of accidents per kilometre road length on unlit road sections is relatively greater than on lit roads during condition of darkness. In other words: the relative increase in hazard at night with respect to the day seems to be less extreme for road sections with street lighting. In a similar fashion, Figure 9 offers an indication that the relative increase in the number of accidents per kilometre of road length on road sections

with better quality street lighting (higher luminance value) is also smaller during night-time conditions. This should be noted with some reservation, however, due to the limited comparability of lit and unlit road sections with respect to otherwise relevant characteristics for road safety, particularly because various interactions seem to be involved. The next paragraph considers this aspect further.

*5.4. Notes to the relationships and the interactions between the various aspects as discussed*

Both preceding paragraphs explore the relationships between 'risk' (expressed in terms of the number of accidents per million vehicle kilometres) and road hazard (represented by accidents per kilometre road length), on the one hand, and traffic intensity and luminance level on the other. The lines with which these relationships are represented in Figures 4 to 9 inclusive are not based on a theoretical model, nor on a calculated, specific design. The visual reproduction of the relationships in question only offer a rough insight into the nature and direction and should therefore be qualified as indicative. This is also attributable to the imbalanced cell fill of the matrixes from which the figures are derived. In Table 1, the results are summarised in an alternative (abbreviated) form. It is attempted to select the number of intensity and luminance categories such that the cell fills are still acceptable. Per cell, the number of kilometres (a), the calculated risk during darkness conditions (b), the calculated risk during the daytime (c) and the calculated night/day risk ratio based on b. and c. are shown.

Apart from a few exceptions, all night/day risk ratios are greater than 1, in other words the risk is in all cases greater at night than during the day, both for lit and unlit road sections. The night/day risk ratios for the unlit road sections prove to be higher on the whole than for lit road sections.
Differentiated according to intensity an luminance level, this impression becomes less clear: However, it is shown that within the intensity interval of between 40,000 and 80,000 vehicles per day, the night/day risk ratio is lower at higher luminance values (viz. with 'better' street lighting); or, put in a different way, the difference between risk during night-time and daytime conditions become smaller as street lighting improves. The other relationships prove to be irregular.
It is likely that an interaction between intensity and luminance level is present. From the available data, it was not possible to determine the effects of both characteristics individually. A reliable correction factor for the intensity effect can therefore not be estimated. Because 80% of the motorways surveyed in the Netherlands have a distribution of 2x2 lanes, it was initially assumed that the influence of road sections with a different lane construction on the ultimate analytical result would be minimal. The nature of the irregularities in the pattern in table 1 does not however exclude the possibility that some of the variations in the relationships may well be traced back to these differences in lane construction. In order to gain a clearer impression in this regard, road sections with 2x2 and 2x3 lanes were subjected to separate analyses. Due to the available number of kilometres for both types of road sections, comparison only proved useful within the intensity interval of 45,000 to 80,000 motor vehicles per day. The results for road sections with 2x2 and 2x3 lanes proved not to deviate markedly, at most it can be noted that with road sections without street lighting and 2x3 lanes that fall within the given intensity interval, the risk is lower both at night and during the day. Increasing the number of lanes under those conditions apparently lowers the risk. In addition, the previous discussion should take into account that the comparison is based on a limited number of kilometres.

## 6. Conclusions

It is emphasised that the conclusions resulting from the restrictions associated with the setup of the study only relate to the through road sections of main carriageways on motorways outside the built up area in the Netherlands.

- In the first place, performing the monograph described in the above has offered a number of useful indications that are relevant to the still to be performed follow-up study of complex situations such as intersections, slip roads, roundabouts and the like. Restrictions associated with the current registration of essential data should first be overcome. A solution should be found for the marked differentiation between intensity and presence, nature and level of street lighting and the computer model used for the calculation of the luminance level should be further developed to allow application in the complex situations referred to.

- The hypothesis employed with the performance of the first phase of the project, viz. for road sections the traffic performance during night-time conditions is roughly one quarter of the average daily traffic performance level, while apparently correct on an average annual basis, does demonstrate a considerable variation in the proportion of traffic performance at night when differentiated according to month (by a factor of 1 to 15 to 18). If, upon further differentiation of accidents according to month, it is shown that the accident pattern also shows significant differences from month to month, then (as follow up activity) correction for example on a monthly basis should still be carried out in order to investigate what the consequences would have been with respect to the results by applying the now dubious hypothesis from the first phase.

- Road sections without street lighting and road sections equipped with street lighting which are fully mutually comparable (with respect to intensity, number of lanes and other aspects which can be associated with road hazard) are hardly found.

- Street lighting is hardly installed along Dutch motorways on those road sections with an average daily vehicle intensity of less than 40,000, while at a level exceeding 80,000, street lighting is virtually always installed.

- There are (modest) indications that the average injury severity and the proportion of accidents at bends is somewhat greater on unlit road sections.

- Both on unlit and on lit road sections, traffic risk during conditions of darkness (represented by the number of accidents per million vehicle kilometres) is greater and road hazard (expressed in terms of accidents per kilometre of road length) is relatively higher than in the daytime; however, for lit road sections the relative increase during darkness with respect to the daytime is smaller in both cases.

- The results of this study also confirm a relationship between traffic intensity and risk. Both in the daytime and at night, a higher traffic intensity is often associated with increased road hazard.

- The results of this study demonstrate that street lighting - and certainly higher quality lighting - is primarily fitted along road sections with a relatively high traffic intensity and road sections which are relatively hazardous in the daytime also (both expressed in terms

of number of accidents per million vehicle kilometres and per kilometre of road length). A particular intensity and degree of road hazard are apparently criteria for the construction of street lighting on the Dutch motorways.

- The results of this study show that an interaction exists between traffic intensity, presence and level of street lighting and traffic risk. On the basis of the available material, it did not prove possible to determine the various effects of street lighting accurately.

- A comparison of the results of analyses on road sections consisting of 2x2 or 2x3 lanes only did not offer a clear indication which would demonstrate the major differences between both road types. Only with unlit road sections, both the night-time and daytime risk for 2x2 lane road sections within the intensity interval of 45,000-80,000 appears to be considerably higher. Under certain conditions, the lane increases from 2 to 3 apparently leads to a reduction in traffic risk.

- Although on the basis of the results of this study, which represents the second part of the trilogy, it is still not absolutely and quantitatively possible to indicate the relationship between the level of street lighting and road safety, all trends seem to point in the direction of a positive effect of street lighting. Given the fact that 80% of the motorways in the Netherlands is still not equipped with street lighting, it is anticipated that much can still be gained from the perspective of road safety.

- However, again following this study it can be concluded that a number of questions still remain unanswered, and this would require follow-up study. In the first place, this applies to research of intersections, slip roads, roundabouts and other road categories which do not form part of through main carriageways which to date have not been considered. In addition, follow-up study should also consider aspects such as lane intensity, saturation level of road sections involved, the actual traffic performance during conditions of darkness and the homogeneity of road sections. For the accidents, a more detailed distinction should be made e.g. on the basis of driving direction, period (peak hours and night-time) type and severity of injury.

## 7. Discussion

The introduction referred to study trilogy consisting of a study into non-motorways within the built up area, a study of motorways outside the built up area and finally, a study of roads inside the built up area. Based on the three parts of the project, the intention was to indicate on which roads the installation of street lighting would be beneficial, above which luminance level no measurable improvement in road safety can be anticipated and which level can ultimately be considered most effective.
The results of the first phase of the study prove to be inadequate to sufficiently answer the posed (policy) questions. Based on the results from the second phase, which has been considerably simplified with respect to the original setup, it still proved impossible to answer these questions directly and accurately. Although the results support those derived from the previous study, offer comparable risk figures and also indicate a positive effect of street lighting on road safety, nevertheless relevant questions still remain unanswered after this (second) monograph. Despite all positive indications, even the key question of whether and to what extent street lighting contributes to a reduction in the number of accidents during conditions of darkness is not entirely answered. The prime impediment to

such a statement must be regarded as the failure to establish a clear relationship between intensity, lighting level and perhaps also the lane distribution as related to traffic risk. The principal restrictions in the study are also found in the limited possibilities to further differentiate the available accident database. For example, it was not possible to allocate accidents to a lane and driving direction, while such data - particular during peak traffic conditions - are indicative of the accident pattern. The effect of street lighting does not have to be the same for all conditions or for all accident phases, either. Various traffic conditions such as, for example, quiet traffic or traffic approaching the congestion stage can in general indicate a different accident pattern. With the given conditions and the corresponding accident patterns, street lighting may fulfil a somewhat different function, so that another effect is likely. The study as described in this contribution is in the first place aimed at determining the actual luminance level per road section as accurately as possible. As a result of the restrictions inherent in the sources of information used, less attention could be devoted to the homogeneity of road sections with respect to other road and environment characteristics. As a result, the possibility is not entirely eliminated that road sections based on the calculated luminance value and intensity category are summarised in one matrix cell, while on the basis of other road, traffic and environment characteristics, it only had a limited comparative value. Furthermore, there is still little insight into the exact influences that other road, traffic and environmental characteristics can bring to bear, both separately and in combination, with respect to the effect of street lighting.

In summary, the insight into the possible effects of street lighting and its relationship to other relevant characteristics could be enhanced by:

- Carrying out a study which, while comparable to the second phase, utilises the experience in its application to intersections, slip roads, roundabouts, and motorway ramps.

- Performing a study comparable to the second phase but more refined, that takes into account (more than previously) the lane intensity, the nature of traffic on the various road sections, more detailed differentiation according to period and time of day (including peak times), the distinction between the various types of accident (head-tail, unilateral etc.), the actual traffic performances during conditions of darkness and per season and month, respectively and the homogeneity of road sections and distribution according to the severity of injury.

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| | Density Category | | | |
|---|---|---|---|---|
| Luminance Category | Average 0-45000 vehicles/24hrs | Average 45000-80000 vehicles/24hrs | Average >80000 vehicles/24hrs | Total |
| Not Lighted | a 1170,4 km | a 403,2 km | a 14,9 km | a 1588,5 km |
| | b 0,35 | b 0,35 | b 0,36 | b 0,35 |
| | c 0,20 | c 0,28 | c 0,22 | c 0,23 |
| | d 1,75 | d 1,25 | d 1,64 | d 1,52 |
| <0,90 cd/m$^2$ | a 9,1 km | a 49,8 km | a 54,9 km | a 113,8 km |
| | b 0,25 | b 0,38 | b 0,33 | b 0,34 |
| | c 0,24 | c 0,27 | c 0,28 | c 0,28 |
| | d 1,04 | d 1,41 | d 1,18 | d 1,21 |
| 0,90-1,10 cd/m$^2$ | a 5,8 km | a 20,0 km | a 35,5 km | a 61,3 km |
| | b 0,47 | b 0,29 | b 0,36 | b 0,35 |
| | c 0,30 | c 0,26 | c 0,27 | c 0,27 |
| | d 1,57 | d 1,12 | d 1,33 | d 1,30 |
| >1,10 cd/m$^2$ | a 8,7 km | a 33,8 km | a 58,6 km | a 101,1 km |
| | b 0,26 | b 0,51 | b 0,49 | b 0,49 |
| | c 0,26 | c 0,52 | c 0,42 | c 0,44 |
| | d 1,00 | d 0,98 | d 1,17 | d 1,11 |
| Lighted | a 23,6 km | a 103,6 km | a 149,0 km | a 276,2 km |
| | b 0,31 | b 0,40 | b 0,40 | b 0,40 |
| | c 0,27 | c 0,35 | c 0,33 | c 0,34 |
| | d 1,15 | d 1,14 | d 1,21 | d 1,18 |

Legend:
a= number of kilometres in database
b= risk during night-time (expressed in number of accidents/vehicle kilometres)
c= risk during daytime (expressed in number of accidents/vehicle kilometres)
d= night/day risk ratio

Table 1. *Relation between traffic density (category), luminance (category) and risk on Dutch motorways.*

Figure 1. Schematic presentation of linking the subdirectories. The linked database (7) ultimately achieved by linking the subdatabases contains 27,724 accidents.

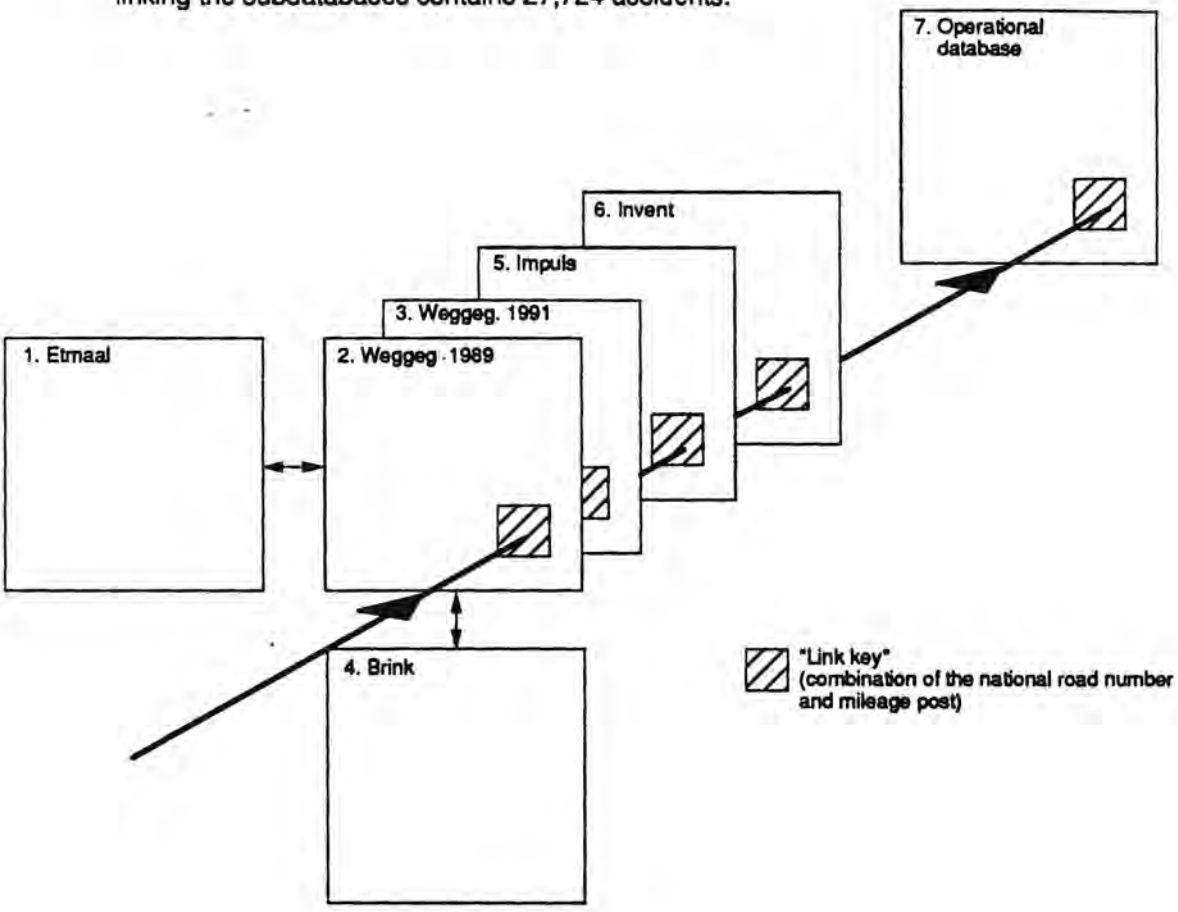



Figure 2. The pattern of day/night traffic ratio's on motorways, the curves of all 80 registration points are situated within the grey area

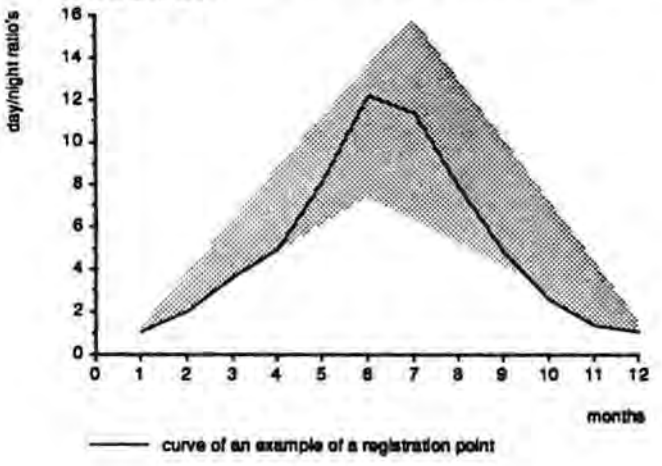



Figure 3. Distribution of luminance values on lit motorways by category interval of 0.10 cd/m2

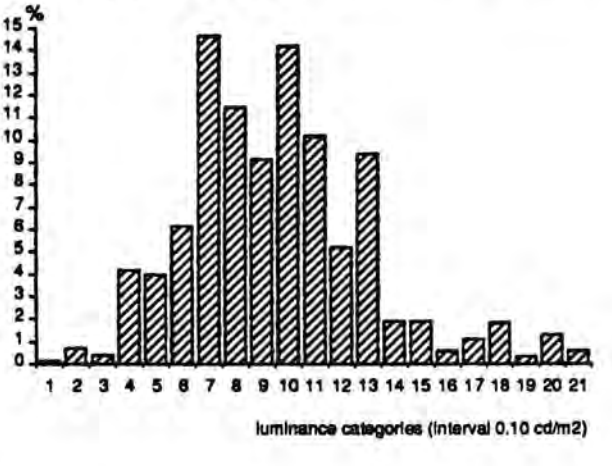


Figure 4. Relation between risk and traffic density on lit motorways

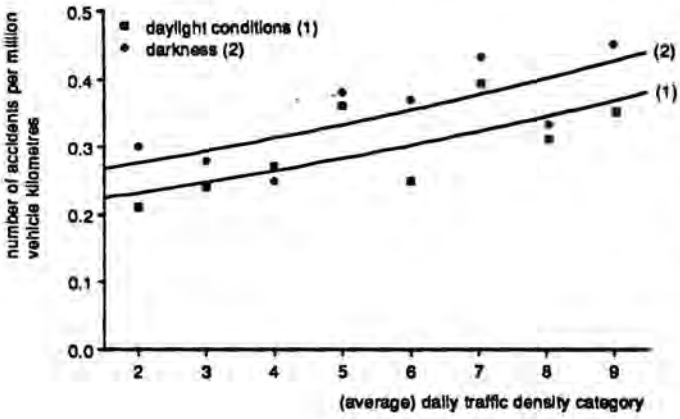



Figure 5. Relation between risk and traffic density on unlit motorways

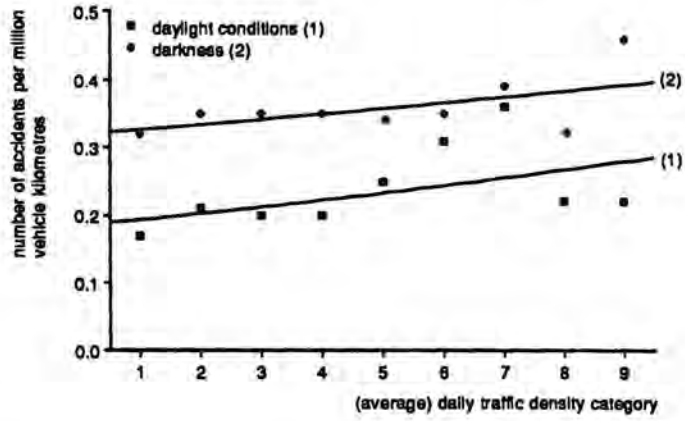
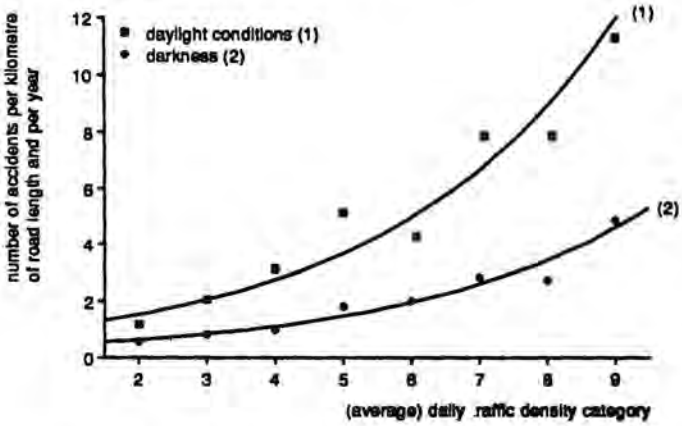



Figure 7. Number of accidents per kilometre road by density category on lit motorways




average daily traffic density

| | |
|---|---|
| 1 = <15.000 | 6 = 55.001 - 65.000 |
| 2 = 15.001 - 25.000 | 7 = 65.001 - 80.000 |
| 3 = 25.001 - 35.000 | 8 = 80.001 - 100.000 |
| 4 = 35.001 - 45.000 | 9 = >100.001 |
| 5 = 45.001 - 55.000 | |

Figure 8. Number of accidents per kilometre road by density category on unlit motorways

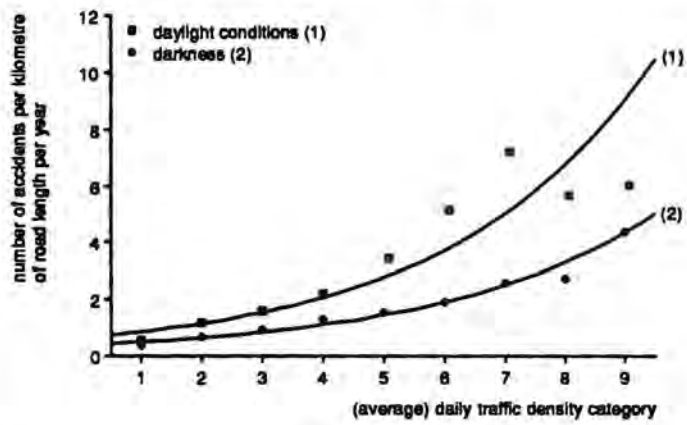



Figure 6. Relation between risk and luminance level

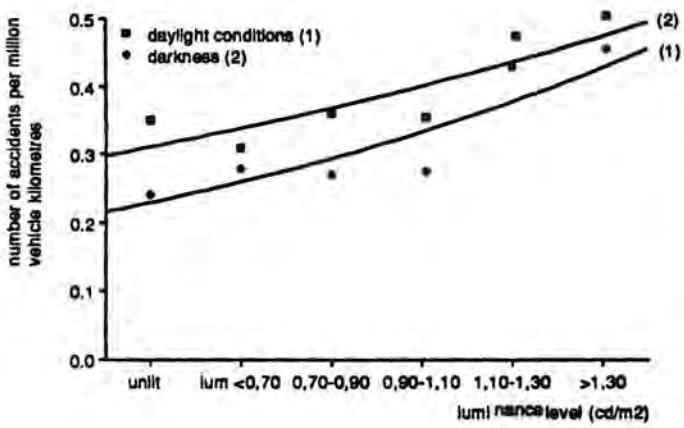



Figure 9. Number of accidents per kilometre road by luminance level