

The balance between environmental impacts and traffic safety on roads

Master of Science thesis

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Preface

This study describes the investigation of traffic safety on municipal roads and the environmental and social impact of the Dutch road network on the society. The study has been performed as final fulfilment for the degree of Master of Science in Road and Railway Engineering at the Delft University of Technology. The activities of this research program have been carried out as a graduate internship at KOAC•NPC. This research is based on literature study, analysis of traffic safety data and development of predictive models. The work was mainly performed at the office of KOAC•NPC in Apeldoorn.

I would like to express my gratitude to the graduation committee, for their assistance, advice and guidance during this research. My deep and sincere appreciation goes to Christ van Gulp, for the opportunity that I got to perform this research at KOAC•NPC. His patience, guidance and technical support were very valuable for the final result of this research. Special thanks go to Lambert Houben for encouraging me, the guidance he gave me with administrative works and solving technical issues that I encountered during my study at Delft University of Technology. My sincere gratitude goes to Tom Scarpas for being the chair leader of this research and his kind contribution during the research activities, especially his guiding at the start of the research. His tranquillity and technical comments during the meeting sessions were essential for the accomplished results of this study. My sincere thanks also go to Michiel Haas for the guidance and support of the second part (environmental part) of this research.

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Summary

Traffic safety and environmental themes are nowadays essential topics in pavement construction and maintenance projects. In the Netherlands the social costs that emerge from traffic accidents are 12500 million euros, i.e. 2.2 percent of the GDP (gross domestic product). These giant costs indicate that attention to the traffic safety of this vital network is of great importance. The environmental costs that emerge from the emissions of the road industry are of great importance to the society and environmental organisations. These costs can be partially controlled by civil engineers by means of using efficient pavement materials.

This study describes the development of a program that predicts the number of injury accidents on roads in the Netherlands, with emphasis on municipal roads. The second part of this research programme addresses the development of a program that predicts the environmental and social costs of the vital road network in the Netherlands. Both tools are applicable for road engineers for acquiring an indication of the environmental and social impact of the designed asphalt pavements in terms of number of traffic accidents, environmental costs and social costs.

The first part of the research presents the development of a predictive program for the traffic safety on municipal roads. Analysis of numerous traffic safety studies performed already, provided data for prediction models for the traffic safety in relation with road surface properties on highways and provincial roads. Development of similar models for local roads is therefore highly recommended. Traffic safety on motorways is in general mainly dependent on the friction between tyre and pavement surface. The alignment of dual carriageways does not contain sharp bends usually. This implies that skid resistance of the pavement surface is the key factor for controlling and improving traffic safety (apart from improvement measures in the domain of the cars, trucks and drivers). Skid resistance measurements on municipal roads are not very popular yet, or are at least not frequently performed. This implies that literature about the relationship between traffic safety and skid resistance on municipal roads is very limited. The situation on municipal roads is completely different from that of trunk roads. The traffic speed is lower, various modes of road traffic make use of the road, crossings allowing traffic from the side stream to intersect the main stream, some bends force traffic to slow down etc. This complex of influence factors is investigated in the first part of the thesis. In this study the relationship between the skid resistance and the traffic safety on municipal roads will be developed for different types of municipal roads namely:

- single carriageways [for all traffic];
- single carriageways [cars and trucks only];
- dual carriageways [cars and trucks only].

The risk for an accident varies per type of municipal roads. The accident risks of the different types of municipal roads are to some degree related to the change of skid resistance with time and the effect of this decay on the traffic safety. With data on provincial roads as input, relationships between the skid resistance and traffic safety for the three types of municipal roads are developed. The modes of road traffic on municipal roads are not only different from those on the arterial network, they also may vary substantially per municipal road. The proportional distribution of the different modes of road transport is broken down per province in the Netherlands. On municipal roads only the traffic accidents with fast traveling traffic are dependent on the skid resistance; accidents with and by slow moving traffic have in general other causes. The traffic accidents on a straight section of municipal road can be counted as the sum of the fast traffic accidents (cars, trucks and motorcycles) and the other accidents (bicycles, mopeds and pedestrians). Another factor that influences the traffic safety on municipal roads are bends that force traffic to slow down. The necessary speed reduction in a bend is an indication for the sharpness of the bend. A higher speed reduction corresponds with a sharper bend; this combination may be regarded as less favourable for the traffic

safety. Finally, crossings are very important in terms of traffic safety on municipal roads. The types of crossing and the presence of traffic controlling systems are instrumental for defining the traffic safety on crossings. Assembly of the different factors results in a predictive program for the traffic safety on municipal roads in the Netherlands.

The second part of the thesis addresses the environmental and social impact of the pavement industry. The environmental impact of the pavement industry is dependent on many factors. This study describes the critical pavement aspects that affect the environment namely:

- emissions due to produced materials;
- emissions due to fuel consumption;
- noise emissions.

Life Cycle Assessment (LCA) is a technique to assess environmental impacts associated with all the stages of a pavement material's life. During the process from mining of raw materials, production of pavement materials and transportation of the materials, various pollutants are emitted. The Life Cycle Assessment results in an environmental cost indicator of the various pavement materials. The cost indicator results from assembling the various pollutants with their associated shadow prices. Fuel consumption of vehicles depends on the type of engine, the vehicle speed, the type of vehicle and the way the vehicle is driven. Different vehicle categories and road types (taking into account the vehicle speed) are emitting various pollutants due to fuel consumption. The shadow prices are different for each pollutant. Assembling the various pollutants and the associated shadow prices results in environmental costs due to fuel consumption.

The noise level on roads is mainly dependent on the vehicle speed, the type of vehicle (car or truck) and the type of wearing course that has been applied. The effect of road noise emissions on the environment depends on where the road is situated (urban or rural area). In urban areas more people are affected by the noise emissions, which results in higher environmental costs. The environmental costs are estimated based upon the preference noise level limit that has been set by the Noise Nuisance Act ('Wet Geluidshinder'). The environmental costs due to noise emissions depend on how much this noise limit is exceeded.

The social impact of the pavement industry depends on the number of injury accidents. Accidents commonly lead to different cost categories e.g. medical costs, material costs, production loss, administration costs, intangible costs, congestion costs etc. The severity of accidents determines the total social costs due to accidents.

The research presented in this thesis results in two predictive programs that are applicable to road authorities in the Netherlands but may also be of any use to other parties involved in pavement design, construction, analysis and monitoring. The first program predicts the number of accidents on municipal roads while the second program indicates the environmental and social costs of an arbitrary road section.

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List of symbols and abbreviations

AIS	Abbreviated Injury Scale
C ₂ H ₄	Ethylene
CBS	Central Bureau of Statistics
CE	Committed to the Environment
CH ₄	Methane
CO	Carbon monoxide
CO ₂	Carbon dioxide
CROW	Technology platform for transport, infrastructure and public space
DAC	Dense Asphalt Concrete
dB(A)	decibel (A-weighted; correction of the normal dB with sensitivity of humans)
GWP	Global Warming Potential
LCA	Life Cycle Assessment
MIRA	Environment report; 'Milieu Rapport'
N ₂ O	Nitrogen oxide
NH ₃	Ammoniac
NO _x	Nitrous oxide
NPV	Net Present Value
NVMOC	Non-Methane Volatile Organic Compounds
ODP	Ozone Layer Depletion
OVD	Only Vehicle Damage
PA	Porous Asphalt
PIARC	World Road Association
PM ₁₀	Fine particles
PO ₄	Phosphate
RAW	Rationalisation and Automation of the Ground-, Water and Road construction. 'Rationalisatie en Automatisering in de Grond-, Water- en Wegenbouw'
RDW	'Rijksdienst voor het Wegverkeer'
RONA	Guideline for the design of non-motorway roads; 'Richtlijn Ontwerp Niet Autosnelwegen'
SCBA	Social Cost Benefit Analysis
SMA	Stone Mastic Asphalt
SO ₂	Sulphur dioxide
SRM 1	Standard Calculation Method 1
SWOV	Institute for Road Safety Research; 'Stichting Wetenschappelijk Onderzoek Verkeersveiligheid'
TNO	Organisation for applied scientific research

PART I: RESEARCH PROGRAMME

1. Introduction

1.1. General

Infrastructure is an important aspect in the development of a country. Transportation of people and goods can be arranged in different modes. The road and railway networks are the most important land transportation systems. The road network is the most intensively used and continuously growing transportation system. Therefore, it is of great importance to pay more attention to the safety of this vital network. The safety of the road network is dependent on many factors. Figure 1.1 illustrates the different factors that influence the traffic safety on roads. Civil engineers can only partially contribute to the traffic safety of roads. Improvement of the road infrastructure can reduce the number of accidents with 44% [Koos Spee, 2014]. They can take into account the different factors, related to traffic safety, in the pavement design. Mechanical engineers also contribute partially to the safety on the road network. Development of safer cars (e.g. automatic breaking systems when approaching a car ahead etc.) is a way how mechanical engineers may contribute to a safer network. Last and certainly not least the behaviour of the road user is a very important parameter in the safety of the road network. This behaviour cannot be controlled by engineers but falls more under the influence of socially and legislatively driven actions.

Analysis of plenty of traffic safety studies performed already, provided data for prediction models for the traffic safety in relation with road surface properties on highways and provincial roads [Silva, 2013]. Therefore, development of similar models for local roads is highly recommended.

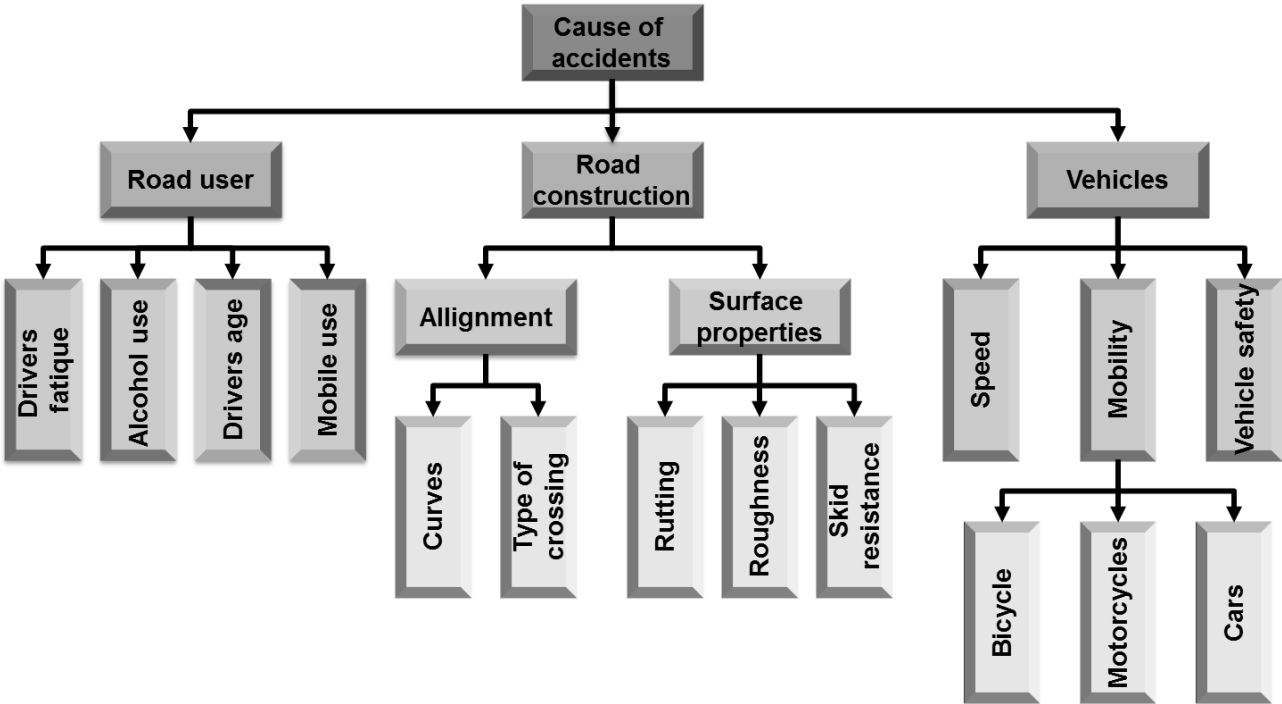


Figure 1.1 Cause of road accidents

The construction and use of the road network has also an impact on the environmental quality. Since nowadays sustainable development has become an important concept in our society, the study of the environmental impact of the road network on the society is also of great importance.

The environmental impact of the road network is evaluated by balancing the three categories of sustainability. Figure 1.2 illustrates the relationship between the road industry and the sustainable categories. The interest of the road user is to maximise the traffic safety of the road network. The environmental organisations are interested in minimising the emissions due to traffic (fuel consumption and noise emission) and the emission due to production of the road materials. The group of pavement surface properties is one of the critical parameters for influencing the traffic safety of the road, the fuel consumption and the noise level. Parameters that effect the pavement surface properties in turn are the pavement materials used in the construction. The available budget for maintaining the pavement network is decided by the government or the road authority. By taking into account the interest of the environmental organisations and the road user, the road authority determines which maintenance measures optimize these interests. Due to limited budget the choices may lead to conflicts among all parties involved.

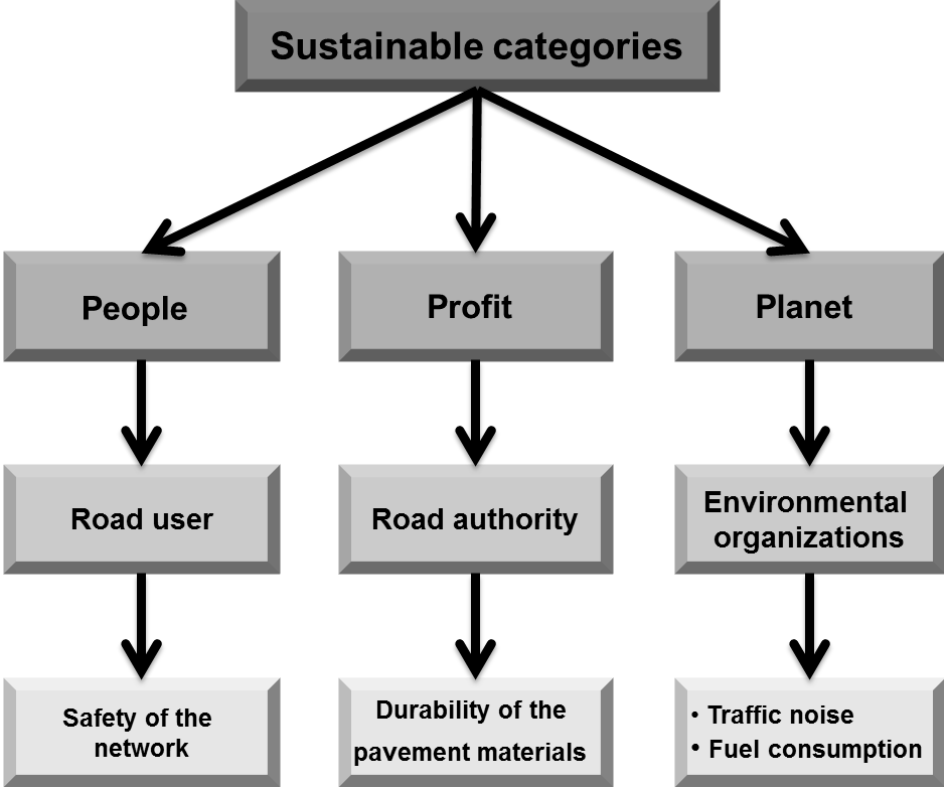


Figure 1.2 Sustainable balance

The main goal of the research programme presented in this thesis is the development of a model that will predict the environmental and social impact of pavements and a model that will predict the traffic safety of municipal and other local roads. Those models can be used by road authorities in their decision-making process to take into account the interest of both parties, the road user and the environmental organisations.

1.2. Research description

In the design and redesign process of pavements, engineers are always confronted with sustainable and safety aspects of the pavement structure. The safety of a pavement structure is dependent on many factors. Figure 1.3 illustrates the main pavement aspects, that affect the sustainability and safety of a pavement.

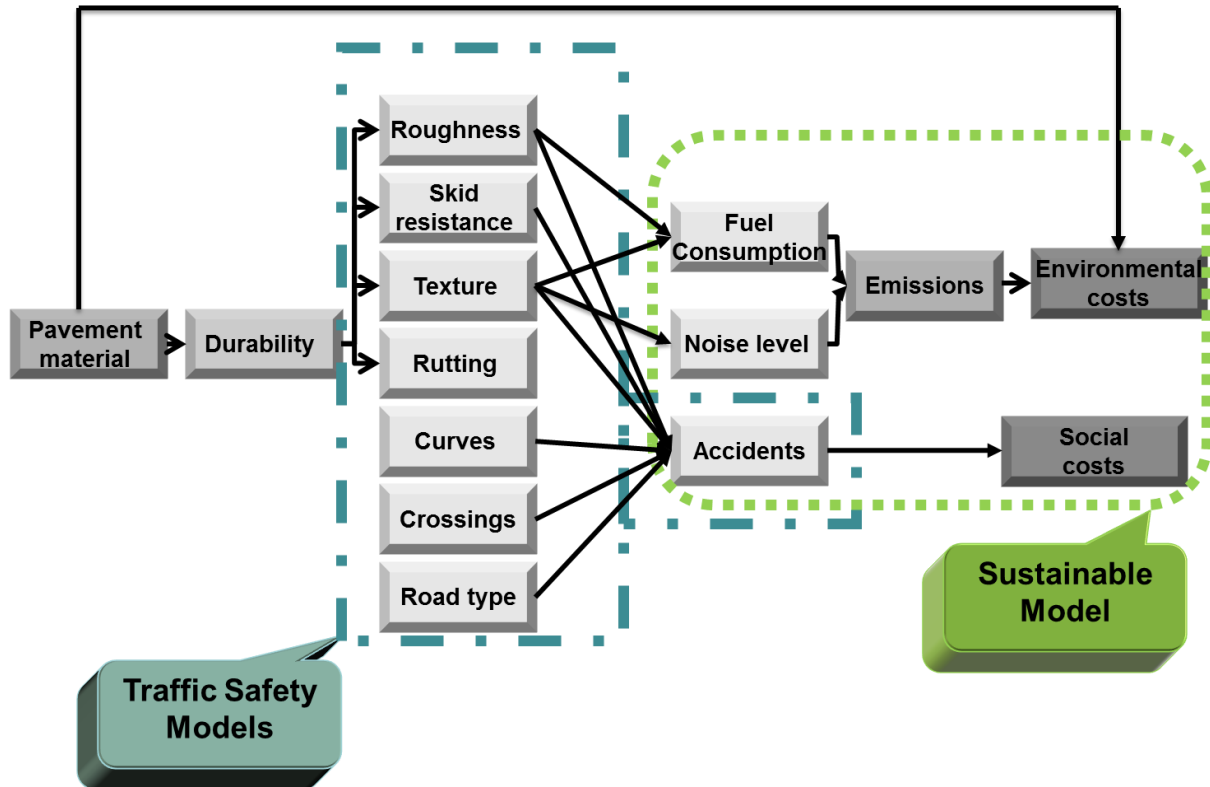


Figure 1.3 Pavement Design

The traffic safety of a road relies on many factors. Pavement engineers with focus on the mechanical behaviour of the road usually deal with the pavement surface only. These properties are related to the pavement materials used and the traffic intensities and distribution. By studying the different pavement surface properties and other pavement aspects, the objective of this thesis was to develop a program that would calculate the number of traffic accidents on municipal and other local roads. Pavement characteristics are seen as a main input parameter in this program.

Secondly, a model will be developed that calculates the environmental costs of a road section. These costs are the sum of the environmental costs due to fuel emissions, noise emissions and the emissions due to production of the pavement materials. The model also calculates the social costs due to the traffic accidents occurring on the road. The input parameters for the sustainable model are:

- traffic distribution (intensity and distribution);
- properties of the road (length, width and type) and crossings (type, traffic signals);
- type of wearing course;
- population living in the area near the road;
- accident rate (calculated with a traffic safety model).

The results of these models can be used by road authorities in their decision making process in the design or redesign of a pavement. Figure 1.4 illustrates how the different pavement aspects can be weighed among each other, taking into account the interest of the road users (maximum safety) and the environmental organisation (minimum environmental damage).

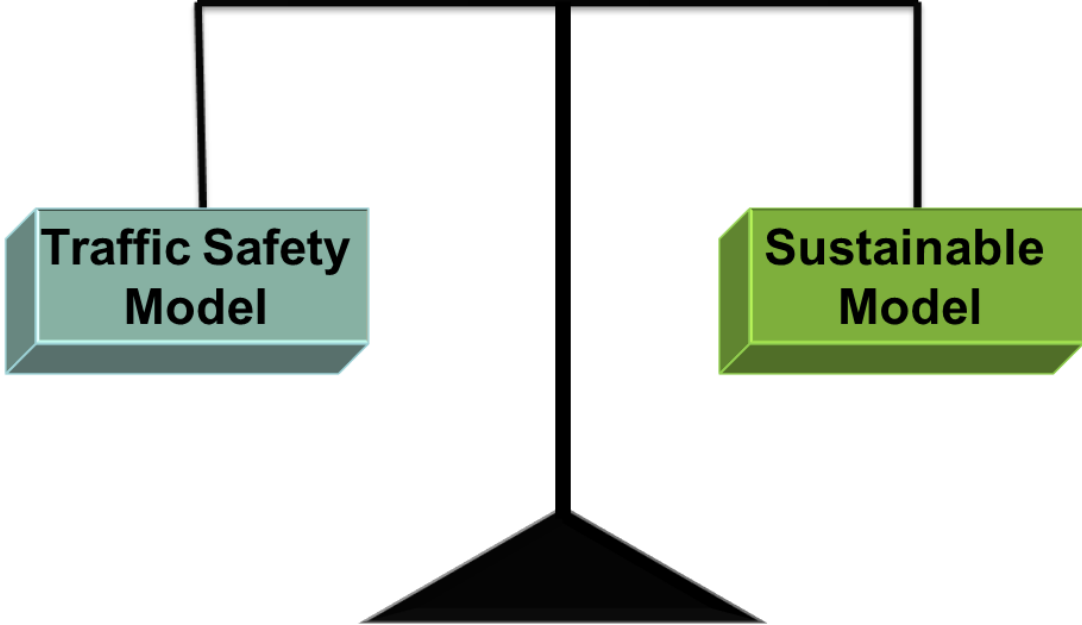


Figure 1.4 Weighting of the different factors

1.3. Goal of the study

The main objectives of the research program are:

- development of a program that predicts the traffic safety on municipal and other local roads, with pavement characteristics as main input parameters;
- development of a program that calculates the environmental costs due to noise emission, fuel consumption and the pavement materials that are used. The social cost due to traffic accidents are also taken into account in this program.

The following research questions have been formulated, to detail the first main objective of the study :

- what are the factors that influence the traffic safety on municipal roads;
- what is the relationship between the type of crossing and the accident risk;
- what is the influence of winding road sections on the traffic safety;
- what is the relationship between the accident rate and the skid resistance on municipal roads;
- how does surface unevenness effect the traffic safety;
- what is the effect of different types of wearing course on the skid resistance;
- what is the relationship between the used mineral aggregates and the skid resistance;
- how can the skid resistance be forecast over a time horizon;
- what is the influence of different modes of transport on the traffic safety;

To detail the second main objective of this study, the following research questions have been formulated:

- what is the relationship between the noise level, the type of wearing course and vehicle speed;
- what is the development of the noise level over a time horizon;
- at which noise level the quality of the environment is affected by noise emissions and what are the environmental costs related to the damage;
- at which noise level human health is affected by noise emissions and what are the costs related to human health;
- what are the factors that have an impact on the quantity of fuel that is burnt;
- what are the pollutants that have an impact on the environmental quality due to fuel consumption, and what are the costs due to emission of these pollutants;
- what is the interaction between types of traffic accidents that occur and the relationship between the severity of these accidents and the social costs;
- how can the number of traffic accidents be forecast over a time horizon;
- what is the relationship between the emissions due to the production of the pavement materials and the environmental costs due to these activities

1.4. Research Methodology

The models will be developed based on findings from literature study and measurements and tests conducted on Dutch pavements. The measurements have been selected from the KOAC•NPC database and the Dutch Bureau for Statistics website.

The methodology used in the programme, based on literature and available data, can be described by the following four steps:

1. Initial phase;

In this phase of the research the goal and scope of the study are defined. The theory and literature study are performed according to these goal and scope.

2. Inventory assessment;

The inventory assessment is the phase where the data and relevant information from the initial phase are collected. The analysis procedure is adjusted after these information is inventoried.

3. Analysis phase;

In this phase, the analysis procedure is further described and the collected data and information are studied and processed. These collected data will be modelled. After the modelling of the data, the results can be described.

4. Final Assessment.

The final phase, which is the most important phase, is the interpretation of the results. In this phase of the research programme the processed and analysed data are discussed.

Figure 1.5 illustrates the discussion, the conclusions and the recommendations are described based on the results and findings of the first three phases.

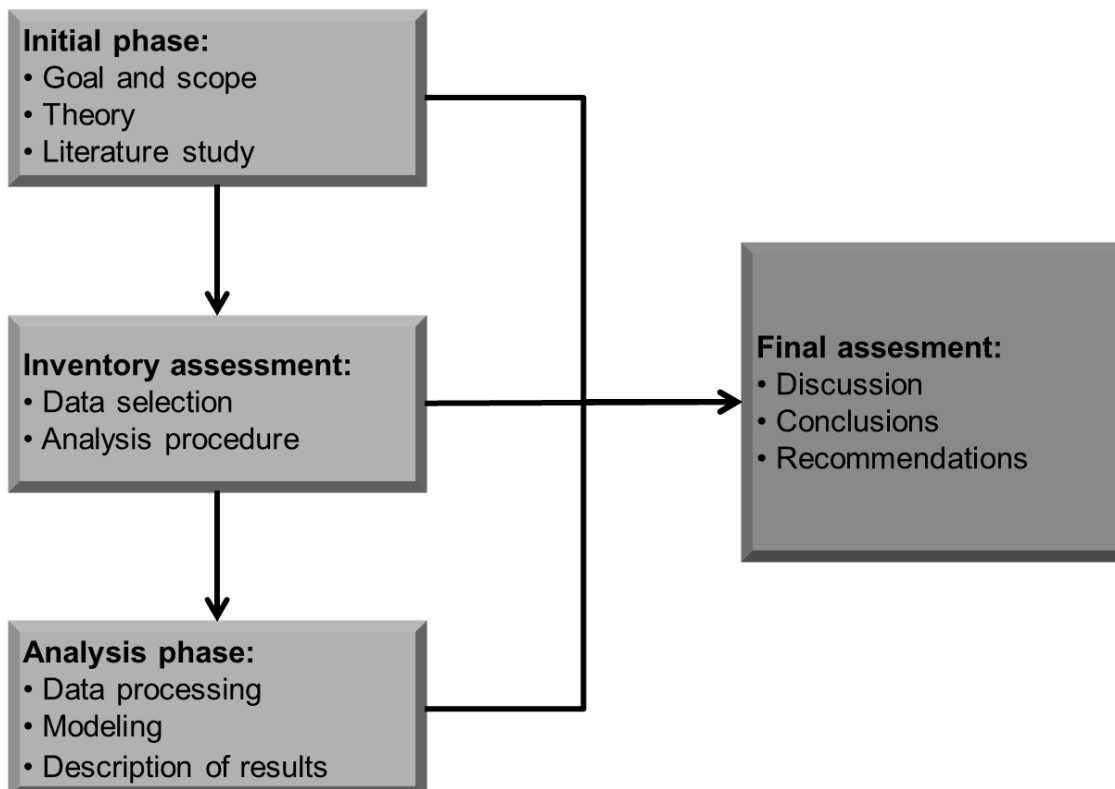


Figure 1.5 Research programme

1.5. Organisation of the report

In this section an organisation overview of this thesis is given. Several chapters will describe the research programme. The previous section showed that the goal of the research programme was the development of two programs. The report is organised in the context of the research programme . The thesis is divided into four parts as illustrated in Figure 1.6.

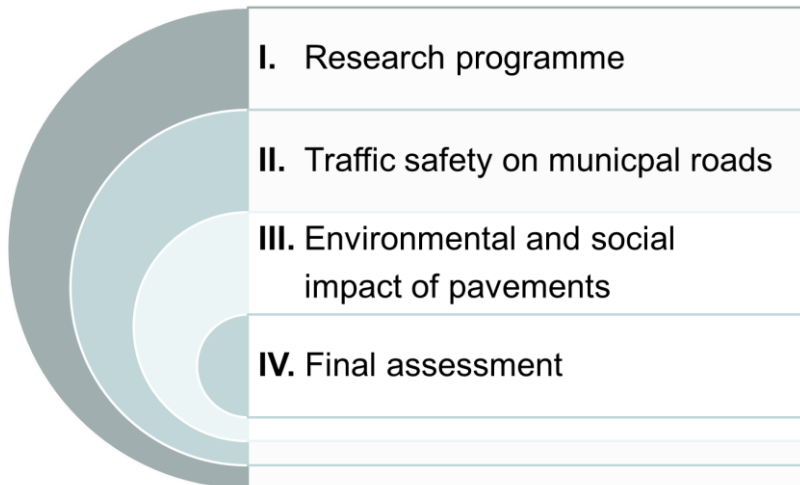


Figure 1.6 Organisation of the report

The first part of this report presents the scope of the research. In this part the goal of the study, the research description and the research methodology are briefly described.

The second part presents the development of the first program, which is a program for the prediction of the number of accidents on municipal roads. In chapter 2 an overview is given of the theory and literature that is used for the development of the first program. This chapter presents the theory of the critical road aspects that will be evaluated. The analysis procedure of the critical road aspects for the prediction of the traffic safety on municipal roads are presented in chapter 3. This chapter describes traffic engineering aspects (type of road, crossings and bends) and pavements surface properties in relationship with traffic safety on municipal roads. Chapter 4 presents the results of the analysis. Different cases are evaluated with the developed program for the prediction of the number of accidents on municipal roads.

The development of the second program, predicting the social and environmental costs of roads, is presented in the third part of the thesis. Chapter 5 presents the environmental aspects that have been considered in the development of that second program. This chapter describes the durability and sustainability of roads, shadow prices of environmental themes and Life Cycle Analyse. Chapter 6 deals with critical pavement aspects that have an effect on the environment (the used materials, the noise level and the fuel consumption). An overview of the available data and the analysis of the selected data of the previous mentioned aspects are briefly described. Chapter 7 addresses case studies that are used for analysing and validating the results of the program. The case studies are categorised in terms of durability, sustainability and sociality.

Finally, the fourth part of this report presents the conclusions of the research programme in chapter 8. Chapter 9 contains recommendations for further studies of the two developed programs.

PART II : Traffic safety on municipal roads

Traffic safety is an important issue for all classes of society. In the Netherlands the social costs due to traffic accidents are estimated to be 12500 million euros, i.e. 2.2 percent of the GDP (gross domestic product) [SWOV, 2014]. Several studies have been performed and various efforts have been deployed to reduce these vital costs. The main goal of these studies was how to reduce the number of traffic accidents when looking at all factors of influence. Road design and road construction are important aspects that were studied as well. Also enforcement and communication with the road user appears to be very important. From an infrastructure point of view not many studies were performed focusing on traffic safety on local or municipal roads, although this is an upcoming issue nowadays. Municipal roads are mostly situated in urban areas. The function of these municipal roads is therefore different from that of provincial roads and motorways. These latter two categories mainly have a flow function making it possible for traffic to travel from A to B safely and smoothly. Municipal roads on the other hand have a more accessibility function allowing traffic to access suburbs, districts or neighbourhoods. Therefore, traffic characteristics and modes on municipal roads are different from those on provincial roads and motorways. The traffic on municipal roads does not only consists of motorised vehicles but also bicycles and pedestrians. This makes the prediction of traffic safety on those types of roads more complex than that on provincial roads and motorways. The presence of crossings and bends on short spatial distance will have their impact on traffic accidents. Therefore, the prediction of traffic accidents on municipal roads will not only rely on road surface properties (road construction) but also on traffic engineering aspects (road design).

Part II of the thesis describes the development of a prediction model for traffic safety on municipal roads in the Netherlands. The model can be used by road authorities to predict the number of traffic accidents that can be faced on a specific road section. The model is based on traffic engineering aspects as well as the road surface properties of the road section under analysis.

2. Theory and literature overview

Traffic safety on municipal roads partly depends on the surface properties of the pavement. However, traffic engineering aspects such as crossings, traffic lights, bends in the road will have their impact as well on the traffic safety on municipal roads. These aspects may be even more instrumental than the pavement characteristics. Although little useful literature about traffic safety on municipal roads is available, this chapter will nevertheless provide an overview of the relevant literature that may be used for the prediction of the number of traffic accidents on municipal roads.

Figure 2.1 illustrates the items that were studied. The diagram also presents the main line of the structure of chapter 2, in which the theory and literature overview is reported.

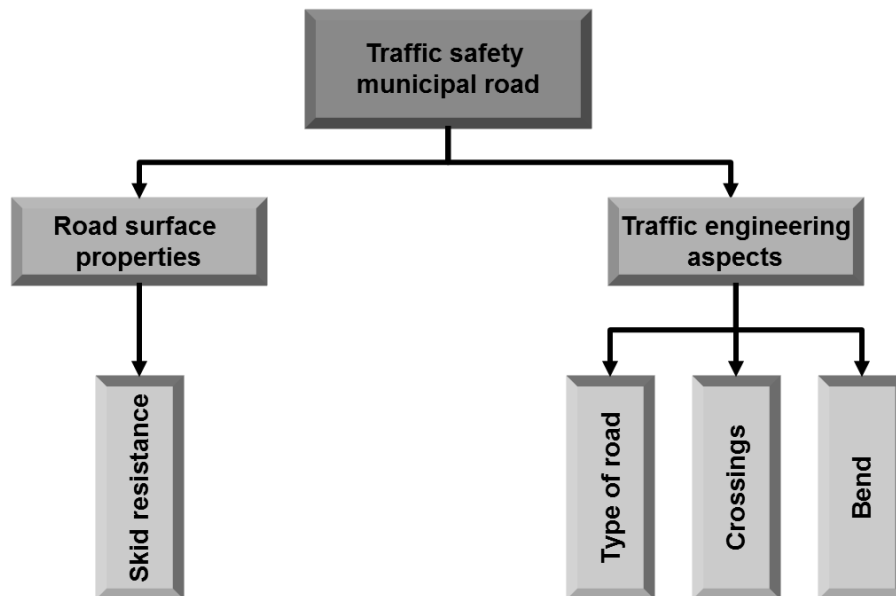


Figure 2.1 Overview of the main line of chapter 2

2.1. Traffic engineering aspects

Traffic engineering aspects are important for the prediction of the number of accidents on municipal roads. The traffic situation on municipal roads is more complex than that of (almost) straight provincial roads and motorways. The difference is in the accessibility function of municipal roads in contrast to the flow function of motorways and provincial roads. The municipal roads are characterised by much more crossings and bends than provincial roads and motorways. Also traffic modality of the municipal roads is different from that on motorways and provincial roads. Pedestrians, bicycles and mopeds are not allowed on motorways and hardly allowed on provincial roads, while these modes of transport are very important on municipal roads. These aspects will undoubtedly have their impact on the number of accidents resulting from this multimodal use. This section gives an overview of the traffic engineering aspects that were analysed.

2.1.1. Type of road

The type of road appears to be an important factor for the prediction of the number of traffic accidents. In the Netherlands, municipal roads can commonly be categorised as follows:

- dual carriageway; for cars and trucks only;
- single carriageway; for cars and trucks only;
- single carriageway; for all traffic.

The accident rate of the different road types are represented in Table 2.1. In 1994 some measurements of traffic intensity and accidents were performed. These measurements were collected on road sections of municipal roads. Road sections of provincial roads and motorways were not considered. The Only Vehicle Damage (OVD) accidents are not taken into account in these accident rates. The accident rate only contains the various injury accidents that may occur.

Table 2.1 Accident rate according to the road type [SWOV, 1997 (b)]

Road type	Injury accidents per mio. veh. km
Dual carriageway [cars and trucks only]	0,224
Single carriageway [cars and trucks only]	0,447
Single carriageway [for all traffic]	0,579

The comparison of the safety of the three different municipal road types is presented in Figure 2.2. Based on the combination of traffic intensity and the road length it can be observed quite easily that dual carriageways are safer than single carriageways. The reason for this difference is that on dual carriageway head on car accidents do not take place, while on single carriageways these type of accidents may occur [SWOV, 1997 (b)].

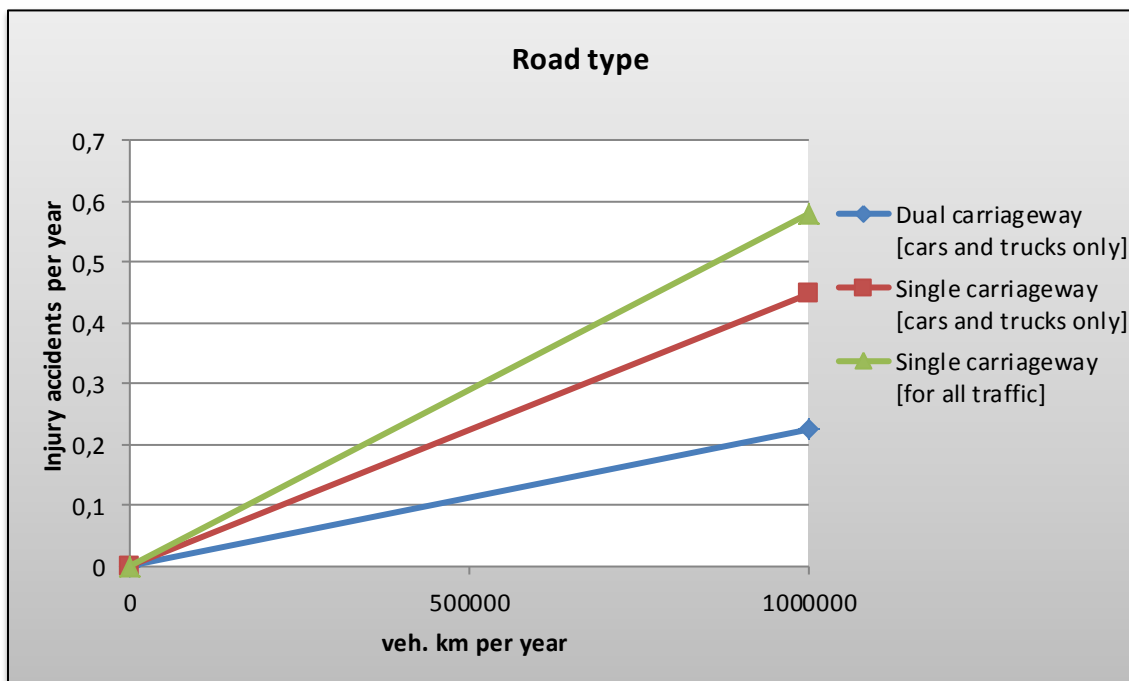


Figure 2.2 Injury accidents according to road type

2.1.2. Crossings

In different countries many studies were conducted to predict the number of traffic accidents on crossings. The models that describe the traffic accidents on crossings, generally have the same form. In Denmark, a lot of knowledge has been gained on the accident risk on crossings. According to the Danish model, the accidents on crossings can be calculated in general with the equation: [SWOV, 1998]

$$A = c * Q_1^a * Q_2^b \quad (\text{Eq. 1})$$

where:

A = injury accidents
 Q₁ = intensity main stream [veh./day]
 Q₂ = intensity side stream [veh./day]
 a, b, c = parameter

Table 2.2 presents the parameters that are used in the Danish model. The estimated parameters and intensities depend on the local circumstances and will be different for another country. The basic form of the model can be fitted to any dataset of measurements as long as the intensities and accidents numbers are available.

Table 2.2 Parameters in the Danish model [SWOV, 1998]

Crossing type	c	a	b
T – crossing; give way sign	2.98.10 ⁻⁶	0.81	0.52
T – crossing; traffic lights	7.04 .10 ⁻⁸	1.36	0.32
4 – way crossing; give way sign	1.68 .10 ⁻⁴	0.36	0.58
4 – way crossing; traffic lights	8.62 .10 ⁻⁵	0.52	0.47

In the Netherlands, several studies were performed on the safety of crossings too. Various Dutch situations of crossings in urban areas were compared in a study reported by Janssen [SWOV, 2004]. That study is based on more than 500 intersections of urban roads with mopeds, motorized vehicles and pedestrians. The crossings that were evaluated are crossings where not only fast traffic is passing. This means that bicycles and pedestrians (slow traffic) are also passing the crossings. The Only Vehicle Damage accidents (OVD) were not taken into account in the registration of the traffic accidents. The results of Janssen's research that are assumed to be relevant for this study are presented in Figure 2.3, Figure 2.4 and Figure 2.6 [SWOV, 2004].

The analysis procedure of Janssen evaluates three different intensity categories over 35 T – crossings with traffic lights. The same is done for 73 crossings with give way signs. Figure 2.3 illustrates that the first data point of the T – crossings with traffic lights for the lowest intensity category (blue line) is apparently not accurate. Commonly one should expect that the point with the lowest intensity category to correspond with the lowest number of accidents. This is not the case apparently. The reason for this observation could be found in the explanation that the evaluated crossings of the lowest intensity category contain proportionally more crossings without on-road bicycle lanes or adjacent bicycle lanes.

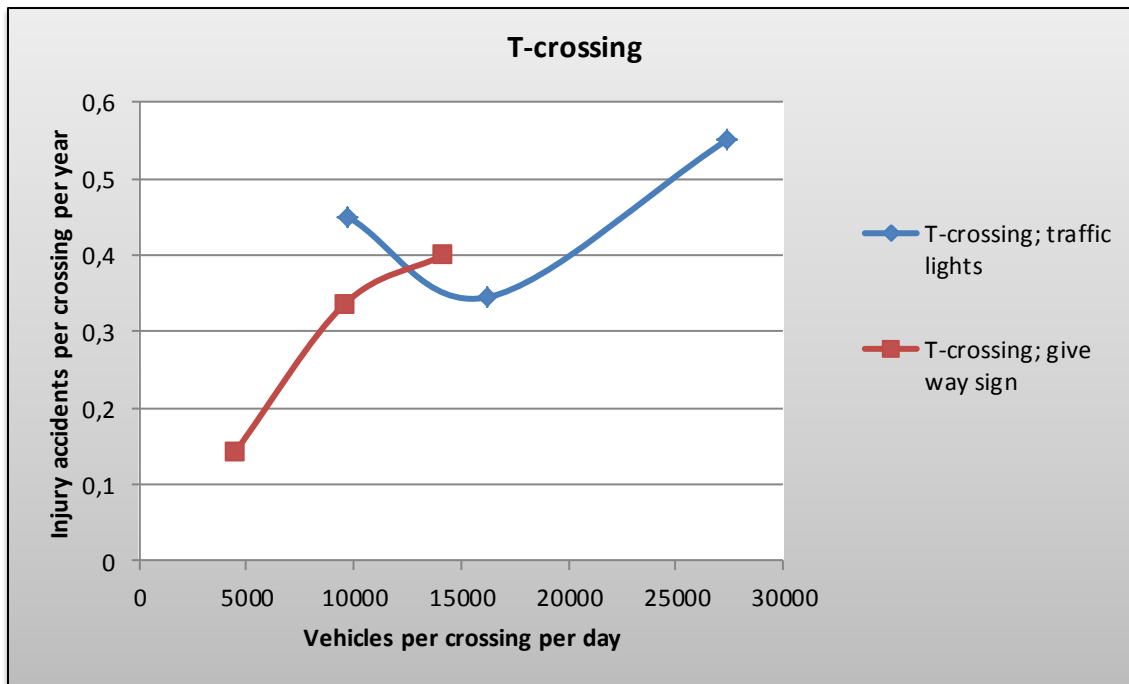


Figure 2.3 Amount of accidents on T – crossings [SWOV, 2004]

The evaluation of the 4 – way crossings was performed for 94 crossings with traffic lights and 33 crossings with give way signs. As for T- crossings, three different intensity categories were evaluated for the two situations. Noteworthy, it can be concluded that crossings with traffic lights are not safer apparently than crossings with give way signs. Looking at the severity of the accidents on crossings with give way signs, these accidents appear to be more severe than those on crossings with traffic lights. Also turning off of the traffic lights in the night is an explanation why more accidents are counted on crossings with traffic lights than on crossings with give way signs. Figure 2.4 illustrates that in general the crossings with traffic lights represent the crossings with higher traffic intensities. Due to these higher intensities more accidents will occur on these type of crossings if the traffic lights are switched off in the night.

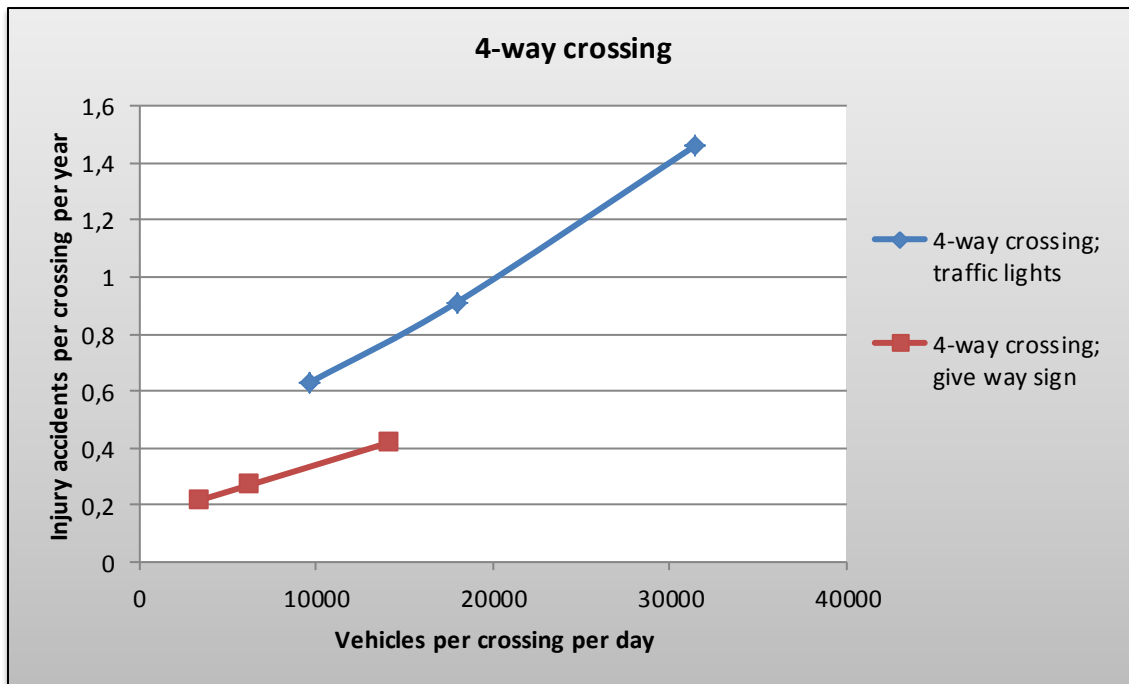


Figure 2.4 Amount of accidents on 4 – way crossings [SWOV, 2004]

Figure 2.5 illustrates the number of conflict points that might rise problems on roundabouts, T – crossings, and 4 – way crossings. On roundabouts there are only 4 conflict points, which makes the roundabout safer than the other two types of crossings.

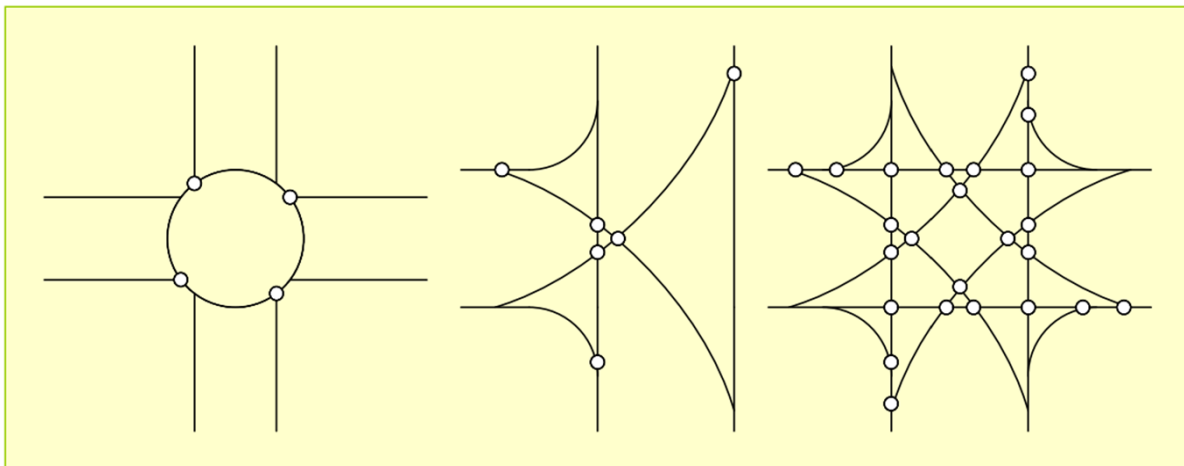


Figure 2.5 Number of conflicts that can occur on different type of crossings [SWOV, 2004]

For the evaluation of the roundabouts, 34 roundabouts were evaluated by SWOV. This analysis was again performed for three different intensity categories. (see blue line in Figure 2.6). The roundabouts that were evaluated are roundabouts with a 4 – way connection. Figure 2.6 also illustrates the comparison of roundabouts on which cars had priority with roundabouts with bicycles having priority. Roundabouts on which cars have priority are safer but not significantly safer. People on bicycles are more vulnerable than drivers and passengers in vehicles, so it is better to give the vehicles priority preventing situations where motorists fail to detect circulating cyclists. This give way regulation is used on all roundabouts outside urban areas in the Netherlands. The northern provinces in the Netherlands use the same regulation for roundabouts in urban areas, whereas for the rest of the country cars have to give way to bicycles on urban roundabouts.

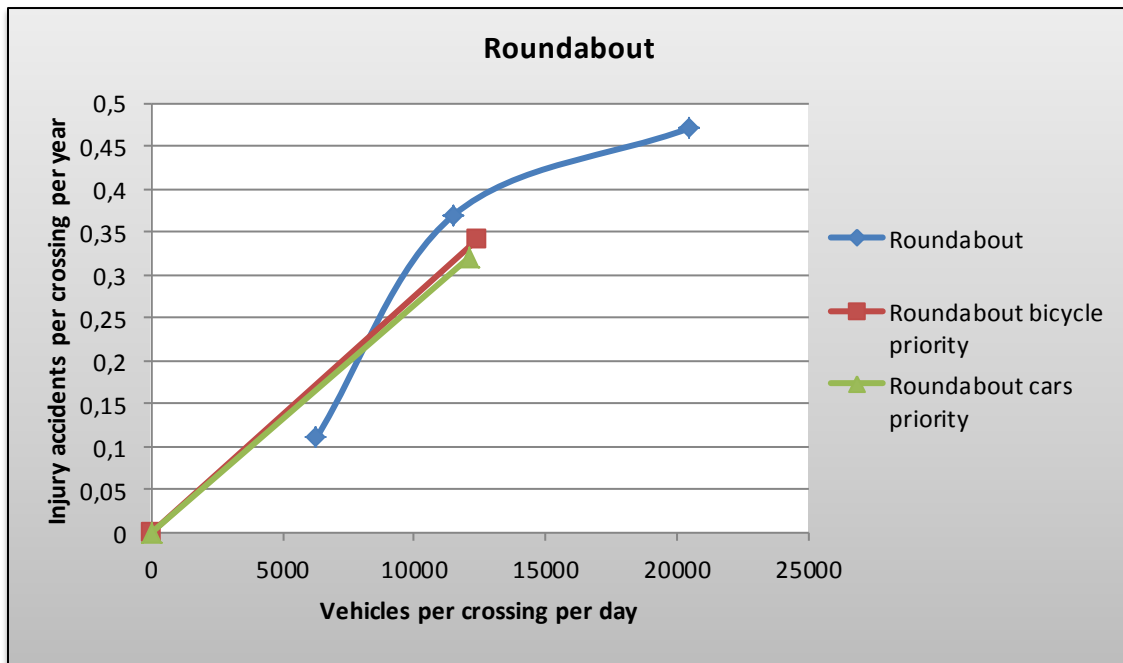


Figure 2.6 Amount of accidents on roundabouts [SWOV, 2004]

2.1.3. Bends

Not only crossings but also bends in the road are instrumental features for the prediction of the number of traffic accidents on municipal roads. No reports could be found during the literature study on previous studies describing the effect of bends in the road on traffic safety on municipal roads for the Dutch situation. Several foreign studies were investigated as basis for modelling the relationship between traffic safety and bends in the road [SWOV, 1998]. These studies were performed in foreign countries and are the result of measurements on rural roads. In most of the studies the reliability of the developed models for the prediction of the traffic safety in bends appears to be less than thirty percent. These models were not considered to be applicable to the Dutch situation because of their origin, the way the reported research programme was analysed and their low reliability. Nevertheless, the traffic safety of bends on municipal roads could be predicted by using previous studies about the traffic safety of motorways in the Netherlands. One of these studies [Groenendijk, 2013] describes the relationship between the skid resistance and the traffic safety for different road situations. These relations are represented in Figure 2.7. This figure presents that straight road sections of the main carriageway of motorways (ASW HR) are in general safer than road sections with interchanges (ASW WV). The interchanges on motorways are mostly bended especially at cloverleaf junctions. The interchanges do not contain data of regular (usually straight) entries to and exits from the motorway. The ratio of accident rates on interchanges and straight motorways sections is assumed to apply on other types of roads too. This assumption makes it possible to predict the traffic safety of bends on municipal roads based on the combination of traffic safety on straight municipal roads and the accident rate ratios (interchanges over straight) on motorways. The needed correction factors (from straight to bended section) take into account the differences in speed between motorways and municipal roads.

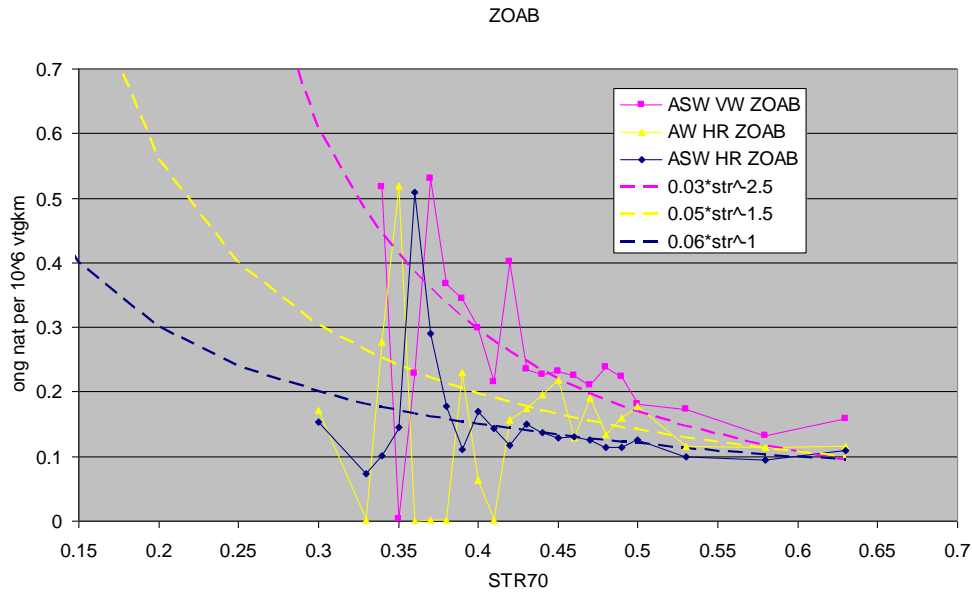


Figure 2.7 Traffic safety different road situations [Groenendijk, 2013]

The fluctuating relations at lower skid resistance values can be explained because of the low numbers of road sections with such low skid resistance values. Therefore, the results are statistical not reliable because of large variations in accidents between the road sections.

In the analysis of the traffic safety on bends, the bend length and bend radius are important parameters. The minimum bend radius for reason of comfort of the road user can be determined with the design guidelines for non-motorway [NOA, 2007]. The relationship between the minimum bend radius, the sight distance in the bend and the line of the restrictive sight due to an object in the inner side of the bend is described in Appendix A.

The bend radius and the bend length are to some extent related to each other. On roads with a high speed limit the road designer makes use of clotoïdes for the transition from straight to bend or vice versa. For local roads and municipal roads the speeds are lower making the use of clotoïdes less necessary. The length of the bend can be calculated from the bend radius as follows:

$$L_{c,i} = \frac{\alpha}{360} * 2\pi R \quad (\text{Eq. 2})$$

where:

- $L_{c,i}$ = length of the bend [m]
- α = angle of the bend [deg.]
- R = radius of the bend [m]

2.2. Pavement surface properties

2.2.1. Introduction

The whole pavement structure but also the road surface must meet minimum requirements to guarantee a sufficient level of traffic safety. Pavement surface properties do not only have an effect on the traffic safety of provincial roads and motorways but also on municipal roads. Traffic safety is an important requirement for both the road user and the road authority. Different road surface properties are decisive for the traffic safety. The road surface properties can be classified into two main categories namely: [Silva, 2013]

- longitudinal properties (skid resistance and roughness) and
- transverse properties (rutting and cross fall)

In contrast to provincial roads and motorways, speed limits and actual speeds on municipal road are generally lower. Pavement surface properties will therefore have less effect on the traffic safety on municipal roads. Skid resistance is one of the most important pavement surface properties in terms of traffic safety [Silva, 2013]. The braking distance is in this situation an important parameter. In general this braking distance is dependent on the reaction time of the driver, the vehicle speed and the skid resistance of the pavement surface. The reaction time of the road user is dependent on age, gender, tiredness, attentiveness etc. The (national and local) government and road authorities make attempts to control the vehicle speed of road users by legislation, training and enforcement. The pavement surface requirements can be controlled by the road engineers. Sufficient friction between tires of the passing vehicles and the road surface is vital for the breaking distance. Sufficient friction between wheel tire and road surface can be reached by use of tires with plenty grip and tired tread, but more important is sufficient friction in the interface of tire and pavement surface. The friction coefficient of a pavement surface is dependent on the type of wearing course applied. Important parameters that affect the friction coefficient of an asphalt wearing course are the mineral aggregates and the composition of the asphalt mix. The shape and micro texture of the mineral aggregates influence the strength, stiffness and friction characteristics of the asphalt mix. Use of sharp aggregates usually leads to higher friction coefficients than using round aggregates. Edgy and sharp aggregates with a high resistance to polishing are therefore a better choice.

2.2.2. Skid resistance measurement methods

The task of the road authorities is to guarantee a good condition of the road surface. The road authority will be held liable when traffic accidents occur because of a bad condition of the road surface. Therefore, road authorities are in a continuous process of planning and managing the required maintenance of their pavement network. A way to control the traffic safety and to determine whenever maintenance is required or not is by measuring the skid resistance. Skid resistance is a pavement surface property that can be measured very easily. The test result gives an indication of the friction coefficient of the pavement surface. Friction measurements of the pavements surface provide for evidence that the requirements are met and when or not that maintenance is required to meet the requirements according to the level of skid resistance. Periodical measurements of the skid resistance provide an indication of the development of the skid resistance over time. This is a convenient method for road authorities to control the required maintenance intervals.

Wet surfaces are more critical for accelerating and decelerating of vehicles than dry pavement surfaces. Wet surfaces will lead to more traffic accidents per unit of time than dry surfaces. The risk of an accident on a wet surface is five times higher than that on a dry surface [CROW, 2005]. Therefore, friction coefficient measurements are generally performed on a wetted surface. In the Netherlands friction-measuring equipment is equipped with self-wetting systems.

The measurement method for the wet skid resistance used in the Netherlands is a method that was developed in 1950. The method, is described in test 72 of 'the standard RAW specifications 2010'. The test trailer, consists of two running wheels travelling at a speed of 50 km/h or 70 km/h and one separate test wheel near the centre of the trailer (see Figure 2.8). This test wheel, is a wheel with a standard PIARC tire without profile mounted. The test wheel has a lower speed than the running wheels (86% retarded). In front of the test wheel a thin waterfilm is jetted. The water layer thickness that is applied amounts 0.5 mm on a theoretically perfectly smooth surface. The actual water layer thickness depends on the macro texture of the surface and the porosity of the asphalt mix. The measured friction is dependent on the properties of the wearing course but also on the speed that the test is carried out. In most cases the test speed is set to 70 km/h except where the speed of 70 km/h cannot be achieved, for example on municipal roads. In that case a test speed of 50 km/h is used.



Figure 2.8 Measurement system for the skid resistance [Gaarkeuken, 2006]

Several studies were performed to investigate the relationship between the skid resistance and the test speeds of 70 km/h and 50 km/h. A lower test speed leads to higher value of skid resistance [TNO, 2007]. The macro texture of the wearing course also has an impact on the relationship between test speed and skid resistance. Therefore, distinction is made in the Netherlands between porous and dense asphalt mixes. Rijkswaterstaat issued different intervention levels for the skid resistance broken down per test speed and type of wearing course. These intervention levels are listed in Table 2.3. The differences in the skid resistance levels between RAW 2005 and RAW 2010 specifications are due to the fact that in RAW 2005 the influence of the macro texture (type of wearing course) was not taken into account and the test speed was fixed at 50 km/h. Due to the innovation in skid resistance measuring methods different correction factors are in use since that time. The factors are dependent on the test procedure (RAW 2005 or RAW 2010).

Table 2.3 Intervention levels skid resistance [TNO,2007]

Measurement method	RAW 2005	RAW 2010		RAW 2010	
Wearing course	porous/dense	porous		dense	
Measure speed [km/h]	50	50	70	50	70
Warning level	0.45	0.54	0.50	0.53	0.47
Level at which maintenance is required	0.38	0.45	0.42	0.44	0.39

2.2.3. Polishing of mineral aggregates

The decay of skid resistance of an asphalt mix with time and/or traffic volume is largely governed by the polishing rate of the mineral aggregates under climate and traffic. The resistance to polishing of the mineral aggregates can be measured in laboratories. The test to determine the PSV (Polish Stone Value) of mineral aggregates is the PSV test (NEN-EN 1097-8).

Road surface unevenness with a wave length smaller than 0.5 mm is formed due to the micro texture of the mineral aggregates. The micro texture of the mineral aggregates is determined by the sharpness and roughness of the mineral aggregates. Therefore, a round mineral aggregate (e.g. an eroded smooth pebble) will have less micro texture than a sharp and edgy aggregate. Mineral aggregates with a good micro texture (sharp and edgy) have a higher value of skid resistance. Whether this value remains high is largely dependent on the PSV, i.e. chemical composition of the mineral aggregate. Asphalt mixes that are composed from mineral aggregates with a high polished stone value have in general a good skid resistance performance. An indication of the polished stone values of different mineral aggregates is listed Table 2.4.

Table 2.4 Indication PSV values of different mineral aggregates [Gaarkeuken, 2006]

Type of mineral aggregate	PSV [-]		
	< 53	53 – 58	> 58
Moraine split 1		X	
Moraine split 2	X		
Greywacke			X
Diabase		X	
Basalt	X		
Granite	X		
Porphyry		X	
German porphyry		X	
Broken Maas granite		X	
Limestone	X		
Sandstone		X	X
Quartzite		X	X
Diorite	X		

The ideal stone for a road pavement has a multi mineral composition. The right distribution between hard and soft minerals is important to reach a high polished stone value of the stone. A hard mineral like quartz has a good impact on the polishing resistance. However, a stone that exist of 100 % quartz has a low polished stone value. Weathering of soft minerals ensures that a new rough surface arises, which protects the hard stone minerals from weathering. This process leads to a continuous variation of the micro texture of the stone and results in a high polished stone value.

2.2.4. Asphalt mix composition

Road surface unevenness with wave lengths between 0.5 mm and 50 mm is categorised as macro texture. The macro texture of road surfaces is determined by the grading and shape of the mineral aggregates and the porosity of the mastic. The degree of compaction during the construction is also very important for the macro texture of the road surfaces. Good compaction during the construction results in less unevenness of the road surface.

The macro texture, the porosity of the mastic and the slope of the road surface have an effect on the thickness of the water film between the pavement surface and the passing tires. The macro texture also determines how fast this water film can be pressed away from the surface between the tire and the road. The higher the porosity of the mastic, the faster the waterfilm is pressed away from the road surface. The thicker the waterfilm between the tire and the road surface the less the skid resistance will be, the higher the risks on aquaplaning, the higher the chances on a traffic accident.

The macro texture of the road surface is quantified by the Mean Profile Depth (MPD). The value of the mean profile depth can be measured by a two dimensional road surface profile that is registered by a texture laser.

The micro texture is decisive for the initial value of the friction coefficient at a speed of 50 km/h. A good micro texture (sharp and edgy aggregates) results in a higher initial friction coefficient at a speed of 50 km/h. If the macro texture is good (=high), the friction coefficient at higher speed limits will be almost the same as the initial friction coefficient at a speed of 50 km/h. If the macro texture is poor, the friction coefficient at higher speed limits will drop faster at increasing speed. The macro texture quality is decisive for the decrease of the friction coefficient.

2.2.5. The relationship between skid resistance and traffic safety

Several reports on studies describing the relationship between the accident rate and skid resistance have been issued. Most of these studies were performed on provincial roads and motorways and not on municipal roads. The relationship between the accident rate and skid resistance on motorways and provincial roads is presented in Figure 2.9. The corresponding skid resistance values of the different skid resistance classes are listed in Table 2.5.

Table 2.5 Skid resistance classes with the corresponding skid resistance values [SWOV, 1974]

Class	Skid resistance value
1	< 0.36
2	0.36 – 0.41
3	0.41 – 0.46
4	0.46 – 0.51
5	0.51 – 0.55
6	0.56 – 0.61
7	0.61 – 0.66
8	0.66 – 0.71
9	> 0.71

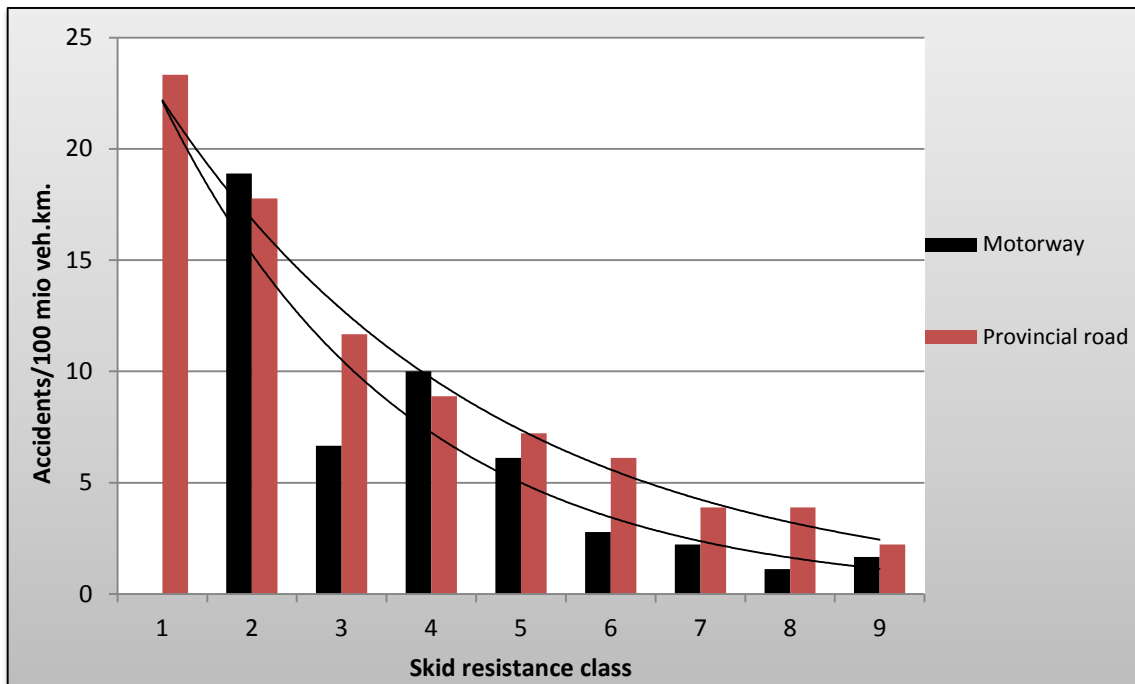


Figure 2.9 Relation between skid resistance and accident rate [SWOV, 1974]

2.3. Conflict types

As discussed earlier, municipal roads have a different function than motorways and provincial roads. Due to their accessibility function, the different conflict types will be a source of the various accidents on the roads in municipal road networks. Pedestrians, mopeds and bicycles are not allowed on provincial roads and motorways, while these categories of slow traffic are important categories of traffic on municipal roads. From this point of view, it makes sense to know which type of accidents are part of the accident rate as reported in many survey reports. Figure 2.10 and Figure 2.11 illustrate the distribution of fatal injuries over different conflict types. The fatal injuries have been determined for a period of 30 years (from 1975 till 2005). The number of fatal injuries show a decreasing trend over time. Therefore, for the sake of the study reported in this thesis it is considered appropriate to use the values of the last 10 years (1995 -2005) to describe the current situation.

Figure 2.10 illustrates the number of fatal injuries for the different conflict types on municipal roads. The conflict type where a car and no other party is involved contains the highest number of fatal injuries. The fatal injuries of car – bicycle collisions and car – car collisions are also very high.

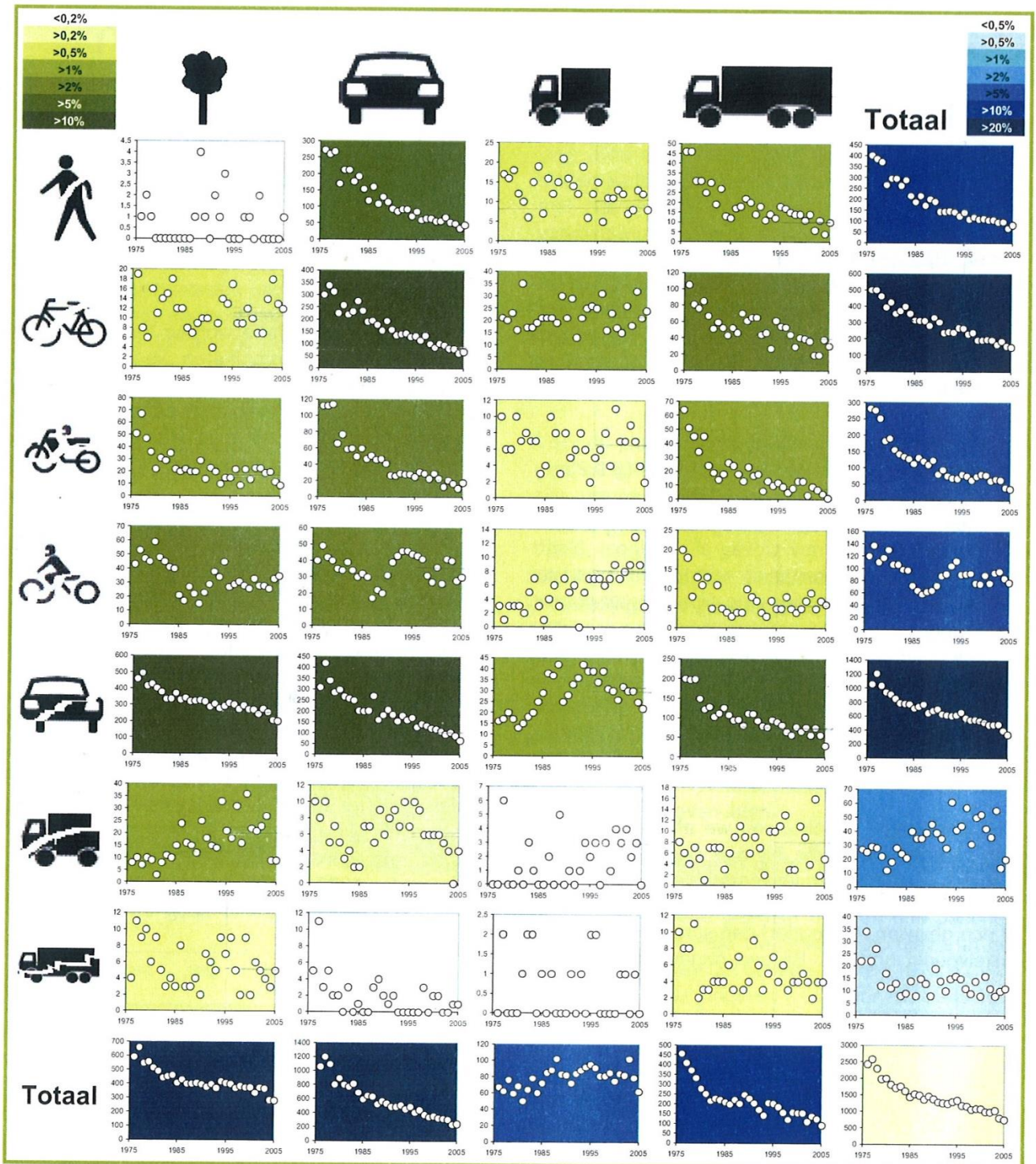


Figure 2.10 Fatal injuries in the Netherlands broke down per type of collision [SWOV, 2007]

Figure 2.11 illustrates the difference between the fatal injuries on crossings and road sections (both travelling speeds between 50 and 80 km/h) for different conflict types. The unilateral fatal injuries are much lower for crossings than for road sections (see diagrams at the top). This result could have been expected since on crossings the chance of a unilateral car (“Auto enkelvoudig”) accident is much smaller than on a road section without crossings. On crossings on the contrary, car – car conflicts (“Auto tegen Auto”) do not depart much from ordinary road sections (see diagrams at the centre). The same applies to car to other (“Auto tegen overig”) conflicts (see diagram at the bottom).

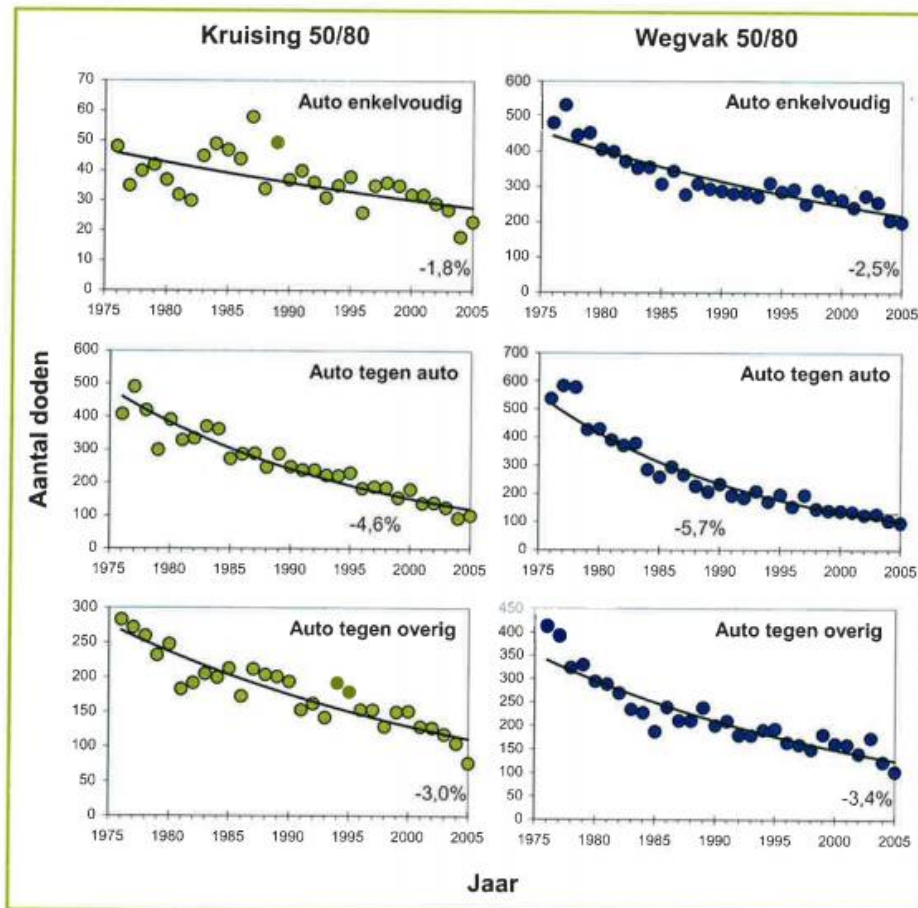


Figure 2.11 Development of the fatal injuries at crossings and road sections [SWOV, 2007]

3. Analysis procedure

3.1. Traffic Engineering aspects

3.1.1. Crossings

This section describes models that have been developed for the prediction of traffic accidents on urban area crossings in the Netherlands. These models were developed with the information of the safety on crossing in the Netherlands (studied by Janssen) as basic instrument for the determination of the parameters of the general formula that calculates the traffic accidents on crossings (the Danish model); (chapter 2.1.2). This general formula uses the distribution of the traffic intensity of the main and side stream as main input. This paragraph shows how the model coefficients were determined to fit the general Danish model for the calculation of accidents on crossings to the Dutch situation. The type of crossings that are analysed are listed in Figure 3.1. The Danish model is not applicable to roundabouts. Therefore the roundabouts will be evaluated with the relationships that were investigated by Janssen.

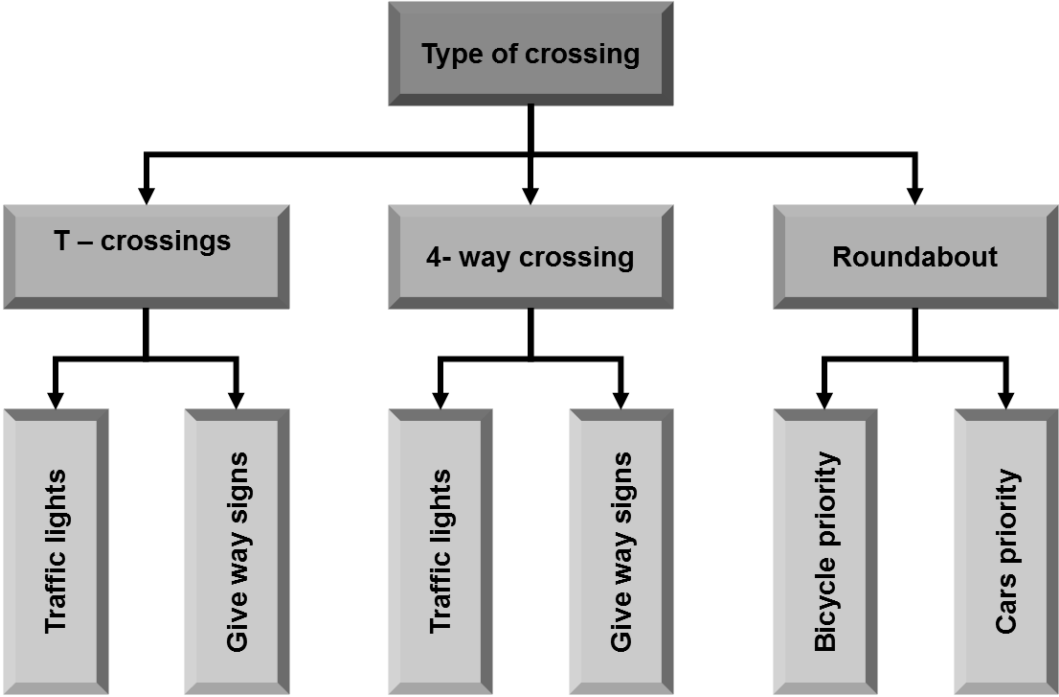


Figure 3.1 Crossings that are analysed

Figure 3.2 illustrates that by evaluating the T – crossings, the situation of intensity distribution that fits the best to the Dutch situation is:

- 85% of the vehicles are approaching the crossing from the main stream while
- 15% of the vehicles are approaching the crossing from the side stream.

The numeric values of the model coefficients of equation 1, are changed. This is done in a way that fits the best to the safety on crossings in the Netherlands (studied by Jansen). The results of the analysis are the following models for the prediction of the traffic safety on T – crossings in the Netherlands, on roads with a speed limit of 50 km/h:

$$\text{T – crossing ; traffic lights:} \quad A = 4.10^{-8} * Q_1^{1,37} * Q_2^{0,35} \quad (\text{Eq. 3})$$

$$\text{T – crossing ; give way sign:} \quad A = 3.10^{-6} * Q_1^{0,82} * Q_2^{0,57} \quad (\text{Eq. 4})$$

where:

A = accidents per crossing per year

Q₁ = intensity of the main stream; 85% of the intensity on the road section [veh./day]

Q₂ = intensity of the side stream; 15% of the intensity on the road section [veh./day]

Other numeric values of the model coefficients will have to be used for other ratios of main stream and side stream. The numeric values of the model coefficients will also be different for other countries.

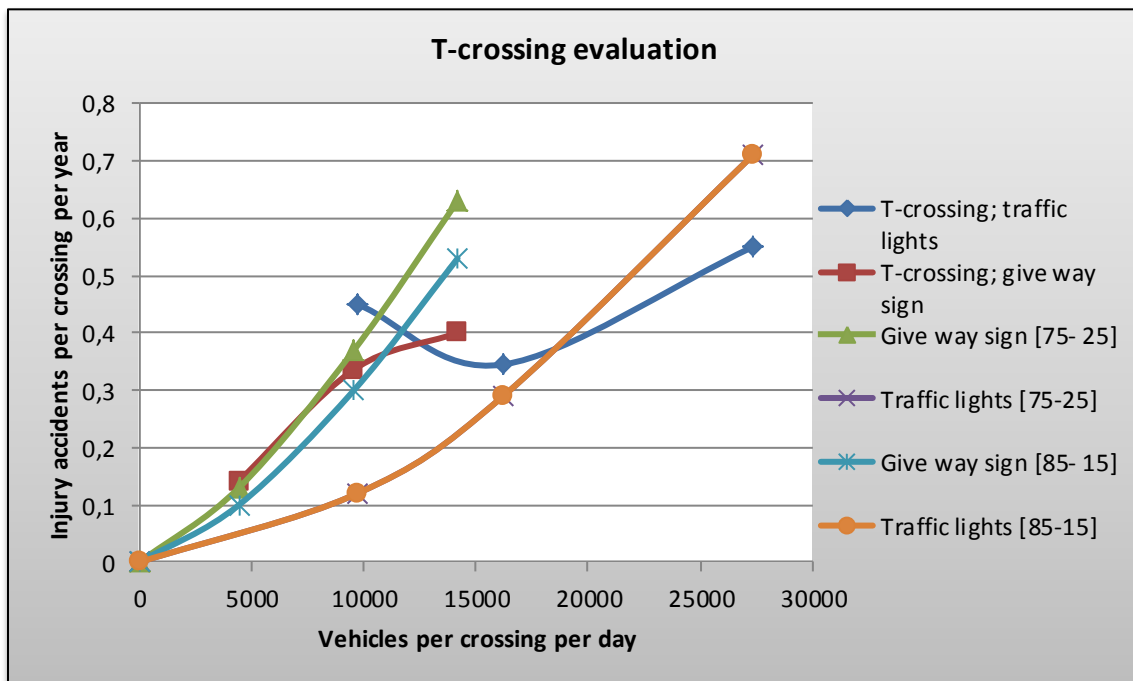


Figure 3.2 Evaluation of the accidents on T – crossings

Figure 3.3 illustrates that by evaluating the traffic safety at the 4 – way crossings, the situation of intensity distribution that fits the best to the Dutch situation is:

- 75% of the vehicles are approaching the crossing from the main stream while
- 25% of the vehicles are approaching the crossing from the side stream.

Similar to the procedure of the T- crossings, the numeric values of the model coefficients have been determined for the 4 – way crossings. The traffic safety on 4 – way crossings in the Netherlands, on roads with a speed limit of 50 km/h, can be predicted by the following models:

$$\text{4 – way crossing ; traffic lights: } A = 9.10^{-5} * Q_1^{0,54} * Q_2^{0,485} \quad (\text{Eq. 5})$$

$$\text{4 – way crossing ; give way sign: } A = 1,6.10^{-4} * Q_1^{0,36} * Q_2^{0,58} \quad (\text{Eq. 6})$$

where:

A = accidents per crossing per year

Q₁ = intensity of the main stream; 75% of the intensity on the road section [veh./day]

Q₂ = intensity of the side stream; 25% of the intensity on the road section [veh./day]

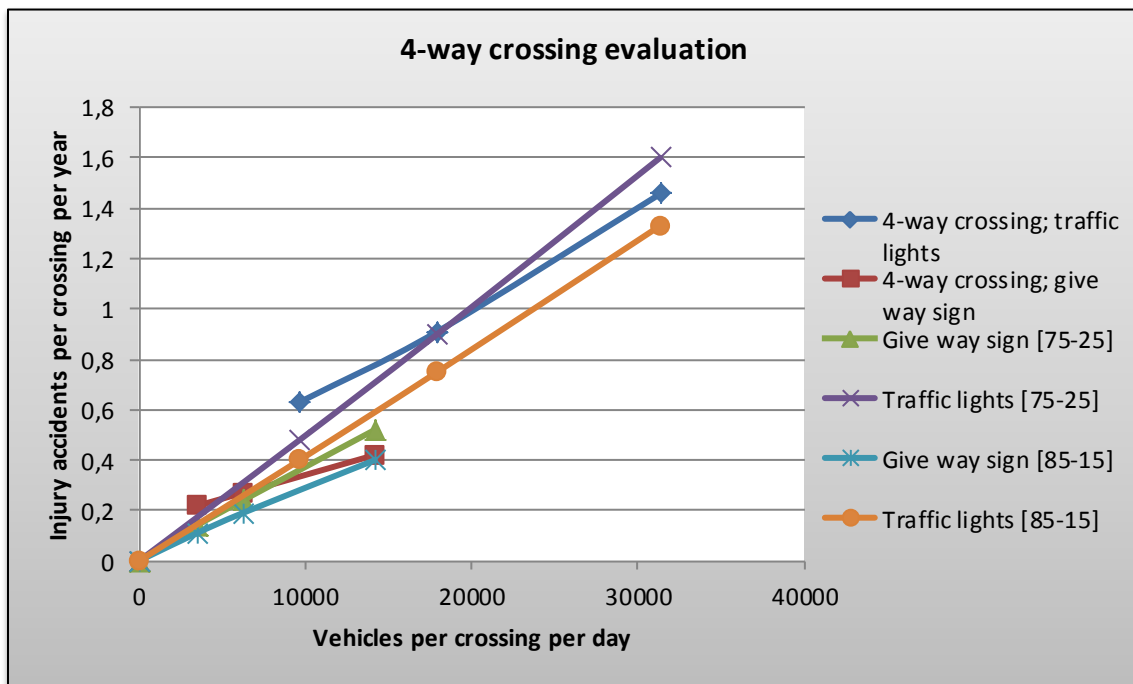


Figure 3.3 Evaluation of the accidents on 4 – way crossings

The traffic accidents on roundabouts are calculated with the help of the linear relations as illustrated in Figure 2.6. Roundabouts where cars have priority over circulating cyclists are not significantly safer than roundabouts where bicycles have priority. The traffic accidents on roundabouts can be calculated as follows:

$$\text{Roundabouts, cars priority: } A = 2.65.10^{-5} * Q \quad (\text{Eq. 7})$$

$$\text{Roundabouts, bicycle priority: } A = 2.75.10^{-5} * Q \quad (\text{Eq. 8})$$

where:

A = injury accidents per roundabout per year

Q = intensity of fast traffic (cars and trucks) on the roundabout [veh./day]

The total of injury accidents on crossings in a road section with one or more crossings can be calculated as follows:

$$A_{\text{cros. tot.}} = \sum A_i * n_i \quad (\text{Eq. 9})$$

where:

$A_{\text{cros. tot.}}$ = total injury accidents due to crossings per year
 A_i = injury accidents on crossing of type ' i '
 n_i = number of crossings type ' i '

3.1.2. Bends

The traffic safety of a road section is not only affected by crossings and roundabouts, but also by the number of bends in the road section. However, not all bends may be considered as risky point in the longitudinal profile of a road. Wide bends with a good visibility in the bend may be regarded as a straight road in terms of behaviour of the driver and number of traffic accidents.

This section describes the analysis procedure of the contribution of bends to the traffic safety of a road section. The influence of the bends is taken into account by calculating ratios between the accident rate of a bended road section and a straight road section and by taking into account the proportional distribution of bends in the total length of the road section under analysis. The bend ratio is calculated with the relationship between the traffic safety on motorways of road sections with a main straight lane and road sections with an interchange of two main lanes (see section 2.1.3)

The traffic safety of bends on municipal roads is described in terms of the traffic safety on municipal roads by making use of correction factors. These correction factors take into account the difference in speed reduction between motorways and municipal roads. The speed limit on motorways in the Netherlands is 120 km/h. The advice speed that road signs display on main interchanges of a motorway is mostly 80 km/h. Therefore, in this study it assumed that the speed reduction on interchanges on motorways is 40 km/h. The difference of accident rates between the motorway interchanges and the straight motorway sections is set to be driven by the speed reduction i.e. 40 km/h. It is assumed that this increase in accident rate (from straight section to interchange) has a linear relationship with the speed reduction. In other words: when the ratio of accident rates motorway straight and motorway interchanges is e.g. 1.2, then the ratio will be 1.1 in case of a speed reduction of 20 km/h and 1.05 for a speed reduction of 10km/h.

The bend ratio on municipal roads is defined as the correction factor to be multiplied by the accident rate found for a straight section of municipal road to adjust this rate for the bend under analysis. The bend ratio value depends on the speed reduction due to the bend and the ratio of the accident rates of the main carriageway and interchanges on motorways. The bend ratio on municipal roads is calculated as follows:

$$r_b = 1 + \frac{\Delta V}{40} \left(\frac{AR_{int.}}{AR_{main}} - 1 \right) \quad (\text{Eq. 10})$$

The accident rate on the main carriageway of a motorway and that of the interchange can be calculated as follows: [Groenendijk, 2013] (see Figure 2.7).

$$AR_{int.} = 0.03 * SR^{-2.5} \quad (\text{Eq. 11})$$

$$AR_{main} = 0.06 * SR^{-1} \quad (\text{Eq. 12})$$

where:

r_b = bend ratio [-]

$AR_{int.}$ = accident rate on the interchange between two main carriageways
[acc./mio veh. km]

AR_{main} = accident rate on the main carriageway of a motorway [acc./mio veh. km]

ΔV = speed reduction on the municipal road [km/h]

SR = skid resistance [-]

The presented model results in a higher bend ratio for higher speed reductions. One should expect that a sharper bend corresponds with a higher speed reduction of the approaching cars and a higher accident rate.

Figure 2.7 illustrates that the accident rates on motorways and other roads are dependent on the skid resistance. Therefore, the bend ratio on municipal roads is also dependent on the skid resistance. The higher the skid resistance the smaller the difference between the accident rate of a straight main lane and the interchange simply because the high friction coefficient allows for higher speeds in the bends without accidents and/ or fatalities (see Figure 2.7).

The skid resistance of a road section is not constant but a parameter that diminishes with time and/or traffic volume. This implies that the bend ratio of a municipal road will also not be a constant but will change yearly based on the development of the skid resistance of the road surface.

A road section under analysis will probably contain more than one bend. The bend ratio of each bend is calculated conform equation 10. The different bend ratios of the road section under analysis are aggregated into an equivalent ratio. This equivalent ratio indicates the overall correction factor to be applied to a winding road section to account for all critical bends in the road section under analysis. An equivalent ratio of 1 corresponds with an accident rate equal to that of a straight road section without bends. The more bends there are and the sharper the bends will be, the higher the equivalent ratio will be. In the developed model only the bends with a significant speed reduction are taken into account. The number of bends and the corresponding speed reduction can be inventoried by inspection of road signs or other sources of information. In most cases the road users are warned by a speed sign when a significant speed reduction is necessary in a curve.

The procedure and the symbols that are used for the calculation of the equivalent ratio of the traffic safety on a winding road section are expressed in Figure 3.4. The following equations describe the calculation procedure of the equivalent ratio:

$$L_{tot} = \sum L_{b,i} + \sum L_{s,i} \quad (\text{Eq. 13})$$

$$r_{eq} = 1 + \frac{\sum r_{b,i} * L_{b,i} - \sum L_{b,i}}{L_{tot}} \quad (\text{Eq. 14})$$

where:

L_{tot} =	total length of the road section [m]
$L_{b,i}$ =	minimum length of the bend [m]
$L_{s,i}$ =	length of straight line section [m]
r_b =	ratio of bend [-]
r_{eq}	equivalent ratio road section [-]

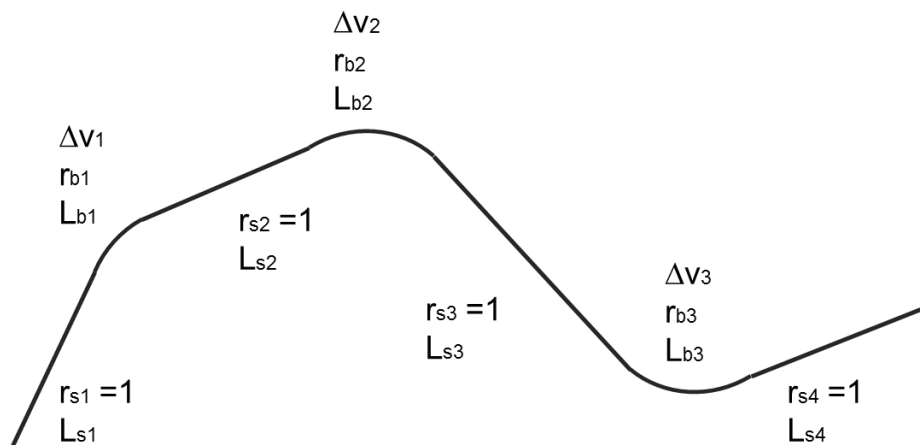


Figure 3.4 Top view of a road section

The speed reduction at the beginning of a bend is commonly a function of the bend radius, bend length, weather conditions, sight distance and the combination of experience, age and gender of the driver. The weather conditions and driver characteristics have not been used in this study for matching speed reduction to the set of bend length, bend radius and sight distance. The bend length is related to the bend radius specifically when bend angles in a road do not vary much. Therefore, the bend length becomes indirectly dependent on the vehicle speed and the sight distance when approaching the bend. The analysis of the relationship between the bend length and the vehicle speed on municipal roads is described in Appendix A.

The speed limit on the main municipal roads in urban areas is in general 50 km/h. In this study a fixed numeric value of 55 km/h is assumed as the speed before speed reduction. This fixed value is determined by assuming that the road users are driving slightly faster than the speed limit allowed on municipal roads. Furthermore, in this study the speed reduction is restricted to three values namely: 5, 10, and 15 km/h. This restriction has been made to simplify the number of bends in a road section into three categories. This restriction makes it rather easy for road inspectors and road designers to categorise the bends of the road section under analysis.

In daily practice it is difficult to assign a bend length to a bend where some speed reduction is expected. Appendix A shows the development of a procedure for assigning a weighted bend length to a bend with a speed reduction. The values displayed in Table 3.1 have been derived for the situation on municipal roads.

Table 3.1 Weighted bend lengths for bends with a speed reduction (approach speed 55 km/h)

Speed reduction [km/h]	Minimum required bend length [m]
$\Delta V = 5$	61
$\Delta V = 10$	109
$\Delta V = 15$	145

3.2. Pavement surface properties

In the analysis of the importance of pavement surface properties on the traffic safety distinction has been made among the types of road. When looking at the pavement surface properties, skid resistance appears to be the most important one in terms of traffic safety on roads [Silva, 2013]. Studies from a long time ago showed for motorways and provincial roads that the more the skid resistance or friction coefficient of the pavement decreases, the higher the accident rate will be [SWOV, 1974]. No reports could be found of studies describing the relationship between the skid resistance and the accident rate on municipal roads. This makes it difficult to predict the traffic accidents on these roads, at least based on pavement surface properties. Due to lack of appropriate historical data, an alternative approach was used in this study to find an acceptable tentative relationship between the traffic accident rate and skid resistance on municipal roads. This relationship has been developed with the available information of previous studies on the accident rate of the three types of municipal roads. In this study these overall traffic accident rate values are assumed to be the values corresponding with skid resistance class 3. That class contains skid resistance values measured on average at a road network. The relationship between the accident rate and skid resistance for provincial roads and motorways (see Figure 2.9) can be described by a simple model. The exponential decrease of the accident rate is stronger for motorways than for provincial roads. The reason for this pattern is that for higher speeds the influences of the skid resistance on the accident rate are of more importance. Therefore, in this study the exponential decrease model of the provincial roads is copied into a model for the proportional change of the accident rate on municipal roads with skid resistance class. The combination of actually reported accidents and the “average” skid resistance class 3 serves as pivotal point. The developed relationship between the skid resistance for the three different types of municipal roads is presented in Figure 3.5.

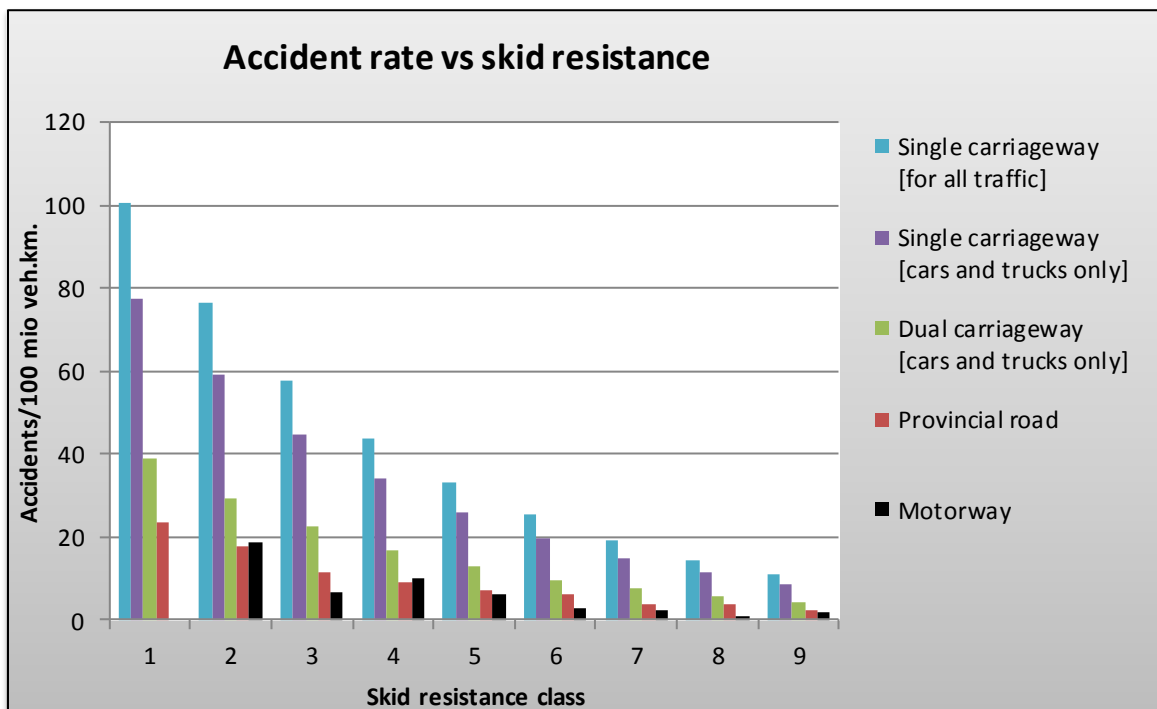


Figure 3.5 Relationship between accident rate and skid resistance

The accident rate of municipal roads is much higher than that of the motorways and the provincial roads. The reason for this is that on municipal roads much more conflict types give cause to accidents. In contrast to provincial roads and motorways, traffic on municipal roads also consists of pedestrians, bicycles and mopeds (slow/or other traffic) and plenty of crossings and intersections where traffic flows meet and cross each other. For the category of slow traffic the skid resistance is of marginal importance. Therefore, the accident rate that was presented for the municipal roads in Figure 3.5 should be reduced to an accident rate that only takes into account the accidents between mutual fast traffic (cars, trucks and motorcycles). This restriction makes it easier to compare the accident rates on municipal roads to those on provincial roads and motorways when analysing the same conflict types. The accidents due to other conflict types should be regarded as independent on the road condition.

The different conflict types that may occur on municipal roads are presented in Figure 2.10. This figure presents the number of fatal injuries over a certain time. In this study it is assumed that proportional distribution of fatal injuries of each different conflict type will be the same for the total of accidents. These different conflict types are analysed by categorising the accidents in three main classes (see Figure 3.6):

- unilateral accidents (1 and 3);
- fast - vs fast traffic accidents (4);
- fast traffic vs other traffic accidents (2).

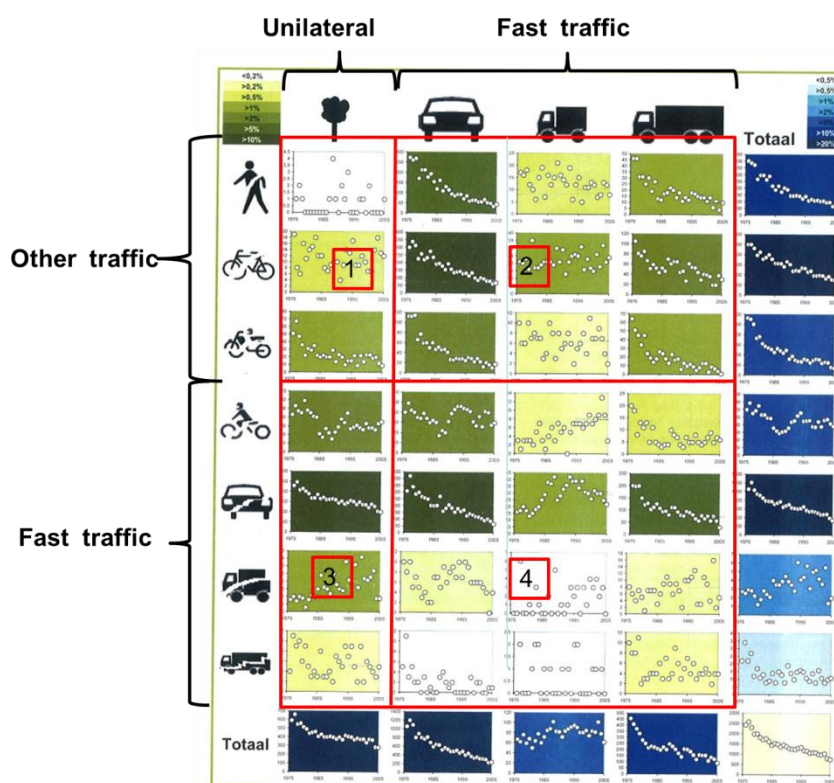


Figure 3.6 Main classes of conflict types

Unilateral accidents are accidents with only one party involved. An example of these accidents is when a road user loses control and crashes against a tree. The category 'fast traffic' contains cars, motorcycles and trucks. The category 'other' contains pedestrians, bicycles and mopeds. This category of traffic is not allowed on motorways, rarely allowed on provincial roads but extensively found on municipal roads. The accident categories fast – vs other traffic (2) and unilateral – vs other traffic (1) are removed from the accident rate calculation of the municipal roads presented in Figure 3.5. The 'adjusted' accident rates of

the municipal roads (approximately 65% of the total accident rate) becomes now comparable to those of the provincial roads and motorways. Figure 3.7 represents the relationship between the skid resistance and the accident rate after cancelling the accidents with bicycles, pedestrians and mopeds. These accidents are not skid resistance dependent and will therefore have to be taken into account separately. The accident rate that is represented in Figure 3.7 only takes into account the fast traffic accidents; the unilateral accidents of fast traffic and the mutual fast traffic accidents. The proportional distribution of the main accident categories listed in Table 3.2 are retrieved from the data of the conflict matrix of Figure 2.10. This figure represents the distribution of the average fatal injuries over the whole of the Netherlands. This figure does not take into account local or provincial differences in the distribution of the different means of transport . Furthermore, in this study it assumed that the average distribution of accidents corresponds to the average proportional distribution of fatal injuries in the Netherlands. The proportional distribution of the average traffic accidents in the Netherlands is approximately 65% for fast traffic and 35 % for slow traffic.

Table 3.2 Proportional distribution of the main accident categories

Accident categories	Number of fatal injuries	Percentage [%]
Unilateral vs other traffic [1]	25.5	2.93
Fast - vs other traffic [2]	284.5	32.74
Total other type accidents		35.67
Unilateral vs fast traffic [3]	305	35.1
Fast - vs fast traffic [4]	254	29.23
Total fast traffic accidents		64.33

The proportional distribution of the main accident categories on crossings and road section listed in Table 3.3 are retrieved from the data of Figure 2.11. The numerical values listed in Table 3.2 are of the same magnitude with the numerical values for the road sections that are listed in Table 3.3. The comparison of both proportional distribution validates the analysis of the retrieved data of the conflict matrix of Figure 2.10. Reading errors may be the explanation of the small differences between the values.

Table 3.3 Proportional distribution accident categories on crossings and road sections

Accident categories	Crossings		Road Sections	
	Number of fatal injuries	Percentage [%]	Number of fatal injuries	Percentage [%]
Unilateral accidents	35	11.11	225	42.86
Fast - vs fast traffic	150	47.62	150	28.57
Fast - vs other traffic	130	41.27	150	28.57
	315		525	

The fast traffic accidents have been extracted from the total accident rate calculation of the municipal roads presented in Figure 3.5 by multiplying the accident rate per skid resistance class by the proportion of the fast traffic in the total distribution of the main accident categories listed in Table 3.2. This multiplier equals approximately 65%. Use of this multiplier results in a relationship between the average accident rate for fast traffic and skid resistance on the three types of municipal roads in the Netherlands. (see Figure 3.7). Only the traffic accidents that are skid resistance dependent (fast traffic accidents) will be taken into account with the developed relationship of the skid resistance and the accident rate as presented in Figure 3.7. The total numeric value of the accident rate on a straight road section of a municipal road is the sum of:

- the accident rate of fast traffic (dependent on skid resistance see Figure 3.7);
- and the accident rate of slow traffic.

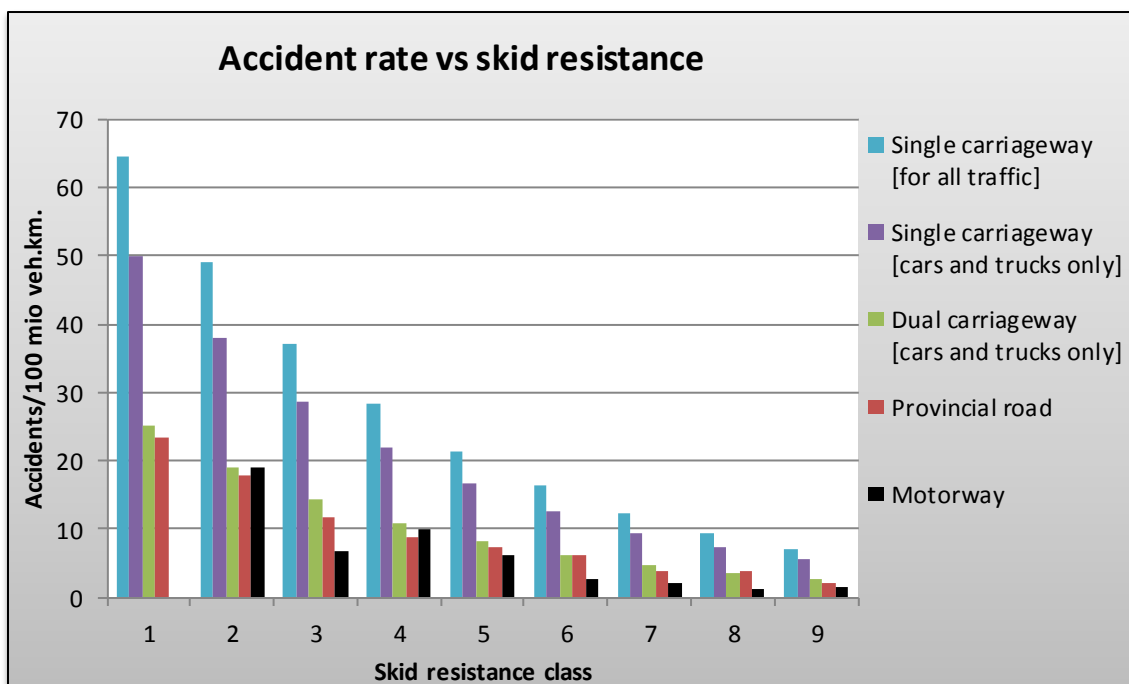
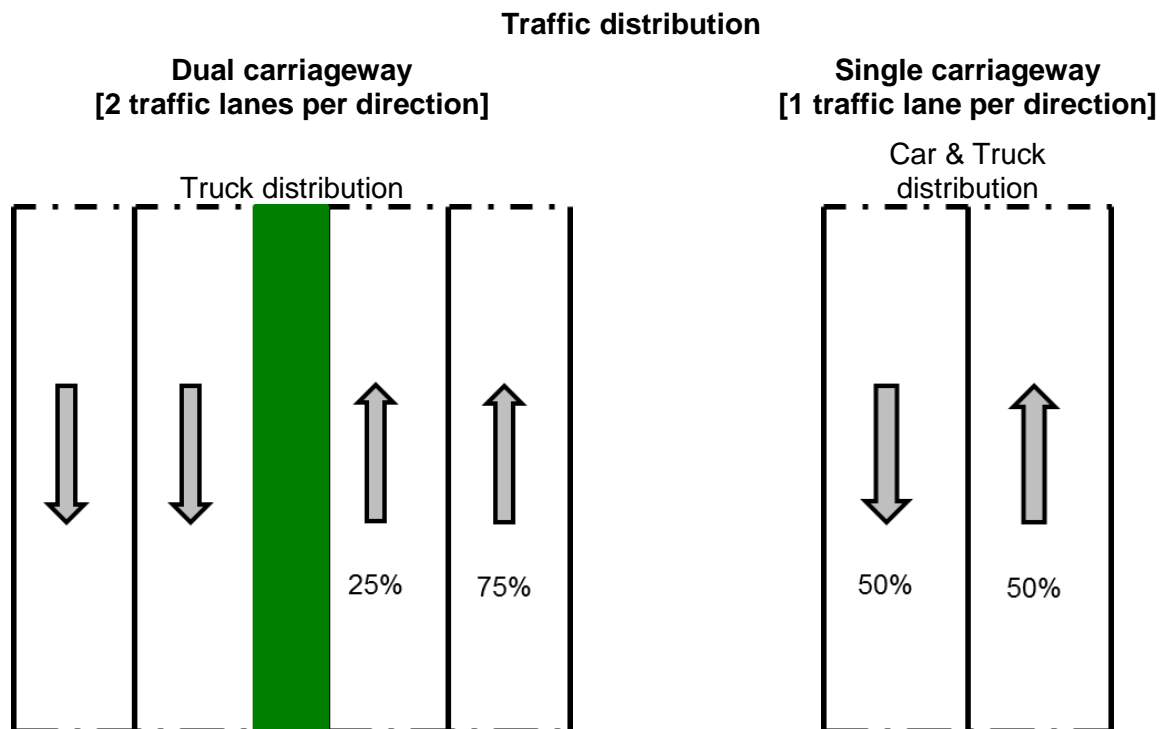


Figure 3.7 Relationship between reduced accident rate and skid resistance in the Netherlands

The skid resistance of the wearing course is dependent on the type of asphalt mix and the aggregates used in the mix. Small element pavements (block paving) are also widely used on municipal roads. Small elements are especially used on residential streets with low speed. The skid resistance of these small element pavements has not been determined in previous studies. The skid resistance on small elements appears to be dependent on the type of small element that is used. Concrete bricks have a much higher skid resistance than burnt bricks. Burnt bricks have almost no skid resistance when their surface is wet. For different SMA, AC and PA asphalt mixes, the skid resistance is determined by the following equations [Silva, 2013]. The number behind the aggregate type refers to the PSV value of the aggregate.

SMA, Greywacke 59	SR= 0.52 – 5.08.10⁻⁸ * number of axles	(Eq. 15)
SMA, Moraine-1 53	SR= 0.54 – 6.36.10⁻⁸ *number of axles	(Eq. 16)
SMA, Moraine-2 44	SR= 0.46 – 2.16.10⁻⁷ *number of axles	(Eq. 17)
SMA, Basalt 47	SR= 0.48 – 2.75.10⁻⁷ *number of axles	(Eq. 18)
SMA, Diabase 55	SR= 0.51 – 2.20.10⁻⁷ *number of axles	(Eq. 19)
SMA, Dolomite 40	SR= 0.44 – 3.81.10⁻⁷ *number of axles	(Eq. 20)
AC, Basalt 47	SR= 0.47 – 9.74.10⁻⁸ *number of axles	(Eq. 21)
PA, Greywacke 60	SR= 0.61 – 3.31.10⁻⁷ *number of axles	(Eq. 22)
PA, Dutch gravel 54	SR= 0.58 – 4.84.10⁻⁷ *number of axles	(Eq. 23)
PA, Porphyry 52	SR= 0.51 – 4.05.10⁻⁷ *number of axles	(Eq. 24)

The intensity of a road section is decisive for the calculation of the number of axles passing by light weight vehicles (cars and vans) are assumed to have two axles (front and rear) and moderate- heavy weight vehicles (trucks) have an average of 3.5 axles [Houben, 2010]. The input for the calculation of the number of axles is the number of vehicles per carriageway per day and the percentage of truck traffic. In this study the traffic intensity distribution of a carriageway is assumed to be as presented in Figure 3.8. In general the traffic on municipal roads drives in the traffic lane indicating direction or destination to go. Therefore, the traffic distribution is assumed to be different than on motorways and provincial roads.



**Dual carriageway
[2 traffic lanes per direction]**

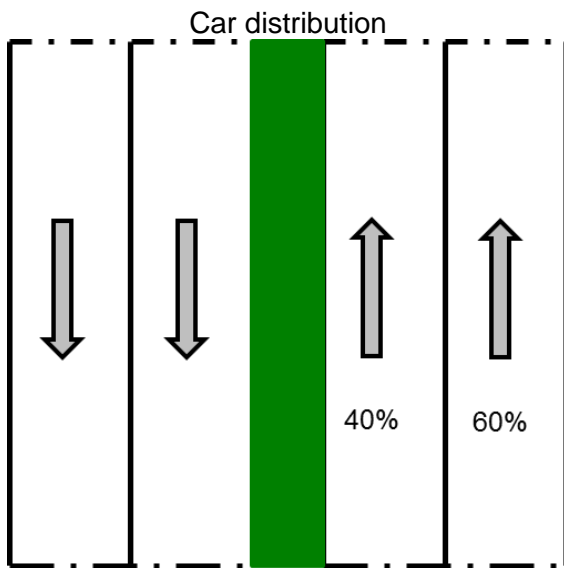


Figure 3.8 Intensity distribution municipal roads

The number of axles used as input for the calculation of the decrease of the skid resistance per year is the total number of axles of the lane with the highest number of axles carried per year. In general, the weekend intensity is lower than the intensity during working days (Monday till Friday). For the compensation of these lower intensities during the weekend it is assumed that a year consists of 275 days instead of 365 days. The total number of axles per lane is calculated as follows:

$$\text{Number of axles} = ((\text{Intensity}_{lw} * p_c * 2) + (\text{Intensity}_{mhw} * p_t * 3.5)) * 275 \quad (\text{Eq. 25})$$

where:

- Number of axles = total number of axles per year
- Intensity_{lw} = intensity light weight vehicles [veh./day]
- Intensity_{mhw} = intensity moderate- heavy weight vehicles [veh./day]
- p_c = proportion cars [-]
- p_t = proportion trucks [-]

The traffic on municipal roads often accelerates and decelerates and is not driving at a constant speed. Therefore, porous asphalt mixes are not to be used on municipal roads. Due to the accelerating and decelerating traffic, the risk of losing bond between the aggregate particles is high due to the high torsional forces at the pavement surface and the limited number of contact and adhesion points in the asphalt mix. The combination of factors will lead to rapid ravelling of the wearing course. Due to the low speed on municipal roads the effect of aquaplaning is of no importance and therefore porous asphalt mixes are not necessary.

If no skid resistance data are available, the developed program allows for estimation of the skid resistance. The type of wearing course sets the skid resistance value to be used. The skid resistance cannot be estimated reliably for all types of wearing courses, because the development of the skid resistance over time has not been determined for all types of aggregates in previous studies. Therefore, the user can choose the option 'different' wearing course in the program developed in the framework of this thesis. The group 'different' wearing courses is applicable to concrete bricks small, thin coatings and surface treatments.

The skid resistance of this group of wearing is assumed to be to that of the average skid resistance measured nationally (class 3) [Gaarkeuken, 2006]. Therefore, in the developed program the accident rate of this group of wearing courses is assumed not to be dependent on skid resistance. The skid resistance for this group is a fixed value which means that the number of accidents will not increase over a time horizon. Nevertheless, the user should keep in mind that the skid resistance decreases over a time horizon which results in an increase of the accident rate. One should expect that burnt brick elements should have a lower skid resistance than the average measured skid resistance value (class 3); especially during winter seasons. Therefore, burnt brick small elements are not categorised in the group 'different' wearing courses. The accident rate of burnt bricks is calculated by assuming that burnt bricks can be placed in skid resistance class 2.

The injury accidents in fast traffic can be predicted by the estimated numeric value of the skid resistance. The rest of the analysis step is identical to the steps describes in the previous sections of this chapter.

The following equations describes the exponential trend line of the relationship between the fast traffic accident rate and the numeric value of skid resistance for the three types of municipal roads based on the average (national) distribution of the fast traffic- and other traffic accidents:

$$\text{Single carriageway (all traffic):} \quad AR_{\text{fast traffic}} = 500.56 \cdot e^{-5.888 \text{ SR}} \quad (\text{Eq. 26})$$

$$\text{Single carriageway (cars and trucks only):} \quad AR_{\text{fast traffic}} = 386.42 \cdot e^{-5.888 \text{ SR}} \quad (\text{Eq. 27})$$

$$\text{Dual carriageway (cars and trucks only):} \quad AR_{\text{fast traffic}} = 193.64 \cdot e^{-5.888 \text{ SR}} \quad (\text{Eq. 28})$$

where:

$AR_{\text{fast traffic}}$ = accident rate of mutual fast traffic injury accidents [injury acc./100 mio. veh. km]
 SR = numeric value of the skid resistance

The proportional distribution of the other traffic accidents is the sum of the main accident categories 1 and 2 (see Table 3.2). These numeric values are based on the average distribution of traffic accidents in the Netherlands and do not cater for the variation across the provinces. Table 3.2 shows that on a national level approximately 35% of the accident rate of a straight section can be assigned to slow or other traffic accidents. The accident rate of the injury accidents on straight sections are listed in Table 2.1. The equations for the calculation of the other traffic accidents are computed as follows. The proportion of other traffic equals approximately 35%. This percentage may vary over the country.

$$AR_{\text{other traffic}} = (p_{\text{other}}/100) \cdot AR_i \quad (\text{Eq. 29})$$

where:

$AR_{\text{other traffic}}$ = accident rate of other traffic injury accidents [acc./mio.veh.km]
 AR_i = accident rate of injury accidents on road type [acc./mio.veh.km]
 p_{other} = proportion of other traffic accidents [%]

The total number of injury accidents on a straight section is the sum of the fast traffic accidents and all other traffic accidents.

$$AR_{\text{straight section}} = AR_{\text{fast traffic}} + AR_{\text{other traffic}} \quad (\text{Eq. 30})$$

3.3. Different modes of road transport

This section describes the proportional distribution of the different modes of road transport broken down per province in the Netherlands. The previous section already addressed that the slow traffic accidents are not skid resistance dependent and have to be taken into account separately. The data listed in Table 3.2 are average values for the Netherlands. This proportion is used as a reference for the situation in the Netherlands. The proportional distribution of fast traffic accidents and other type of traffic accidents is not the same in every province in the Netherlands. Therefore, computation of the proportional distribution of the different modes of transport per province is recommended. A province with a higher percentage of bicycles will face a higher percentage of other traffic accidents than a province with a lower percentage of bicycles. Beware that the proportional distribution of the transport modes is not the same as the distribution of the traffic accidents to be assigned to those transport modes. The proportional distribution for the different modes of transport are retrieved from the Central office of statistics (statline CBS) for the different provinces. The proportional distribution of the fast traffic and other traffic accidents is presented in Figure 3.9. The analysis procedure of assessing these traffic accidents based on intensity data and the resulting numeric values are presented in Appendix A.

The daily vehicle kilometres for cars and trucks and the proportion slow traffic for each province form the input for the computation of the proportional distribution of the traffic accident rates per province.

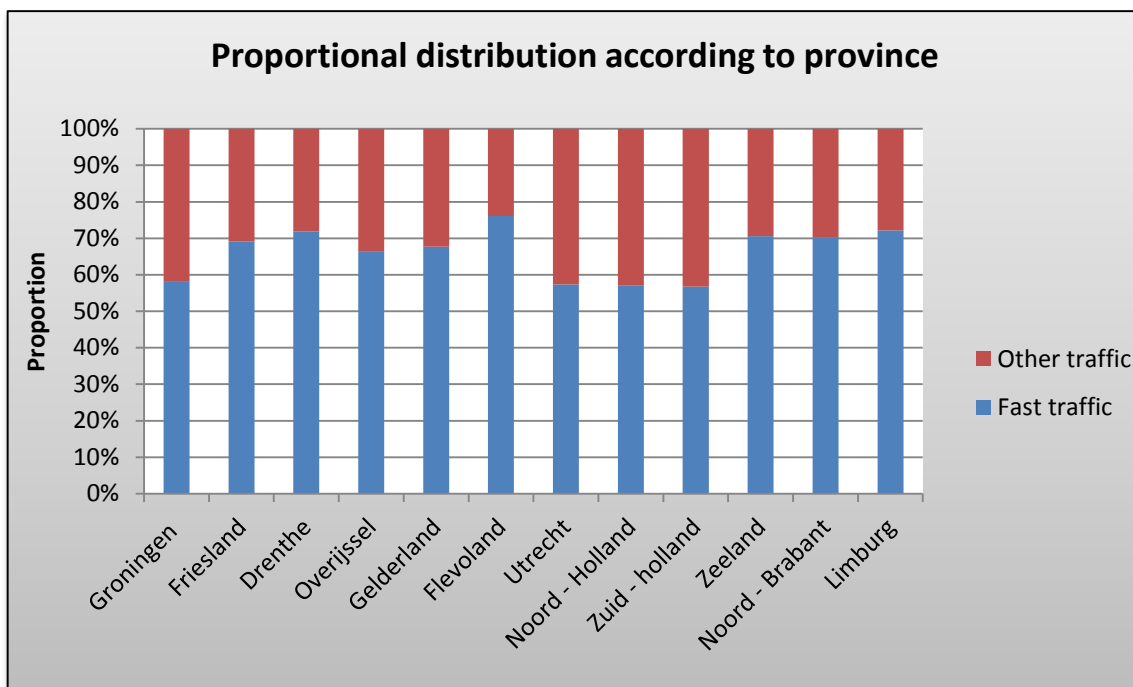


Figure 3.9 Proportional distribution of the type of accidents.

The numeric values of the proportion of fast traffic accidents is broken down per province are now used for the computation of the fast traffic accident rate for municipal roads in a specific province with the total traffic national accident rate as major input data. The basic decrease of the accident rate of each province with skid resistance is the same as presented in Figure 3.7. The analysis procedure for the calculation of the accident rate per category is furthermore the same as described in section 3.3. The numeric value of the equations may vary per province under analysis.

3.4. Accidents on a road section

The previous sections of this chapter describe the analysis of the calculation of the number of injury accidents on different parts of the road section. A road section under analysis can contain crossings, bends and straight lanes. Therefore, the three different road aspects have been combined to acquire an indication of the total traffic safety of a specific road section.

First of all the traffic safety of bends in a road section is addressed by combining the bends with the straight section. This step is made by assigning an equivalent ratio (see chapter 3.1.2) to the traffic safety of a straight section. This results in an accident rate of the winding section (bends and straight lanes), that can be calculated as follows:

$$AR_{\text{winding section}} = r_{\text{eq}} * AR_{\text{straight section}} \quad (\text{Eq. 31})$$

where:

r_{eq} = equivalent ratio straight line [-]
 $AR_{\text{road section}}$ = accident rate winding section [injury acc./mio veh.km]
 $AR_{\text{straight line}}$ = accident rate straight section [injury acc./mio veh.km]

It should be noted that if the road section under analysis does not contain speed reducing bends or any sharp bends, the equivalent ratio should be 1. The accident rate of the winding section is then equal to the accident rate of a straight section.

The next step is to take into account the number of accidents on the existing crossings on the road section. Summing up the injury accidents of the different types of crossing (see chapter 3.1.1) results in a total number of injury accidents on the crossings in the specific road section.

$$A_{\text{cross-tot.}} = \sum A_i * n_i \quad (\text{Eq. 32})$$

where:

$A_{\text{cross-tot.}}$ = total injury accidents due to crossings per year
 A_i = injury accidents on crossing of type ' i '
 n_i = number of crossings type ' i '

The last step is to combine the traffic safety of the winding section with that of the crossings to predict the traffic safety of the road section under analysis. The unit of traffic safety of the crossings differs with that of the traffic safety of the winding road section. The traffic safety of a winding road section is expressed in a safety ratio, while that of the crossings is expressed in the number of injury accidents. Prior to combination of the traffic safety of the crossings with that of the winding section, the accident rate of the winding section should have the same unit as the traffic safety of the crossings. Taking into account the number of vehicle kilometres (intensity, and length of road section), the number of injury accidents of the winding section can be calculated as follows:

$$A_{\text{winding section}} = AR_{\text{winding section}} * \text{intensity} * \text{length}_{\text{tot.}} \quad (\text{Eq. 33})$$

where:

$A_{\text{winding section}}$ = total injury accidents on the road section per year
 $AR_{\text{winding section}}$ = accident rate winding section [injury acc./mio veh.km]
intensity = number of vehicles per year
 $\text{length}_{\text{tot}}$ = total length of the road section [km]

The number of annual injury accidents on the road section under analysis is the sum of the injury accidents of the winding section and the injury accidents that on crossings.

$$A_{\text{road section}} = A_{\text{winding section}} + A_{\text{cross. tot}} \quad (\text{Eq. 34})$$

4. Developed program

4.1. Introduction

The previous chapters presented a literature overview and the analysis of the principal road aspects that are decisive for the prediction of injury accidents on municipal roads. The principal road aspects are illustrated in the introduction sheet of the program (see Figure 4.1). The findings of the research actions resulted in the development of a program that predicts the injury accidents on municipal roads. The program is applicable to road authorities in the Netherlands but also to other parties involved in pavement design, construction, analysis and monitoring. The program distinguishes between the provinces of the Netherlands. In this chapter practical examples will be described to demonstrate the use of the program and discussion of the results. In these examples different road situations will be inter-compared to investigate if the results agree with the expectations.

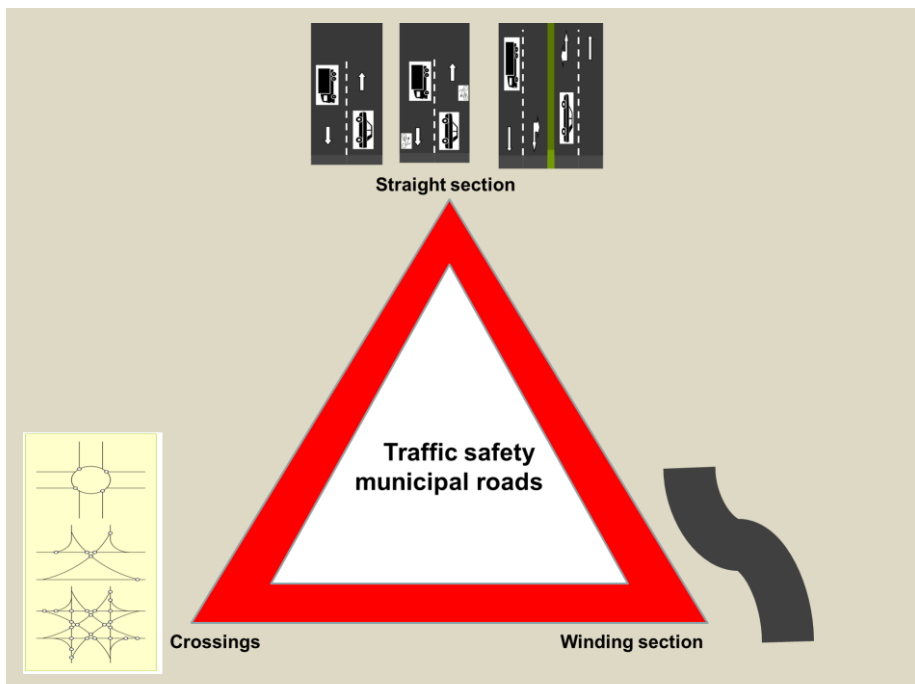


Figure 4.1 Introduction sheet of the developed program

The program has been developed in Microsoft Excel. The first sheet is the introduction sheet as illustrated in Figure 4.1. This sheet presents the possibilities of the developed tool in relationship with the critical road aspects that must be taken into account. The second sheet is the sheet with the input parameters and the results of the analyses. The other sheets are the calculation sheets, where the selected data are processed based on the models described in the previous chapters.

4.2. Input parameters

The input parameters to the program are standard pavement details, traffic engineering aspects and road surface properties of the road section under analysis. The input parameter sheet is presented in Figure 4.2.

Pavement details	
Select type of road	Dual carriageway [cars and trucks only]
Total length [meters]	1740
Intensity per carriageway	
Light weight [veh./day]	5000
Moderate - heavy weight [veh./day]	500
Traffic growth [% per year]	2
Select province	Zuid - holland
Traffic engineering aspects	
Number of crossings	
T-crossing; give way sign	0
T-crossing; traffic lights	1
4-way crossing; give way sign	3
4-way crossing; traffic lights	0
Roundabout bicycle priority	0
Roundabout cars priority	0
Number of bends with:	
Speed reduction of 5 km/h	0
Speed reduction of 10 km/h	1
Speed reduction of 15 km/h	0
Road surface aspects	
Skid resistance	Estimated value
Measured skid resistance value	
Age wearing course [years]	0
Minimum skid resistance	Estimated value
Minimum skid resistance value [default]	0,39
Select type of wearing course	Burnt_bricks
Select type of aggregate	N.A.

Notes:

1. For dual carriageway the input of the length should be the sum of both directions.
2. For dual carriageway the input of the intensity should be the average intensity in both directions.
3. For dual carriageway the input of the crossings should be the sum in both directions. The same holds for the number of curves.

These notes only holds when both direction of the dual carriageway are evaluated!!

Always choose type of aggregate after the wearing course is selected!!!!

Figure 4.2 Sheet with the input parameters

4.2.1. Pavement details

One of the standard pavement details to be inputted is the type of municipal road. The program distinguishes between the following types of municipal roads in the Netherlands:

- single carriageway [for all traffic];
- single carriageway [cars and trucks only];
- dual carriageway [cars and trucks only].

Roads with a closure statement for slow traffic (mopeds, bicycles) are the roads that are designated to carry 'cars and trucks only'.

The road section length is also important in the analysis. This parameter is needed to convert output data per unit of length to absolute numbers for the road under analysis. If both directions of a dual carriageway are evaluated, the input road section length should be the sum in both directions.

The intensity input is the daily intensity of the fast traffic per carriageway. If both directions of a dual carriageway need to be evaluated, the intensity input should be the average intensity of the two carriageways. The slow traffic intensities (bicycles and mopeds) are taken into account as percentages of the fast traffic intensities. Slow traffic is therefore indirectly taken into account.

4.2.2. Traffic engineering aspects

The traffic safety on municipal roads is to a great extent governed by the lay-out, alignment and traffic situation on the road section and to a lesser extent by the pavement and road surface properties. The traffic situation on crossings is very important for the quantification of the traffic safety. In the program, the crossings are categorised as follows:

- T – crossing, give way sign;
- T – crossings, traffic lights;
- 4 – way crossings, give way sign;
- 4 – way crossing, traffic lights
- roundabouts, bicycle priority;
- roundabouts, cars priority.

The number of crossing per category has to be counted, if the user wants to analyse the traffic safety on a stretch of road. If both directions of a dual carriageway must be evaluated, the input is the sum of the total number of crossings in both directions. This approach also applies to the total number of bends. The bends are categorised in three types. Bends with a speed reduction of 5-, 10- and 15 km/h. Bends with no to hardly any speed reduction are not counted as bends. The bends can be counted by road inspectors by looking to the road signs where speed reduction is advised to the road user. In general drivers intend to reduce their speed more speed when the bend is sharper.

4.2.3. Road surface aspects

Skid resistance and the wearing course details are the main road surface input parameters in the program. The program has the possibility to analyse traffic safety based on a measured or an estimated skid resistance value. If the user selects the option of a measured skid resistance value, the road user is obliged to enter the measured skid resistance value. The allowable range of the value is set between 0.35 and 0.70. The model in the program takes into account ageing and wear of a wearing course in terms of skid resistance. Therefore, the age of the wearing course under analysis is an input parameter tool. The minimum level of skid resistance at which maintenance is required must also be entered into the program. The program provides the user the possibility to choose whether the analysis has to be performed based on the measured value or an estimated value of skid resistance.

The program has the possibility to select the following types of wearing courses:

- Stone mastic asphalt (SMA);
- Dense Asphalt (DA);
- burnt brick elements;
- different.

Porous asphalt is in general not used on municipal roads because of the detrimental effects by accelerating and decelerating traffic on these roads. Therefore, porous asphalt wearing courses cannot be selected in this program. The decrease of the skid resistance with time and traffic volume is not available for all types of wearing courses. If the combination of type of wearing course and the type of aggregate is not present in the material list of the program, the user should select 'Different' for categorizing the type of wearing course. The group 'different' wearing courses is applicable to concrete bricks, surface treatments, thin coatings and SMA or DA mixes of which the type of aggregate is not listed. The skid resistance value is assumed to be constant for the category 'different'. This constant skid resistance value is fixed to the average measured skid resistance value (skid resistance class 3) as described in section 3.2. The skid resistance of the group of burnt bricks elements is in general lower. Therefore, the estimated value of the skid resistance is assumed to be fixed to skid resistance class 2.

4.3. Practical case 'Schiekade'

4.3.1. Introduction

The assessment of traffic engineering aspects and pavement surface properties of the developed program will be demonstrated on the basis of case on a road section of 1740 m on the Schiekade in Rotterdam. The road section as presented in Figure 4.3 is a dual carriageway where slow traffic is not allowed on the main lane with the fast traffic. The evaluated road section consists of three 4-way crossings with traffic lights, one T-crossing with traffic lights and one bend with a speed reduction of 10 km/h. The effect of the traffic engineering aspects will be evaluated vary the traffic situation of this road section. The assessment of pavement surface properties will be demonstrated by applying different wearing courses..

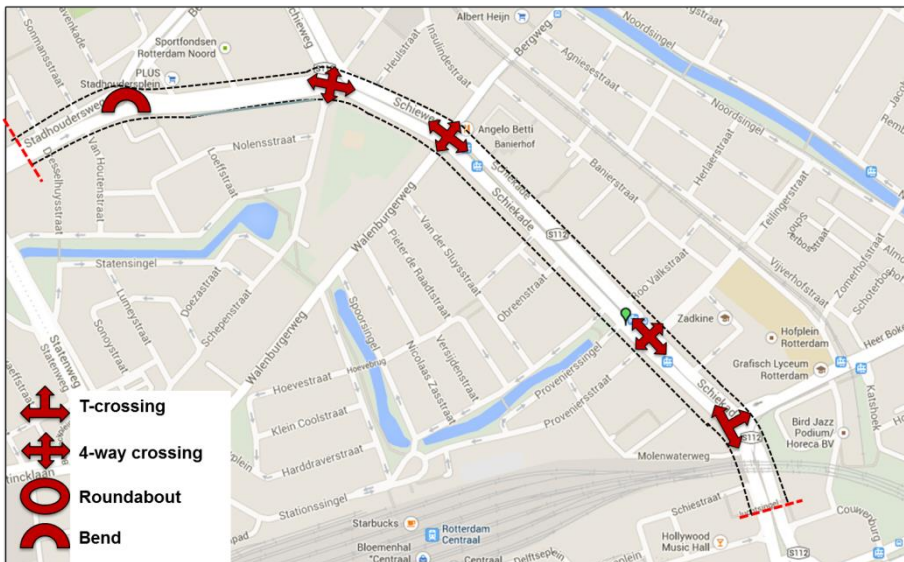


Figure 4.3 Road section Schiekade [google maps]

The effect of the traffic engineering aspects and the pavement surface properties on the road section Schiekade are demonstrated with the following assumptions:

- the intensity of light weight vehicles is 5000 vehicles per day and the intensity of the moderate-heavy weight vehicles is 500 vehicles per day;
- the traffic growth is 2% per year;
- the development of the skid resistance over time is estimated and not measured.

The assumptions have been not changed for the different cases that will be evaluated.

4.3.2. Traffic engineering aspects

The traffic engineering aspects are evaluated by varying the road design. The reference case is that the road section consist of three 4-way crossings with traffic lights, one T-crossing with traffic lights and one bend with a speed reduction of 10 km/h. The evaluation is performed with a reference wearing course. The reference wearing course is a Stone Mastic Asphalt with Greywacke mineral aggregates with a polished stone value of 59. The effect of changing the three 4-way crossings into three roundabouts (cars priority) will be evaluated in the first case.

The number of injury accidents on the road section Schiekade for the reference case is presented in Figure 4.4. The number of injury accidents increases over time because of the assumed 2% traffic growth per year. The contribution of the crossings on the traffic accident data is relatively high on the dual carriageways.

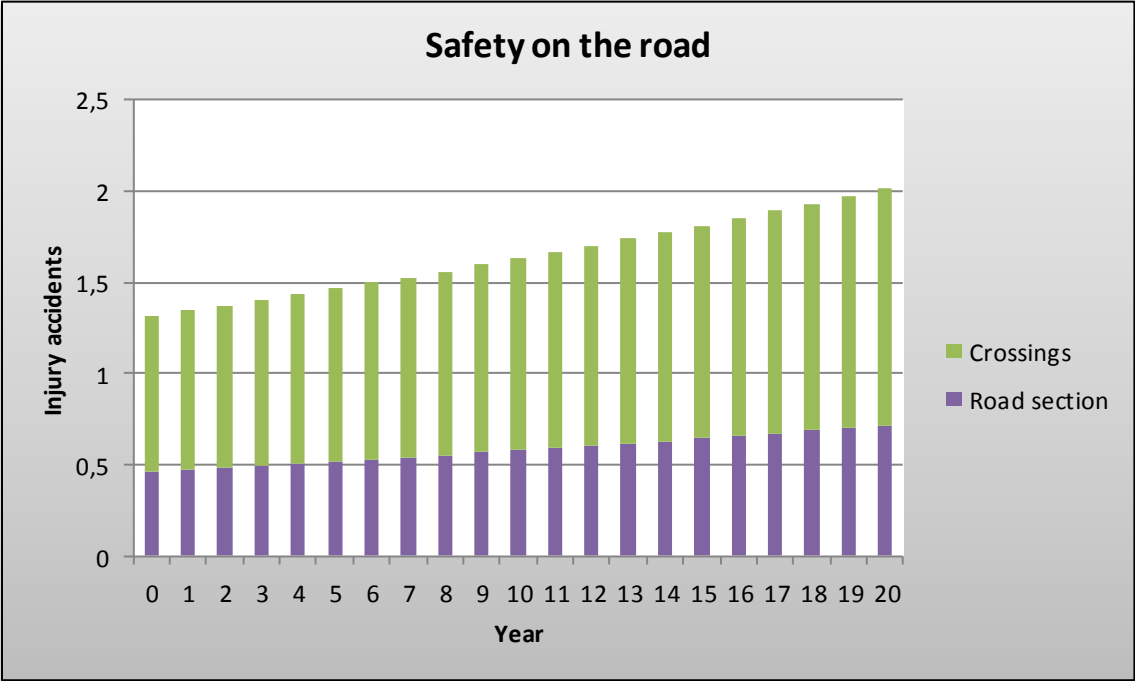


Figure 4.4 Injury accidents reference case

The option of changing the three 4-way crossings into three roundabouts (cars priority) is presented Figure 4.5. The number of injury accidents on crossings decreases if the 4-way crossings are replaced by roundabouts.

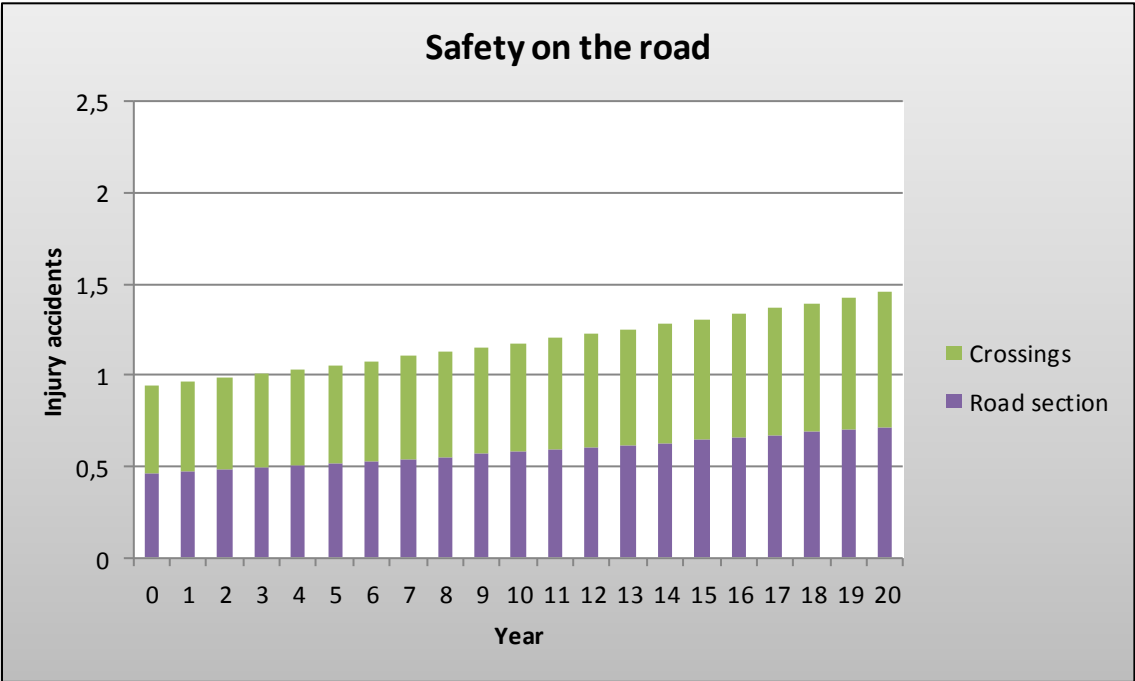


Figure 4.5 Injury accidents case one

The road section of the Schiekade contains one bend with a speed reduction of 10 km/h. From comparing the results of the winding section (including the bend with a speed reduction of 10 km/h) with that of a straight section, it can be concluded that the bend has a negligible effect on the traffic safety of the road section under analysis (see Figure 4.6 and Figure 4.7). The assumed reference course for the sake of the evaluation is a Stone Mastic Asphalt with Greywacke mineral aggregate. This wearing course has relatively good skid resistance properties and will therefore result into a low bend ratio. The effect of bends on the traffic safety is lower for wearing courses with a good skid resistance performance. Wearing courses with a relatively low skid resistance result in a higher proportion of the bend on the overall traffic safety.

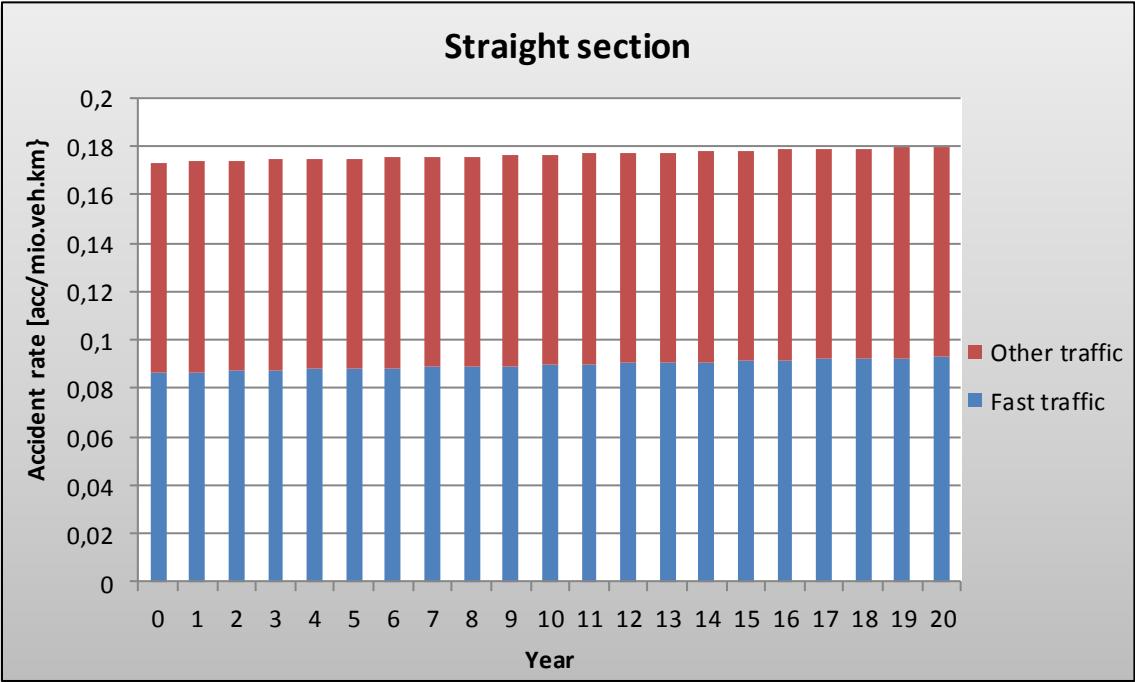


Figure 4.6 Accident rate straight section

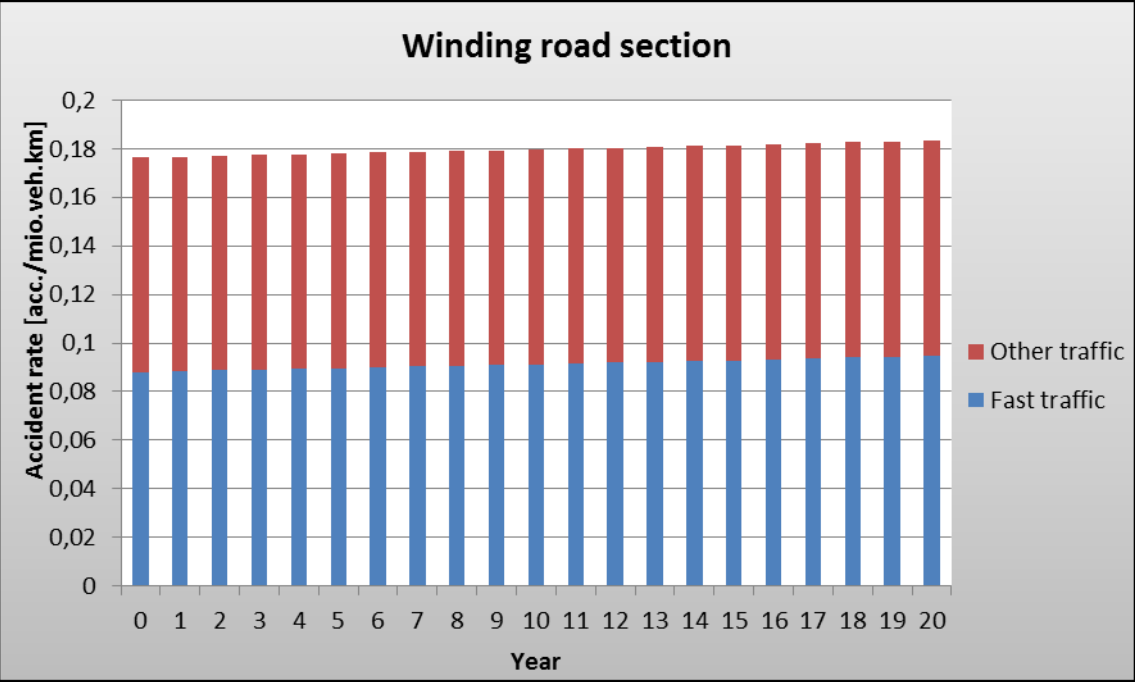


Figure 4.7 Accident rate winding section

4.3.3. Road surface properties

Apart from traffic engineering aspects (crossings, bends and type of road), pavement surface properties are of major importance for the traffic safety on municipal roads. The pavement surface properties can be controlled by road engineers.

The assessment of the effect of pavement surface properties will be demonstrated on the basis of the case of the Schiekade section presented already. Different wearing courses will be assumed to be constructed for demonstrating the effect of the pavement surface properties.

The effect of the pavement surface properties are demonstrated with the same traffic assumptions as described in the introduction of this section.

The other assumptions were not changed for the different cases that will be evaluated. The only differences between the cases are the applied wearing courses. The results of the road section, without crossings will be used to demonstrate the effect of different wearing courses. The evaluation starts with a Stone Mastic Asphalt with Greywacke mineral aggregate with a polished stone value of 59 as reference. The corresponding results are illustrated in Figure 4.8. The reason for the increase of the number of injury accidents per year can be explained by the decrease of the skid resistance and the growth of traffic intensities each year.

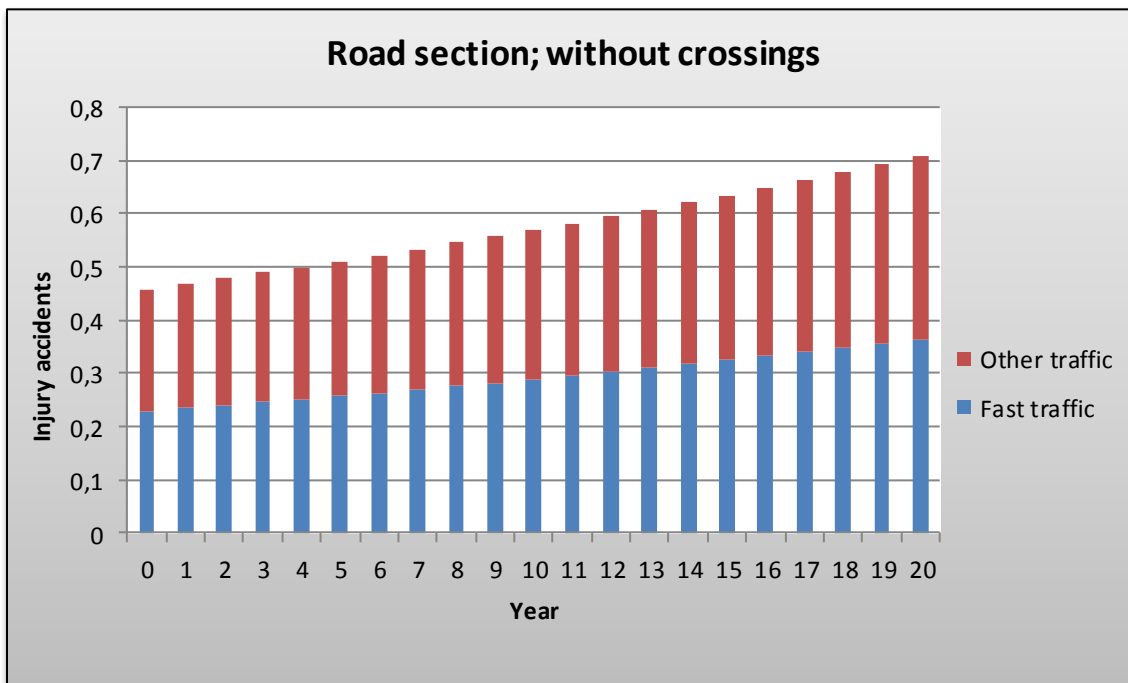


Figure 4.8 Accident distribution, SMA (Greywacke, 59)

In the first case the effect of the mineral aggregates will be evaluated. The alternative wearing course to be applied is a Stone Mastic Asphalt with Dolomite mineral aggregate (polished stone value of 40).

A lower polished stone value does not necessarily result in an overall lower skid resistance and therefore a higher accident rate. The PSV indicates that the skid resistance decreases faster than that of the reference, but the Dolomite SMA may have started at a higher initial skid resistance level. Figure 4.9 illustrates that the number of injury accidents are increasing if Dolomite mineral aggregate is applied in the Stone Mastic Asphalt mix. Figure 4.9 also illustrates that the number of injury accidents decreases in year 13. The reason for this is that in year 13 the skid resistance drops below the acceptance level of the skid resistance value. The program assumes that the user applies the same wearing course again if the skid resistance threaten to fall below the intervention level.

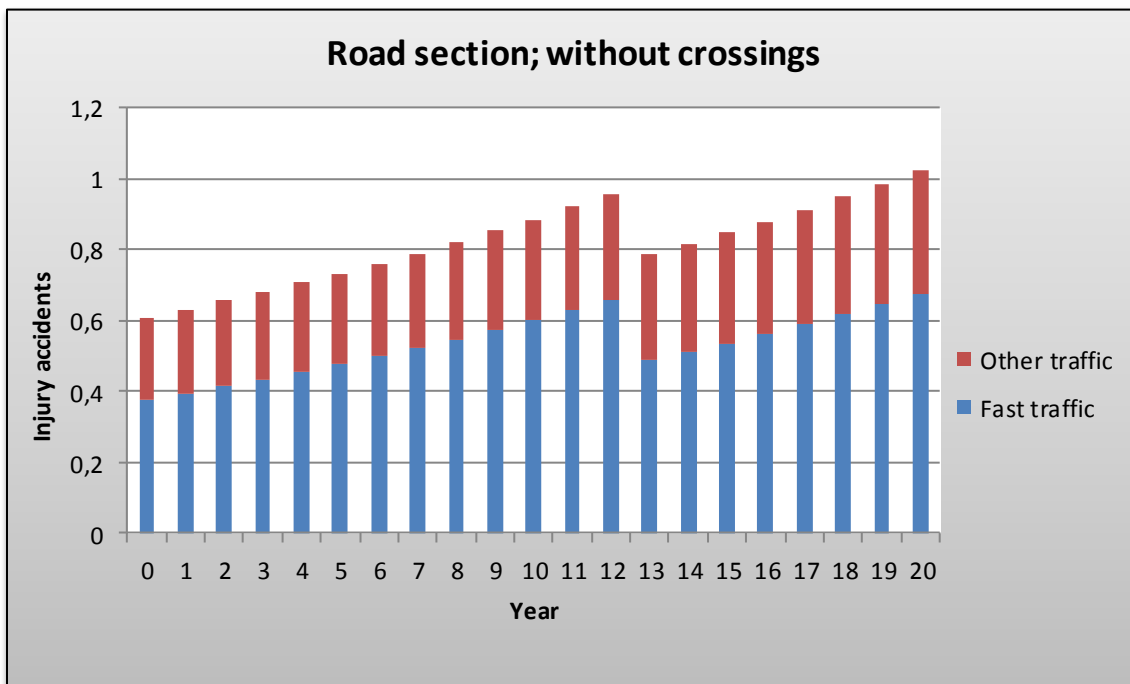


Figure 4.9 Accident distribution, SMA (Dolomite, 40)

The last case encompasses the effect of application of a wearing course with burnt bricks. Small elements are normally not used on main municipal roads. Nevertheless, this case still describes the effect of small elements on the road section Schiekade just to demonstrate the effect that small elements have on the traffic safety and to address the functionalities of the developed program. The skid resistance of burnt brick elements is very low especially during winter seasons. Therefore a high accident rate is expected to be the result for a wearing course laid with burnt bricks. The number of injury accidents as illustrated in Figure 4.10 is higher than the number of accidents of the reference wearing course (SMA, Greywacke 59). The program does not take into account the decrease of the skid resistance of the small elements over time. Nevertheless, the user of the program should keep in mind that the skid resistance will decrease over time. The increasing trend of the annual number of accidents is only due to the traffic growth of 2% per year.

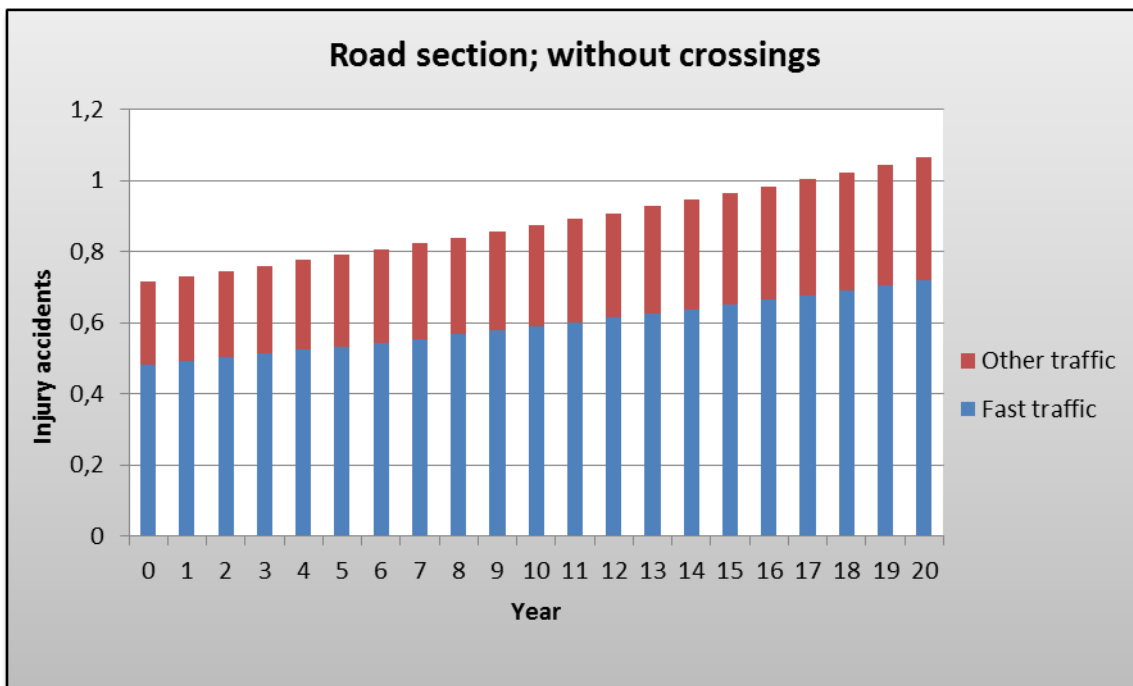


Figure 4.10 Accident distribution, burnt bricks

PART III: Environmental and Social Impact of Pavements

In the building industry, environmental themes are an interesting topic nowadays. Worldwide the quality of the environment is increasingly considered to be an item that cannot be neglected nowadays. In developed countries, such as the Netherlands, more environmental funds are available to control the environment. This implies that environmental aspects play an important role in the planning and decision making process for pavement construction and maintenance projects. An overview of the environmental costs related with the pavement structure is therefore an important tool in the planning process of a pavement construction or maintenance project. Furthermore, the social costs that emerge from traffic accidents also form a very important topic. The social cost due to these accidents yearly sum up to approximately 12500 million euro's [SWOV, 2014]. Part III of the thesis describes the development of a model that takes into account the environmental and social impact of the pavement industry on the society. The main pavement aspects that have an impact on the society are:

- the pavement building materials;
- the noise level of the pavements;
- the fuel consumption of the vehicles;
- and the traffic accidents that occur.

The various environmental themes and emissions of the different pavement aspects can be weighted using Shadow Prices. The result of this process is an indicator for the environmental and social costs that a given pavement structure has for the society.

5. Environmental aspects

5.1. Introduction

5.1.1. Durability and sustainability

Durability

Durability of a pavement structure is defined as the ability to resist weathering actions, while maintenance ensures the desired pavement engineering properties. Pavement engineering properties are:

- load carrying capacity of the road;
- pavement surface properties (skid resistance, rutting, roughness etc.).

The ability of the pavement to ensure the engineering properties has an effect on the number of traffic accidents that may occur. Maintenance and the use of durable pavement materials are therefore potential measures to reduce the number of potential accidents.

Durability of structures depends to a large extent on the mechanical loading of the structure and the possibilities of ingress of water, gases and ions into porous materials. Ingress of water, gases and ions depends on the type of asphalt mix that is used. Figure 5.1 illustrates the aspects that are critical for the determination of the durability of asphalt mixes. Angular aggregates have a better structural and functional performance than round aggregates. The grading of the aggregates has an effect on the amount of pores in the asphalt mix. The higher the amount of pores the less durable the asphalt mix will be. The percentage of bitumen is also of importance for quantifying the durability of the asphalt mix. The higher the percentage of bitumen in an asphalt mix, the more durable the asphalt mix will be. In addition the degree of compaction has a major effect too. The higher the degree of compaction, the more durable the asphalt mix and the smaller the rutting.

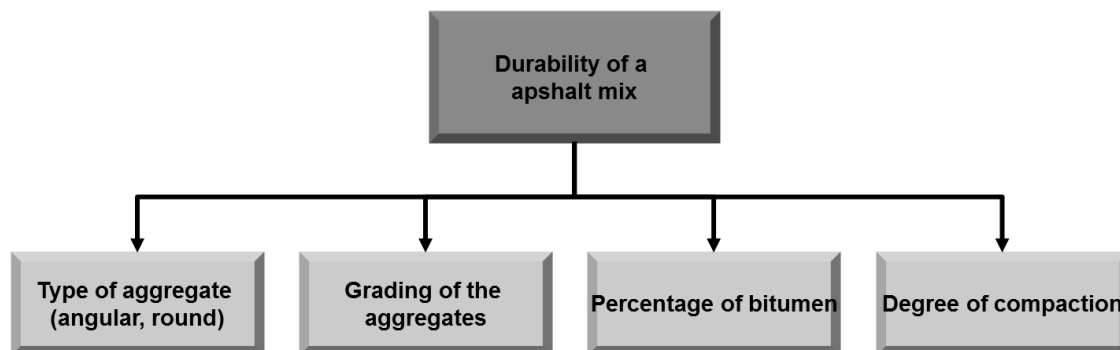


Figure 5.1 Durability of Asphalt mixes

Sustainability

Sustainable development means: "Forms of progress that meet the needs of the present without compromising the ability of future generations to meet their needs". [Sookram, R.]

Sustainability is one of the properties that cannot be quantified precisely. Sustainability means having no negative effect on the environment. There are different pavement aspects that have a negative impact on the environment. The most common ones are:

- the pavement materials;
- the noise emission;
- the fuel consumption.

The environmental impact can be quantified by weighing these pavement aspects with environmental themes by using the related environmental prices.

5.1.2. The Sustainable balance

The balance of sustainable development can be divided in three parts, the “three P’s concept” of sustainability:

- **Environmental sustainability, Planet;**
Nowadays this component of sustainability has the main focus because depletion of raw materials has become a serious issue.
The environmental component is measured by a Life Cycle Assessment (LCA) of the materials that are used.
- **Social sustainability, People;**
At the moment this component of sustainability is in development and can be brought into balance with a Social LCA.
- **Economic sustainability, Prosperity;**
The economic component is still very important in the sustainability balance, but receives less attention.

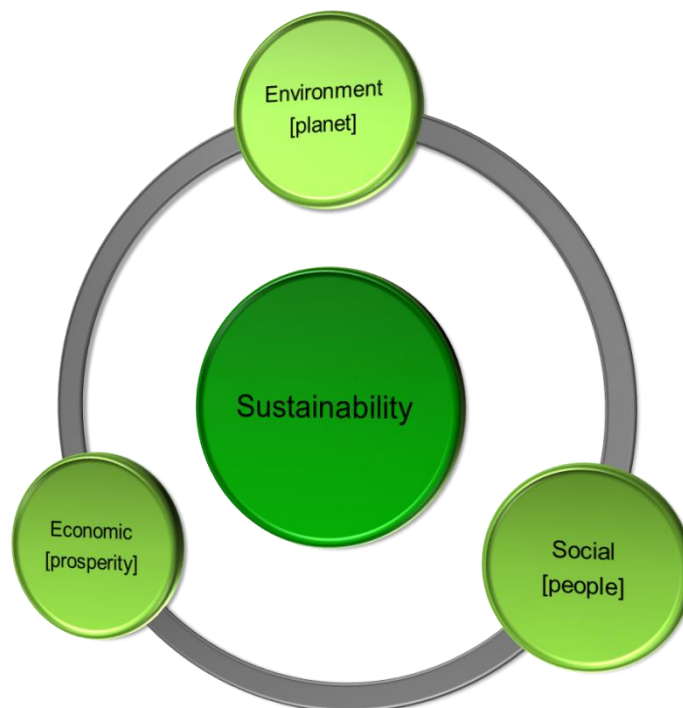


Figure 5.2 Sustainability balance

In this study, the focus will be laid on the first component of the sustainability balance. The components People and Prosperity are outside the scope of this research project. This study will address the environmental impact of the most common pavement materials. Furthermore, the influence of fuel - and noise emissions on the environmental component of the sustainability balance will also be addressed in this study.

The relation between the sustainability balance and the pavement industry is illustrated in Figure 5.3. The different parties have their own interests which in some cases leads to conflicts between the parties. The interest of the road authority is to minimise the economic costs and to optimise the pavement network for the road users. The interest of the environmental organisations, is having available a pavement structure with less environmental impact (e.g. low noise levels and low emission of greenhouse gasses due to

fuel consumption). The costs due to maintenance and construction of an environmental friendly (green) pavement are in general much higher than that of a normal pavement structure where environmental aspects are not taken into account. This is one of the conflicts that can emerge between the road authority and the environmental organisation. The principal interest of the road users is to have the opportunity of using a pavement network with maximum safety and availability. This interest may lead to a conflict with the road authority because of the limited budget that is made available to invest in maintenance of the road network.

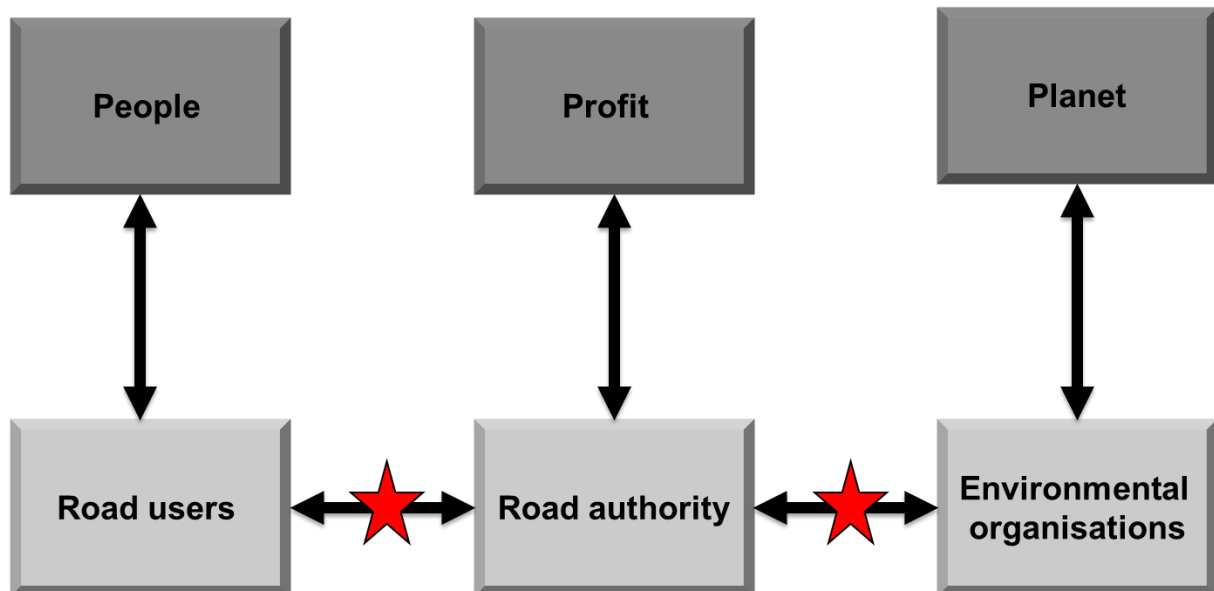


Figure 5.3 Possible conflict relations between various interest groups

5.2. Shadow prices

5.2.1. Introduction

Shadow prices are artificial prices for goods or production factors that are not traded in an actual market, e.g. environmental quality. Shadow prices can provide an indication of the environmental quality [CE,2010]. Therefore the emission of the different pollutants should be known. The shadow prices that are used in this study are average values for emissions from an average emission source at an average location in the Netherlands. Financial aspects such as grants and taxes are not included in the shadow prices.

In practice, shadow prices can provide input to the decision making process in two ways:

1. Valuation

Valuation is used in analysing the wider social consequences of investment decisions. With the aid of shadow prices, environmental impacts can be taken on board along with financial considerations and compared with one another in a Social Costs Benefit Analysis (SCBA's). Environmental impacts play a major role in many economic decisions. In the case of a new road for example, it is not only the cost-effectiveness of the road that needs to be considered but also the unintended side-effects, including those relating to the environment. Assigning shadow prices to these environmental impact means that they are expressed in similar units to the financial and economic data, permitting a better underpinned decision on the desirability and

practicalities of the investment. With valuation, use is generally made of the shadow prices of individual emissions [CE,2010].

2. Weighting

In contrast, weighting is mainly used in environmental analyses like Life Cycle Assessment or Environmental Impact Assessment. Here the main aim is environmental weighting, with shadow prices providing a means of comparing disparate environmental impacts. With weighting a company, organisation or country can use shadow prices to compare its environmental performance with that of other companies, organisations or countries. The various environmental impacts need to be weighed in some way and are compared with each other. For example, a consultant can use shadow prices to assess whether a porous asphalt (PA) wearing course will environmentally perform better than a stone mastic asphalt (SMA) wearing course. With weighting, use is generally made of shadow prices of environmental themes [CE,2010].

The link between shadow prices of individual emissions (valuation) and environmental themes (weighting) are being established using characterisation factors. Characterisation factors provide indicators of the relative importance of a pollutant in terms of its contribution to a particular environmental impact. For example characterisation factors are numbers indicating how much a given pollutant (e.g. 1 kg CO₂) contributes to a particular environmental impact (e.g. climate change).

In this study, both valuation and weighting are used. Because of the wider social consequences of the noise level and fuel consumption shadow prices according to valuation are used for these aspects. For the comparison of the different pavement building materials, according to the LCA procedure, shadow prices according to weighting are used.

5.2.2. Abatement- and damage costs.

Shadow prices are implicit prices: the price of environmental quality cannot be determined directly in the marketplace and so it needs to be calculated [CE, 2010]. In general terms, there are two ways to assign shadow prices to environmental quality. The first approach proceeds from the costs that need to be incurred to secure environmental policy targets and is known as the abatement costs method. The second approach assigns a value to environmental quality based on the estimated damage occurring as a result of emissions and other changes in natural capital and is known as the damage cost method. Both methods have their own specific areas of application.

Abatement costs method:

The abatement costs method calculates the shadow price as the cost of the most expensive technique required to meet government targets. From an economic perspective, the abatement costs are thus based on negative externalities that would have to be paid to achieve a set of targets that are set by the government. The abatement costs primarily express the impact of the company itself in relation to its operating environment, particularly the government [CE,2010].

Damage costs method:

The damage costs method proceeds from people's willingness to pay for not damaging the environment. The damage costs approach attempts to estimate the demand function for the environmental quality. This demand is driven by the ability of people to pay for that quality. In other words: how much of their income would they be willing to sacrifice to obtain an additional unit of environmental quality. Or the extent to which people are willing to accept

the environmental damage [CE,2010]. What damage costs primarily express is the impact on social welfare in the Netherlands.

Choice between damage – and abatement costs

The choice of which type of shadow prices are to be used, the damage costs or abatement costs, is not obvious. The general rule is that if a project leads to changes in the environmental quality, damage costs should be used, while if it leads to changes in the efforts required to secure environmental targets, abatement costs are preferable [CE,2010]. In practice, every new development (e.g. pavement construction) leads to additional emissions and these should be valued using damage costs. Emissions for which the government has agreed absolute targets, abatement costs should be used. The Dutch government has set absolute caps on emissions of CO₂, SO₂, NO_x, NVMOC (Non-Methane Volatile Organic Compounds) and NH₃. In cases of these emissions, the environmental impacts of a project are valued using abatement costs.

Future Perspectives

The shadow prices used in this thesis are valid for the situation in 2008 but can be used without any problem for a time horizon to come. Therefore, the Net Present Value (NPV) is not taken into account in the calculation of the environmental costs. The shadow price to be assigned to CO₂ emission increases more with time according to the damage estimates and, if increasingly stringent climate policy is assumed for the abatement costs too. Therefore the shadow price of CO₂ is higher when it is used over a time horizon.

5.3. LCA methodology

A Life Cycle Assessment (LCA) is a technique to assess environmental impacts associated with all the stages of a product's life. A Life Cycle Assessment is carried out in four steps [Jonkers, 2013]:

1. determination of goal and scope;
2. inventory Analysis of environmental data;
3. impact assessment;
4. interpretation.

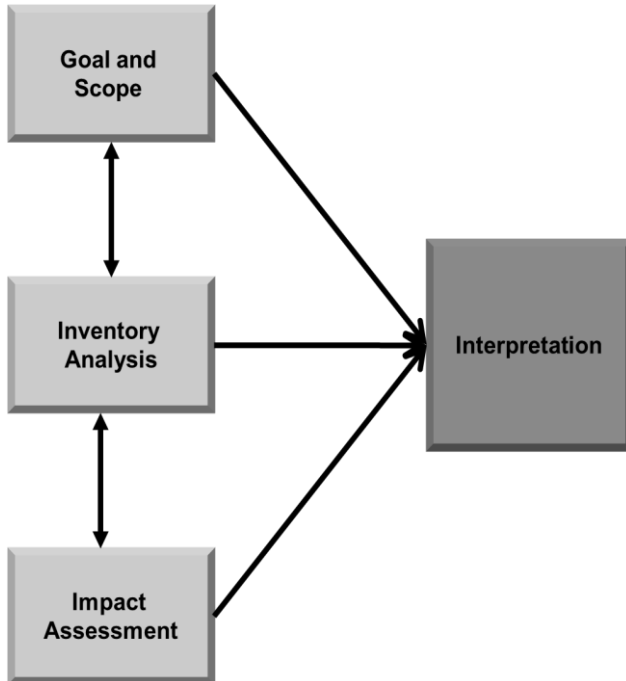


Figure 5.4 LCA procedure

1. Determination of goal and scope

In this step of the LCA procedure the central objective, the research question and the system boundaries are determined. The scope of the LCA in this study is to make a comparison based on environmental damage between the main types of pavement construction materials that are used in the pavement industry in the Netherlands. The goal of this study is to find the pavement type that will lead to an optimum of durability and sustainability. The traffic accident rate is to some extent determined by the condition of the road. A well maintained pavement structure leads to less accidents. On the other hand, a pavement construction material with less environmental damage has currently become a tender requirement criterion for the Netherlands Ministry of Infrastructure and the Environment ('Rijkswaterstaat') for the construction of new motorways. By weighing up both aspects, traffic safety and the environment (sustainability), the economically best fitting pavement wearing course can be chosen.

2. Inventory analysis of Environmental data

The inventory analysis of environmental data consists of definition of all the input from the environment (raw materials, fuels) and outputs to the environment (energy emissions). The inventory analysis has been performed by an impact assessment considering the pollutants and categorising them in environmental themes, according

to several environmental impacts. The different environmental impact categories are listed in Table 5.1. The environmental load assigned qualitatively to one or more impact categories in the classification phase are quantified in terms of a common unit for that category by using characterisation factors. [Wang, Y.]

Table 5.1 Environmental themes [CE, 2010]

Environmental theme	Characterisation factor	Unit
Photo chemical oxidation	The potential of photochemical ozone formation of each substance emitted to the air.	kg of ethylene (C ₂ H ₄) equivalents per kg of emission
Acidification	The acidification potential for each acidifying emission to the air.	kg of sulphur dioxide (SO ₂) equivalents per kg of emission.
Eutrophication	The potential of eutrophication of each eutrophying emission to the air, water and soil.	kg of phosphate ion (PO ₄ ⁻) equivalents per kg of emission.
Ozone layer Depletion (ODP)	The potential of ozone layer depleted by each substance emitted to the air.	kg Chlorinated Fluor Carbon CFC-11 eq
Global Warming Potential (GWP)	The potential of global warming of each greenhouse gas emission on the air.	kg of carbon dioxide (CO ₂) equivalents per kg of emission.
Abiotic Depletion	The potential of abiotic depletion of the extraction of those minerals and fossil fuels.	kg of antimony (SB) equivalents per kg of extracted mineral.
Human toxicity	The potential of human toxicity of toxic substances emitted to the air, water or/and soil.	kg of dichlorobenzene (1.4-DB) equivalents per kg emission
Terrestrial Eco Toxicity	The potential of terrestrial toxicity of each substance emitted to the air, water or/and soil.	kg of dichlorobenzene (1.4-DB) equivalents per kg emission
Fresh water aquatic Eco toxicity	The potential of fresh water aquatic toxicity of each substance emitted to the air, water or/and soil.	kg of dichlorobenzene (1.4-DB) equivalents per kg emission
Marine aquatic Eco toxicity	The potential of marine aquatic toxicity of each substance emitted to the air, water or/and soil.	kg of dichlorobenzene (1.4-DB) equivalents per kg emission

Characterisation factors provide an indication of the relative importance of a pollutant in terms of its contribution to a particular environmental theme. The result of the inventory analysis is an emission factor for each environmental theme. The environmental themes have impact on humans health, the ecosystem quality and the resources. Figure 5.5 illustrates a schematisation of the emissions, their contribution to an environmental theme and the source of damage.

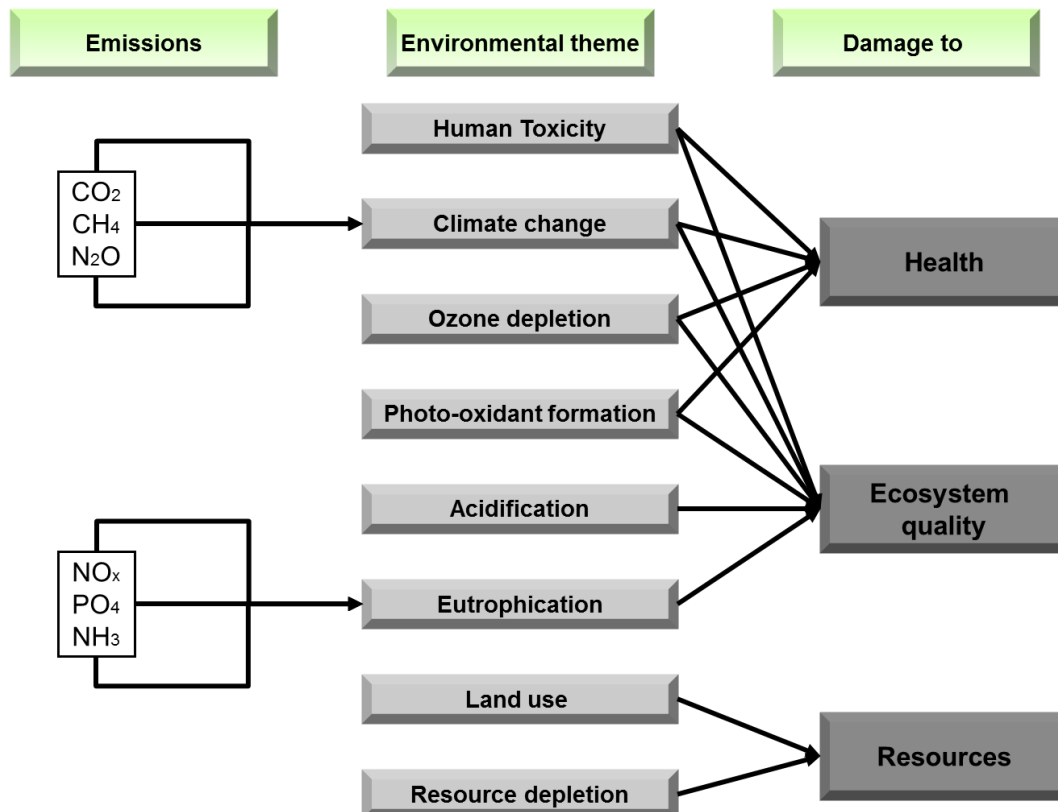


Figure 5.5 Pollutants, environmental themes and their damage source [CE, 2010]

3. Impact Assessment

The impact assessment is an important phase in the LCA. In this phase the environmental impact of the different environmental categories are compared to each other. This is performed by weighing the environmental themes of each variant for which the Life Cycle Assessment is conducted. Shadow prices of each environmental theme are multiplied by the emission factors calculated in the inventory phase. This results in an environment cost indicator (ECI) for each variant

4. Interpretation

Interpretation is the technique to identify, check and evaluate information from the results of the inventory analysis and the impact assessment. In this phase the results of the impact assessment and the inventory phase are summarised and conclusions are drawn according to the goal and scope of the project

6. Pavement aspects

There are many pavement aspects that have their impact on the environment and the society. The environmental and social impact of a pavement construction is analysed for the following pavement aspects:

- pavement building materials;
- noise level;
- fuel consumption;
- traffic accidents.

6.1. Pavement Building Materials

6.1.1. Introduction

In environmental analyses, the various environmental impacts identified can be weighted using shadow prices. In many cases these will be Life Cycle Assessments (LCA's), inventorying the environmental impacts of a product during the production, consumption and possibly waste phase. The environmental impact of the pavement building materials in the Netherlands is analysed with DuboCalc. DuboCalc is a tool developed by 'Rijkswaterstaat' for calculation of the environmental aspects and the energy required by materials from extraction to demolition (the entire lifecycle). The environmental impact is calculated according to the Life Cycle Analysis (LCA) procedure. In a LCA calculation the environmental damage is calculated by taking into account the environmental impact of the raw materials that are used (including produced energy) and the emission (including emission due to waste) during the lifecycle of the work.

In DuboCalc the lifecycle of an object has four different stages:

1. construction (including mining, production, transport of the raw materials and waste);
2. usage (only aspects of the object itself; for roads emission due to traffic is NOT included);
3. maintenance (including: waste)
4. rest lifetime (re-use or waste)

The result of a LCA calculation is a ECI value (Environment Cost Indicator). The lower the ECI value is, the less the environmental impact and the more environmental friendly the project will be. DuboCalc does not take into account the environmental costs due to transportation of the asphalt from plant to worksite and the usage stage. To take into account the environmental costs of these aspects, they should be modelled separately. These extra costs have been modelled in the developed program. The analysis of the environmental costs of the pavement building materials can be performed for an arbitrary time horizon. By taking into account the ECI value of the different pavement building materials, the road authority can make a decision which building material should be used for the construction or reconstruction of the pavement, with the environmental impact as reference criterion.

6.1.2. Data selection

The emissions according to the different environmental themes are selected from the DuboCalc database. These emissions are described in Appendix B. The shadow price of each environmental theme is listed in Table 6.1. The emissions for the calculation of the transportation costs from plant to worksite are retrieved from the ERA-NET project 'CEREAL; The Carbon Road Map'.

Table 6.1 Environmental themes [CE, 2010]

Environmental theme	Unit	Shadow price (€/unit)
Photo chemical oxidation	kg C ₂ H ₄ eq.	2.00
Acidification	kg SO ₂ eq.	4.00
Eutrophication	kg PO ₄ eq.	9.00
Ozone layer DePletion (ODP)	kg CFC-11 eq.	30.0
Global Warming Potential (GWP)	kg CO ₂ eq.	0.05
Abiotic Depletion	kg SB eq.	0.16
Human toxicity	kg 1.4-DB eq.	0.09
Terrestrial EcoToxicity	kg 1.4-DB eq.	0.06
Fresh water aquaticEco toxicity	kg 1.4-DB eq.	0.03
Marine aquaticEco toxicity	kg 1.4-DB eq.	0.0001

6.1.3. Analysis procedure

The environmental cost due to production of different pavement building materials is calculated according to the LCA procedure. The wearing course on local roads is generally an asphalt layer or a layer of small elements (block paving). Figure 6.1 illustrates the most common pavement building materials for which a LCA calculation is made.

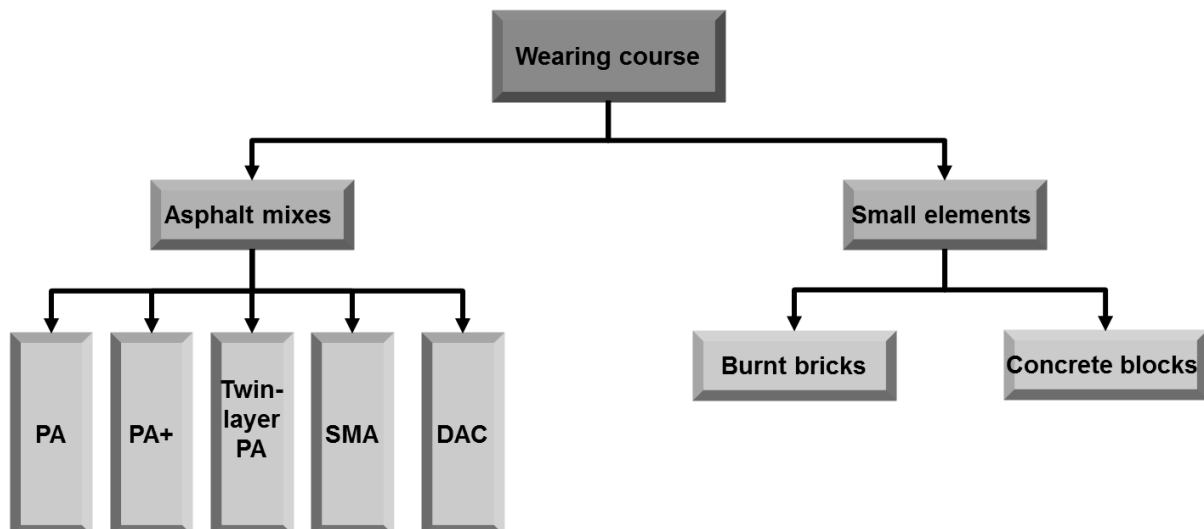


Figure 6.1 Wearing courses

Small elements are available in different shapes and sizes and are mostly used on municipal roads. The three most important shapes that are used in the Netherlands are; with their rounded horizontal dimensions:

- 'waalformaat' (4:1) → (200 x 50 mm);
- 'dikformaat' (3:1) → (210 x 70 mm);
- 'keiformaat' (2:1) → (200 x 100 mm).

It should be noted that the ratio of the sizes (length versus width) is standard, but there might be differences in actual size. The difference in size is indirectly taken into account in the calculation of the sustainable costs. A total material density is calculated by taking into account the element thickness and the total road surface area.

The durability of the pavement materials is important in the calculation of the environmental costs over a time horizon. Each pavement material has a certain structural life. Table 6.2 illustrates the average structural life of the considered wearing courses.

Table 6.2 Structural life of the wearing courses [CROW, 2012]

Pavement material	Structural life [years]
PA	11
PA +	15
PA twinlayer	8
SMA	10
DAC	17
Burnt bricks	40
Concrete blocks	25

Figure 5.1 illustrates that the durability of an asphalt mix depends on the percentage of pores and the percentage of bitumen. PA+ has a higher percentage of bitumen ($\pm 5.5\%$), which leads to a longer structural life (more durable) than that of the more common PA ($\pm 4.5\%$). PA twinlayer contains more pores and has subsequently a shorter structural life (less durable).

If the time horizon is longer than the structural life or design life of the wearing course, maintenance costs are added for keeping the total pavement structure at the requested quality level.

The environmental costs due to transport from plant to worksite depend on:

- amount of material to be transported [ton];
- transport distance [km];
- transport mode.

Road transport is the main transport mode from the plant to the worksite. Therefore, the emissions of carbon dioxide based on road transport in the Netherlands are used for the calculation of the environmental costs due to transport from plant to worksite.

The environmental costs over a time horizon are calculated as follows:

The ECI value of an asphalt mix / small elements:

$$ECI = \sum ET_i * SP_i \quad (\text{Eq. 35})$$

where:

- ECI = environmental costs of asphalt mix or block element [€/ton];
 ET_i = emissions of environmental theme 'i' [kg-eq./ ton];
 SP_i = environmental price of environmental theme 'i' [€ / kg –eq];

The ECI over time horizon:

$$ECI_{\text{time horizon}} = (TH / LBM) * ECI \quad (\text{Eq. 36})$$

where:

EKI = environmental costs of asphalt mix or block element [€/ton];
EKI_{time horizon} = environmental costs over time horizon [€/ton];
TH = time horizon [year];
LBM = structural life of building material [year].

The emission costs due to transport from plant to worksite are calculated as follows:

$$EC_T = W * TD * E_{CO_2} * SP_{CO_2} \quad (\text{Eq. 37})$$

Where:

EC_T = environmental costs due to transport [€];
W = weight of material [ton];
TD = transport distance [km];
E_{CO₂} = emission of CO₂ [kg / ton.km];
SP_{CO₂} = shadow price [€/kg].

6.1.4. Validation of the analysis methods

The emissions associated with the different environmental themes were copied from the DuboCalc database. The calculated Environmental Cost Index (ECI) for the different pavement materials is therefore validated with the ECI calculated by DuboCalc (see Appendix B). The maximum difference between the calculated ECI value and the DuboCalc value is approximately five percent (Table A 9). This difference is assumed to be small enough for a reliable calculated ECI value. Appendix B describes the validation of these two approaches.

6.2. Noise Level

6.2.1. Introduction

Noise nuisance is caused by industry, road, rail, air traffic and various other sources. Since the late 1970s the Noise Nuisance Act ('Wet Geluidshinder') has provided the legislative framework for Dutch government policy on noise. It contains an extensive set of provisions to prevent and control noise nuisance caused by industry, road and rail traffic. For noise there is in principle a 'preference limit' of 50 dB(A) at the front of houses. The present Noise Nuisance Act is under pressure because autonomous growth of road traffic may lead to an uncontrolled rise in noise levels.

In the current situation, Rijkswaterstaat, the Directorate-General for Public Works and Water Management, uses a so called 'efficiency criterion' to establish what kind of measures (and on what scale) are to be deemed cost effective in preventing violation of the standards. For this purpose the criterion contains reference costs for damage measurements.

Perceptions of noise and noise annoyance do not originate from sound level only, but also on characteristics as peak value of the sound, predictability and personal factors like noise sensitivity and age. Noise levels are often expressed in dB(A), which, as an approximation, makes due allowance for human perception of noise and corrects for frequency. In policy circles, noise is generally expressed in L_{eq} , a measure of the number of decibels spread over the entire year.

The damaging effects of traffic noise are illustrated in Figure 6.2. The damaging effects of traffic noise are:

- loss of possible building sites due to government regulations;
- effects on ecosystems or recreation areas;
- effects on human health at school, at work or at home.

Most studies only value the effects on human health at school, work or at home.

The two main impacts of noise on human health are (*HEATCO, 2006*):

- annoyance, reflecting the disturbance that individuals experience when exposed to noise;
- health impacts; mainly stress related health effects like hypertension and myocardial infarction.

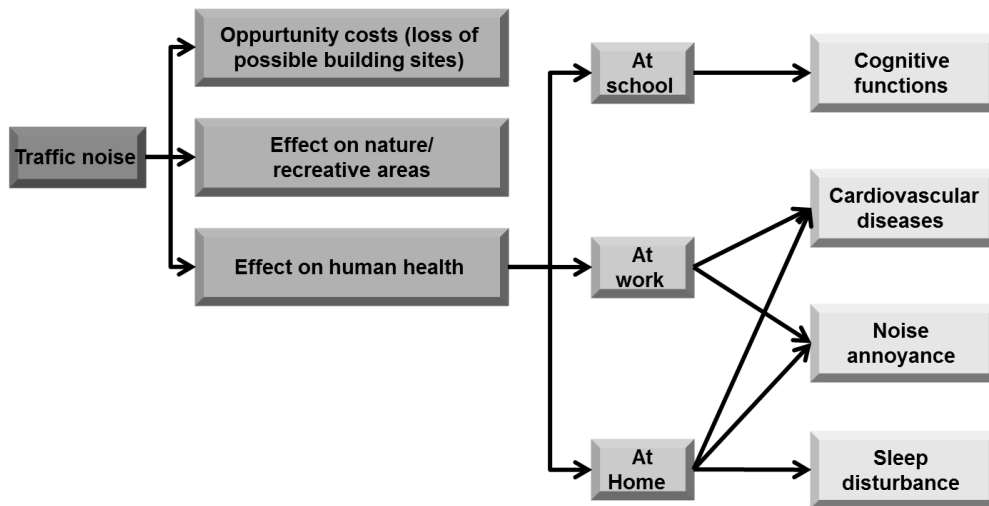


Figure 6.2 Damaging effects of traffic noise [CE, 2010]

6.2.2. Data selection

The noise level is calculated according to the procedure described in CROW publication 316 [CROW 316, 2012]. The environmental costs due to noise emissions are calculated using the damage costs method. The damage of human health due to noise is decisive for this assumption. The effect on human health in the environmental cost calculation can only be taken into account with the damage costs method and not with the abatement costs method. Asking people about their behaviour in a hypothetical situation, is a direct way to determine an individual 'willingness to pay'. Taking those impacts into account, damage costs are estimated due to noise hindrance. Table 6.3 presents the estimated damage costs due to noise emission for roads. Up to 70 dB (A) the damage costs consists only of annoyance costs. Above 70 dB (A) the damage costs include annoyance costs and costs related to health effects occurring above these noise levels.

Table 6.3 Damage costs (€ per dB (A) above the threshold per year per person) [CE, 2010]

L_{eq} [dB (A)]	Costs [euro]
Threshold < 50	
50 – 70	12.71
>70	20.33
> 70 (add for health effects)	62.27

6.2.3. Analysis procedure

The first input parameter for the estimation of the environmental costs due to noise emission is the noise level (L_{eq}). The noise level performance of the different types of wearing course is determined by using the Standard Calculation Method 1 (SRM 1) described in publication 316 issued by CROW [CROW 316, 2012]. The input parameters for the calculation of the noise performance of a wearing course are traffic data and the type of wearing course of the pavement structure. The Standard Calculation Method 1 (SRM1) determines a road surface correction, being the difference in noise level between a wearing course under consideration and the reference wearing course. This reference wearing course has more or less the characteristics of Dense Asphalt Concrete (DAC). When the road surface correction is negative, the wearing course produces less traffic noise than the reference wearing course.

The wearing course is then called a 'silent wearing course'. The reference wearing course includes all DAC and SMA grading's with a maximum grain size of 11 mm. Therefore, the ageing correction factor of the reference wearing course is calculated based on a coarse graded SMA. The road surface correction factor accounts for the traffic distribution and the average speed on the pavement (road type). The road surface correction factor is calculated for two vehicle categories;

- category 1 (m =1): light weight vehicles;
reference speed = 80 km/h
- category 2, 3 (m = 2, 3): moderate and heavy weight vehicles.
reference speed = 70 km/h.

Figure 6.5 illustrates the type of vehicles that are in the range of the two vehicle categories.

According to the vehicle speed, the pavements are categorized in the following types:

- type 1: municipal roads (max. 50 km/h)
mean value traffic speed = 50 km/h;
- type 2: provincial roads (max.80 km/h)
mean value traffic speed = 80 km/h;
- type 3: motorways (> 80 km/h)
mean value traffic speed = 100 km/h.

According to publication 316 of CROW, the noise level of an arbitrary wearing course is calculated in 4 steps. [CROW 316, 2012]:

- **Step 1: Calculation of the road surface correction factor:**

$$C_{\text{road surface},m}(v_m) = \sigma_m + T_m \log (v_m / v_{0,m}) \quad (\text{Eq. 38})$$

- **Step 2: Calculation of the initial correction factor:**

$$C_{\text{initial},m}(v_m) = \Delta L_m + T_m \log (v_m / v_{0,m}) \quad (\text{Eq. 39})$$

- **Step: 3 Calculation of the ageing correction factor:**

$$C_{\text{time},m} = C_{\text{road surface},m}(v_m) - C_{\text{initial},m}(v_m) \quad (\text{Eq. 40})$$

- **Step 4 Calculation of the noise level:**

$$L_{\text{eq}} = E_{\text{reference}} + C_{\text{initial}} + \text{NG} * \text{time} \quad (\text{Eq. 41})$$

where:

$C_{\text{road surface},m}$ =	road surface correction factor [dB(A)];
$C_{\text{initial},m}$ =	initial correction factor [dB(A)];
$C_{\text{time},m}$ =	ageing correction factor [dB(A)];
σ_m =	parameter that takes into account the ageing of a wearing course [dB(A)];
ΔL_m =	parameter for the calculation of the initial road surface correction [dB(A)];
T_m =	parameter for the calculation of the initial road surface correction [dB(A)];
v_m =	traffic speed [km/h];
$v_{0,m}$ =	reference speed [km/h].
L_{eq} =	noise level [dB(A)];
$E_{\text{reference}}$ =	noise emission of the reference wearing course [dB(A)];
NG =	noise growth per year [dB(A)];
Time =	number of years.

The values of the parameters are described in Appendix B. The correction factors are calculated for the type of wearing course and are also listed in Appendix B.

The noise emission of the reference course depends on the type of road (vehicle speed) and the intensity of the vehicle categories. The overall reference noise emission containing all traffic categories is calculated as follows: [CROW 316, 2012]

$$E_{lv} = 70 + 29,8 \log(v_{lv} / v_o) + 10 \log((Q / v)_{lv}) \quad (\text{Eq. 42})$$

$$E_{mv} = 73,2 + 19 \log(v_{mv} / v_o) + 10 \log((Q / v)_{mv}) \quad (\text{Eq. 43})$$

$$E_{hv} = 76 + 17,9 \log(v_{hv} / v_o) + 10 \log((Q / v)_{mv}) \quad (\text{Eq. 44})$$

$$E_{\text{reference}} = 10 \log (10^{E_{lv}/10} + 10^{E_{mv}/10} + 10^{E_{hv}/10}) \quad (\text{Eq. 45})$$

where:

- $E_{\text{reference}}$ = noise level of the reference wearing course [dB(A)]
- E_{lv} = noise emission of light weight vehicles [dB(A)]
- E_{mv} = noise emission of moderate weight vehicles [dB(A)]
- E_{hv} = noise emission of heavy weight vehicles [dB(A)]
- $V_{lv, mv, hv}$ = design speed limit for the road type [km/h]
- $V_{o,lv}$ = reference speed light weight vehicles [80 km/h]
- $V_{o,mv, hv}$ = reference speed moderate and heavy weight vehicles [70 km/h]
- Q = intensity [number of vehicles /hour]

The calculated noise emission for the different road types and types of wearing course are listed in Appendix B.

The noise growth (NG) per year depends on two parameters:

- the structural life of the wearing course (75% of the average service life)
- the vehicle distribution over the vehicle categories

The traffic distribution is taken into account in the ageing factor as follows:

$$C_1 = C_{\text{time},1} + 10 \log(p_1 / 100) \quad (\text{Eq. 46})$$

$$C_{2,3} = C_{\text{time},2,3} + 10 \log(p_{2,3} / 100) \quad (\text{Eq. 47})$$

$$C_{\text{time}} = 10 \log (10^{C_1/10} + 10^{C_{2,3}/10}) \quad (\text{Eq. 48})$$

where:

- C_{time} = ageing correction factor [dB(A)];
- $C_{\text{time},1}$ = ageing correction factor based on vehicle category 1 [dB(A)];
- $C_{\text{time},2,3}$ = ageing correction factor based on vehicle categories 2 and 3 [dB(A)];
- C_1 = weighted ageing factor based on distribution vehicle category 1 [dB(A)];
- $C_{2,3}$ = weighted ageing factor based on distribution vehicle category 2,3 [dB(A)];
- P_1 = percentage of vehicles in category 1 [%];
- $P_{2,3}$ = percentage of vehicles in categories 2 and 3 [%];

The noise growth (NG) per year is calculated as follows:

$$NG = 2 * C_{\text{time}} / \text{structural lifetime} \quad (\text{Eq. 49})$$

The calculations of the noise growth per year are listed in Appendix B.

The threshold for traffic noise is instrumental for the calculation of the environmental costs due to the noise emissions. The more the threshold is exceeded, the more the environmental costs will rise. Figure 6.3 illustrates the procedure for the analysis of the environmental costs due to noise emission.

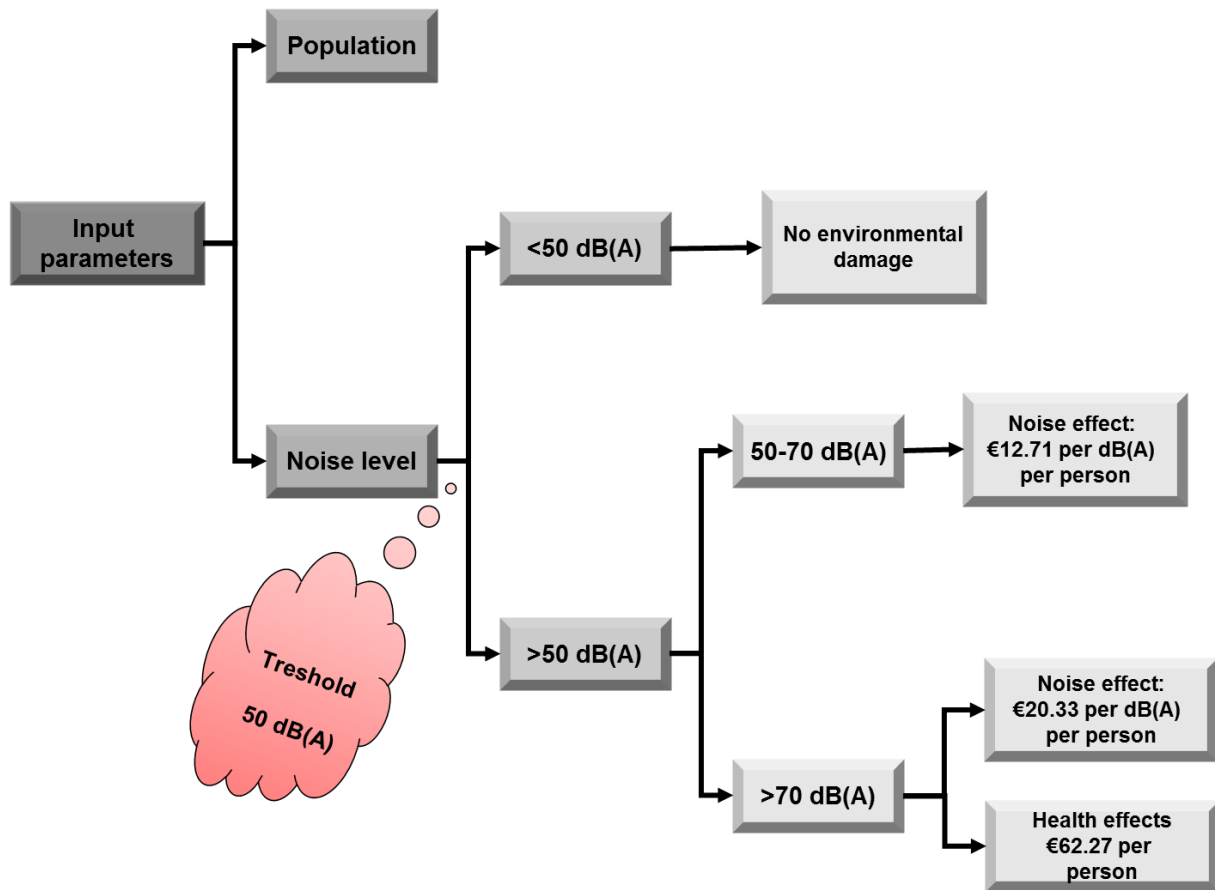


Figure 6.3 Analysis procedure

Population

Another parameter for the calculation of the environmental costs due to noise emission is the population density of the area where the pavement is situated. In urban areas the environmental costs due to noise hindrance are higher than in rural areas. The number of pollutants for the calculation of the environmental costs of a road situated in a urban area is higher than in a rural area. The number of pollutants that are affected due to noise nuisance has been calculated per kilometre road length. The number of pollutants and the length of roads in the Netherlands are listed in Table 6.4. The numeric values are retrieved from the Central bureau of Statistics.

Table 6.4 Number of pollutants and road length

Pollutants NL	16800000
Municipal road [km.]	125230
Provincial road [km.]	7778
Motorways [km.]	5191
Totaal [km]	138199

The user of the developed program has the possibility to enter the number of pollutants that are affected by noise nuisance. If the number of pollutants is not known the user may choose for an estimated value based on the area where the road is situated (rural or urban). The assumptions for the calculation of these estimated value are listed in Table 6.5. [Groenendijk, 2014]. The number of pollutants and the road length per road type are subdivided to two areas (urban and rural). The number of pollutants that are affected due to noise nuisance has been expressed per kilometre road length. The analysis results in 149 pollutants per km length in urban areas and 45 pollutants per km length in rural areas.

Table 6.5 Proportion of pollutants in urban area and rural area

	Urban area	Rural area	Default
Assumptions			
Pollutants [%]	90	10	
Municipal road [%]	80	20	
Provincial road [%]	10	90	
Motorways [%]	5	95	
Pollutants	15120000	1680000	
Municipal road [km.]	100184	25046	
Provincial road [km.]	777.8	7000.2	
Motorways [km.]	259.55	4931.45	
	101221.35	36977.65	
Pol./km.	149	45

The environmental costs per pollutant due to noise emission are calculated as follows:
 If the noise level (L_{eq}) is smaller than 70 dB(A), the environmental costs due to noise emission for each person per year are:

$$EC_{\text{noise emission}} = (L_{eq} - \text{threshold}) * 12.71 \quad (\text{Eq. 50})$$

If the noise level (L_{eq}) is higher than 70 dB(A), the environmental costs due to noise emission for each person per year will be:

$$EC_{\text{noise emission}} = (70 - \text{threshold}) * 12.71 + (L_{eq} - \text{threshold}) * 20.33 + 62.27 \quad (\text{Eq. 51})$$

where:

$EC_{\text{noise emission}}$ = environmental costs per person due to noise emission [€];

L_{eq} = calculated noise level beside the road [dB(A)];

threshold = maximum allowed noise level [dB(A)].

6.3. Fuel consumption

6.3.1. Introduction

The emission of pollutants is one of the controlling parameters in the calculation of the sustainable costs due to fuel consumption. The emission of pollutants depends on the amount of fuel that is consumed by a vehicle. That amount of fuel depends on many factors. Figure 6.4 illustrates the most common factors. Because so many parameters have their influence, a precise calculation of the environmental costs due to fuel consumption is complex. In this part of the 'Sustainable Model' a prediction is made for the calculation of the environmental costs due to fuel consumption. This model is a prediction based on the average emissions in the Netherlands.

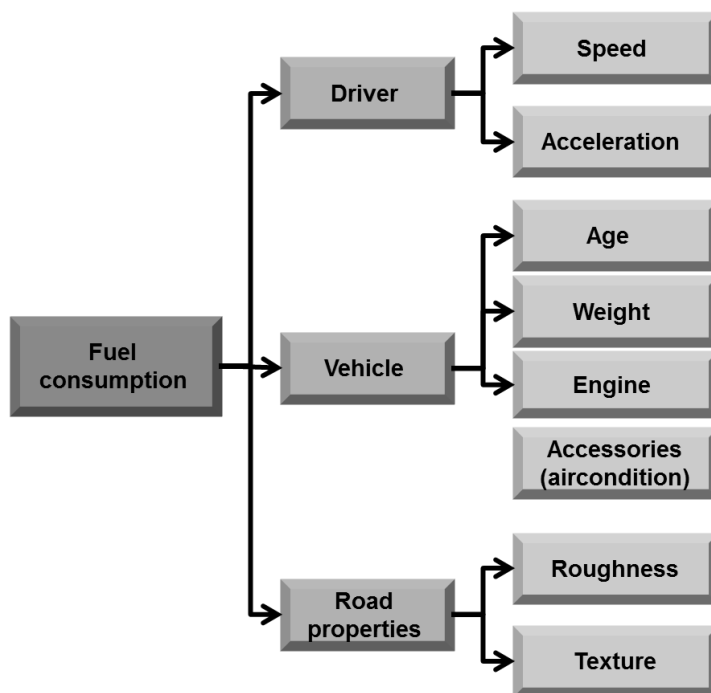


Figure 6.4 Factors that influence the fuel consumption

6.3.2. Data selection

The emission factors of the different pollutants were retrieved from the CBS (Central Bureau of Statistics) database. These emission factors are average emission factors based on the traffic distribution in the Netherlands. Those emissions may differ from country to country. For example, the cars in the United States are different from those in the Netherlands. In the United States the vehicles are usually bigger, percentages of diesel engines is lower and different engines are used.

The emission factors are selected for the following pollutants:

- Carbon monoxide (CO);
- Non-methane Volatile Organic Compounds (NMVOC);
- Nitrogen oxide (NO_x);
- Fine particles (PM₁₀);

- Sulphur dioxide (SO₂);
- Carbondioxide (CO₂);
- Nitrous oxide (N₂O);
- Methane (CH₄).

The shadow prices of the different pollutants are presented in Table 6.6 For the pollutants CO₂, SO₂, NO_x and NVMOC abatement prices are used because the Dutch government has set absolute limit values for these emissions. For the other pollutants the damage cost approach is used because emissions due to fuel consumption lead to changes in the environmental quality.

Table 6.6 Pollutants and the according prices [CE, 2010]

Pollutant	Shadow price (€ /kg)
CO	0.009
NVMOC	5.00
NO _x	9.00
PM ₁₀	41
SO ₂	5.00
CO ₂	0.05
N ₂ O	7.45
CH ₄	0.625

The emission factor depends on the type of vehicle, vehicle speed and the type of fuel. The pavements are classified into three main categories based on the speed limit:

- type 1: municipal roads (max. 50 km/h)
- type 2: provincial roads (max.80 km/h)
- type 3: motorways (> 80 km/h)

For the following types of vehicles the emissions were taken from the CBS database:

- cars
- vans
- trucks
- articulated trucks
- motorcycles
- mopeds

6.3.3. Analysis procedure

The input parameters for the calculation of the environmental costs are:

- traffic information (type of vehicle and intensity);
- type and length of pavement.

Figure 6.5 illustrates the most important input factors for the analysis of the environmental costs due to fuel consumption. As Figure 6.5 clearly illustrates that the emission factor depends on the type of fuel used (petrol, diesel, LPG, electricity etc.). Based on CBS statistics more than 96% of the vehicles in The Netherland are powered by petrol or diesel engines. Therefore, in this model the contribution of the other types of fuel is ignored.

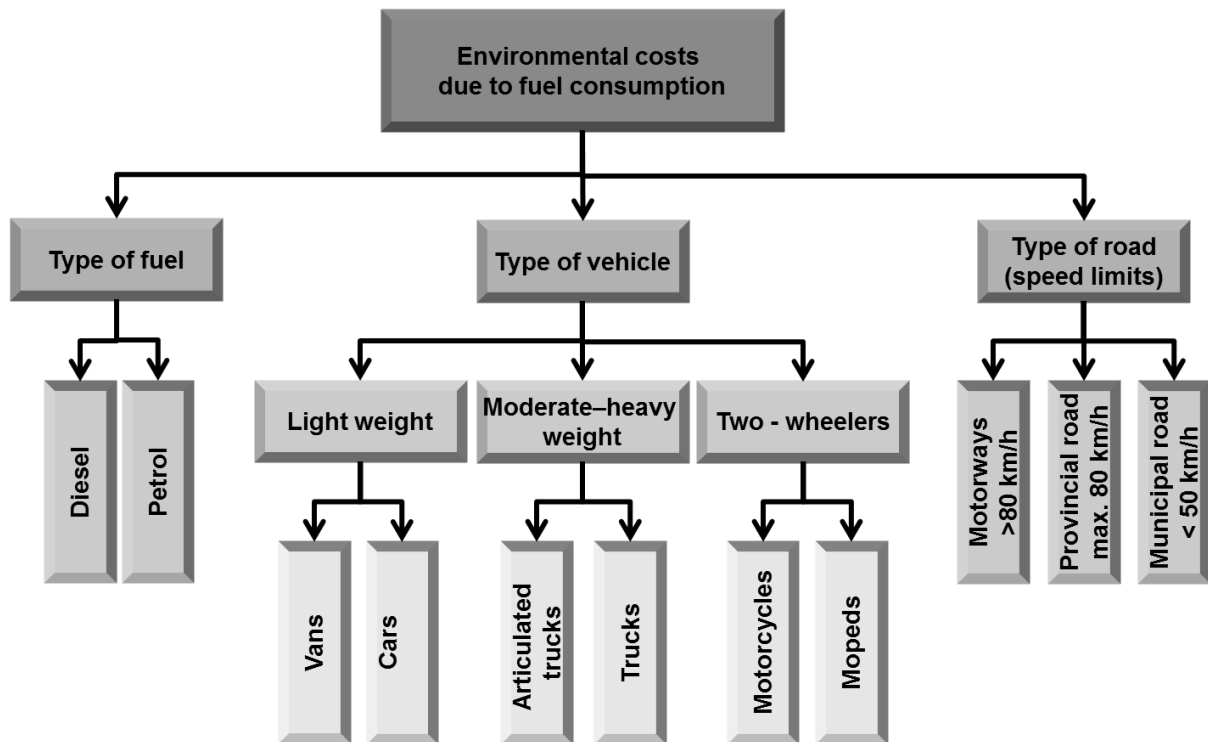


Figure 6.5 Factors that have an impact on the costs due to fuel consumption

Based on the distribution over petrol and diesel engines per type of vehicle a weighed emission factor has been calculated for each vehicle category. Therefore, the type of fuel is not a direct input parameter for the calculation of the environmental costs anymore but is taken into account directly via the vehicle category (Appendix B). It is relevant to take into account the distribution of petrol and diesel engines per type of vehicle because the environmental costs per vehicle kilometre due to a diesel engine are higher than that of a petrol engine. From comparing Figure 6.6 to Figure 6.7 it can be concluded that the environmental costs due to emitted CO₂ by a passenger car with a petrol engine is higher than that of a diesel engine. On the other hand the environmental costs of emitted NO_x for a diesel engine are higher than for a petrol engine.

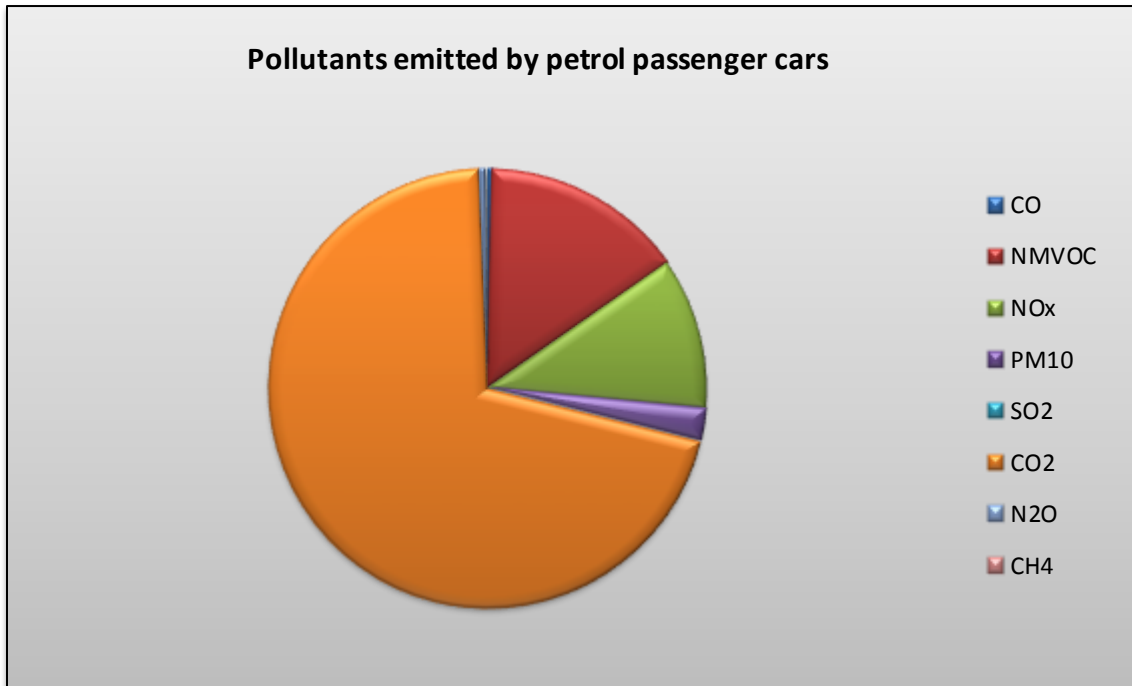


Figure 6.6 Environmental cost distribution of pollutants emitted by a petrol passenger car

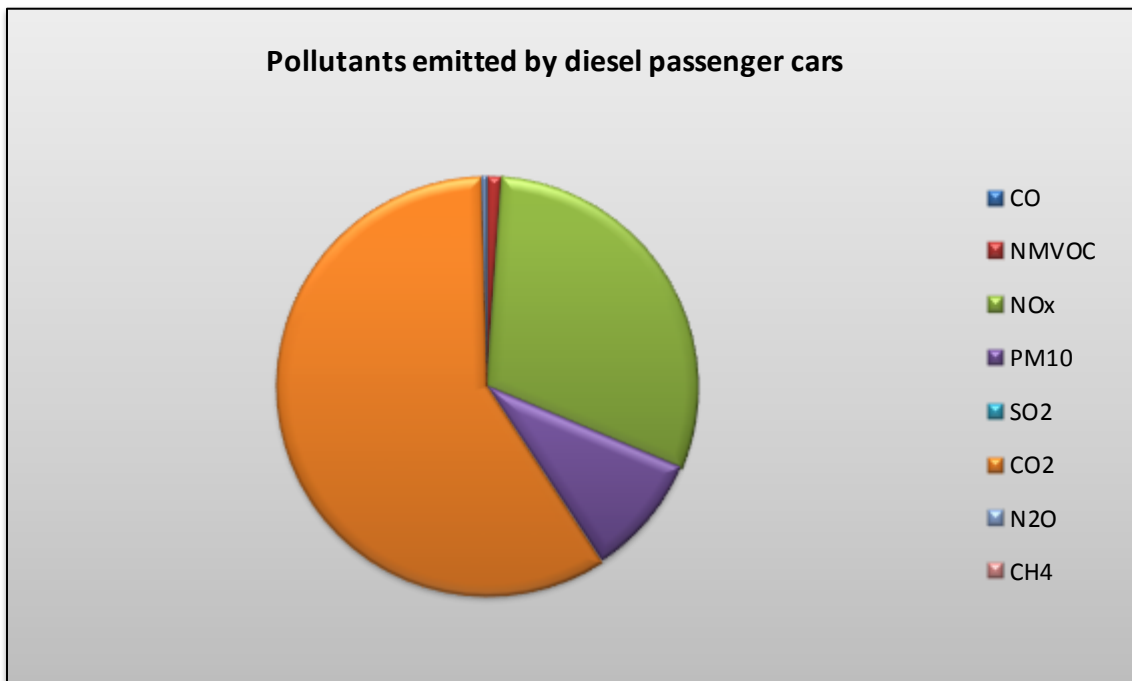


Figure 6.7 Environmental cost distribution of pollutants emitted by a diesel passenger car

Vehicles can move because of the transmission of chemical energy (petrol, diesel, LPG) in the engine into mechanical energy via crankshaft, gearbox, wheels etc. During this transmission process a lot of pollutants are emitted. Other particles are emitted too due to the evaporation of engine fuels and coolants, tire wear, wear of the break disc lining etc. All these components are compiled in the emission factors of the CBS data base.

The emission factors are instrumental for the calculation of the environmental costs due to fuel consumption. The length of the pavement is also an important parameter for the calculation of the absolute environmental costs.

The environmental costs of vehicle category 'x' is calculated as follow:

$$EC_x = \sum EF_i * SP_i * I_x * L \quad (Eq. 52)$$

The total environmental costs due to fuel consumption are:

$$EC_F = \sum EC_x \quad (Eq. 53)$$

Where:

EC_x = environmental costs of vehicle category 'x' [€]

EC_F = total environmental costs due to fuel consumption [€];

EF_i = emission factor pollutant 'i' [gram / veh.km];

SP_i = environmental price [€/kg];

I_x = intensity vehicle category 'x' [number of vehicles];

L = length of road [km].

The calculated environmental costs for the different vehicle categories and road types are listed in Appendix B.

The emission factors are decreasing over a time horizon. The reason for this is improvement of the engine technology of the vehicles over time. The environmental costs are therefore decreasing over time as well. This effect is taken into account in the model by evaluating the emission factors over a time horizon of 5 years (2008 - 2012). Over these 5 years an exponential regression line is calculated with which the effect of future technical improvements of a vehicle engine is predicted. This approach has been performed for the different road types and the different types of vehicles. In Appendix B (Figure A. 3 - Figure A. 6) the results of this evaluation are described.

6.4. Traffic accidents

6.4.1. Introduction

There are different reasons that might be found for the explanation of the causes of a traffic accident. Figure 1.1 illustrates the main reasons that may lead to accidents. Civil engineers can only partly contribute in the reduction of the amount of traffic accidents. The amount of accidents is decisive for the calculation of the social costs associated to those accidents. The accident rate of a pavement, in other words the sensitivity of a road pavement to the probability of an accident, can be calculated with the use of traffic safety models. The number of accidents on a road can be calculated based on the accident rate, the traffic intensity and the length of the road. The severity of the accidents is a very important criterion in the calculation of the total social costs due to accidents. The social costs for a fatal injury are much higher than those for an accident with only damage to the car. Therefore, the distribution of the severity of the accidents is important for the calculation of the total social costs due to traffic accidents.

6.4.2. Data Selection

The social costs due to accidents and the growth rate of the number of traffic victims over a time horizon were taken from a study performed by SWOV [SWOV, 2007]. The data on the distribution of the traffic accidents over severity was retrieved from a study published by CROW [CROW,2005]. The values of the social cost and the growth rate of the number of victims of each accident category are presented in Table 6.7.

Table 6.7 Social costs related to the severity of the accident in the Netherlands [SWOV, 2007]

Accident category	Main categories	Percentage [%]	Costs per victim [mln. €]	Total costs/ year [mln. €]	Growth rate victims [%]
AIS 0 (no injury)	OVD incidents	38.8	-	3900	
AIS 1 (minor injury)	victims with a marginal injury	41.4	-	400	
AIS 2 (moderate injury)					
AIS 3 (severe injury)	first aid victims	10.7	0.008		-1.0 / year
AIS 4 (very severe injury)	hospital victims	5.2	0.249		-0.5 / year
AIS 5 (perilous injury)					
AIS 6 (fatal injury)	fatal incidents	3.9	2.426		-3.4 / year

6.4.3. Analysis procedure

The accidents are classified by severity of the injury (see Figure 6.8). The severity of the injury is indicated by a severity score, calculated by a software tool, ICDMAP90. The result is a subdivision of the accidents, with an international used measure, the so called AIS (Abbreviated Injury Scale). The subdivision of the AIS system is as follows:

- AIS 0: no injury;
- AIS 1: minor injury;
- AIS 2: moderate injury;
- AIS 3: severe injury;
- AIS 4: very severe injury;
- AIS 5: perilous injury;
- AIS 6: fatal injury.

The classification of the AIS ratings is broken down over five main categories with different social costs. The five main categories of accidents that may be distinguished are:

- OVD accident (Only vehicle damage)
- victims with a marginal injury;
- first aid victims;
- hospital victims;
- fatal accident.

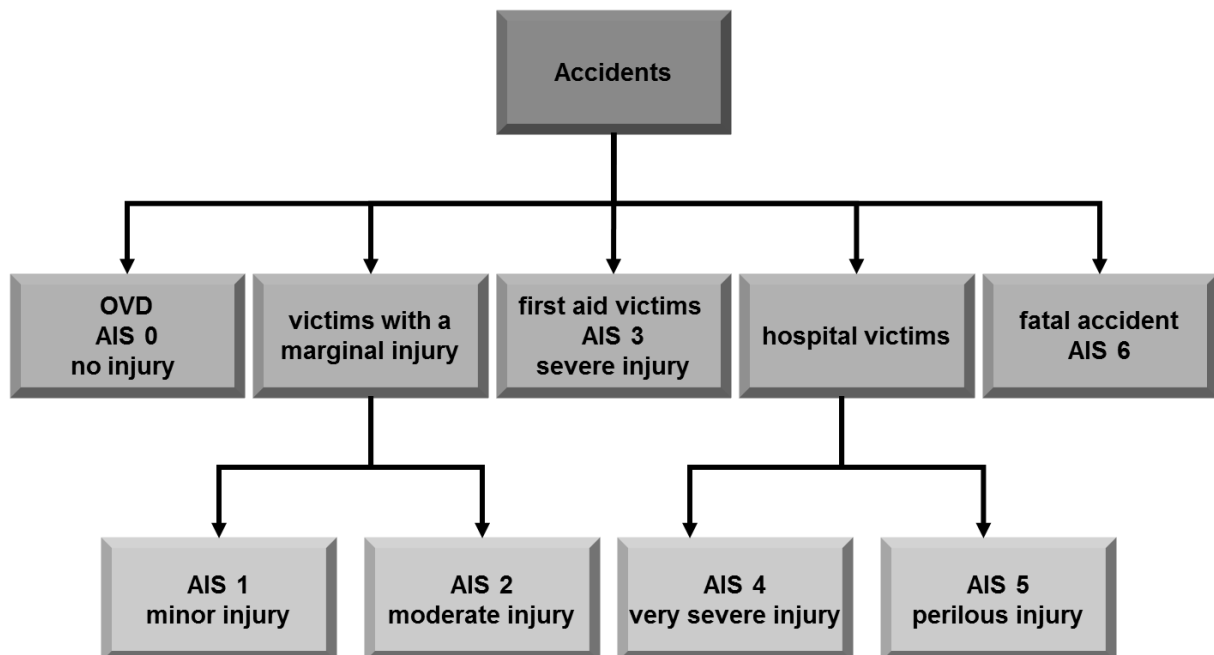


Figure 6.8 Subdivision of accidents

Traffic accidents commonly lead to different categories of social costs. These costs may be broken down into the following categories:

- medical costs: costs for hospital, revalidation, drugs and aids for disabled people;
- material costs: costs assigned to damage of vehicles, freight, roads and road furniture;
- production loss: costs to disability of victims or total loss of production due to a fatal injury;

- administration costs: costs made by organisations like police, fire brigades, justice, insurers for the dispatch of the victims and the created damage;
- intangible costs: costs assigned to pain, disappointment and loss of happiness. These costs are estimated by interviewing the road users, and asking them about their willingness to pay for a mortality rate. These cost are difficult to estimate;
- congestion costs: costs for loss of availability of the road to other road users because of the accidents.

Depending on the type of accident, the costs are calculated as the sum of the costs of the different cost categories. Table 6.7 shows that the growth rate of the number of victims decreases each year. The reason for this is improvement of the pavement properties, traffic measures (roundabouts, marking, speed cameras, etc.) and vehicle measures (airbags, safety belts, etc.). The costs in this model are based on values estimated in 2003 by SWOV and are not corrected for the standard inflation rate [SWOV, 2007], because in most cases the calculation is based on a prediction of the costs due to accidents in the current year. By taking into account the inflation rate, the costs over a time horizon will be much higher than for the year in which the cost are calculated.

The total costs of traffic accidents is calculated per accident category and aggregated to the total costs. The total costs of the accidents, that occur in year 'n' of the pavement life are calculated by the following equations:

$$CA = \sum VC_i * SC_i * (1 + GR_i/100)^n \quad (Eq.54)$$

$$VC_i = AR * VK * P_i \quad (Eq.55)$$

where:

- CA = costs of accidents [€]
- VC_i = number of victims in category 'i';
- SC_i = costs of victim 'i' [€];
- GR_i = percentage of growth rate of the victims in category 'i';
- AR = accident rate [accidents/veh.km];
- VK = number of vehicle kilometres [veh.km];
- P_i = percentage of accidents in category 'i'.

7. Results of the analysis

7.1. Introduction

Evaluation of traffic safety and the environmental impact of the road industry is important for any member of society. These aspects should be taken into account in the planning process of construction of any new road structure or maintenance project. The previous chapters presented a literature overview and the analysis procedure of the most common pavement aspects related to these topics. The findings of those research actions have resulted in development of a tool for the prediction of durability, sustainability and sociality impact of different road types, with pavement characteristics as one of the main input parameters. The tool predicts the environmental costs due to noise emission, fuel consumption and the production of the road building materials. Furthermore, the tool predicts the social costs due to the traffic accidents that are likely to occur on the road. This is illustrated in Figure 7.1 , i.e. the introduction sheet of the developed tool.



Figure 7.1 Introduction sheet of the developed tool

The tool for the calculation of the environmental and social costs is developed in Microsoft Excel. The first sheet is the introduction sheet (Figure 7.1). The second sheet is the sheet with the input parameters and the results. The four other sheets are the calculation sheets, where the selected data are processed based on the models described in the previous chapters.

Figure 7.2 presents the sheet with the input parameters for the calculation of the environmental and social costs for a certain road section. The length of the road section and the pavement type are the first input parameters. For the pavement type the user can choose between the following:

- municipal road (max. 50 km/h);
- provincial road (max. 80 km/h);
- motorways (> 80 km/h).

Traffic data is the next parameter that have to be entered into the model. Traffic must be expressed in number of vehicles per day per type of vehicle on the road. The expected percentage traffic growth per year is also necessary for the calculation.

When entering the pavement properties, the user can choose from the following types of asphalt wearing course:

- PA (Porous Asphalt);
- PA + (Porous Asphalt with a higher percentage of bitumen);
- PA twinlayer (Twinlayer Porous Asphalt);
- SMA (Stone Mastic Asphalt);
- DAC (Dense Asphalt Concrete).

For small elements wearing courses the user can choose between:

- burnt bricks;
- concrete blocks.

As Figure 7.2 illustrates, the program has the possibility to choose two types of wearing courses simultaneously. This enables the user to evaluate a road section that has two types of wearing courses. For example the road section is constructed with a SMA wearing course over a length of 5 km and the rest of the road consists of block paving. If the considered road section is constructed with only one type of wearing course, the user should enter 'not present' for the second type of wearing course.

The input parameter time horizon is needed for the evaluation of the durability of the selected wearing course. For the time horizon the user should not enter the design life of the wearing course but the design life of the whole pavement structure.

The input parameters for the calculation of the environmental costs due to noise emission are the type of wearing course, the number of pollutants in the area where the road is situated and the design life of the wearing course. For the prediction of the noise emission of block paving it is important to know if the elements are laid in herringbone pattern or not. The pattern has influence on the level of traffic noise emission. The pattern is irrelevant in the calculation of the environmental costs due to production of the materials.

In case of a road maintenance project the residual structural life of the existing wearing course is of importance for the prediction of the noise level on the road. In case of a complete redesign or reconstruction of the road, this residual life value should be set to '0'.

The principal input parameter for the calculation of the social costs due to accidents is the accident rate. This accident rate can be calculated by using a traffic safety model, best fitted to the type of road that is considered.

Input parameters:	
Pavement details	
Select road type	Motorways >80 km/h
Length [km]	10
Traffic distribution [veh./carriageway]	
Light weight [veh./day]	15000
Moderate - heavy weight [veh./day]	1500
Motorcycles [veh./day]	250
Mopeds [veh./day]	0
Growth rate [%]	1
Production of materials	
Select wearing course 1	PA
Select wearing course 2	Not present
Thickness wearing course 1 [m]	0,06
Thickness wearing course 2 [m]	0
Surface area wearing course 1 [m2]	30000
Surface area wearing course 2 [m2]	30000
Transport distance; plant - work [km]	10
Time horizon [years]	40
Noise emission	
Area	Default
Default pollutants [pol./km.]	100
Select wearing course	PAC
Age current wearing course [years]	3
Accidents	
Year	0
Accidents /100 mio. veh. km	281,9

Figure 7.2 Input parameters

The results of this model will be explained in the next sections of this chapter by addressing different cases. The results will be described according to the relation with the three aspects:

- durability;
- sustainability and
- sociality

7.2. Durability

The durability of a wearing course is important for the engineer in making a choice which type of wearing course has the lowest maintenance costs. The time horizon of the project is important for assessment of the durability. By entering the time horizon and the type of road the user can choose a certain wearing course for a project.

Example 1:

Road type: municipal road

Time horizon: 40 years

Figure 7.3 displays the Environmental Cost Indicator (ECI) for the type of wearing course that can be chosen for municipal roads. No bars are presented for the porous asphalt mixes since these type of mixes should not be used for the type of road used in this example. The program prohibits selection of wearing courses that are not suited for the selected road type. In the decision making process of which type of wearing course should be used, different factors have to be considered. For environmental impact reasons, Dense Asphalt Concrete (DAC) appears to be a better choice than a Stone Mastic Asphalt wearing course over a time horizon of 40 years.

If the road authority prefers a small element pavement instead of an asphalt wearing course, burnt bricks would be a better choice than concrete blocks. This is because burnt bricks have a longer structural life than concrete blocks, which results in lower maintenance costs. Concrete blocks may structurally last long, but are generally not recycled too much because of deterioration in colour.

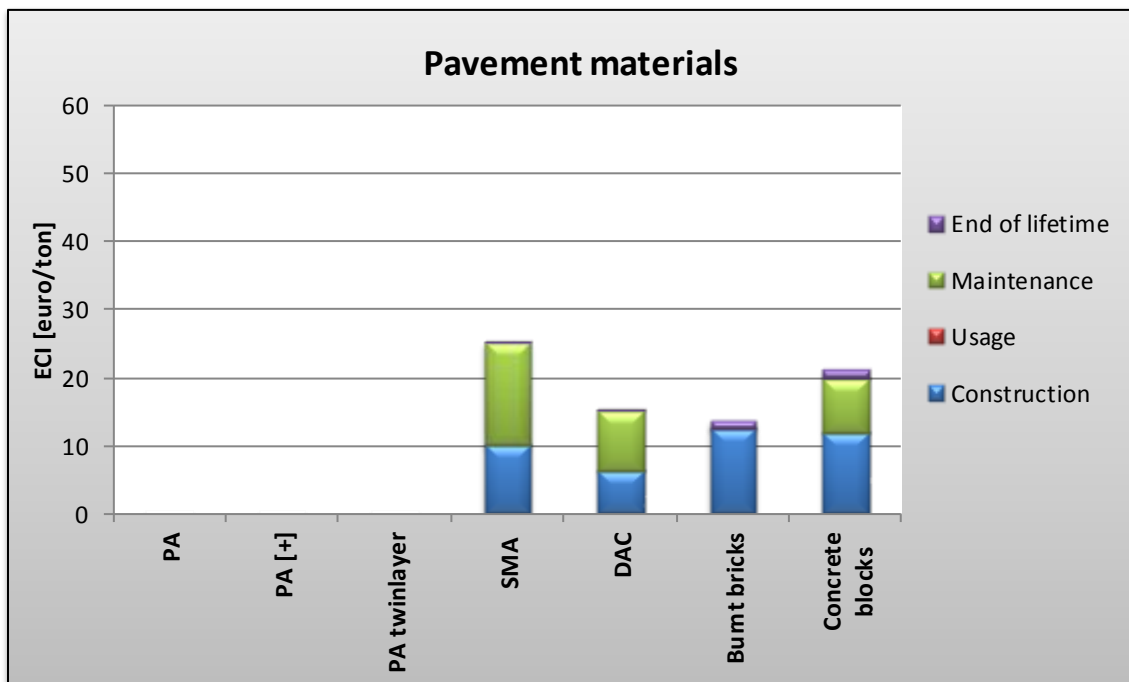


Figure 7.3 Durability of wearing courses on municipal roads

Example 2:

Road type: motorway

Time horizon: 40 years

Figure 7.4 shows that for motorways small elements and a SMA wearing course are not preferable, although existing motorways sometimes include SMA wearing courses. Small element pavements are simply not safe and comfortable enough for the high speed on the motorways. As can be seen in Figure 7.4 the production costs of the three different types of PA are the same. The differences in these asphalt mixes may be found in their design lives. These differences have a significant impact on the maintenance cost of each wearing course. PA has a design life of 11 years while PA + has a design life of 15 years. This difference will result in lower maintenance costs for PA +, making this asphalt wearing course more durable over a time horizon of 40 years. The reason that PA + has a structural life of 15 years instead of 11 years for PA is because of the higher percentage bitumen in PA, $\pm 5.5\%$ instead of 4.5% . The twinlayer PA exists of a coarse (11/16 mm) bottom layer and a fine (4/8 mm) top layer. The benefit of twin layer PA is a higher noise reduction because there are more pores in this asphalt mix. The disadvantage is a lower design life, which results in more maintenance costs over a time horizon of 40 years. A Dense Asphalt Concrete (DAC) wearing course is the most durable wearing course over a time horizon of 40 years.

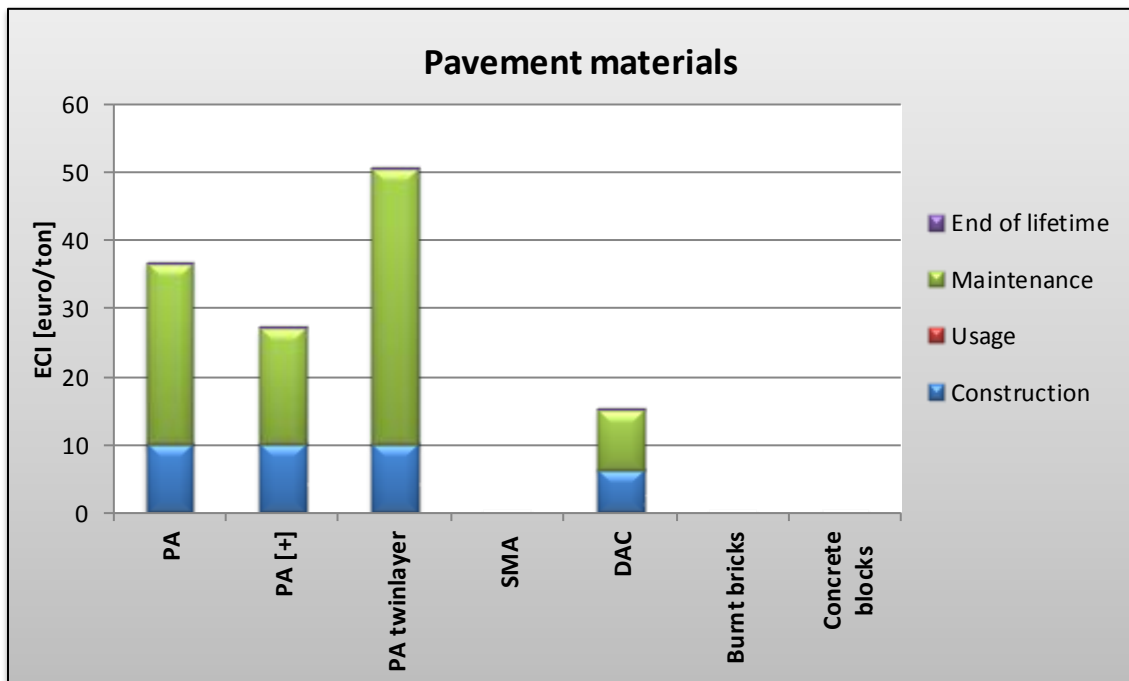


Figure 7.4 Durability of wearing courses on motorways

Figure 7.3 and Figure 7.4 illustrate that porous asphalt wearing courses are the least durable wearing courses. A SMA wearing course has an Environmental Cost Indicator (ECI) of approximately 25 €/ton over a time horizon of 40 years while the ECI of a PA wearing course equals approximately 35 €/ton over the same time horizon.

7.3. Sustainability

7.3.1. Fuel consumption

The environmental costs due to fuel consumption are affected by the following aspects:

- type of road;
- traffic intensity;
- length of the road section.

The difference of the following aspects will be illustrated with two examples

Example 3

Road type	municipal road
Length:	1 km
Traffic intensity:	
Light weight:	2000 vehicles/day
Moderate – heavy weight:	150 vehicles/day
Motorcycles:	50 vehicles/day
Mopeds:	20 vehicles/day
Growth rate per year:	2 %

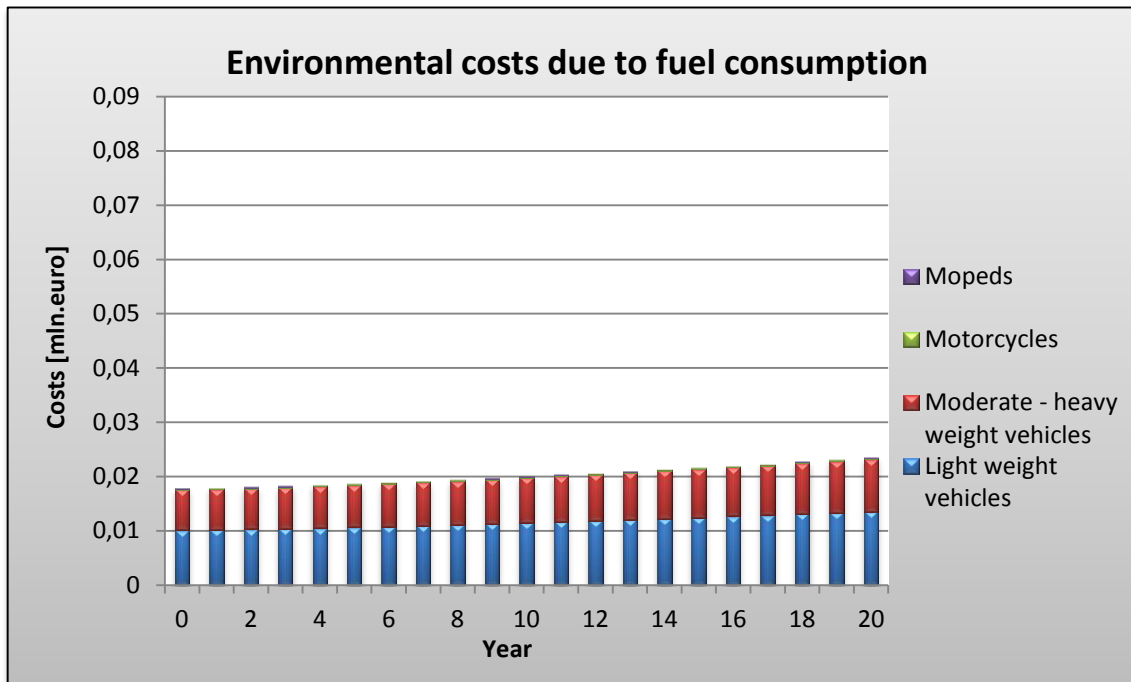


Figure 7.5 Environmental costs due to fuel consumption (e.g. 3)

Figure 7.5 exhibits that the contributions of the moderate – heavy weight vehicles and the light weight vehicles are by far the most important ones. The other categories may be ignored. Although the intensity of the moderate to heavy weight vehicles is a factor 10 smaller than that of the light weight vehicles, the environmental costs are not very much different. This means that the moderate – heavy weight vehicles have a higher contribution to the environmental costs than the light weight vehicles.

Example 4

Road type	provincial road
Length:	1 km
Traffic intensity:	
Light weight:	10000 vehicles/day
Moderate – heavy weight:	1000 vehicles/day
Motorcycles:	200 vehicles/day
Mopeds:	0 vehicles/day
Growth rate per year:	2 %

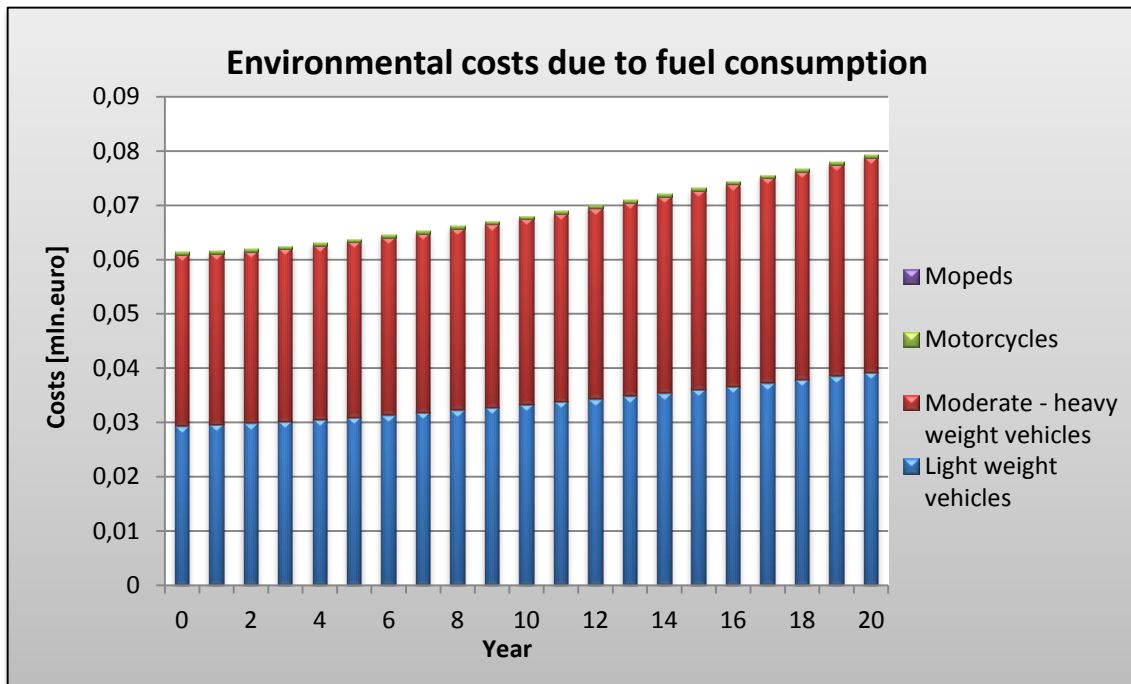


Figure 7.6 Environmental costs due to fuel consumption (e.g. 4)

Figure 7.6 shows that the environmental costs of a provincial road are higher than that of a municipal road. The reason for this is that the intensity on provincial roads is in general higher than that on municipal roads. The emission factors on motorways and provincial roads are in general much lower than the emission factors on municipal roads because on these latter roads drivers are accelerating and decelerating much more because of traffic regulation systems and sharp corners at the beginning of the road.

7.3.2. Noise level

The traffic noise emission level is dependent on the type of wearing course, traffic intensity and the type of road (speed). The environmental costs due to noise emissions are in turn dependent on the noise emissions and the population living nearby. The environmental costs calculation due to noise emissions will be explained by some examples.

Example 5

Road type	municipal road
Length:	1 km
Traffic intensity:	
Light weight:	5000 vehicles/day
Moderate – heavy weight:	250 vehicles/day
Motorcycles:	100 vehicles/day
Mopeds:	50 vehicles/day
Growth rate per year:	2 %
Wearing course	small elements not in herringbone pattern
Age current wearing course	3 years

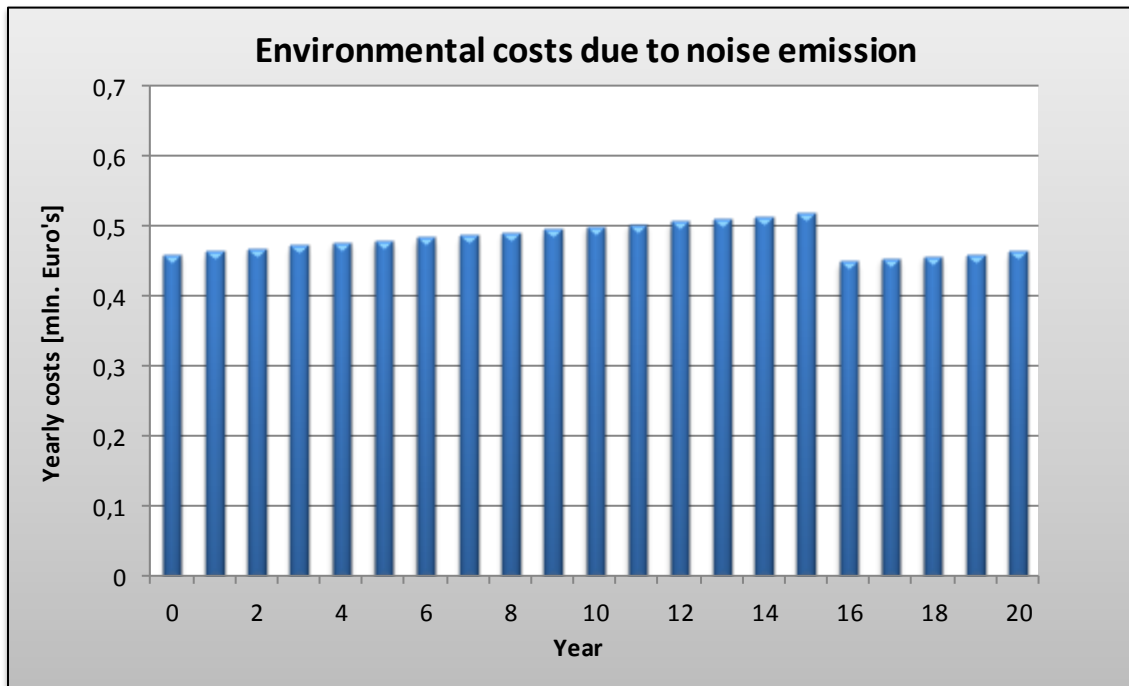


Figure 7.7 Environmental costs due to noise emission (e.g. 5)

Figure 7.7 illustrates that there is a drop in noise level in year 16. This is because of the structural design life of the small element pavement. It is recommended to perform maintenance to the wearing course around that year. Figure 7.7 also shows that the noise emission in year 16 is lower than the noise emission in year 0. The reason for this is that in year 0 the wearing course already has an age of 3 years and is therefore generating more noise under trafficking than a newly constructed wearing course. The difference between example 5 and example 6 is in the type of wearing course. In Example 6 the elements are laid in herringbone pattern, while in Example 5 that was not the case. Figure 7.8 illustrates that the environmental costs due to noise emissions are lower when the elements are laid in

herringbone pattern. The reason for this is that in herringbone pattern the joints are situated under an angle of 45° with the direction of travel.

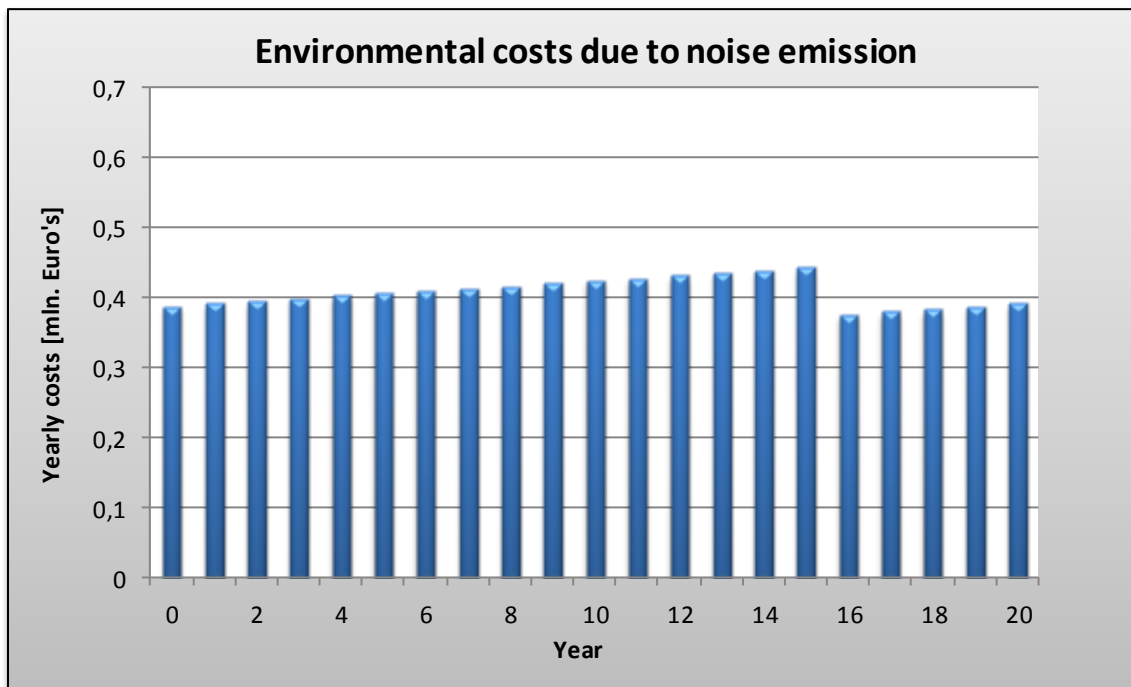


Figure 7.8 Environmental costs due to noise emission (e.g. 6)

Example 7

Road type	motorway
Length:	20 km
Traffic intensity:	
Light weight:	15000 vehicles/day
Moderate – heavy weight:	1500 vehicles/day
Motorcycles:	250 vehicles/day
Mopeds:	0 vehicles/day
Growth rate per year:	0 %
Wearing course	PA
Age current wearing course	0 years

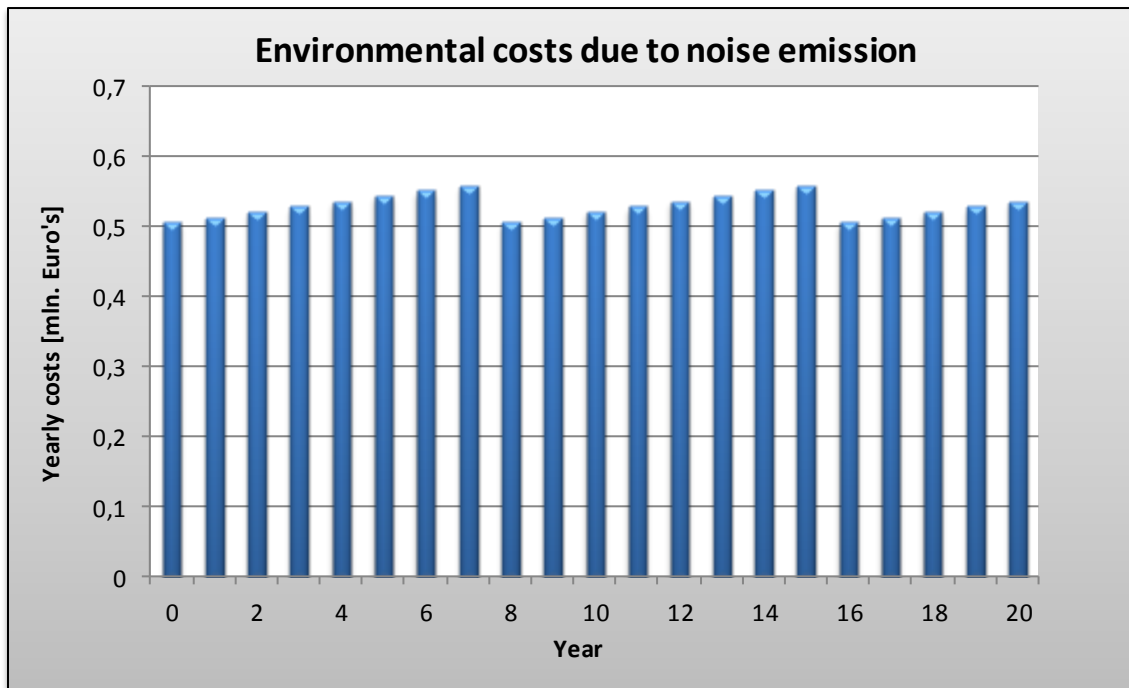


Figure 7.9 Environmental costs due to noise emission of PA – motorways (e.g. 7)

In general the noise emissions of a porous asphalt mix are lower than that of a dense asphalt mix. This is because of the composition of the PA mix. The PA mix is more open graded than the DAC mix, in which the mineral aggregate is continuously graded. The result is more voids in a PA mix. The noise emission will be reduced because of this higher void content, because the voids behave like a noise damper. The disadvantage of the high void content in a porous asphalt mix is the lower structural life of a porous asphalt mix compared to a dense asphalt mix. Due to the voids in a PA mix, moisture can come into contact with the aggregate. This may result in stripping of the aggregate causing the bond between the aggregate and the bitumen get lost. Furthermore, because of the higher void content, the bitumen in porous asphalt ages more rapidly which also reduces the structural life. The damage (mainly ravelling) in older PA occurs especially during winter seasons.

The rate of change of the noise emissions over a long time horizon is higher for a porous asphalt mix than for a dense asphalt mix. The reason for this is the reduction of the damping effect of the voids with time. The voids become clogged with fine dust although fast traffic will act as a vacuum cleaner.

The difference between Example 7 and Example 8 is the type of porous asphalt wearing course. When comparing Figure 7.9 to Figure 7.10 can be concluded that the environmental costs of a twinlayer porous asphalt (PA) are lower than that of a normal porous asphalt mix. The noise emissions of twinlayer PA are lower, because of the fine top layer of the twinlayer PA. The fine top layer of twin layer PA prevents the voids in the PA mix becoming clogged with fine dust.

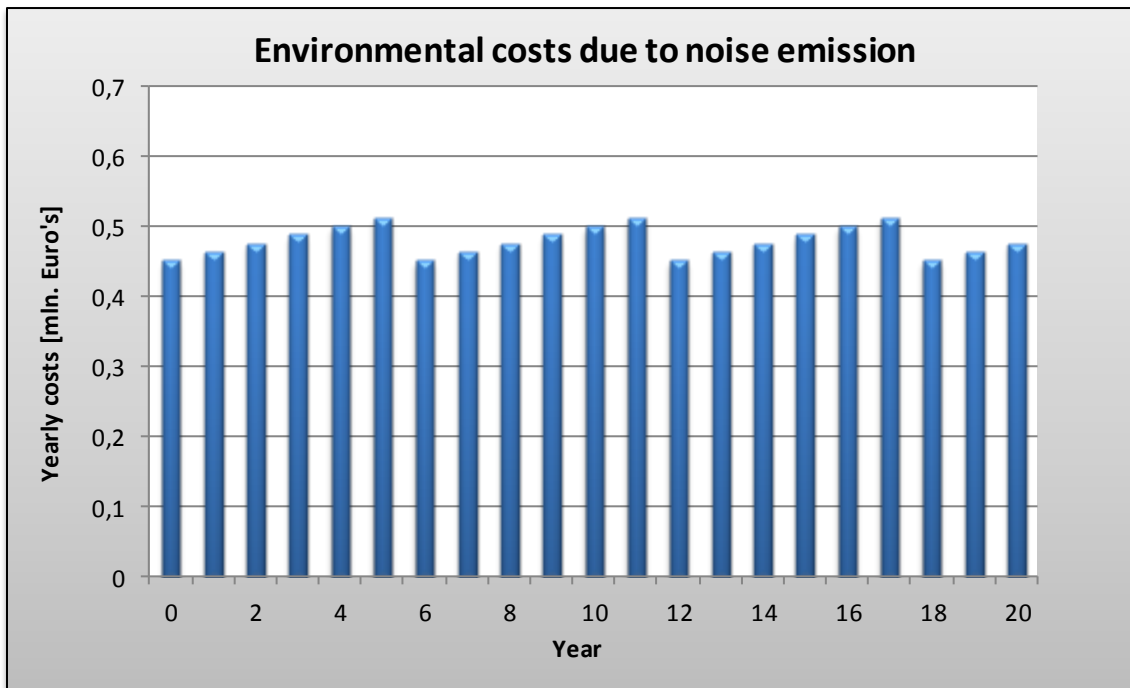


Figure 7.10 Environmental costs due to noise emission PA twinlayer- motorways (e.g. 8)

7.4. Sociality

An important input parameter for the calculation of the social costs due to traffic accidents is the accident rate. The accident rate can be calculated with a traffic safety model associated with the type of road under analysis. Figure 7.11 shows the social costs due to accidents for an accident rate that is calculated with the traffic safety model for motorways. The accident rate that is calculated with this model is elaborated in Appendix B.

Figure 7.11 and Figure 7.12 illustrate that the social costs due to a fatal accident have the highest contribution to the aggregated value of the social costs. The category hospital victims has the second highest contribution on the social costs.

The number of accidents is important for the calculation of the social costs due to accidents. This number can be calculated from the accident rate, the traffic intensity and the length of a specific road section. An increasing number of vehicle kilometres will lead obviously to a rising number of accidents and higher social costs due to the accidents. In example 9 the length and the traffic intensity of the road section are twice as high than those in example 10. When the accident rate remains the same for both examples the social costs due to the accidents will be four times lower. This is illustrated in Figure 7.11 and Figure 7.12.

Example 9

Length: 100 km
 Intensity
 Light weight: 10000 vehicles/day
 Moderate – heavy weight: 1500 vehicles/day

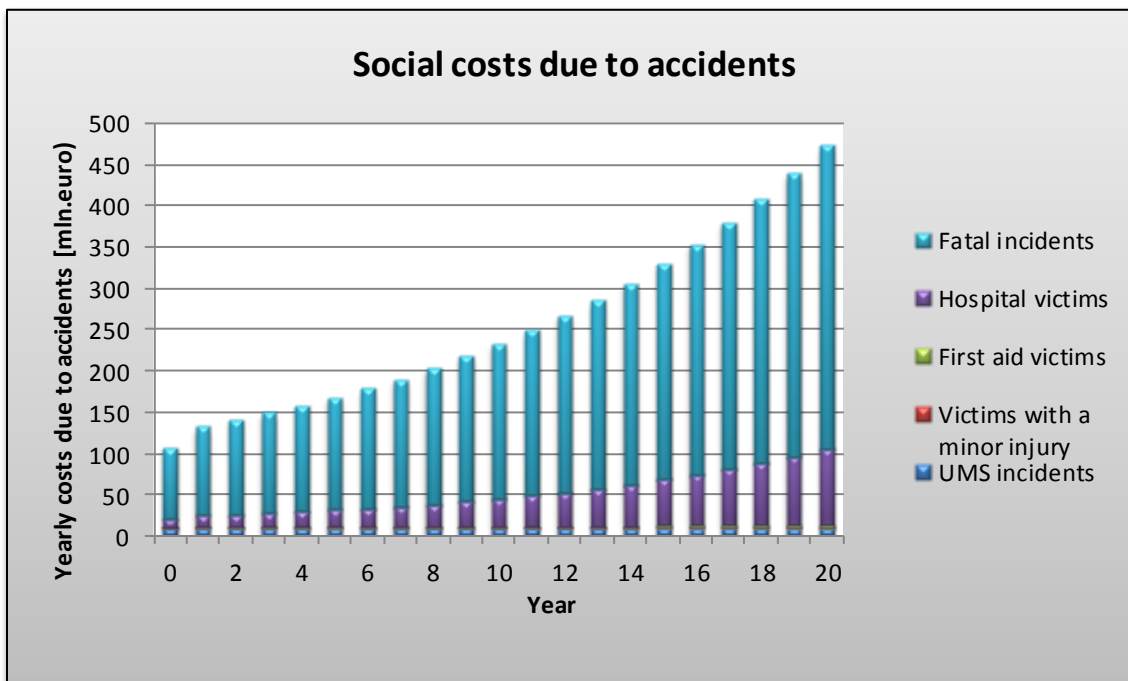


Figure 7.11 Social costs due to accidents (e.g. 9)

Example 10

Length: 50 km
Intensity
Light weight: 5000 vehicles/day
Moderate – heavy weight: 750 vehicles/day

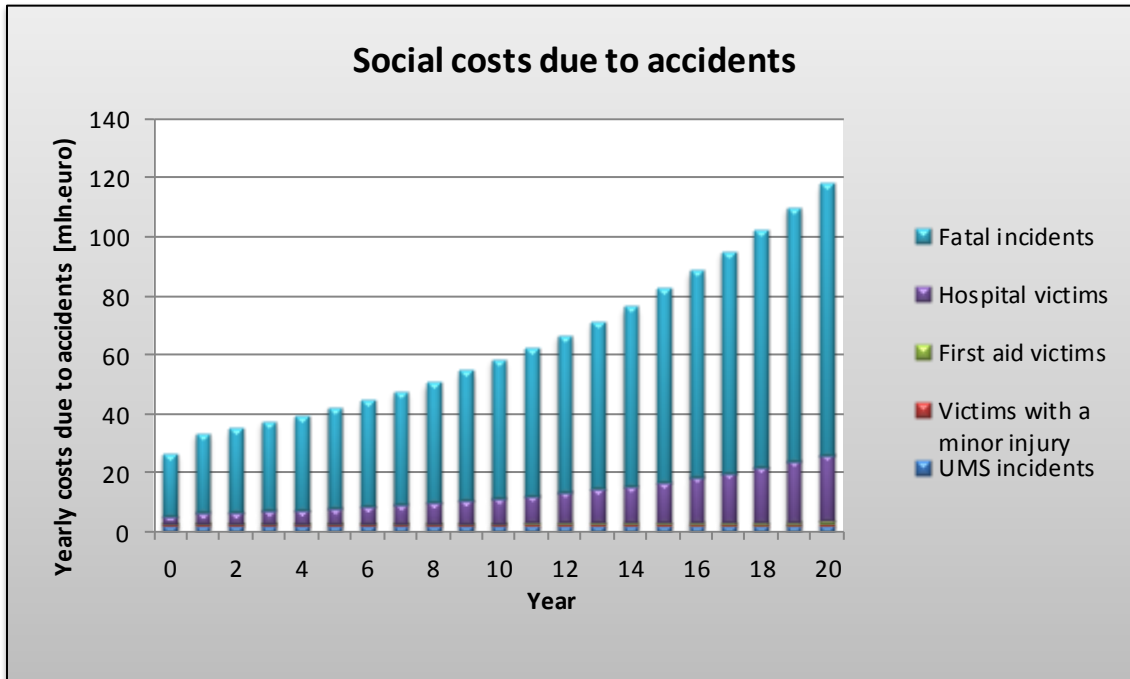


Figure 7.12 Social costs due to accidents (e.g. 10)

PART IV: FINAL ASSESSMENT

The last part of the research programme is the final assessment. The final assessment addresses the main conclusions in chapter 8 and looks back whether the original objectives have been reached. The assessment ends in chapter 9 with several recommendations for further research efforts based on the study that was performed in the framework of this thesis. The conclusions and recommendations cover both the traffic safety on municipal roads as well as the environmental issues and the social impact of pavements.

8. Conclusions

8.1. Traffic safety on municipal roads

The first part of the research presented in this thesis consisted of the development of a program for predicting the traffic safety on municipal roads.

Traffic safety on motorways is in general mainly dependent on the friction between tyre and pavement surface. The alignment of dual carriageways usually does not contain sharp bends. This implies that skid resistance of the pavement surface may be seen as the key for controlling and improving traffic safety (apart from improvement measures in the domain of the cars, trucks and drivers). Measurements of skid resistance on municipal roads are not very popular yet. This implies that the literature about the relationship between traffic safety and skid resistance on municipal roads was limited. The risk for an accident is different for the three types of municipal roads specified in this thesis. The relationship between the traffic safety and skid resistance has been developed for the three types of municipal roads based on the accident rate on these roads in correlation with the progress of the relationship between the skid resistance and traffic safety on provincial roads. The situation on municipal roads is completely different. The traffic speed is lower, various modes of road traffic make use of the road, the dependency of the various modes of road traffic on the skid resistance, crossings allow traffic from the side stream to intersect the main stream, some bends force traffic to slow down. This complex of influence factors was investigated in the first part of the thesis.

The goal was to develop a tool that would predict the number of accidents on municipal roads with critical road aspects as input parameter. The research actions resulted in a program that predicts the traffic safety on municipal roads in the Netherlands not only based on road surface properties but also on traffic engineering aspects such as crossings, roundabouts, and bends.

The study results in some interesting conclusions on both topics namely:

- the risk on an accident on a straight stretch of a dual carriageway is lower than on a straight stretch of a single carriageway. On dual carriageways all the traffic travels in one direction avoiding risks for an accident with oncoming traffic.
- the presence of crossings plays an instrumental role in the number of traffic accidents. The proportional influence of a crossing on the total number of accidents on a straight stretch of a dual carriageway is higher than on single carriageways. This negative effect is usually limited due to the in general lower number of crossings on dual carriageways.
- bends on dual carriageways are in general wider (less sharp). This implies that the risk for an accident is lower.
- winding sections have a relatively small effect on the traffic safety on municipal roads, the contribution of crossings appears to be of more importance;
- the effect of bends on the traffic safety is lower for wearing courses with a good skid resistance performance. The higher skid resistance leads to a better friction

performance of a driving vehicle when taking a turn (too fast). In other words, the high skid resistance level contains some spare traffic safety.

- skid resistance is the main and actually the only road surface property that contributes to the traffic safety on a road with slow speed regime from a structural point of view. The higher the skid resistance, the lower the accident rate will be. The proportional effect in the total number of accidents increases with increasing nominal speed.
- mineral aggregates with high polished stone values provide an overall better skid resistance performance over time and are therefore to be preferred for reasons of traffic safety. In everyday practice, however, aggregates with high polished stone values usually need to be imported, are more expensive and are only applied in heavily trafficked routes.
- the distribution of the different modes of transport (cars, bicycles, mopeds, etc.) has an effect on the distribution on the fast traffic accidents and other types of accidents. Higher percentages bicycles in a province result in higher percentages other traffic accidents. The differences in other traffic accidents may vary approximately 15% among provinces. On single carriageways where bicycle are allowed, the number of bicycle accidents is higher than on carriageways closed for slow traffic.

The first part of the research programme resulted in a tool that predicts the number of injury accidents on municipal roads in the Netherlands. The tool distinguishes between fast and slow/other traffic. The default distribution between the accidents of these two modes of transport is based on intensity statistics collected per province in the Netherlands. The developed program can be used by road engineers, contractors, road authorities and city councils. Road engineers can also use this program in their decisions about which type of wearing course should be applied from a traffic safety point of view.

8.2. Environmental and social impact of pavements

The second part of the thesis addresses the development of a tool for predicting the environmental and social impact of pavements. The main focus was on the environmental and social costs related with the critical road aspects. The conclusions of this part are listed in two main categories. The first category contains the conclusions related to the environmental impact of pavements. In this category the environmental impact due to noise emissions, emissions due to consumed fuel and the emissions due to the production of road building materials are described. The second category of conclusions encompasses the conclusions related with the social costs that occur due to traffic accidents.

Environmental impact of pavements:

- the choice for a type of wearing course in a pavement design depends on many factors. The wearing course may be selected for reasons of durability by looking at the type of road that is to be designed and the time horizon over which the wearing course must function. The structural life of the wearing course is therefore very important. The structural life of a porous asphalt wearing course is shorter than that of a dense asphalt wearing course. Therefore the maintenance cost will be higher for the porous asphalt wearing course. By only looking at durability aspects dense asphalt will be a better choice than porous asphalt over a time horizon of more than 20 years.
- on the other hand, a porous asphalt mix has a better traffic noise performance than a dense asphalt mix. This implies that the environmental costs due to noise emissions will be lower for a porous asphalt mix than for a dense asphalt mix.
- municipal roads that are constructed with burnt bricks perform better than municipal roads with concrete blocks from a durability point of view. The functional life of burnt bricks is 40 years while that of concrete blocks is limited to only 25 years. If the time

horizon for which the road is constructed is larger than twenty five years, burnt bricks may have lower maintenance costs and is therefore a better choice. The wear of the concrete is higher than that of the burnt bricks making concrete blocks less suitable for re-use. Another drawback of concrete blocks is their decay of colour over time.

- the noise emissions of pavements with a wearing course of small elements is mainly dependent on the way the elements are laid. Block pavements laid in herringbone bond have lower noise emissions than pavements laid in stretcher bond, basket weave or similar patterns. Elements in herringbone bond are laid under a 45 degrees angle with the direction of travel and therefore produce less noise. Lower noise emissions result in lower environmental costs.
- the emission factors of pollutants due to fuel consumption are lower on motorways than on municipal road. On municipal roads drivers accelerate and change speed more often because of traffic controlling systems. Therefore, more fuel will be burnt. This results in higher environmental costs per vehicle kilometre on municipal roads than on motorways.

Social impact of pavements:

the social costs due to traffic accidents depend strongly on the severity of the accident. Fatal accidents and accidents with hospital victims are the type of accidents with the highest contribution to the social costs due to traffic accidents.

The study of the environmental and social impact of pavements resulted in a prediction tool balancing between the durability, sustainability and sociality of pavements based on a cost estimation. The developed tool can be used by road engineers in their decisions making process on environmental and social aspects in a pavement construction or reconstruction project.

9. Recommendations

9.1. Traffic safety on municipal roads

The skid resistance of the wearing course is an important instrument for improving traffic safety. The change of skid resistance over time has been determined for various asphalt mixes and mineral aggregates in the wearing course. Studies reporting on this issue do not forecast the change of skid resistance for all wearing courses that may be applied to municipal roads. Better understanding of the change of the skid resistance for most types of wearing courses is therefore recommended (e.g. skid resistance measurements on thin coatings, surface treatments and small elements (burnt bricks and concrete blocks)).

The effect of the skid resistance on crossings is not taken into account in the framework of this thesis. Also the distribution of the fast traffic accidents and other types of accident on crossings is not taken into account in this study. Implementation of these aspects is recommended to make this program more valuable.

The proportion fast traffic accidents and other traffic accidents is distinguished per province in this study irrespective of the type of municipal road. However, the proportion other traffic accidents on a single carriageway closed for slow traffic will be lower than on a single carriageway on which slow traffic is allowed. The program can be extended by taking into account the differences in proportion of other traffic accidents for each of the three types of municipal carriageways that have been considered.

In this study the influence of bends on traffic accidents has been derived from data and models from previous studies describing the relationship between the traffic safety and skid resistance in different road situations on motorways. The bend ratio on municipal roads is determined by correlating the traffic safety on a straight section of a motorway with that of a bending interchange. To make the developed program more accurate the influence of bends on municipal road sections should be investigated into much more detail.

9.2. Environmental and social impact of pavements

The environmental aspects that have been taken into account in this model are the main environmental aspects of the paving industry. These aspects are not all the environmental aspects that are related to the paving industry. Additional research of other environmental aspects is highly recommended to extend the applicability of the model. The shadow price of fine dust is one of the highest shadow prices because of the hazardous effect that fine dust has on human health. For this reason, extending this model by studying the different fine dust (PM_x) emissions in the paving industry is highly recommended. The fine dust emissions due to wear of vehicles tyres can be studied, but also the fine dust that is emitted due to construction of the road is of importance.

The environmental costs of the materials that are used in the substructure of the pavement construction are not taken into account. The developed program is restricted to maximum two wearing courses. To make the developed program more valuable the environmental impact of the materials that are used in the substructure could be investigated and taken into account as well.

References

Books and reports:

- Bicycle commission (2011). *Grip on bicycle accidents with vehicles*. Utrecht.
- CE (2003). *Environmental effects of salt reprocessing*. Delft.
- CE (2010). *Shadow price handbook, Valuation and weighting of emissions and environmental impacts*. Delft.
- CROW (2004). *C_{road surface} 200 for traffic noise*. Ede. Publication nr. 200.
- CROW (2005). *Traffic safety aspects in relation with road surface properties*. Ede. Report nr. 05-03
- CROW (2010). *Silence road surfaces*. Ede. Publication nr. 287.
- CROW (2012). *The road surface correction factor for noise of road traffic*. Ede. Publication nr. 316.
- EAP and Eurobitume joint task group fuel efficiency (2004). *Environmental impacts and fuel efficiency of road pavements*.
- Elling, R., Andeweg, B., Jong de J. & Swankhuisen, C. (2004). *Reporting technique*. Groningen: Noordhof publishers.
- Gaarkeuken, G., Groenendijk, J. & Gerritsen, W. (2006). *Skid resistance in relation with the mix composition and the characteristics of the mineral aggregates*. Apeldoorn. Report nr. e0500614.
- Groenendijk, J. (2013); *The relationship between skid resistance and traffic safety*. Apeldoorn
- Groenendijk, J. (2014). *RE. Personal communication*. Apeldoorn, KOAC-NPC
- Gurp, C.van (2014). *RE: Personal communication*. Apeldoorn, KOAC-NPC.
- Haas, M., Sminia, M. & Groot, M. (2010). *Functional specification DuboCalc*.
- HEATCO (2006). *Developing Harmonised European Approaches for Transport Costing and project assessment; Economic values for key impacts valued in the Stated Preference surveys*. Norway
- Houben, L.J.M. & Molenaar, A.A.A (2010); *Roads and Railways*. Delft
- Jonker, H (2013). *CIE 4000 Materials and Ecological Engineering lecture notes*. Delft
- Koos Spee (2014). *Speaker on the VNMG conference 'Road and Safety'*
- MIRA (2009). *Actualisation of the emission model for road traffic*.
- Mobility & Public works (2012). *The influence of traffic management on emissions*.
- Molenaar, A.A.A. (2010). *Asphaltic materials*.

- Nes, R. van, Sanders, F.M., Lint, J.W. van & Wiggenraad P.B., (2010). *CT 2710, Transport & planning. Delft.*
- NOA (2007). *New design guideline for motorways.* Nijkerk: Van de Ridder bv.
- RDW (2012). *Handbook fuel consumption.*; The Hague, Netherlands.
- Scarpas, A. (2013). *Lecture slides pavement design.*
- Silva, M. da (2013). *The relation between road surface properties and environmental aspects.* Rotterdam.
- Sookram R. & Kistow B. *Capital Budgeting and Corporate Responsibility.*
- SWOV (1974). *Traffic accidents en skid resistance.* Leidschendam.
- SWOV (1997a). *Risk indicators distinguished to road type.* Leidschendam. Report nr. R-96-62.
- SWOV (1997b). *Risk indicators of roads in urban areas.* Leidschendam. Report nr. R-96-64.
- SWOV (1998). *Orientation on quantitative relations between road design aspects and indicators for traffic safety.* Leidschendam. Report nr. R98-49.
- SWOV (2002). *Safety standards for road design and redesign.* Leidschendam.
- SWOV (2004) . *Safety on crossings on roads in urban areas.* Leidschendam. Report nr. R-2003-36.
- SWOV (2005). *Costs of traffic safety.* Leidschendam.
- SWOV (2007). *Balance of traffic safety in the Netherlands.* Leidschendam.
- SWOV (2014). *Factsheet, cost of accidents.* Leidschendam.
- Task group traffic and transport project group emission registration (2007). *Methods for the calculation of Mobile Sources*
- TNO (2007). *Skid resistance measurements: relationship between test speed of 50 km/h and 70 km/h.*
- TNO/CE (2012). *Fuels for road traffic, characterisation and perspectives.* Delft.
- Vromans, E., & Ven, D. van der. (2014). *RE: Personal communication.* Apeldoorn, KOAC-NPC.
- Wang, Y. *Performance Assessment of cement- based materials blended with micronized sand: microstructure, durability and sustainability.* Delft

Web Sources:

<http://www.gwwmaterialen.nl/asfalt-gegevens/>

<http://statline.cbs.nl/StatWeb/publication/?DM=SLNL&PA=7063&D1=36-39&D2=0-8&D3=I&VW=T>

<http://statline.cbs.nl/StatWeb/publication/?DM=SLNL&PA=80211NED&D1=2&D2=0&D3=a&D4=a&D5=I&VW=T>

Appendix A

Bends

The design value of the bend radius is dependent on the vehicle speed and the minimum sight distance when approaching the bend. The sight distances for different speeds are listed in Table A 1 [NOA, 2007]. This table illustrates that when the speed gets higher the required sight distance must increase. The decisive sight distance for the calculation of the bend radius is 70 m on municipal roads. The bend radius can be determined using Figure A. 1 when the critical sight distance and the restrictive sight distance due to an object in the bend are known.

Table A 1 Summary of sight distances for different speeds [NOA, 2007]

ontwerp-snelheid	toetsing alle wegvakken			alleen plaatselijke toetsing	
	rijzicht: wegverloop continue situatie (m)	stopzicht: zicht op stilstaande file (m)	uitwijkzicht: zicht op obstakel op één strook (m)	discontinuïteit strookbeëindiging (m)	discontinuïteit onverwacht krappe horizontale boog (m)
120 km/h	165	260	235	500	zie figuur 7-2 waarin R_{hor} = de straal van de boog krappe boog
100 km/h	135	170	190	415	
80 km/h	105	105	145	335	
50 km/h	45	40	70	210	

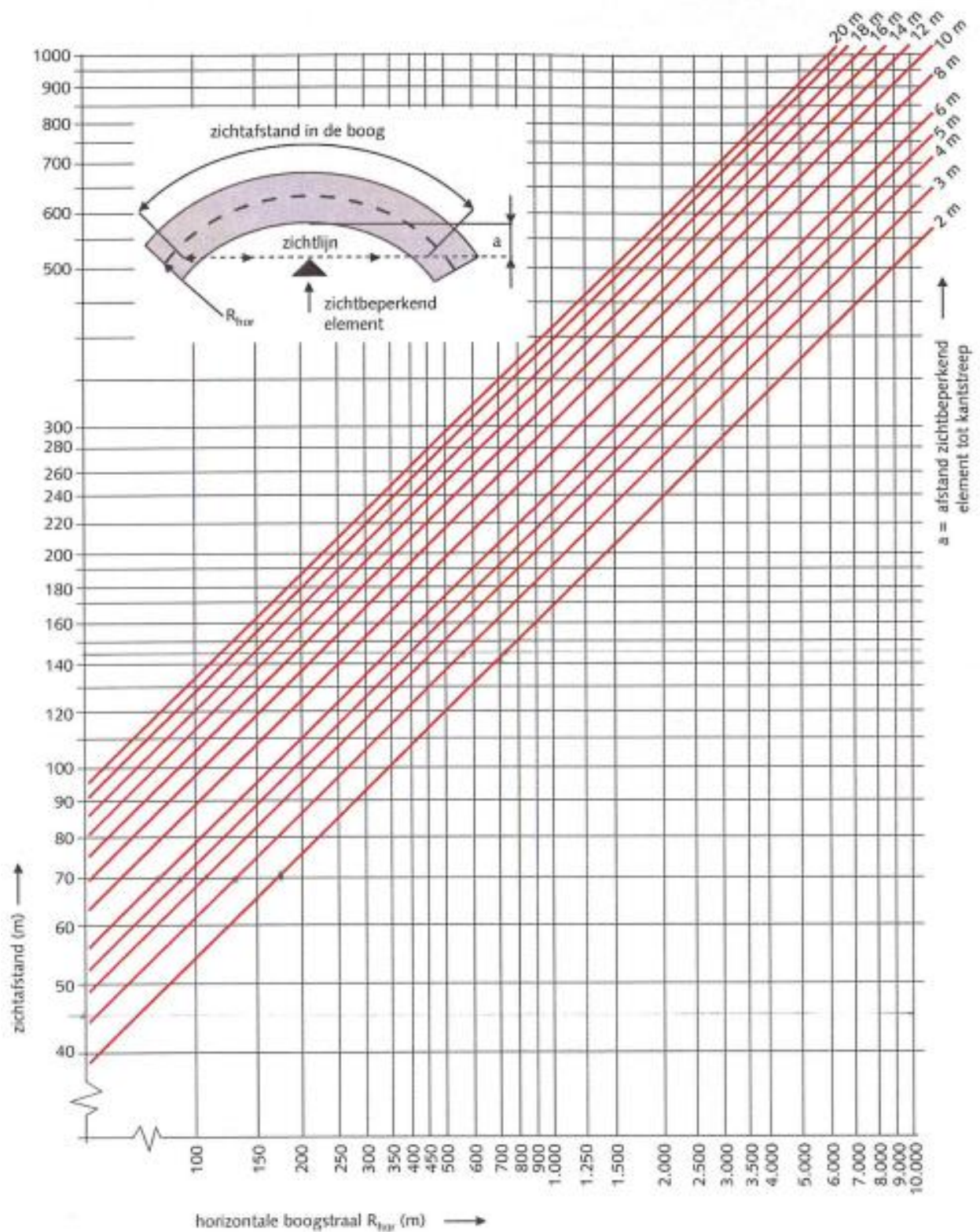


Figure A. 1 Relationship between the sight distance and the bend radius [NOA, 2007]

For the sake of this research programme the bend radius is determined with Figure A. 1 for two restrictive sight distances due to an object ($a=2$ and $a=4$). The bend length is correlated to the bend radius specifically under the assumption, the nominal speed are nearly constant and bend angles in a road do not vary much. Therefore, the bend length is indirectly

dependent on the vehicle speed and the sight distance when approaching the bend. The bend length is calculated for three different bend angles (22.5°, 33,75° and 45°). The bend radius and bend lengths are listed in the table below.

Table A 2 Bend lengths for different bend angles and different sight distances

Bend angle α [°]→				22.5	33.75	45.00
Speed [km/h]	Sight distance [m]	line of restrictive sight to object	Bend radius [m]	Bend length [m]	Bend length [m]	Bend length [m]
120	260	2	2300	902.75	1354.13	1805.5
100	190	2	1250	490.63	735.94	981.25
80	145	2	725	284.56	426.84	569.13
50	70	2	175	68.69	103.03	137.38
120	260	4	1500	588.75	883.13	1177.50
100	190	4	875	343.44	515.16	686.88
80	145	4	460	180.55	270.83	361.10
50	70	4	115	45.14	67.71	90.28

A relationship between the bend length and vehicle speed is developed on the basis of four data points, namely 50 km/h, 80 km/h, 100 km/h and 120 km/h. The bend length is calculated for different angles (α) of connecting roads and for two distances of the line of the restrictive sight due to object in the bend ($a=2$ and $a=4$). The developed relationships of the bend lengths and vehicle speeds are illustrated in Figure A. 2. The higher the bend angle is, the higher the bend length will be. Shorter distances of the restrictive sight due to an object in the bend require higher bend radii resulting in higher required bend lengths. Figure A. 2 illustrates the bend length is higher for higher speeds, this is also according to expectations.

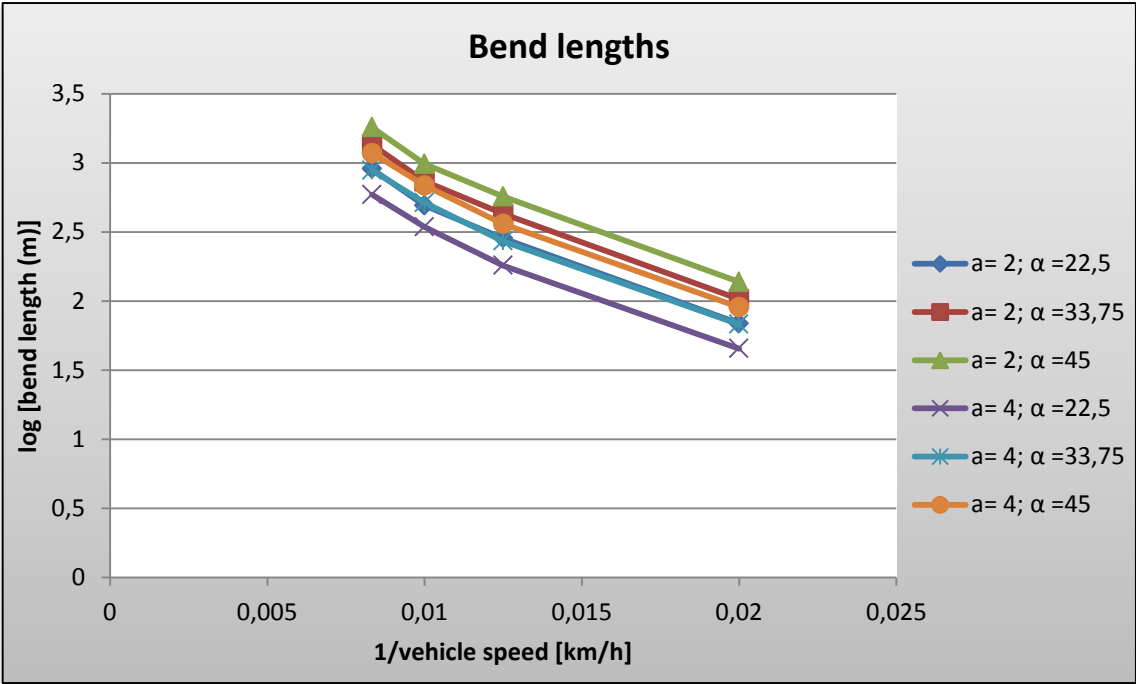


Figure A. 2 Relationship between bend length and vehicle speed

The relationship between the bend length and vehicle speed is illustrated in Figure A. 2. The equation that describes this relationship is:

$$\log (L_b) = \frac{a}{v} + b \quad (\text{Eq. 56})$$

where:

- L_b = bend length [m]
- V = speed [km/h]
- a, b = regression coefficient based on the bend angle and the restrictive sight distance due to object [-]

The minimum required bend length to fulfil the requirement of the sight distance can now be calculated with the developed relationship between the bend length and the vehicle speed

The bend length to be assigned to a bend with speed reduction is assumed to be the difference between the bend length based on the speed before the speed reduction minus the bend length based on the speed after the speed reduction. In equation form this is:

$$L_{min} = L_{b,b} - L_{b,a} \quad (\text{Eq. 57})$$

where:

- L_{min} = minimum required bend length [m]
- $L_{b,b}$ = bend length based on speed before speed reduction [m]
- $L_{b,a}$ = bend length based on speed after speed reduction [m]

The minimum required bend length is dependent on the speed limit that is allowed on the road and speed reduction of the road user due to the bend. The speed limit on the main municipal roads is 50 km/h. In this study a fixed numeric value of 55 km/h is assumed as the speed before speed reduction ($L_{b,b}$). The calculation procedure of the numeric values of the minimum required bend length is listed in Table A 3. The analysis has been performed for 4 cases with different bend angles and different restrictive distances due to object in the bend. The equivalent ratios for the 4 cases are also listed in Table A 3. The equivalent ratio is for all the cases calculated for a road section of 2000 m with one bend for each speed reduction (5, 10 and 15 km/h). The highest equivalent ratio is calculated for a bend angle of 45° and a restrictive sight distance to object of 2 m. This is the worst situation according to traffic safety in winding sections. Therefore, in this study the minimum required bend lengths are calculated by assuming an bend angle of 45° and a restrictive sight distance to object of 2 m.

Table A 3 Calculation sheet for the minimum required bend length

Situation	a= 2; $\alpha =22.5$			a= 4; $\alpha =22.5$			a= 4; $\alpha =45$			a= 2; $\alpha =45$		
Initial vehicle speed [km/h]	55			55			55			55		
log (bend length [m])	1.875			1.798			2.10			2.278		
Bend length initial speed [m]	74.914			62.823			125.637			189.806		
Speed reduction [km./h]	5	10	15	5	10	15	5	10	15	5	10	15
Speed in bend	50	45	40	50	45	40	50	45	40	50	45	40
log (bend length [m])	1.70	1.486	1.22	1.63	1.424	1.166	1.931	1.725	1.467	2.111	1.906	1.651
Bend length after speed reduction [m]	50.109	30.652	16.583	42.621	26.526	14.664	85.235	53.049	29.326	129.104	80.608	44.738
Minimum bend length [m]	24.805	44.262	58.332	20.202	36.297	48.159	40.402	72.588	96.311	60.702	109.198	145.068
Regression coefficients [-]	a		b	a		b	a		b	a		b
	3.621		-96.054	34.831		-92.674	37.841		-92.674	3.952		-92.053
Equivalent bend ratio r_eq	1.006			1.005			1.009			1.015		

Province traffic distribution

The percentages fast traffic accidents ($P_{\text{fast acc.}}$) and other traffic accidents ($P_{\text{other acc.}}$) are retrieved from Figure 3.6. With this accident distribution on national scale as basis, a proportional distribution of fast traffic and other traffic accidents was made on provincial scale. The data of the analysis are retrieved from the Central Bureau of Statistics (CBS).

Table A 4 Accident distribution on national scale

	Average accidents distrib. (national) [%]
Fast traffic	64.33
Other traffic	35.67

The total vehicle movements in a specific area is dependent on the density of the population of that area, the movements of each person and the distance of the movements of that person. In equation form this is described as follows:

$$VM = P_d * M_p * D_p \quad (\text{Eq. 58})$$

where:

- VM= total vehicle movements [veh.mov./km.day]
- P_d = population density [persons/km²]
- M_p = movements of each persons per day [veh.mov./persons.day]
- D_p = distance of each person per day [km]

The vehicle movements per province are divided with the average vehicle movements in the Netherlands. This proportion gives an indication of the vehicle volume of the provinces compared to the average vehicle volume in the Netherlands. A province with a ratio higher than one is a province with a high vehicle intensity. In the provinces Utrecht, North-Holland, South-Holland and Limburg the vehicle movements are higher than the average vehicle movements in the Netherlands. (see Table A 5).

$$PR_{vm} = VM_P / VM_N \quad (\text{Eq. 59})$$

where:

- VM_P = provincial vehicle movements [veh.mov./km.day]
- VM_N = average vehicle movements in the Netherlands [veh.mov./km.day]
- PR_{vm} = proportion vehicle movements per province [-]

The proportion of the fast traffic accidents per province is calculated by multiplying the proportion of vehicle movements per province with the national percentage of fast traffic accidents (Table A 4).

$$PR_{\text{FAST acc. prov.}} = PR_{\text{VM}} * P_{\text{fast acc.}} \quad (\text{Eq. 60})$$

where:

- PR_{VM} = proportion vehicle movements per province [-]
 $P_{\text{fast acc.}}$ = average national percentage fast traffic accidents [%]
 $PR_{\text{FAST acc. prov.}}$ = proportion fast traffic accidents per province [%]

The percentage fast traffic accidents per province is calculated by taking into account the proportion of the fast traffic accidents and the other traffic accidents per province. The sum of the percentages fast and other traffic accidents should be 100% per province. The numeric values are listed in Table A 5.

$$P_{\text{FAST acc. prov.}} = PR_{\text{FAST acc. prov.}} / (PR_{\text{FAST acc. prov.}} + PR_{\text{OTHER acc. prov.}}) \quad (\text{Eq. 61})$$

where:

- $PR_{\text{FAST acc. prov.}}$ = proportion fast traffic accidents per province [%]
 $PR_{\text{OTHER acc. prov.}}$ = proportion other accidents per province [%]
 $P_{\text{FAST acc. prov.}}$ = percentage fast traffic accidents per province [%]

Table A 5 Fast traffic accident distribution on provincial scale

Vehicle intensity analysis	Population [aantal/km ²]	Vehicle movements of each person per day	Distance of each person per day [km]	Vehicle movements per km per day	Proportion vehicle movements [-]	Proportion fast traffic accidents [%]	Percentage fast traffic accidents [%]
Netherland	496.35	0.89	15.63	6904.51			
Groningen	249.53	0.79	14.42	2842.63	0.41	26.38	58.02
Friesland	193.73	0.93	17.86	3217.75	0.47	30.24	69.05
Drenthe	185.5	0.94	20.15	3513.6	0.51	32.81	71.87
Overijssel	342.43	0.94	16.73	5385.08	0.78	50.18	66.3
Gelderland	405.13	0.92	17,00	6336.24	0.92	59.18	67.74
Flevoland	280.71	0.94	17.86	4712.74	0.68	43.74	76.11
Utrecht	897.59	0.83	15.66	11666.68	1.69	108.72	57.37
Noord - Holland	1018.26	0.8	14.35	11689.59	1.69	108.72	56.99
Zuid - holland	1253.15	0.77	13.47	12997.57	1.88	120.94	56.74
Zeeland	213.32	0.93	17.29	3430.11	0.5	32.17	70.63
Noord - Brabant	502.48	1.02	16.68	8548.97	1.24	79.77	70.19
Limburg	521.62	1.07	15.69	8757.11	1.27	81.7	72.13

The total bicycle movements in a specific area is dependent on the density of the population of that area, the bicycle movements of each person and the distance of the movements of that person. In equation form this is described as follows:

$$BM = P_d * M_p * D_p \quad (\text{Eq. 62})$$

where:

BM= total bicycle movements [veh.mov./km.day]

P_d = population density [persons/km²]

M_p = movements of each persons per day [veh.mov./persons.day]

D_p = distance of each person per day [km]

The bicycle movements per province are divided with the average bicycle movements in the Netherlands. This proportion gives an indication of the bicycle volume of the provinces compared to the average bicycle volume in the Netherlands. A province with a ratio higher than one is a province with a high bicycle intensity. In the provinces Utrecht, North-Holland and South-Holland the bicycle movements are higher than the average bicycle movements in the Netherlands (see Table A 6).

$$PR_{BM} = BM_p / BM_N \quad (\text{Eq. 63})$$

where:

BM_p = provincial bicycle movements [veh.mov./km.day]

BM_N = average bicycle movements in the Netherlands [veh.mov./km.day]

PR_{BM} = proportion bicycle movements per province [-]

Table A 6 Bicycle intensity analysis

Bicycle intensity analysis	Population [aantal/km ²]	Bicycle movements of each perosn per day	Distance of each person per day [km]	Bicicycle movements per km per day	Proportion bicycle movements [-]
Nederland	496.35	0.7	2.47	858.18	
Groningen	249.53	0.8	2.81	560.95	0.65
Friesland	193.73	0.8	2.5	387.45	0.45
Drenthe	185.5	0.73	2.7	365.63	0.43
Overijssel	342.43	0.86	2.8	824.57	0.96
Gelderland	405.13	0.75	2.58	783.93	0.91
Flevoland	280.71	0.56	1.72	270.38	0.32
Utrecht	897.59	0.82	2.92	2149.19	2.5
Noord - Holland	1018.26	0.73	2.49	1850.89	2.16
Zuid - holland	1253.15	0.65	2.4	1954.92	2.28
Zeeland	213.32	0.67	2.41	344.45	0.4
Noord - Brabant	502.48	0.66	2.42	802.56	0.94
Limburg	521.62	0.48	1.75	438.16	0.51

The pedestrian movements in a specific area is dependent on the density of the population of that area, the pedestrian movements of each person and the distance of the movements of that person. In equation form this is described as follows:

$$PM = P_d * M_p * D_p \quad (\text{Eq. 64})$$

where:

PM= total pedestrian movements [veh.mov./km.day]
 P_d = population density [persons/km²]
 M_p = movements of each persons per day [veh.mov./persons.day]
 D_p = distance of each person per day [km]

The pedestrian movements per province are divided with the average bicycle movements in the Netherlands. This proportion gives an indication of the pedestrian volume of the provinces compared to the average pedestrian volume in the Netherlands. A province with a ratio higher than one is a province with a high pedestrian intensity. In the provinces Utrecht, North-Holland, South-Holland and Limburg the pedestrian movements are higher than the average pedestrian movements in the Netherlands (see Table A 7).

$$PR_{PM} = PM_P / PM_N \quad (\text{Eq. 65})$$

where:

VM_P = provincial pedestrian movements [veh.mov./km.day]
 VM_N = average pedestrian movements in Netherlands [veh.mov./km.day]
 PR_{vm} = proportion pedestrian movements per province [-]

Table A 7 Pedestrian intensity analysis

Pedestrian intensity analysis	Population [aantal/km ²]	Pedestrian movements of each person per day	Distance of each person per day [km]	Pedestrian movements per km per day	Proportion pedestrian movements [-]
Nederland	496.35	0.5	0.83	205.98	
Groningen	249.53	0.48	0.72	86.24	0.42
Friesland	193.73	0.45	0.74	64.51	0.31
Drenthe	185.5	0.41	0.78	59.32	0.29
Overijssel	342.43	0.42	0.67	96.36	0.47
Gelderland	405.13	0.48	0.71	138.07	0.67
Flevoland	280.71	0.45	0.74	93.48	0.45
Utrecht	897.59	0.53	0.88	418.64	2.03
Noord - Holland	1018.26	0.53	0.93	501.9	2.44
Zuid - holland	1253.15	0.54	0.88	595.5	2.89
Zeeland	213.32	0.45	0.75	72	0.35
Noord - Brabant	502.48	0.49	0.8	196.97	0.96
Limburg	521.62	0.53	0.94	259.87	1.26

The pedestrians and bicycles are categorised as other traffic. The average of the bicycle and pedestrian movements are the other traffic movements. Table A 8 illustrates that the other traffic movements of the provinces Utrecht, North-Holland and South-Holland are higher than the average in The Netherlands.

The proportion of other traffic accidents per province is calculated by multiplying the average other traffic movements per province with the national percentage of other traffic accidents (Table A 4).

$$PR_{\text{FAST acc. prov.}} = PR_{\text{OM}} * P_{\text{fast acc.}} \quad (\text{Eq. 66})$$

where:

PR_{OM} = proportion other traffic movements per province [-]
 $P_{\text{Other acc.}}$ = average national percentage other traffic accidents [%]
 $PR_{\text{OTHER acc. prov.}}$ = proportion other traffic accidents per province [%]

The percentage other traffic accidents per province is calculated by taking into account the proportion of the fast traffic accidents and the other traffic accidents per province. The sum of the percentages fast and other traffic accidents should be 100% per province.

$$P_{\text{OTHER acc. prov.}} = PR_{\text{OTHER acc. prov.}} / (PR_{\text{FASTt acc. prov.}} + PR_{\text{OTHER acc. prov.}}) \quad (\text{Eq. 67})$$

where:

$PR_{\text{OTHER acc. prov.}}$ = proportion fast traffic accidents per province [%]
 $PR_{\text{OTHER acc. prov.}}$ = proportion other accidents per province [%]
 $P_{\text{FAST acc. prov.}}$ = percentage fast traffic accidents per province [%]

Table A 8 Other traffic accidents on provincial scale

	Proportion bicycle movements [-]	Proportion pedestrian movements [-]	Proportion other traffic [-]	Proportion other traffic accidents [%]	Percentage other traffic accidents [%]
Other traffic					
Nederland					
Groningen	0.65	0.42	0.535	19.08	41.97
Friesland	0.45	0.31	0.38	13.55	30.94
Drenthe	0.43	0.29	0.36	12.84	28.13
Overijssel	0.96	0.47	0.715	25.5	33.69
Gelderland	0.91	0.67	0.79	28.18	32.26
Flevoland	0.32	0.45	0.385	13.73	23.89
Utrecht	2.5	2.03	2.27	80.79	42.63
Noord - Holland	2.16	2.44	2.3	82.04	43.01
Zuid - holland	2.28	2.89	2.59	92.21	43.26
Zeeland	0.4	0.35	0.375	13.38	29.37
Noord - Brabant	0.94	0.96	0.95	33.89	29.82
Limburg	0.51	1.26	0.885	31.57	27.87

Appendix B

Validation of the calculated ECI and the DuboCalc ECI value

The environmental cost index is calculated using the procedure of the Life Cycle Analysis (LCA). This calculated numeric ECI value is compared to the ECI value of DuboCalc. The maximum difference between the calculated ECI value and the DuboCalc value appears to be approximately 5% (Table A 9). The ECI values that are calculated with DuboCalc version 2.2 are copied in Table A 9 and are listed in Table A 10.

Table A 9 Validation of the Calculated MKI (ECI) and the MKI of DuboCalc

	PAC	PAC (+)	PAC twinlayer	SMA	DAC	Burnt bricks	Concrete blocks
Wearing course							
LCA Calculation spreadsheet							
MKI mix (€ / ton)	10.08	10.16	10.15	10.04	6.45	13.77	13.23
DuboCalc							
Bouw MKI (€ / ton)	10.46	10.55	10.54	10.51	6.76	12.88	12.29
MKI end of lifetime (€ / ton)	0.04	0.04	0.04	0.04	0.04	0.81	0.82
MKI waste scenario (€ / ton)	0.02	0.02	0.02	0.02	0.02	0.49	0.49
MKI mix (€ / ton)	10.5	10.59	10.58	10.55	6.8	13.69	13.11
Difference between MKI DuboCalc and calculated MKI (%)	4.00	4.06	4.06	4.83	5.15	0.58	0.92

Table A 10 The MKI values of DuboCalc version 2.2

Burnt Bricks		
Eigenschappen	Omschrijving	Brongegevens
1. Algemeen		
Naam	Straatbaksteen waalformaat	
Materiaal type	Steenachtig	
Afvalscenario	AFV_BU	
Afval Scenario - Einde Levensduur	AFV_EL	
Afval percentage	0 %	
Uitval Percentage	5 %	
Levensduur item (in jaren)	40	
Actuele levensduur (in jaren)	1	
Vervangingen	0	
Primaire hoeveelheid	1	
Primaire eenheid	m2	
2. Transportafstand		
Transportafstand item	50	
3. MKI waarden		
MKI	13,68	
Bijdrage aan variant	100 %	
Bouw MKI	12,88	
Gebruik MKI	0	
Onderhoud MKI	0	
Einde Levensduur MKI	0,81	
MKI onderliggende objecten	13,19	
MKI Afvalscenario	0,49	

Concrete blocks		
Eigenschappen	Omschrijving	Brongegevens
1. Algemeen		
Naam	Betonstraatstenen waalformaat	
Materiaal type	Beton	
Afvalscenario	AFV_BU	
Afval Scenario - Einde Levensduur	AFV_EL	
Afval percentage	0 %	
Uitval Percentage	5 %	
Levensduur item (in jaren)	25	
Actuele levensduur (in jaren)	1	
Vervangingen	0	
Primaire hoeveelheid	1	
Primaire eenheid	m2	
2. Transportafstand		
Transportafstand item	50	
3. MKI waarden		
MKI	13,11	
Bijdrage aan variant	100 %	
Bouw MKI	12,29	
Gebruik MKI	0	
Onderhoud MKI	0	
Einde Levensduur MKI	0,82	
MKI onderliggende objecten	12,62	
MKI Afvalscenario	0,49	

PAC	
Eigenschappen	Omschrijving Brongegevens
1. Algemeen	
Naam	Asfalt (ZOAB)
Materiaal type	Asfalt
Afvalscenario	AFV_BU
Afval Scenario - Einde Levensduur	AFV_EL
Afval percentage	0 %
Uitval Percentage	2 %
Levensduur item (in jaren)	11
Levensduur toegepast (in jaren)	11
Actuele levensduur (in jaren)	1
Vervangingen	0
Primaire hoeveelheid	1
Primaire eenheid	ton
2. Transportafstand	
Transportafstand item	30
3. MKI waarden	
MKI	10,5
Bijdrage aan variant	100 %
Bouw MKI	10,46
Gebruik MKI	0
Onderhoud MKI	0
Einde Levensduur MKI	0,04
MKI onderliggende objecten	10,46
MKI Afvalscenario	0,02

PAC+	
Eigenschappen	Omschrijving Brongegevens
1. Algemeen	
Naam	Asfalt (ZOAB+)
Materiaal type	Asfalt
Afvalscenario	AFV_BU
Afval Scenario - Einde Levensduur	AFV_EL
Afval percentage	0 %
Uitval Percentage	2 %
Levensduur item (in jaren)	15
Levensduur toegepast (in jaren)	15
Actuele levensduur (in jaren)	1
Vervangingen	0
Primaire hoeveelheid	1
Primaire eenheid	ton
2. Transportafstand	
Transportafstand item	30
3. MKI waarden	
MKI	10,59
Bijdrage aan variant	100 %
Bouw MKI	10,55
Gebruik MKI	0
Onderhoud MKI	0
Einde Levensduur MKI	0,04
MKI onderliggende objecten	10,57
MKI Afvalscenario	0,02

PAC twinlayer	
Eigenschappen	Omschrijving Brongegevens
1. Algemeen	
Naam	Asfalt (ZOAB, dubbellaags)
Materiaal type	Asfalt
Afvalscenario	AFV_BU
Afval Scenario - Einde Levensduur	AFV_EL
Afval percentage	0 %
Uitval Percentage	2 %
Levensduur item (in jaren)	8
Levensduur toegepast (in jaren)	8
Actuele levensduur (in jaren)	1
Vervangingen	0
Primaire hoeveelheid	1
Primaire eenheid	ton
2. Transportafstand	
Transportafstand item	30
3. MKI waarden	
MKI	10,57
Bijdrage aan variant	100 %
Bouw MKI	10,54
Gebruik MKI	0
Onderhoud MKI	0
Einde Levensduur MKI	0,04
MKI onderliggende objecten	10,56
MKI Afvalscenario	0,02

SMA	
Eigenschappen	Omschrijving Brongegevens
1. Algemeen	
Naam	Asfalt (SMA, 0/11)
Materiaal type	Asfalt
Afvalscenario	AFV_BU
Afval Scenario - Einde Levensduur	AFV_EL
Afval percentage	0 %
Uitval Percentage	2 %
Levensduur item (in jaren)	16
Levensduur toegepast (in jaren)	16
Actuele levensduur (in jaren)	1
Vervangingen	0
Primaire hoeveelheid	1
Primaire eenheid	ton
2. Transportafstand	
Transportafstand item	30
3. MKI waarden	
MKI	10,55
Bijdrage aan variant	100 %
Bouw MKI	10,51
Gebruik MKI	0
Onderhoud MKI	0
Einde Levensduur MKI	0,04
MKI onderliggende objecten	10,53
MKI Afvalscenario	0,02

DAC	
Eigenschappen	Omschrijving Brongegevens
1. Algemeen	
Naam	Asfalt AC 0/16 Surf D3 (DAB) 0 % PR
Materiaal type	Asfalt
Afvalscenario	AFV_BU
Afval Scenario - Einde Levensduur	AFV_EL
Afval percentage	0 %
Uitval Percentage	2 %
Levensduur item (in jaren)	17
Levensduur toegepast (in jaren)	17
Actuele levensduur (in jaren)	1
Vervangingen	0
Primaire hoeveelheid	1
Primaire eenheid	ton
2. Transportafstand	
Transportafstand item	30
3. MKI waarden	
MKI	6,79
Bijdrage aan variant	100 %
Bouw MKI	6,76
Gebruik MKI	0
Onderhoud MKI	0
Einde Levensduur MKI	0,04
MKI onderliggende objecten	6,78
MKI Afvalscenario	0,02

LCA calculation pavement wearing courses

The emission factors of the different pollutants are listed in Table A 11 for the different type of wearing courses. The table also lists the shadow prices of the pollutants and the structural life of the wearing courses.

Table A 11 Emission of pollutant

			Asphalt mixes					Small elements	
			PA	PA [+]	PA twinlayer	SMA	DAC	Burnt bricks	Concrete blocks
Life time pavement material [year]			11	15	8	16	17	40	25
Bulk density assumption [kg/m ³]			2150	2150	2150	2500	2500	2150	2250
Process	Unit	Prices[€ /kg-eq.]	Emissions (kg-eq/ton)	Emissions (kg-eq/ton)	Emissions (kg-eq/ton)	Emissions (kg-eq/ton)	Emissions (kg-eq/ton)	Emissions (kg-eq/ton)	Emissions (kg-eq/ton)
Photochemical oxidation (smogvorming)	Ethyleen(C2H2)	2	0.043822764	0.043822764	0.043822764	0.049468513	0.026847287	0.023124138	0.023124138
Acidification (verzuring)	SO2-eq	4	0.36486145	0.36486145	0.36486145	0.36646341	0.16034249	0.2366728	0.2366728
Eutrophication (vermesting)	PO4-eq	9	0.07069861	0.07069861	0.07069861	0.068187071	0.024657545	0.052733226	0.052733226
Ozone depletion (aantasting ozonlaag)	CFC-11-eq	30	0.000009	0.000009	0.000009	0.000008	0.000006	0.000004	0.000004
Climate change (broeikaseffect)	CO2-eq	0.05	88.909	88.909	88.909	80.893	57.689	78.955	78.955
Abiotic depletion (abiotische uitputting)	Sb	0.16	0.00004	0.00004	0.00004	0.00005	0.00004	0.0001	0.0001
Human toxicity (humane toxiciteit)	1.4 DB-eq	0.09	18.089	18.089	18.089	19.367	10.779	11.417	11.417
Terrestrial ecotoxicity (ecotoxiciteit terrestisch)	1.4 DB-eq	0.06	0.25555495	0.25555495	0.25555495	0.26652727	0.14631636	0.22930327	0.22930327
Fresh water aquatic eco toxicity	1.4 DB-eq	0.03	0.66500008	0.66500008	0.66500008	0.72332295	0.47672819	0.21327163	0.21327163
Marine aquatic eco toxicity	1.4 DB-eq	0.0001	5684	5684	5684	6507	3762	2219	2219

Noise emissions

The Standard calculation method 1 (SRM1) as described in CROW publication 316 determines a road surface correction factor of a wearing course under consideration and the reference wearing course. The parameters and the correction factors for the different type of wearing course are listed in Table A 12. These correction factors are calculated for the 3 different road types. The initial noise emissions for the different wearing courses are listed in Table A 13.

Table A 12 Correction factors of the type of wearing course

	Lifetime material	Technical lifetime material	σ_m	τ_m	ΔL_m	$v_0(1)$	80	C_roadsurface.m			C_initial.m			C_time.m			
						$v_0(2/3)$	70	Municipal road max 50 km/h	Provincial road max 80 km/h	Motoways >80 km/h	Municipal road max 50 km/h	Provincial road max 80 km/h	Motoways >80 km/h	Municipal road max 50 km/h	Provincial road max 80 km/h	Motoways >80 km/h	
v_m						v_{min}	v_{max}	50	80	100	50	80	100	50	80	100	
SMA NL-8	17	12.75	m=1 m=2.3	-0.8 0	-1 0	-1.9 0	50 70	130 100	-0.6 0	-0.8 0	-0.9 0	-1.7 0	-1.9 0	-2 0	1.1 0	1.1 0	1.1 0
PAC	11	8.25	m=1 m=2.3	-1.4 -3.1	-6.5 0.2	-3 -4.5	50 70	130 100	-0.1 -3.1	-1.4 -3.1	-2 -3.1	-1.7 -4.5	-3 -4.5	-3.6 -4.5	1.6 1.4	1.6 1.4	1.6 1.4
PAC twinlayer	8	6	m=1 m=2.3	-4.5 -5.2	-3 4.7	-6.3 -7	50 70	130 100	-3.9 -5.9	-4.5 -4.9	-4.8 -4.5	-5.7 -7.7	-6.3 -6.7	-6.6 -6.3	1.8 1.8	1.8 1.8	1.8 1.8
SMA NL-5	16	12	m=1 m=2.3	-1.9 0	-1 0	-2.9 0	40 40	80 80	-1.7 0	-1.9 0		-2.8 0	-2.9 0		1.1 0	1 0	0 0
Small elements in 'herringbone bond'	25	18.75	m=1 m=2.3	2.4 3.5	2.5 2.5	0.8 0.8	30 30	60 60	1.9 3.1			0.3 0.4			1.6 2.7	0 0	0 0
Small elements not in 'herringbone bond'	25	18.75	m=1 m=2.3	6.1 6.9	2.9 2.9	4.4 4.4	30 30	60 60	5.5 6.5			3.8 4			1.7 2.5	0 0	0 0

Table A 13 The initial noise emissions [dB(A)]

Noise emissions [dB(A)]		Municipal road max 50 km/h	Provincial road max 80 km/h	Motorways > 80 km/h	Municipal road max 50 km/h	Provincial road max 80 km/h	Motorways > 80 km/h
Reference DAC	m=1	73.92	77.96	79.88	77.59	80.41	81.87
	m=2.3	75.15	76.76	77.52			
PAC	m=1	72.22	74.96	76.28	74.52	76.83	77.96
	m=2.3	70.65	72.26	73.02			
PAC twinlayer	m=1	68.22	71.66	73.28	70.86	73.94	75.38
	m=2.3	67.45	70.06	71.22			
SMA	m=1	71.12	75.06		76.6	79	
	m=2.3	75.15	76.76				
Small elements in 'herringbone bond'	m=1	74.22			77.95		
	m=2.3	75.55					
Small elements not in 'herringbone bond'	m=1	77.72			81.5		
	m=2.3	79.15					

The development of the noise over a time horizon is calculated for the different road types.

The correction factors for the calculation of the noise growth and the structural life of the different wearing course are listed in Table A 14.

Table A 14 Noise growth per year [dB(A)]

		C time,m					C time,m (traffic distribution)			Noise growth per year [dB(A)]
		Lifetime material	Technical lifetime material	Municipal road max 50 km/h	Provincial road max 80 km/h	Motonways >80 km/h	Municipal road max 50 km/h	Provincial road max 80 km/h	Motonways >80 km/h	
SMA NL-8	m=1	17	12.75	1.1	1.1	1.1				
	m=2.3			0	0	0	0.98	0.98	0.98	0.15
PAC	m=1	11	8.25	1.6	1,6	1,6				
	m=2.3			1.4	1,4	1,4	1.58	1.58	1.58	0.38
PAC twinlayer	m=1	8	6	1.8	1.8	1.8				
	m=2.3			1.8	1.8	1.8	1.8	1.8	1.8	0.6
SMA NL-5	m=1	16	12	1.1	1	0				
	m=2.3			0	0	0	0.98	0.98		0.16
Small elements in 'herringbone bond'	m=1	25	18.75	1.6	0	0				
	m=2.3			2.7	0	0	1.76			0.19
Small elements not in 'herringbone bond'	m=1	25	18.75.	1.7	0	0				
	m=2.3			2.5	0	0	1.82			0.19

Emissions due to fuel consumption

The environmental costs due to fuel consumption are listed in Table A 15.

These environmental costs are dependent on the type of road (speed) and the type of engine (diesel or petrol).

Based on the distribution over diesel and petrol engines a weighed environmental cost is calculated for each vehicle category (see Table A 15).

Based on the proportional distribution of the different vehicle categories a subdivision is made into the following main categories:

- light weight vehicles;
- moderate- heavy weight vehicles;
- motorcycles;
- mopeds.

The weighted environmental costs of these main vehicle categories are listed in Table A 16.

Table A 15 Environmental costs of fuel consumption

Vehicle category	Petrol			Diesel			Fuel distribution		Environmental costs [€/veh.km]		
	Environmental costs [€/veh.km]			Environmental costs [€/veh.km]			Percentage Petrol [%]	Percentage Diesel [%]	Municipal road max 50 km/h	Provincial road max 80 km/h	Motorways >80 km/h
Cars	0.016	0.009	0.011	0.01786	0.01277	0.01487	82.41	17.59	0.01633	0.00966	0.01168
Vans	0.023	0.015	0.017	0.02935	0.01881	0.02381	3.31	96.69	0.02914	0.01868	0.02358
Trucks	0.144	0.143	0.183	0.14771	0.09979	0.07733	1.36	98.64	0.14766	0.10038	0.07877
Trailer trucks	0.143	0.139	0.185	0.19666	0.11908	0.08809	0.04	99.96	0.19664	0.11909	0.08813
Motorcycles	0.014	0.011	0.014				100	0	0.014	0.011	0.014
Mopeds	0.016	0.016	0				100	0	0.016	0.016	0

Table A 16 Environmental costs main vehicle categories

Vehicle category	Vehicle distribution		Environmental costs [€ / veh.km]			Vehicle type	Municipal road max 50 km/h	Provincial road max 80 km/h	Motorways >80 km/h
	Number of vehicles	Percentage [%]	Municipal road max 50 km/h	Provincial road max 80 km/h	Motorways >80 km/h				
Cars	7915613	90.49	0.01633	0.00966	0.01168	Light weight	0.0175	0.0105	0.0128
Vans	832121	9.51	0.02914	0.01868	0.02358				
	8747734								
Trucks	67096	48.79	0.14766	0.10038	0.07877	Moderate -heavy weight	0.1727	0.11	0.0836
Trailer trucks	70422	51.21	0.19664	0.11909	0.08813				
	137518								
Motorcycles	653245		0.014	0.011	0.014	Motorcycles	0.014	0.011	0.014
Mopeds	511684		0.016	0.016	0	Mopeds	0.016	0.016	0

Accident rate that is used in the examples of chapter 7.4

The accident rate that is used for the calculation of the social costs due to accidents, as described in chapter 7.4, are listed in Table A 17. These accident rates are calculated with a tool that describes the traffic safety on provincial roads on motorways.

Table A 17 Accident rate

Accidents																					
Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Accidents /100 mio. veh. km	281,9	369,0	403,7	445,3	488,3	536,2	589,5	646,9	713,0	796,7	878,7	970,0	1071,8	1185,1	1312,3	1460,9	1617,5	1791,9	1986,1	2202,5	2443,4

Decrease of the emission factors of the fuel consumption

The fuel emission factors steadily decrease over time because of improvement of the engine technology. The decrease of fuel consumption over time is taken into account with a logarithm function. This approach is applied for the main vehicle categories. These functions are presented in Figure A. 3, Figure A. 4, Figure A. 5 & Figure A. 6.

The function that are describing the decrease of the environmental costs are different according to the road type. The following functions are describing the decrease of the environmental costs for the light weight vehicles:

$$Y_{\text{municipal road}(x)} = 0.0198 - 0.001 \ln(x) \quad (\text{Eq. 68})$$

$$Y_{\text{provincial road}(x)} = 0.0115 - 0.0006 \ln(x) \quad (\text{Eq. 69})$$

$$Y_{\text{motorways}(x)} = 0.0148 - 0.001 \ln(x) \quad (\text{Eq. 70})$$

where

$Y_{\text{municipal road}(x)}$ = environmental cost indicator on municipal roads in year 'x'

$Y_{\text{provincial road}(x)}$ = environmental cost indicator on provincial roads in year 'x'

$Y_{\text{motorways}(x)}$ = environmental cost indicator on motorways in year 'x'

X = year that is being considered

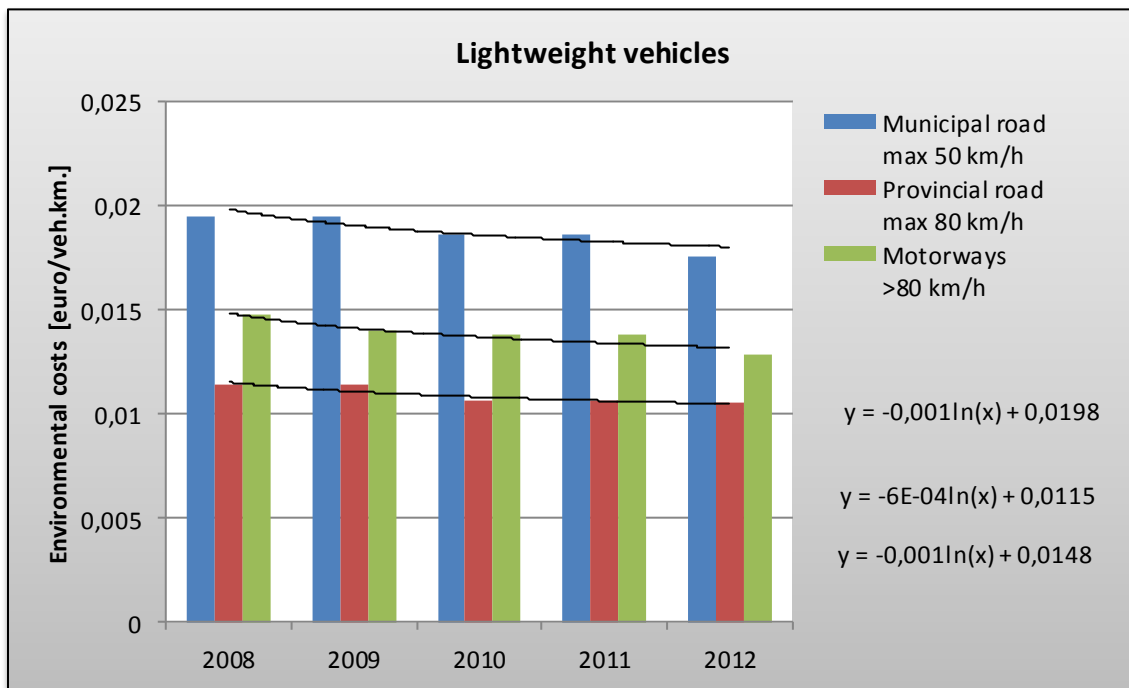


Figure A. 3 Environmental costs over a time horizon of light weight vehicles

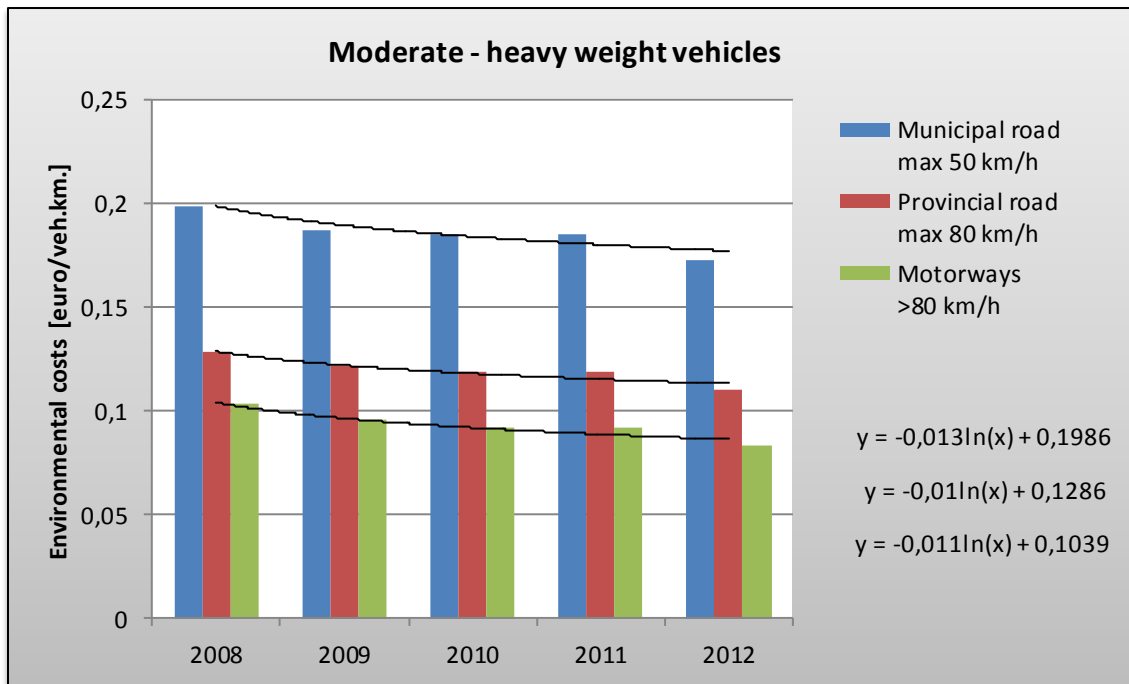


Figure A. 4 Environmental costs over a time horizon of moderate – heavy weight vehicles

The following functions describe the decrease of the environmental costs for the moderate – heavy weight vehicles:

$$Y_{\text{municipal road}(x)} = 0.1986 - 0.013 \ln(x) \quad (\text{Eq. 71})$$

$$Y_{\text{provincial road}(x)} = 0.1286 - 0.01 \ln(x) \quad (\text{Eq. 72})$$

$$Y_{\text{motoways}(x)} = 0.01039 - 0.011 \ln(x) \quad (\text{Eq. 73})$$

where

$Y_{\text{municipal road}(x)}$ = environmental cost indicator on municipal roads in year 'x'

$Y_{\text{provincial road}(x)}$ = environmental cost indicator on provincial roads in year 'x'

$Y_{\text{motoways}(x)}$ = environmental cost indicator on motorways in year 'x'

X = year that is being considered

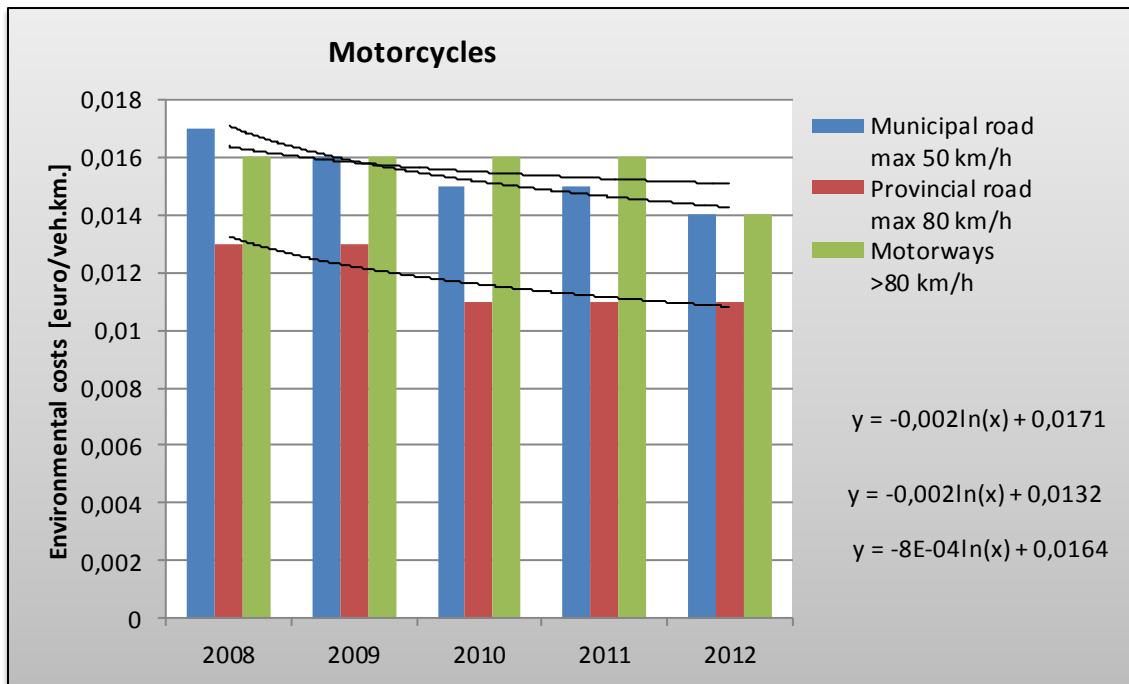


Figure A. 5 Environmental costs over a time horizon of motorcycles

The following functions describe the decrease of the environmental costs for the motorcycles:

$$Y_{\text{municipal road}(x)} = 0.0171 - 0.002 \ln(x) \quad (\text{Eq. 74})$$

$$Y_{\text{provincial road}(x)} = 0.0132 - 0.002 \ln(x) \quad (\text{Eq. 75})$$

$$Y_{\text{motorways}(x)} = 0.0164 - 0.0008 \ln(x) \quad (\text{Eq. 76})$$

where

$Y_{\text{municipal road}(x)}$ = environmental cost indicator on municipal roads in year 'x'

$Y_{\text{provincial road}(x)}$ = environmental cost indicator on provincial roads in year 'x'

$Y_{\text{motorways}(x)}$ = environmental cost indicator on motorways in year 'x'

X = year that is being considered

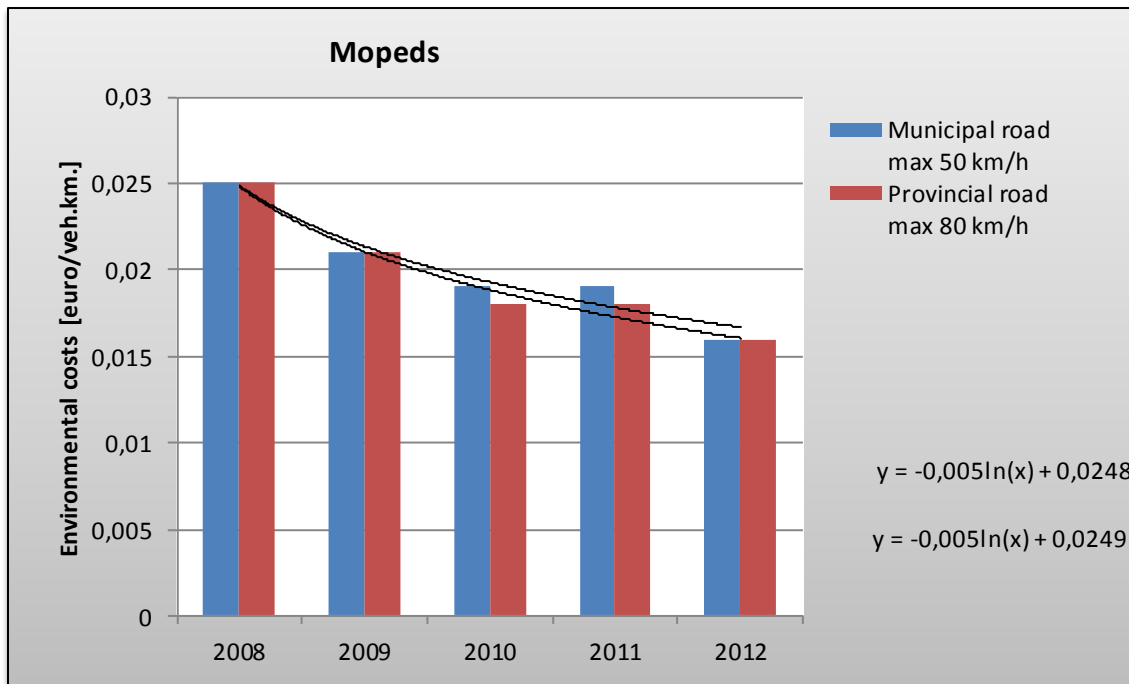


Figure A. 6 Environmental costs over a time horizon of mopeds

The following functions describe the decrease of the environmental costs for the mopeds:

$$Y_{\text{municipal road}(x)} = 0.0248 - 0.005 \ln(x) \quad (\text{Eq. 77})$$

$$Y_{\text{provincial road}(x)} = 0.0249 - 0.005 \ln(x) \quad (\text{Eq. 78})$$

where

$Y_{\text{municipal road}(x)}$ = environmental cost indicator on municipal roads in year 'x'

$Y_{\text{provincial road}(x)}$ = environmental cost indicator on provincial roads in year 'x'

X = year that is being considered

The difference in the decrease of environmental costs of mopeds is negligible. Mopeds is a vehicle category that are mainly exists on the municipal roads, rarely on the provincial and is not allowed on the motorways.

Appendix C

Developed programs [digital]

