Road Design for Future Maintenance – Life-cycle Cost Analyses for Road Barriers

HAWZHEEN KARIM

KTH Architecture and
the Built Environment

Doctoral Thesis in Civil and Architectural Engineering
Stockholm, Sweden 2011

PREFACE

This doctoral thesis presents the results of a research conducted in co-operation with the Swedish Royal Institute of Technology (KTH), Dalarna University (HDa), the Centre for Research and Education in Operation and Maintenance of Infrastructure (CDU) and the Swedish Transport Administration (STA). A major part of the research was conducted at Dalarna University.

First of all, I would like to express my sincere thanks to my supervisor Professor Rolf Magnusson at Dalarna University. Thank you for your valuable comments, suggestions, wise advice and never-ending patience.

I am also most grateful to Professor Ulf Isacsson at the Royal Institute of Technology for his supervision and support.

Particular thanks to the members of the steering committee who have been a constant source of support. The steering committee included Anders Wengelin (STA), Bengt Holm (Svevia), Björn Granqvist (Skanska Roads), Björn Stigberg (STA), Bo Skogwik (STA), Hans Cedermark (CDU), Håkan Westerlund (CDU), Jan Moberg (STA), Jan-Erik Elg (STA), Karin Renström (Traffic Design), Rolf Magnusson (HDa), Rolf Svahn (STA) and Ulf Isacsson (KTH).

Owen Eriksson at Dalarna University and Arne Carlsson at the Swedish National Road and Transport Research Institute (VTI) are gratefully acknowledged for their valuable ideas and guidance.

I would also like to express my appreciation to Peter Jardskog, Anders Asp, Dag Axelsson at Svevia and Anders Håkansson, Åke Löfkvist and Östen Johansson at Swedish Road Administration as well as Henrik Hansson at NCC Roads and all the experts who have participated in the interviews and contributed with their time, experience and ideas.

Thanks to my co-authors Kenneth Natanaelsson, Mats Wikund and Muodud Alam. Sincere appreciation is also expressed to Sandra Cross Rosell for proof reading the manuscripts.

I also wish to express my gratitude to all my colleges at Dalarna University and the Swedish Transport Administration, especially Karin Edvardsson, Farhad Darabian, Linda Wennbom, Conny Lundgren, David Steen, Hossein Alzubaidi, Lars Preinfalk, Catherine Selvén, Rickard Stridbeck, Fred Larsson, Sarbaz Othman, Inger Alfredsson, Marie-Louise Prahl, Carl-Gösta Enocksson and Mikael Johansson for creating a good working environment and for all enjoyable discussions.

Financial support, provided by the Swedish Transport Administration through the Centre for Research and Education in Maintenance and Operation of Traffic Channels, is gratefully acknowledged. Appreciation is extended to the Nordic Road Association (NVF) for their valuable Scholarship.

Finally to my family, my wonderful parents, Carmen, Darsim, Diana, Hanna and Kurddost, thanks for your love and for being there for me. To my sweet daughters Laura and Minna I can only say stop growing up so fast, because we have a lot of fun things to do together. To my beloved wife Khandan, thanks for all your love, support and endless patience.

Göteborg, Mars 2011
Hawzheen Karim, Author

ABSTRACT

The cost of a road construction over its service life is a function of design, quality of construction as well as maintenance strategies and operations. An optimal life-cycle cost for a road requires evaluations of the above mentioned components. Unfortunately, road designers often neglect a very important aspect, namely, the possibility to perform future maintenance activities. Focus is mainly directed towards other aspects such as investment costs, traffic safety, aesthetic appearance, regional development and environmental effects.

This doctoral thesis presents the results of a research project aimed to increase consideration of road maintenance aspects in the planning and design process. The following subgoals were established:

- Identify the obstacles that prevent adequate consideration of future maintenance during the road planning and design process; and
- Examine optimisation of life-cycle costs as an approach towards increased efficiency during the road planning and design process.

The research project started with a literature review aimed at evaluating the extent to which maintenance aspects are considered during road planning and design as an improvement potential for maintenance efficiency. Efforts made by road authorities to increase efficiency, especially maintenance efficiency, were evaluated. The results indicated that all the evaluated efforts had one thing in common, namely ignorance of the interrelationship between geometrical road design and maintenance as an effective tool to increase maintenance efficiency. Focus has mainly been on improving operating practises and maintenance procedures. This fact might also explain why some efforts to increase maintenance efficiency have been less successful.

An investigation was conducted to identify the problems and difficulties, which obstruct due consideration of maintainability during the road planning and design process. A method called "Change Analysis" was used to analyse data collected during interviews with experts in road design and maintenance. The study indicated a complex combination of problems which result in inadequate consideration of maintenance aspects when planning and designing roads. The identified problems were classified into six categories: insufficient consulting, insufficient knowledge, regulations and specifications without consideration of maintenance aspects, insufficient planning and design activities, inadequate organisation and demands from other authorities. Several urgent needs for changes to eliminate these problems were identified.

One of the problems identified in the above mentioned study as an obstacle for due consideration of maintenance aspects during road design was the absence of a model for calculating life-cycle costs for roads. Because of this lack of knowledge, the research project focused on implementing a new approach for calculating and analysing life-cycle costs for roads with emphasis on the relationship between road design and road maintainability. Road barriers were chosen as an example. The ambition is to develop this approach to cover other road components at a later stage.

A study was conducted to quantify repair rates for barriers and associated repair costs as one of the major maintenance costs for road barriers. A method called "Case Study Research Method" was used to analyse the effect of several factors on barrier repairs costs, such as barrier type, road type, posted speed and seasonal effect. The analyses were based on documented data associated with 1625 repairs conducted in four different geographical regions

in Sweden during 2006. A model for calculation of average repair costs per vehicle kilometres was created. Significant differences in the barrier repair costs were found between the studied barrier types.

In another study, the injuries associated with road barrier collisions and the corresponding influencing factors were analysed. The analyses in this study were based on documented data from actual barrier collisions between 2005 and 2008 in Sweden. The result was used to calculate the cost for injuries associated with barrier collisions as a part of the socio-economic cost for road barriers. The results showed significant differences in the number of injuries associated with collisions with different barrier types.

To calculate and analyse life-cycle costs for road barriers a new approach was developed based on a method called "Activity-based Life-cycle Costing". By modelling uncertainties, the presented approach gives a possibility to identify and analyse factors crucial for optimising life-cycle costs. The study showed a great potential to increase road maintenance efficiency through road design. It also showed that road components with low investment costs might not be the best choice when including maintenance and socio-economic aspects.

The difficulties and problems faced during the collection of data for calculating life-cycle costs for road barriers indicated a great need for improving current data collecting and archiving procedures.

The research focused on Swedish road planning and design. However, the conclusions can be applied to other Nordic countries, where weather conditions and road design practices are similar. The general methodological approaches used in this research project may be applied also to other studies.

Keywords: road maintenance, road management, road planning, road design, life-cycle cost, road barrier, guardrails, cable barrier, road traffic injuries, barrier collisions and barrier repair costs.

LIST OF PUBLICATIONS

This doctoral thesis is based on the work presented in the following publications, referred to in the text by their Roman numerals (I-V):

I.   Hawzheen Karim. (2010). "Evaluation of Attempts for Efficient Road Maintenance – Knowledge Compilation." *The Baltic Journal of Road and Bridge Engineering*, Vol. 5 (4), pp. 229-239.

       This copyrighted review article is printed with the publisher's permission and may not be copied or redistributed without the permission of the Journal.

II.   Hawzheen Karim and Rolf Magnusson (2008). "Road Design for Future Maintenance - Problems and Possibilities." *The Journal of Transportation Engineering*, Vol. 134 (12), pp. 523-531.

       This copyrighted review article is printed with the publisher's permission and may not be copied or redistributed without the permission of the Journal.

III.   Hawzheen Karim, Moudud Alam and Rolf Magnusson. "Road Barrier Repair Costs and Influencing Factors." Accepted for publication in *The Journal of Transportation Engineering*.

IV.   Hawzheen Karim, Rolf Magnusson and Mats Wiklund. "Assessment of Injury Rates Associated with Road Barrier Collisions." Submitted to *The Journal of Accident Analyses and Prevention* for possible publication.

V.   Hawzheen Karim, Rolf Magnusson and Kenneth Natanaelsson. "Life-cycle Cost Analyses for Road Barriers." Submitted to *The Journal of Transportation Engineering* for possible publication.

Apart from the above mentioned publications, two other reports have been published on the same subject:

Hawzheen Karim and Rolf Magnusson. *Vägprojektering för Minskade Drift- och Underhållskostnader* [Road Design for Lower Maintenance Costs – Problems and Possibilities]. Report 2006:01, Dalarna university, Borlänge, Sweden, 2006, ISSN 1653-9362 (In Swedish).

Hawzheen Karim and Rolf Magnusson. *Vägbarriärens Inverkan på Snöplogning* [The Influence of Road Barriers on Snow Removal Activities], Report 2008:03, Dalarna University, Borlänge, Sweden, 2009, ISSN 1653-9362 (In Swedish).

THE AUTHOR'S CONTRIBUTION TO THE PAPERS

Most of the data collection, interviews, calculations and analyses were conducted by the author. The manuscripts were written by the author and revised by the co-authors. In Paper III, co-author Moudud, and in Paper IV, co-author Mats Wiklund, contributed by performing statistical analyses. In Paper V, co-author Kenneth Natanaelsson, contributed by calculating the socio-economic costs.

In addition to reading the manuscripts and suggesting improvements to them, Professor Rolf Magnusson, my supervisor, and co-author, participated in discussions of the research problems and analyses of the results.

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

1.1 Background

Road maintenance includes all activities carried out to maintain the properties for which the road was designed. In some countries, e.g. Sweden, road maintenance is divided into operation and maintenance activities. Operation activities include short-term measures with the primary purpose of keeping a road open for traffic, e.g. winter maintenance, grass mowing and cleaning of reflectors. Maintenance activities relate to long-term measures ensuring durability of the road network, e.g. paving works and bridge repairs.

As funding sources for road infrastructure dwindle, to insure implementation of new projects and maintenance of existing roads, road authorities worldwide are forced to increase efficiency and reduce costs (Prarche 2007). Because maintenance costs constitute a large portion of the annual expenditure on road infrastructures, road authorities are continuously trying to increase road maintenance efficiency and reduce related costs. For this purpose, different strategies and contract forms have been used, such as maintenance outsourcing in competitive markets as well as development of life-cycle cost models and new funding and subsidiary forms. Even if these efforts have reduced maintenance costs considerably, the general opinion is that some of these efforts have resulted in reduced maintenance standards and impaired road conditions, as focus mostly has been on reducing the rate of recurring maintenance activities.

The cost of a road over its service life is a function of design, quality of construction, maintenance strategies and maintenance operations. An optimal life-cycle cost for a road requires estimations of the above mentioned components. Unfortunately, road designers often neglect a very important aspect, namely the possibility to perform future maintenance activities. The focus is mainly aimed towards other aspects, such as investment costs, traffic safety, aesthetic appearance, regional development and environmental effects.

During the road planning and design process, the number of hours devoted to analysis of future maintenance activities and the associated costs, is negligible compared to the hours devoted to technical structural calculations, technical descriptions and quantity calculations. This is the case despite the fact that construction usually takes only a few years while the maintenance period lasts for thirty to forty years or more.

The need for specific maintenance measures often arises during the road's service life due to problems in certain locations along the road. Those locations could, in many cases, have been identified by experienced maintenance staff. In some cases, the construction documents are sent to the maintenance department for revision. Unfortunately, the limited resources of maintenance departments often obstruct sufficient revision of these documents.

Sometimes, the insignificant considerations of the maintenance aspects during the planning and design process can be on purpose. For example, because of limited investment budgets, designers are often forced to select road equipment with low initial costs, even if they are aware of the high maintenance costs this equipment will generate in the future.

In other cases, maintenance aspects are neglected for aesthetic reasons. This often occurs in urban regions with high aesthetic requirements. For example, in Sweden, there are specific

aesthetic requirements for the design of motorway approaches to cities. Designers have to follow the requirements, even if they are aware of high future maintenance costs associated with the selected designs. One example is the use of pipe barriers in urban regions. Other examples include the selection of certain types of vegetation that result in increased maintenance costs and the use of glass noise barriers, despite the high maintenance costs associated with these barrier types.

Figure 1.1 shows a noise barrier which is installed along road E6 in the city of Gothenburg, Sweden. The glass elements are repeatedly vandalized or damaged by flying stones from the road. According to the maintenance contractor, the repair cost for each glass element is 8000 SEK (≈800 EUR).

Figure 1.1 *Damaged noise barrier along road E6 in the city of Gothenburg in Sweden*

In some cases, maintenance aspects are neglected because the designers do not have enough experience of road maintenance. Figure 1.2 shows a design proposal for a new road where the designers propose a concrete roadside barrier very close to the road. The designers have not considered how to get rid of the snow piles left by the snowploughs along the verges, because they have falsely presumed that the snow heaps do not need to be removed. However, the verge must be free from snow and ice according to Swedish maintenance regulations (Vägverket 2008a). This means that the snow has to be loaded onto trucks and transported away from the road after each snowfall, both at considerable cost and possible traffic disruptions.

Figure 1.2 *Design proposal for a new road section (Source: SRA)*

1.2 Objectives and Delimitation

The overall goal of this PhD project was to improve the possibilities to consider maintenance aspects during the road planning and design process. The results are expected to provide a basis for a new method for the road planning and design process using life-cycle cost analysis.

More specifically, the objective of the project was to:

- Compile and evaluate experiences regarding efforts made by road authorities to satisfy the needs for efficient maintenance (Paper I);
- Evaluate the extent to which maintenance aspects are considered during road planning and design as an improvement potential for maintenance efficiency (Paper I);
- Identify the problems which obstruct due consideration of maintainability during the road planning and design process and identify the urgent need for changes to eliminate these problems (Paper II);
- Quantify and compare the rate of barrier repairs and the average repair cost for different barrier types (Paper III);
- Analyse how factors, such as road barrier type, road type, speed limits and seasonal effects, influence the number of barrier repairs and the associated costs (Paper III);
- Quantify and compare the rate of different injury categories associated with collisions with different barrier types (Paper IV); and
- Examine the possibility to implement a new approach for calculation and analysis of life-cycle costs for road barriers during the road planning and design process (Paper V).

The research was focused on the planning and design processes at the Swedish Road Administration, SRA, which is in charge of both country and urban roads in Sweden. SRA is also responsible for guidelines and specifications for road planning and design in Sweden, as well as maintenance specifications. Another reason for this delimitation is that SRA is the initiator for this research. However, the conclusions can be applied to other Nordic countries where weather conditions and road design practises are similar. The methodological approaches of this research project are general and may be applied to similar studies.

The research is mainly limited to geometrical design of roads. The structural design of the roads is not included, as this subject has already been included in several other research studies.

1.3 Scientific contribution

Generally, the scientific contribution of this PhD project lies in the fact that it provides a basis for a new method for planning and designing roads based on life-cycle cost analyses as an appropriate way to increase road authorities' efficiency.

The PhD project also provides long-awaited information regarding maintenance aspects for road barriers and injury costs associated with road barrier collisions. For road authorities, road designers and barrier producers this information is a crucial and much needed piece of a puzzle for life-cycle cost analyses.

By mapping out the problems and difficulties, which prevent sufficient consideration of maintenance aspect during the road design process, this project constitutes a basis for future research aiming at increased efficiency in the road infrastructure sector.

1.4 Research method

The project started with a review of previous studies of the research subject with the intention of gathering existing knowledge and defining the outline of the PhD project (Paper I). The focus was on attempts made to increase road maintenance efficiency through consideration of maintenance aspects during the planning and design process. More details about the literature study can be found in Chapter 2.

The second stage of the research was to identify problems and difficulties, which prevent consideration of maintenance aspects during the road planning and design process (Paper II). For this purpose, actors involved in both road maintenance and road planning and design were interviewed. The most urgent needs for changes, which would contribute to an increased consideration of the maintenance aspect, were identified (Paper II). A method called "Change Analyses" (Goldkuhl and Röstlinger 1998) was used to analyse and identify problems, planning and design activities and goals which govern those activities. This part of the PhD project is described in Chapter 3.

Results obtained in the second stage showed that one of the obstacles preventing consideration of maintenance aspects during road design is the absence of a reliable approach for analyses of life-cycle costs. This initiated the later stages in the PhD project, namely development of a new approach for road design based on life-cycle costs. Difficulties in obtaining reliable data and the complexity of a road structures and its influence on society, prevented the creation of an approach for life-cycle cost analyses, which would cover all road components. Therefore, the initial focus was on analysis of the life-cycle costs of one road component. After consulting with road design and maintenance experts, road barriers were selected as a suitable component.

The third stage in the PhD project was quantification and analysis of barrier repairs and associated costs (Paper III). Repair costs constitute a considerable part of the life-cycle costs for road barriers. This stage of the research was carried out for two purposes. Firstly, to establish a model to calculate barrier repair costs. Secondly, to analyse how parameters, such as road types, posted speed limits, road barrier types, road barrier placement, road section types, alignment and climate affect barrier damages and associated repair costs. The analysis of the repair costs was based on data collected from repairs of 1625 road barriers in Sweden. The method used for this proposes was the "Case Study Research Method" (Yin 2003). This part of the PhD project is explained more in detail in Chapter 4.

Another considerable part of life-cycle costs for road barriers is the injury costs associated with barrier collisions. Quantification of the injury costs required quantification of the injury rates in the fourth stage in this PhD project (Paper IV). The study was based on documented data associated with 1019 barrier collisions between 2005 and 2008 along two motorways in Sweden. Chapter 5 contains more details about this study.

Results from the third and fourth stages were used in the fifth stage to create and evaluate a new approach for calculation and analysis of the life-cycle costs of road barriers (Paper V). This new approach was based on a method called "Activity-based Life-Cycle Costing" (Emblemsvåg 2003). The fifth stage is described in Chapter 6.

CHAPTER 2

MAINTENANCE ASPECTS IN ROAD DESIGN - A LITERATURE REVIEW

As funding resources for road infrastructure are seldom sufficient, road authorities are facing the following challenges:

- insufficient funding sources to face the increased need for new road infrastructure (Prarche 2007), increased demand for proper management of both newly constructed and existing roads;
- Increased maintenance backlogs (Gahm 2008);
- Increased demands for safety, accessibility and use of advanced traffic management systems to reduce socio-economic costs in terms of reduced maintenance-related environmental impacts, traffic disturbances and fatalities.

Due to the funding challenges, road authorities are facing a great need for increased efficiency and reduced expenditures. Focus is on efficient road maintenance, as maintenance costs constitute approximately 50% of the annul road infrastructure financing (Prarche 2007). To increase maintenance efficiency, different strategies and contract forms have been used by road authorities. This includes outsourcing of maintenance activities in competitive markets, development of life-cycle cost models, as well as new funding and subsidiary forms. Even if these attempts have reduced maintenance costs considerably, the general opinion is that some efforts have resulted in reduced maintenance standards and impaired road conditions, as focus mainly has been on reduction of the rate of recurring maintenance activities.

The aim of the literature study was to:

- Compile experiences regarding attempts made by road authorities to satisfy the needs for efficient maintenance and the results of these efforts; and
- Evaluate the extent to which maintenance aspects are considered during road planning and design as an improvement potential for maintenance efficiency.

The studied attempts were outsourcing of maintenance, consideration of maintenance aspects during road design, life cycle cost analyses for road infrastructure, Public-Private Partnership Project (PPP projects) and performance-based contracting.

2.1 Outsourcing maintenance activities

Outsourcing maintenance activities in a competitive market has been used as an option to increase maintenance efficiency and reduce costs. Due to maintenance outsourcing in Sweden between 1992 and 2001, transaction costs for maintenance contracts for the outsourced maintenance areas, e.g. bid preparation and contract monitoring and evaluation, were estimated to be at least 5% lower than for non-outsourced maintenance areas (Liljegren 2003). In Sweden, outsourcing of several maintenance areas in a competitive market during the first year reduced bid prices on average with 22–27% compared to in-house maintenance costs (Arnek 2002). These cost reductions are often attributed to reorganisation and reduction of personal rather than to technical progress in machinery and methods (Stenbeck 2006).

Such reforms have also been used by the Swedish government as an incentive to cut grants for road maintenance. However, these reforms have negatively affected road maintenance, primarily for pavement and bridge maintenance, because short-term maintenance measures, such as winter maintenance, cleaning and grass mowing, have been prioritised. The situation is the same in all Nordic countries (Gahm 2008). Studies of road-user opinions have indicated increased dissatisfaction regarding road maintenance, which, in turn, indicates that the maintenance standards in Sweden have decreased after the reforms, primarily on roads in sparsely populated areas (Österberg 2003).

By outsourcing maintenance activities, SRA tried to encourage contractors to develop technical improvements. Unfortunately, effects of outsourcing on innovation have been limited (Stenbeck 2007; Thorsman and Magnusson 2004). Development interest among contractors has been low because development costs are often high compared to the benefits obtained. In addition, contractors often have refused to share knowledge with others in order to maintain competitiveness. As a result, Stenbeck (2007) claimed that long-term technical developments in Sweden have decreased. He also mentioned that maintenance costs for outsourced contracts in Canada were 26% higher than for in-house contracts. The quality and technical development were neither noticeably higher nor lower in outsourced contracts than in in-house contracts.

2.2 Consideration of maintenance aspects during the road planning and design process

Problems faced while conducting maintenance activities often trigger debates on road planning and design as a crucial underlying factor (Freer-Hewish 1986). The cost of a road project over its service life is, among other things, a function of design standards, construction quality control, maintenance strategies and maintenance quality. These aspects control the rate of road deterioration and dictate the maintenance workload throughout the life of the road (Figure 2.1). However, very few studies considering the interrelationship between these components have been found in the literature.
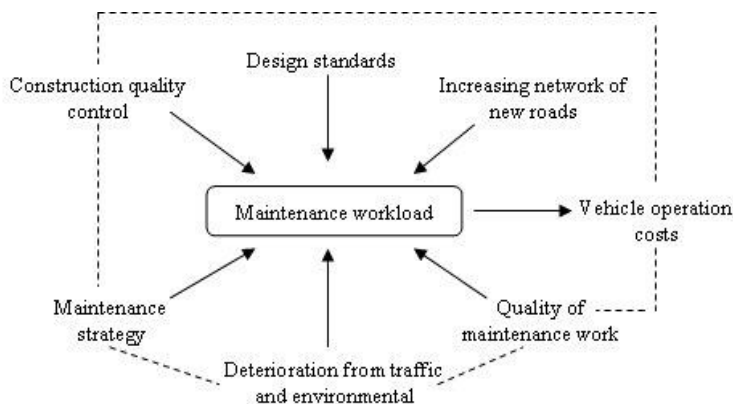

Figure 2.1 *Development of maintenance workload (Freer-Hewish 1986)*

According to Thorsman and Magnusson (2004), insufficient consideration of maintenance aspects as well as inadequate support for the designers during the planning and design process are two major factors contributing to high maintenance costs. They suggest the following improvements:

- Improving methods and technologies for reducing maintenance costs through reduction in intervention time and use of efficient tools;
- Creating functions for supporting designers and coordinating maintenance-related consulting between involved parties; and
- Improving coordination and information sharing between contractors.

Gaffeny and Gane (1970) compiled a list of some aspects of road design, which contribute to decreasing the need for future road maintenance. Based on experience from the United States, some general advice is given concerning design of cuttings, embankments, bridges, bridge abutments, steelworks, street lighting, pavement types, pavement thicknesses and surface types. Regrettably, calculations for quantifying the positive effects were not performed.

Olsson (1983) describes a new method for road construction design using annual cost calculations. The major factors, which prevent consideration of road management and maintenance costs during the road design process, include difficulties in quantifying administration costs, time shortage and inadequate experience of road maintenance among road designers. A road design model is recommended consisting of the following three steps:

- Study different design alternatives and calculate annual costs, including investment and maintenance costs, to choose an optimal design;
- Clarify the calculation suppositions to offer enough information for decision makers concerning calculations and included cost items; and
- Estimate calculation accuracy statically or based on practical experiences.

Other studies concerning design of pavements, bridges and specific roadside components have also indirectly considered maintenance aspects. A study made by (Neuzil and Peet 1970) examined the fill height of embankments, whereby flattening slopes proved to be cheaper than installing guardrails. Wolford and Sicking (1997) developed guidelines to determine the need for road barrier installations based on cost-benefit analyses. Mattingly and Ma (2002) compared different road barrier end-terminals in order to identify the most profitable ones in order to decrease future maintenance needs. This study was based on practical experiences, which did not include life-cycle cost analyses or any evaluation of how factors, such as traffic volume and road design would, affect maintenance costs of the end-terminals.

2.3 Life-cycle cost analyses

Life-cycle costs for road objects are considered as a more important decision basis than only investment costs, and, consequently, road authorities are encouraged to overweigh life-cycle cost analyses and provide calculation methods (Bajaj et al. 2002; Gransberg and Molenaar 2004). Life-cycle costs are also suggested as a parameter for selecting road designs or evaluating bids (Adams and Kang 2006; Stenbeck 2004). Both road authorities' costs and socio-economic costs must be included in the calculation of life-cycle costs. Road authority

costs consist of costs for planning, design, construction, maintenance and rehabilitation. These costs are usually covered by governments using tax revenue. Socio-economic costs include:

- Road users' costs, such as vehicle operation costs, and costs for the time people spend on the road;
- Accident costs; and
- Environmental costs.

Many road authorities have developed models for life-cycle cost analyses with the intention of reducing the total cost for the road infrastructure and maximize the socio-economic benefits. Some models are simple and include only road authority costs. Other models are very complex including calculation of socio-economic costs and models for prediction of road deterioration. A study of life-cycle cost models used in the Nordic countries showed that these models often considered the road authority's costs, such as investment costs, maintenance costs and to some extent, user and environmental costs (Holmvik and Wallin 2007). Still none of the models can be used as a standard model without considerable improvements, since they are developed for specific road projects. The disadvantages of the studied models also included use of roughly calculated maintenance costs and insufficient consideration of how design influences maintenance costs.

Huvstig (1998) has studied several models for calculation of life-cycle costs made by road authorities such as, COMPARE (Great Britain), QUEWZ (Australia), Whole Life Costing System (USA) and Highway Design and Management (HDM I to IV) developed by The World Bank. These models have mainly been used for design of road construction and pavement types.

Life-cycle cost is suggested as a parameter when selecting road designs or evaluating bids (Adams and Kang 2006; Stenbeck 2004). Unfortunately, life-cycle cost analyses are still of less importance in bid evaluations due to, among other things, difficulties related to the absence of reliable data and methods for calculating life-cycle costs for road objects (Karim 2008). Lack of maintenance and investment related data is attributable to the fact that most road authorities do not have proper methods for systematic data collection or follow-up procedures regarding planning, design, construction and maintenance. Absence of reliable life-cycle cost methods is due to lack of accurate road deterioration models as well as models for calculating societal costs. Current deterioration models are based on experience and empirical models (Huvstig 2004). Such models can give acceptable results, if the historical circumstances are similar to future circumstances. However, such circumstances seldom exist for a road construction due to, among other things, traffic development, use of heavier vehicles and new types of tires.

Life-cycle cost analyses may in some cases result in higher investment costs. The lowest possible yearly life-cycle cost has been tested as an award criterion by SRA (Stenbeck 2007). This has resulted in higher investment costs, causing budgetary problems. A conspiratorial explanation, according to the same study, is that the contractors are taking advantage of the situation, trying to sell expensive solutions with long-term speculative promises that can't be verified or corrected until too late.

It is worth noting that the above mentioned life-cycle cost models have been established for structural road design as a tool for selecting the most economical solution for investment and maintenance. The geometrical road design is ignored in almost all the models despite the

fact that geometrical road design, such as road alignment and road restraint systems, affects costs during the road's life-cycle (Freer-Hewish 1986).

2.4 Public-private partnership projects

Road authorities aspire to develop new funding forms to bridge infrastructure funding gaps. Public-Private Partnership Project (PPP project) is a new funding form used to deal with the increasing demand for new road infrastructures (Arnek et al. 2007). In PPP projects, governments, or another public sector, assign the obligation to finance, design, build, operate, maintain and rehabilitate an infrastructure project to a private-sector partner (the concessionaire). The concession duration is usually 5 to 30 years. The archetypal PPP project is a build–operate–transfer project (Queiroz 2007). Other forms of contract are also possible, such as operation-maintenance projects. The concessionaire collects revenue from users by way of road tolls, while the balance of the revenue comes from the government. When the volume of traffic, combined with the agreed toll, do not generate sufficient revenue to cover all costs, governments must accept shared costs.

Benefits of PPP projects include increasing efficiency during the design, construction and operation phases of a project, enhancing implementation capacity, mobilizing financial resources and freeing scarce public funds for other users (United Nations 1998).While PPP projects in the road sector only recently have been used in the United States and Europe, they are common in countries such as Chile, Argentina, South Korea, Malaysia, Chad and The Philippines (World Bank 2002).

A basic principal of PPP projects is the consideration of maintenance aspects during planning and design, especially the influence of road design on maintenance. This will lead to increased maintenance efficiency and reduced overall costs. As the contract is awarded to the concessionaire who provides the highest value, often at the lowest cost over the term of the concession, the bidders strive to minimize the overall cost of the project, not only the initial cost for design and construction, but also the costs for operation, maintenance and rehabilitation. This leads to a solution that is not derived from the availability of funds, but is determined by what is most cost efficient (Prarche 2007). However, a review of guidelines developed by the World Bank (2002) and the European Commission (2004) for PPP projects shows that consideration of maintenance aspects in the planning and design process is not prioritized. Experiences from the Nordic countries and other European countries indicate that the influence of geometrical road design on road maintenance has been ignored in most of the PPP projects carried out up to now (Karim and Magnusson 2006).

2.5 Performance-based contracts

Performance-based contracting in the infrastructure sector means that public sector representatives and a commercial enterprise sign a contract for both construction and maintenance, or solely maintenance, of an infrastructure object. The contract terms are based on certain specified services that must be given to future users, and not for the fulfilment of technical specifications. It is the performance of the assets over the contracting period that matters (Nilsson et al. 2006). Performance-based contracts have mostly been used for road pavements with a span of 4 to 10 years. The main reasons for using performance-based contracts are to:

- Maximize performance by allowing contractors to deliver the required service based on their own best practices and the customer's desired outcome;
- Maximize competition by encouraging innovation from the supplier by using performance requirements;
- Minimize burdensome reporting requirements and reduce the use of contract provisions and requirements;
- Shift risk to contractors so they are responsible for achieving the objectives through the use of their own best practices and processes; and
- Achieve solutions which give optimal life-cycle cost.

The most important characteristic of performance-based contracts is to give contractors freedom to decide the best methods and materials based on the road authorities' direction of road performance. Performance-based road management and maintenance contracts preserve road assets according to predefined performance standards on a long-term basis. The most challenging task is to develop performance-related specifications, which ensure that the objective is achieved as efficiently as possible. These performance-based specifications provide guidelines for the design and construction of the road project (Carpenter et al. 2003). Payments are based on how well the contractor manages to comply with the performance specifications defined in the contract, and not on the amount of work and services executed. According to Zietlow (2004), development of "right" performance specifications is a challenging task, since they have to satisfy a set of goals such as:

- Minimizing total system costs, including the long-term cost of preserving roads, bridges and traffic assets and costs for the road users;
- Satisfy road users' comfort and safety.

Introduction of performance-based contracts in USA, Australian and New Zeeland has resulted in cost reductions of between 10% and 20% compared to traditional contract forms (Carpenter et al. 2003). In Latin America, 40 000 km of the national roads are maintained under performance-based contracts. Rough estimates indicate that performance-based contracts in Latin America have resulted in cost savings of around 10% compared to traditional unit price contracts (Zietlow 2008).

There are also examples of performance-based contracts that have turned out to be more expensive than traditional contracts. A study of four performance-based contracts showed an increase in costs between 10% and 50% compared to traditional contracts (Stenbeck 2007). Regarding quality aspects, studies also show different results. In Denmark, a summary from six years of experience of performance-based maintenance contracts for a total of 300 km roads indicates that in the first year of the contracts, municipalities experienced a more frequent rate of surface renewal than the budget typically allows (Baltzer 2007). Experience from two performance-based contracts in Sweden shows significant road quality improvement (Ydrevik 2009). However, Stenbeck (2007) presents an anonymous case where a performance-based contract resulted in inferior quality. According to the study, unsuccessful cases could be due to lack of experience in implementing long-term maintenance contracts for road projects and absence of sufficient follow-up procedures.

Despite many successful performance-based contracts, acceptance of this kind of contract is limited. According to Carpenter et al. (2003), the primary reasons for this can be hypothesized as follows:

- Lack of knowledge in implementing long-term maintenance contracts in the road construction sector;
- The extra work involved in developing specifications for such projects;
- Lack of research and evaluation comparing in-house maintenance with outsourced maintenance;
- Road authorities are not sure what types of projects benefit most from performance-based contracting;
- Road authorities have concerns about the ability of the contractors to manage the road over long-term warranties;
- Contractors are not willing to take great risks; and
- Road authorities are concerned about losing their knowledge base.

An evaluation of the above presented studies of performances-based contracts do not give any reason to believe that the interrelationship between geometrical road design and future maintenance measures has been sufficiently considered.

2.6 Strategies to increase road maintenance efficiency

The governmental road net in Sweden of 98 300 km is managed by SRA. SRA is divided into seven regions: the Northern Region, the Central Region, the Stockholm Region, the Mälardalen Region, the South-eastern Region, the Western Region and the Skåne Region (Figure 2.2). Each region has a separate department responsible for road maintenance.

Figure 2.2 SRA regional divisions

Each region is divided into several geographical areas called "Maintenance areas". The maintenance activities within these areas are outsourced to one or more maintenance contractors. The contracts are usually four years long with a possibility for a few years extension depending on the type of contract.

To deal with future funding challenges in Sweden, various strategies are stated in the strategic plan for 2007-2017 established by SRA to improve efficiency and reduce costs, including maintenance expenses (Vägverket 2007). Strategies to improve the efficiency of road maintenance are:

- Develop new forms of cooperation and contracts as well as performance-based requirements to stimulate innovations and promote productivity growth within road infrastructure;
- Exploit SRA's purchasing volume to guarantee a competitive market for road construction and maintenance contractors;
- Coordinate guidelines and requirements with adjacent countries in order to increase the number of international and domestic bidders;
- Focus on applied research in order to improve road management efficiency;
- Use life-cycle cost analyses to achieve an optimal total cost; and
- Develop new funding forms, such as PPP projects, road usage fees or short-term loans, to increase flexibility and efficiency.

SRA's strategic plan states that the efficiency of maintenance and operation activities must be increased by 1% per year. It also states that the possibilities to make savings concerning operational activities are very limited. SRA has, therefore, made efforts to increase maintenance efficiency through, among other things, prioritization of some maintenance activities (e.g., snow removal) before other maintenance measures (e.g., pavement maintenance). However, some efforts made by SRA to increase maintenance efficiency are mainly cost-cutting efforts rather than stimulation of maintenance efficiency. Focus is on reducing recurrence rates of maintenance activities and prioritising some activities before others. Many of these efforts might decrease road maintenance standards. One example is the developmental project "Review of Maintenance Activities (GAD)" which has been carried out by SRA with the intention of increasing maintenance efficiency. GAD and other similar projects are expected to give SRA 70 million SEK ($\approx$ 7 million EUR) per year in cost-savings, i.e., 1% of the annual maintenance budget. However, some measures proposed by GAD have resulted in lower standards. For instance, road visibility has decreased due to a reduction of the roadside mowing width along the road sides from seven to three meters and a reduced frequency of cleaning road reflectors. This type of cost-cutting with its negative consequences is not unique for Sweden. A study of maintenance costs in Newfoundland and Labrador in Eastern Canada showed that the maintenance budget was reduced by a third in three years (Stenbeck 2007). Several actions that have been undertaken to keep the budget in balance such as reducing sand quality, fewer depots for material and equipment, narrowing shoulders and changing double lines to single line markings. According to the study, innovation has been interpreted as the capacity to cut quality without too many negative effects. In addition to the direct effects of the cuts, the study points out that productivity also may decline because of displeased staff and more relocation time needed as a result of fewer equipment depots per area.

2.7 Reflections based on the literature study

To face road infrastructure gaps, road authorities have continuously made efforts to increase efficiency, especially maintenance efficiency.

Some of these efforts have resulted in reduced costs. However, in some cases, such as outsourcing of maintenance contracts, it seems that sometimes standards have deteriorated. In the ambition to increase maintenance efficiency, focus often has been on cost-cutting through reducing the recurrent rate of maintenance activities, prioritising some measures before others, e.g. the prioritization of winter maintenance, cleaning and grass mowing over bridge and pavement maintenance. Road authorities should consider such efforts as cost-savings rather than an increase in efficiency as the definition of efficiency is to get more value from the same resources or to get the same value from less resources. This might explain why some efforts to increase maintenance efficiency have been less successful.

Implementation of performance-based contracts, PPP projects and life-cycle cost analyses requires the consideration of maintenance aspects during the planning and design phase. However, in almost all the projects and literature evaluated in this study, focus has been on structural design, such as pavement design, rather than geometrical design. In guidelines for these types of contracts, recommendations to analyse the influence of geometrical design on maintenance are seldom considered. Despite this fact, performance-based contracts and life-cycle cost analyses have, in many cases, resulted in reduced maintenance costs and improved road structure quality. However, these contract types and analyses are still uncommon in the road sector owing mainly to a lack of knowledge in implementing long-term maintenance contracts and poor follow-up procedures for these contracts. The bidders have perceived a higher risk and the contracts have been more expensive than traditional contract forms (Stenbeck 2007). There are also reasons to believe that road authorities in many cases have used performance-based contracts and PPP projects only to transfer risk to the contractors and to obtain a financing partner.

One of the most important characteristics of performance-based contracts and PPP projects is to give the contractors freedom to decide upon the best design and construction method and materials for the road project. In some cases, especially in PPP projects, this can be difficult, since the concessionaires are often foreign companies with a limited experience of risks and conditions existing in a specific country. In these cases, contracts may become more expensive than traditional contracts as the concessionaires are taking higher risks. In the long run this could lead to poor competition in the infrastructure market, as only large actors will have the required knowledge and resources for these contract types. In addition, road authorities may lose valuable knowledge, if only contractors prosecute technological development.

It is obvious that road authorities have mostly emphasized reducing costs in the construction or maintenance stages, instead of in the design stages. According to Emblemsvåg (2003), such emphasise leads to a reactive cost management, as opposed to reducing costs before they are incurred; proactive cost management. Reactive cost management is insufficient as 80% of the total costs for a product are committed to the activities prior to production. Many organisations or companies realize this fact but still employ reactive cost management. Emblemsvåg (2003) claims that this might simply be a matter of bad habits or that people dislike learning new things, unless the consequences of not learning are worse than those of learning.

All maintenance efficiency attempts evaluated in this study have one thing in common, namely ignorance of the interrelationship between geometrical road design and maintenance as an efficient tool to increase maintenance efficiency. Focus has mainly been on improving operating practises and maintenance procedures. This might also explain why some attempts at increasing maintenance efficiency have been less successful. Ignorance of maintenance aspects during the planning and design process is a well-known issue. However, there are very few studies published concerning the underlying factors (Freer-Hewish 1986), which is confirmed in this study by the limited amount of literature found. This fact was the reason for conducting a study highlighting the problems and difficulties preventing due consideration of maintenance aspects during the road planning and design process. The study is presented in Chapter 3.

CHAPTER 3

ROAD DESIGN FOR FUTURE MAINTENANCE – PROBLEMS AND POSSIBLITIES

Road planning includes examining conditions relevant to the building of new roads or the improvement of old ones, such as transportation demands, climate, topography, geology and material supplies. It also includes evaluation of the consequences for society, such as environmental impact, transportability, traffic safety and economic development.

Road design means selecting material and dimensions of the road and its components, e.g. width of traffic lanes, road profile and type of road equipment. The process of road planning and design is very complicated due to the numerous components of which the road consists and other aspects which have to be considered for an optimal solution. The road planning and design process in Sweden consists of four subprocesses: the feasibility study, the road survey, creation of the work plan and creation of the construction documents. The first two subprocesses are called road planning and the third and fourth ones are called road design.

The possibility to execute future maintenance activities is an important aspect which has to be considered during the road planning and design process. The designers should consider maintainability to a higher extent than today. According to the actors involved in the planning and design process, there are many different reasons for improper consideration of maintainability. The problems of performing maintenance activities and costs associated with improper road design are often a subject for discussion. However, the literature study for this PhD project shows that the problem is not reflected in the literature as there are very few articles published within the subject. Because of this, a study was carried out with the intention of identifying the problems obstructing due consideration of maintainability during the road planning and design process. The objective was also to identify the urgent needs for changes to eliminate these problems. The focus was on the planning and design processes at the SRA.

3.1 Method

The investigation was carried out in two stages: data collection and data analysis. Data was collected through interviews and reviews of planning and design related documents. The main objective of the interviews was to formulate situations perceived as problems by the actors involved in maintenance activities or in the road planning and design process. The respondents were divided into four categories: consultants, maintenance contractors, persons involved in maintenance activities and persons involved in planning and design at the SRA. Semi-structured interviews (Trost 2005) were chosen to give respondents the possibility to answer in their own words and to generate a dialogue.

The second part of the data collection phase was to review documents describing the processes of planning and design, construction and consignment in Sweden (Vägverket 2004a; Vägverket 2004c; Vägverket 2004d; Vägverket 2004e; Vägverket 2004f; Vägverket 2004g). Other reviewed documents were guidelines for road planning and design (Vägverket 2004h), and documents related to the purchasing process (Vägverket 2004b). These documents were examined to identify planning and design activities, and the goals governing these activities. The collected data was later analysed using a method calls "Change analysis". This method is

mostly used in the preliminary phases of a study for organization development and activities (Goldkuhl and Röstlinger 1998).

According to "Change analysis", the collected data was analysed in the following four steps:

1. *Problem analysis*: The aim of this analysis was to obtain an overview of the situations identified as problems and to describe their causes and consequences. This analysis was carried out in four steps: formulation, classification, delimitation of problem areas and analysis of the relationship between the problems.

2. *Activity analysis*: This analysis was aimed at evaluating the activities included in the planning and design process in order to understand how the process was conducted and to identify problems not mentioned by the respondents. This was done by describing action patterns within each subprocess and by clarifying how different documents were treated and how administrative activities were performed within the processes.

3. *Goal analysis*: The aim of this analysis was to identify the goals which the planning and design process must fulfil, and to examine and evaluate correlations between them. This analysis was carried out in three steps: identification of the goals, analysis of the interrelationship between the goals followed by an evaluation of the goal.

4. *Analysis of the needs for change*: This analysis was aimed at identifying the most urgent needs for change, which are necessary for sufficient consideration of maintenance aspects in the road planning and design process.

Analysis of the need for change was conducted in two steps: problem evaluation and formulation of the needs for change. During the problem evaluation, the problems were divided into four different statuses:

- No problem (NP): the situation was misunderstood or incorrectly evaluated.
- No solution for the problem (NPS): this type of problem has no solution or has a solution outside the scope of this investigation.
- Solved problem (SP): this category contained problems which were already solved or in the process of being solved.
- Need for change (NC): these problems were deemed urgent for elimination and could be eliminated by changes within the planning and design process.

For the last category of problems, a high priority was set based on the following criteria:

- A problem which caused several other problems.
- A problem connected to high costs or one which could result in serious consequences.
- A problem which was crucial to the solution of another problem.
- A problem which was stressed during the interviews.
- A problem which was relatively simple to eliminate, thus generating a large positive effect for little effort.

Generally, low priority was given to problems which could be solved entirely by solving another problem.

The evaluated problems formed the basis for formulating the need for changes. The aim of this activity was to indicate the needs for change which could contribute to the elimination of

the identified problems. The changes were identified without specifying any measures to fulfil them. In this phase of the investigation, it was important to focus not only on the problems but also to study the strengths of the road authority or the other actors involved in planning and design as well as possibilities within relevant fields.

3.2 Results

During the interviews more than 100 situations perceived as problems for sufficient consideration of maintainability were presented by the respondents. The analyses reduced that number to 45 problems (Paper II, Appendix 1). Most of the problems were identified during the interviews. A few more were identified during the analysis phase.

The problems were classified into six problem areas:

1. **Insufficient Consulting**: This problem area is related to insufficient consulting between the actors involved with maintenance activities and planning and design. Consultation between these actors is limited to only a few meetings. Those meetings are often arranged during the construction phase. Any design corrections during this late phase will be difficult and costly.

2. **Insufficient knowledge**: This problem area is related to knowledge regarding road planning and design and road maintenance. Insufficient consideration of maintainability is often due to project managers or consultants not having adequate knowledge pertaining to the costs and performance of maintenance activities.

3. **Regulations without maintainability consideration**: This problem area is related to regulations within the planning and design process, which are often developed without sufficient consideration for maintainability.

4. **Insufficient planning and design activities**: This problem area are related to deficiencies in planning and design activities These deficiencies often result in the selection of road designs which require costly and unnecessary maintenance activities. For example, limited investment budgets force project managers and consultants to select cheaper road designs which require costly maintenance measures.

5. **Inadequate organisation**: Problems collected in this area relate to the organisational structure of road authorities. A linear organisation often leads to poor coordination between the different processes and activities within the organisation resulting in an inadequate exchange of knowledge and experience.

6. **Demands from other authorities**: Problems in this area are related to requirements from other authorities. During the planning and design phases, municipalities and county administrators present arguments which are perceived as more important than maintainability. This is the reason why maintainability is often overlooked.

The subjects for further analysis were in problem areas 1-4, which were directly connected to the planning and design process.

Analysis of the relationship between these problems revealed the causes and consequences of each problem. A structure in the form of graphs called "problem graphs" was established for problems within each problem area (Paper II, Figures 2-5). These graphs constitute an important basis for the elaboration of the proposals for the demand for changes.

The analysis of activities made the correlation between planning and design activities more understandable. The divisions involved with planning and design activities at SRA and other

involved organisations were identified. In addition, input and output for each activity was illustrated. A few more problems mentioned in the problem list were identified during this analysis.

Analysis of the goals indicated that SRA has not established any clearly defined, long-term goals considering future maintenance. No goals cover maintainability, even if the overall transportation-related policy goal indicates a cost efficient transportation system. The absence of well-defined goals concerning maintainability leads to insufficient consideration of this aspect. Because of this, requirements to fulfil existing operational goals concerning other aspects of road design often direct planning and design towards the selection of a road design, which may require costly maintenance measures.

The budget frame is considered as a non-documented goal, which directs planning and design. For each project, a budget is established during the road investigation subprocess. This budget is often made many years before construction is started. The suppositions and calculations in the budget can have lost actuality, meaning that the costs could be underestimated. This can force road authorities to select designs with low acquisition costs, which can later incur high maintenance costs.

To identify the most urgent needs for change, which are necessary for satisfactory attention to the maintenance aspects in the planning and design phase, the identified problems were classified into four different statuses: 36 problems were classified as 'need for change' (NC), six problems as 'no solution to the problem' (NPS), two problems as 'solved problem' (SP) and one problem as 'no problem' (NP).

A prioritising of the NC problems in accordance with the five criteria, mentioned in Section 3.1, resulted in 26 problems with high priority and 16 problems with lower priority.

Based on the mentioned analyses, several needs for changes were identified. The most urgent one is establishment of well-defined and long-term goals for road maintenance. These goals should be possible to break down into operational goals which, give the maintainability significance in the planning and design process. It must also be possible to evaluate the fulfilment of the operational goals at the end of each road project. A minimum life-cycle cost including maintenance costs can be such an operational goal.

During the planning and design process, there is a great need for well-structured systems for consulting and knowledge exchange between all actors involved in maintenance activities and in planning and design. The consulting process has to be carried out by designated actors and through well-defined activities in accordance with the established guidelines. Consulting expenses should be a specified part of the planning and design budget.

Increased knowledge of road designs, which support future maintenance, is needed for road authorities, contractors and consulting firms. Such knowledge is the basis for an adequate consideration of maintainability. Increased knowledge requires an efficient feedback system from the maintenance process to the planning and design process and vice versa. One part of such a system is the registration of expenses for supplementary maintenance measures which have to be performed because of inappropriate road design.

An evaluation process with clear guidelines is recommended for each completed road project as a part of a quality assurance system. This process should ensure that probable future maintenance measures are considered to a sufficient extent for each road project.

There is a great need to supplement guidelines, legislation and other documents governing planning and design with maintenance aspects.

Requests for quotations and other purchasing related documents should contain clear guidelines regarding maintainability, e.g. requirements for maintenance management plans or requirements to minimize life-cycle costs.

There is a need for increased incentives for consulting firms to get them to pay more attention to maintainability during planning and design. Compensation in the form of bonus points during the evaluation of quotations could be an option for consultants, who have demonstrated a consideration of the maintainability aspect.

3.3 Discussion and conclusions

The problem analysis indicates a complex combination of problems which result in an insufficient consideration of maintainability aspects during the road planning and design process. The problem areas, which contribute to the main problem, are also affected by the existence of related problems found in other problem areas. This indicates that the problem areas are closely related. None of the problems can be solely eliminated without affecting the others. On the other hand, the elimination of a problem area can also contribute to the elimination of problems in other problem areas.

The non-existence of a well-defined goal concerning maintenance is a fundamental basis for insufficient consideration of maintainability aspects. This state of things is often the reason why improper planning and design regarding maintainability is not considered as a problem. The non-existence of such goals makes road authorities more concerned with fulfilling other goals regarding other aspects. Such a situation often results in road designs with costly and unnecessary maintenance requirements.

The analysis of the activities confirms the claims made by the interviewed respondents regarding poor consulting among actors involved in maintenance activities and in planning and design. One reason for poor communication between the actors could be the road authority's inadequate organisational structure.

The following needs for changes have been identified to eliminate inadequate consideration of maintenance aspects during the planning and design process:

- An urgent need to establish well-defined long-term goals regarding maintenance and to develop methods to evaluate the fulfilment of those goals;
- Development of well-structured systems for experience exchange and consulting among actors involved in maintenance activities and in the planning and design process;
- Increased knowledge regarding road maintenance among all actors involved in the planning and design process;
- Development of a systematic evaluation process with clear guidelines for the examination of completed road projects to ensure adequate consideration of maintenance as a part of a quality assurance system;
- Addition of maintainability in planning and design related guidelines, regulations and other documents;
- Creation of guidelines and requirements for future maintenance considerations which should be incorporated into quotation requests and other purchasing related documents; and
- Creation of incentives for consultants to sufficiently consider maintainability aspects during the planning and design process.

The implementation of these changes requires further studies to establish effective and long-term solutions. Avoiding measures requiring lot of resources is important. At the same time, it must be recognized that efforts for change and development always require new resources. The optimal solution would be to select measures which can solve several problems at the same time. It is also important to study all possible positive and negative consequences of the measures for everyone involved in road planning and design.

Based on the results of this study, road authorities are encouraged to create an approach to calculate and analyse life-cycle costs in order to support due consideration of maintenance aspects during road design. The approach will constitute a basis for selecting a design giving a minimum life-cycle cost. Creating such an approach became one of the main objectives of this PhD project. The approach and the necessary data collection are presented in the following chapters.

CHAPTER 4

ROAD BARRIER REPAIR COSTS AND INFLUENCING FACTORS

The studies presented in Chapters 2 and 3, indicated that absence of an approach for analysis of life-cycle costs for road infrastructure is an underlying factor for insufficient consideration of maintenance aspects during planning and design of roads.

An approach for analysis of life-cycle costs during road design should consider all costs associated with all road components, such as costs for acquisition and maintenance as well as socio-economic costs. This requires an extensive data collection because several factors affect these costs. Some of the data is often archived in a way that makes data collection difficult, and some data is even non-existent. This fact was the reason to focus on one road component initially and gradually develop the approach to include other road components. After consultation with maintenance experts, road barriers were chosen as a suitable component to study.

Life-cycle costs for road barriers consist of investment costs, maintenance costs and socio-economic costs. Each of these costs was examined in this PhD project as input towards the desired approach for analysis of life-cycle costs for barriers.

One of the costs examined was repair costs associated with barrier damage repairs. This chapter presents a study conducted to quantify the rate of barrier repairs (i.e., number of barrier repairs per vehicle kilometres travelled) and the associated costs. Several influencing factors, such as barrier type, road type, posted speed limits and seasonal effects, were analysed.

The scientific contribution of this study lies in the fact that it provides information regarding the maintenance aspects of road barriers. For road authorities and road design consultants, this information is a crucial and much needed piece of a puzzle for life-cycle cost analyses.

4.1 Road barrier types

Road barriers are usually categorized as flexible (e.g., cable barrier), semi-rigid (e.g., w-beam barrier) or rigid (e.g., concrete barrier), depending on their deflection characteristics on impact (Figure 4.1). Flexible systems generally impose lower impact forces upon vehicles than the other categories since more of the impact energy is dissipated by the deflection of the barrier (AASHTO 2006).

During the road planning and design process, a barrier type is selected according to several criteria regarding performance and safety, such as containment level, impact severity, level of deflection, and the possibility to modify the deflection level. These criteria are specified by the EN 1317-5 standard (European Committee for Standardization 1998).

4.2 Road barrier maintenance

The most frequent maintenance measure for road barriers is damage repairs, generally caused by vehicle collisions or impacts by snow removal equipment. Damage caused by vehicle collisions usually require immediate repairs as the damaged barriers usually lose their efficiency after the impact. In some cases, the damaged components, such as damaged posts or

beams on the road surface or protruding into the traffic area, constitute additional hazards for road users. These parts have to be removed as fast as possible. However, some kinds of barriers, e.g. w-beam barriers and Kohlswa-beam barriers retain some degree of efficiency after minor impacts due to the rigidity of their elements (AASHTO 2006). Therefore, repair of these barriers sometimes has a low priority after minor impacts.

Figure 4.1 The most common barrier types in Sweden

Barrier damage caused by snow removal equipment is another maintenance issue. However, this kind of damage often does not require immediate repair, because many barrier types, such as w-beam barriers and Kohlswa-beam barriers, retain a degree of their efficiency even after such damage.

Barrier repair costs differ depending on the type of road barrier. For example, owing to their rigidity and strong construction, repair costs for concrete barriers are very low compared to other barriers because they seldom need to be repaired.

For the same type of barriers, repair costs differ depending on the design. For example, repair costs for cable barriers differ considerably as different manufacturers use different structures and components for their products. Unfortunately, due to procurement regulations, road authorities can only specify performance requirements for the barriers but not a specific barrier type known for its low maintenance costs.

Road type is another factor which probably influences barrier damage and repair costs. For instance, the number of barrier collisions along motorways in Sweden is considered to be less

than along collision-free roads, because motorways normally show broader lanes and a better road standard. However, this opinion expressed by road authorities is purely anecdotal and not scientifically verified.

Posted speed limits also influence barrier repair costs. Evaluation of the performance of collision-free roads shows that the barrier collision rates (i.e., number of barrier collisions per vehicle kilometre) along roads with a posted speed limit of 110 km/hr is 20% higher than along roads with a posted speed limit of 90 km/hr (Carlsson and Brüde 2005). This result may indicate that annual repair costs for barrier damages are probably higher for barriers along roads with a posted speed limit of 110 km/hr as well.

Another factor which likely affects repair costs for barrier damage is seasonal effects. Repair costs for barriers seem to be higher during winter. This opinion is based on experiences regarding difficulties in conducting repair measures for some specific barrier types during the winter months. For example, replacement of cable barrier posts is difficult and time-consuming during the winter due to frozen water inside the post sleeves or at the concrete foundations. It has also been proven that barrier collision risks (measured in number of barrier collisions per vehicle kilometre) for barriers along collision-free roads in the northern regions of Sweden are 20% higher than in the southern regions (Carlsson and Brüde 2006). This difference is attributable to poor road conditions due to colder winters in the northern regions. Therefore, the repair costs are probably higher in northern Sweden owing to a higher number of barrier collisions.

4.3 Method

Experimental analyses of the correlation between repair costs and influencing factors was considered as unrealistic because of the high number and combinations of influencing factors. It would be very difficult to simulate such a large number of accidents in an experimental way, Instead, the study focused on barrier repairs that already had been carried out.

The study was based on 1625 repairs conducted in four regions of the SRA. Cable barriers, w-beam barriers, Kohlswa-beam barriers, pipe-beam barriers and concrete barriers were studied. The analysis focused on cable barriers and w-beam barriers because they are the most common barrier types in Sweden. Furthermore, the analyses were focused on median barriers, as the data concerning roadside barriers were too limited. For the same reason only motorways, four-lane roads and collision-free roads were analysed.

The necessary data regarding barrier repair, such as barrier type, repair cost, etc., were obtained from barrier repair invoices. The Swedish National Road Database (NVDB) was used to collect data, such as road type, barrier lengths and posted speed limits. Data regarding annual average daily traffic (AADT) was obtained from the AADT-maps. Interviews with maintenance experts and contractors were used to obtain general information about procedures for repair actions, problems faced during the repairs as well as factors influencing repairs and the associated costs.

A method called "Case Study Research Method" was used for the analysis (Yin 2003). Figure 4.2 shows the steps which were followed to carry out the case study. The case study started by defining the research question, research propositions, units of analysis and logic of linking data to the propositions. The research question to be answered was "How do factors, such as posted speed limits, road types, barrier types and seasonal effects, affect barrier repairs and the associated costs?"

The following research propositions were formulated based on common opinions expressed by the interviewed maintenance experts:

- The number of barrier repairs and the associated costs are higher for cable barriers than for other barrier types.
- The number of barrier repairs and the associated costs are higher along collision-free roads than along other types of roads.
- The number of barrier repairs and the associated costs are higher along roads with a posted speed limit of 110 km/hr than along roads with a posted speed limit of 70 km/hr or 90 km/hr.
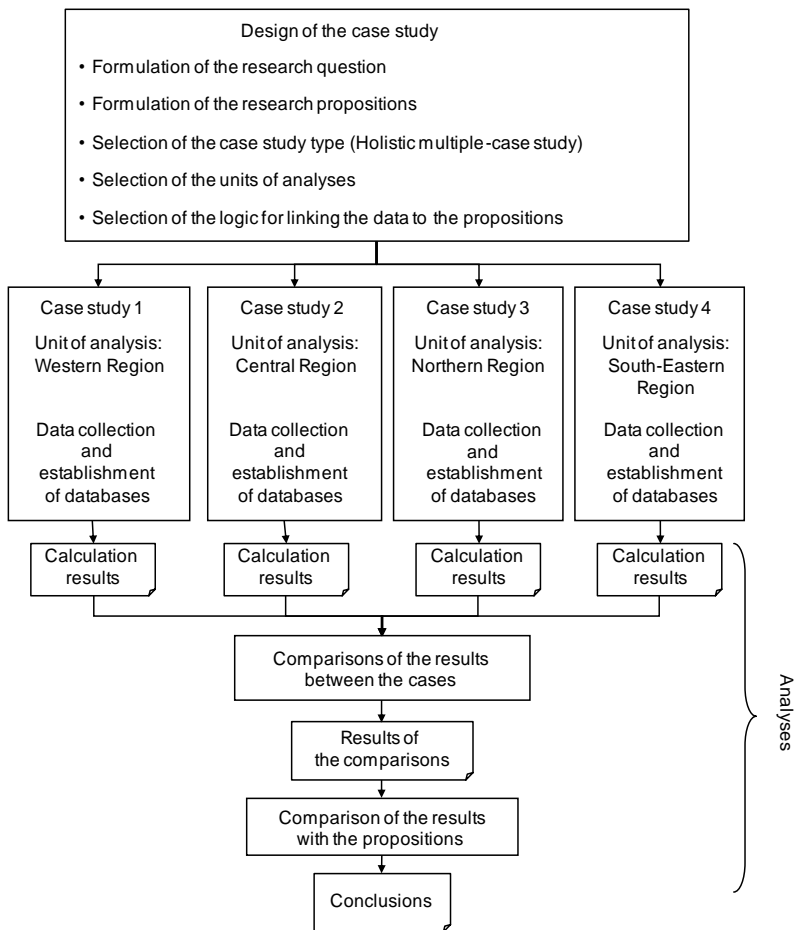- The number of barrier repairs and the associated costs are higher during winter than during summer.

Figure 4.2 *Structure of the case study*

For this investigation, a holistic multiple-case study was selected for four regions in the SRA: the Northern, Central, Western and South-Eastern. These regions were the most appropriate units for analysis, because each region is unique regarding costs, subsidiary prices and climate. The regions themselves are also archiving their own information about barrier repairs. It was important to investigate more than one region in order to establish a strong base for the analyses and generalization of the findings.

To link the data to the propositions, pattern matching logic was chosen (Trochim 1989). The empirically based data pattern (i.e., the findings from each unit of analysis) was linked to the predicted patterns (i.e., the propositions). The findings from each region were compared to determine, if they predicted the same results or not. If the findings coincided, they were considered as an actual empirically based pattern. Later, the findings were compared to the propositions to support or reject them. The findings were presented in terms of repair cost per vehicle kilometre and repair rate measured in number of repairs per vehicle kilometre. The reason for using these two terms was to neutralize the effects of barrier length and AADT on the rate of recurrence of barrier repairs and on the repair costs.

The repair rate and the average repair cost per vehicle kilometre for different combinations of road types, barrier types and posted speed limits were calculated for each studied region using the following equations:

$$BRR_{r,b,s} = \frac{NR_{r,b,s}}{TATW_{r,b,s}} \qquad (4.1)$$

$$TATW_{r,b,s} = \sum_{l=1}^{l=n} AADT_{l,r,b,s} \cdot (1+TGF)^{ys-ym} \cdot LL_{l,r,b,s} \cdot 365 \qquad (4.2)$$

$$ARC_{r,b,s} = BRR_{r,b,s} \cdot AVCR_{r,b,s} \qquad (4.3)$$

$$AVCR_{r,b,s} = \frac{\sum_{br=1}^{br=n} RCBR_{r,b,s,br}}{TATW_{r,b,s}} \qquad (4.4)$$

where

BRR = Barrier repair rate measured in number of repairs per vehicle kilometre.
r = Road type.
b = Barrier type.
s = Posted speed limit.
NR = Number of barrier repairs during the studied year.
$TATW$ = Total annual traffic work measured in vehicle kilometre.
$AADT$ = Annual average daily traffic for the studied year.
l = Road link.
TGF = Traffic growth factor.
ys = Year of the study.
ym = Year of AADT measurement.
LL = Link length.
ARC = Average repair cost per vehicle kilometre.

AVCR = Average cost per repair for links with the same combination of road type, barrier type and posted speed limit.

br = Barrier repair.

RCBR = Cost for one single barrier repair.

The repair rate and average repair cost per vehicle kilometre could only be calculated for median barriers, as the lengths of the roadside barriers were unknown.

For statistical analysis of the results, the methods of linear and generalized linear models were used (Olsson 2002). More details about the statistical analysis can be found in Paper III.

4.4 Results and discussion

4.4.1 Effect of barrier type

To analyse the effect of barrier type on barrier repair costs, barrier repairs on the same type of road were compared. This was only possible for cable barriers and w-beam barriers installed as median barriers along motorways in the Western and the South-Eastern Region. The result shows that the average repair cost per vehicle kilometre is higher for cable barriers than for w-beam barriers in both regions mainly because the repair rate for cable barriers is approximately two times higher than for w-beam barriers (Table 4.1). These differences are statistically significant (P-value = 0.0001) (Paper III, Appendix).

Table 4.1 *Barrier repairs and associated costs for road median w-beam and cable barriers along motorways in two regions, regardless speed limits.*

Region	Barrier type	Number of barrier repairs	Annual traffic work (Mvkm)	Repair rate (Rep/Mvkm)	Average repair cost per vehicle kilometre (SEK/Mvkm)
Western	Cable	105	514	0.20	2 200
	W-beam	207	2453	0.08	900
South-Eastern	Cable	165	1403	0.12	3 700
	W-beam	15	190	0.08	2 800

Note: 1 SEK ≈ 0.1 EUR

It is worth noting that no repairs were found in this study for the examined 41 kilometres of concrete barriers. The limited number of repairs may be explained by the fact that normal collisions do not result in any damage to this kind of barrier. From a pure maintenance perspective, the absence of repairs might indicate that concrete barriers can be the most cost effective. Especially along urban road sections with a high traffic volume and a high risk for collisions, concrete barriers may be the best alternative. As mentioned before, cable barriers have to be repaired even after minor collisions because of its weaker construction, while w-beam barriers often retain some degree of efficiency.

4.4.2 Effect of road type

The average repair costs per vehicle kilometre in the Central and the Western Regions are higher for barriers along collision-free roads than for barriers along motorways and 4-lane roads (Table 4.2). This difference is statistically significant at a less than 5% level of

significance (Paper III, Appendix). The difference is mainly based on a higher repair rate along collision-free roads. One explanation could be that road barriers along collision-free roads are more exposed to damage due to the relatively short distance between the barriers and the edge of the traffic lane. Another explanation could be that the geometrical standard for motorways is higher than that for collision-free roads. The higher repair rate on collision-free roads can also be due to the fact that this type of road is mainly equipped with cable barriers with a high repair rate as mentioned in the previous section.

In contrast with the Central and Western Region, in the South-Eastern Region, the average repair cost per vehicle kilometre is higher for barriers along motorways than along collision-free roads. This divergence might be due to the fact that the average cost per repair in the South-Eastern Region is much higher along motorways than along collision-free roads (Table 4.2). Another underlying factor for this divergence could be that motorways in the South-Eastern Region are mainly equipped with cable barriers, while motorways in the Western Region and the Central Region are mainly equipped with w-beam barriers. As mentioned before, the average repair cost per vehicle kilometre is higher for cable barriers than for w-beam barriers.

Table 4.2 *Barrier repairs and associated costs for road median barriers along different road types, regardless of barrier type or speed limit*

Region	Road type	Number of damage repairs	Annual traffic work (Mvkm)	Number of repairs per vehicle kilometre (Rep/Mvkm)	Average cost per repair (SEK)	Average repair cost per vehicle kilometre (SEK/Mvkm)
Northern	Collision-free roads	93	241	0.39	11 200	4 300
	4-Lane roads	4	33	0.12	6 800	800
Central	Motorways	74	270	0.27	16 300	4 500
	Collision-free roads	235	555	0.42	14 200	6 000
	4-Lane roads	19	78	0.24	17 800	4 300
Western	Motorways	315	2980	0.11	10 700	1 100
	Collision-free roads	60	199	0.30	11 200	3 400
	4-Lane roads	40	649	0.06	8 300	500
South-Eastern	Motorways	180	1689	0.11	31 700	3 400
	Collision-free roads	142	700	0.21	10 000	2 100

4.4.3 Effect of posted speed limit

Based on the results from the different regions, it is not possible to present a reliable correlation describing how posted speed limits affect barrier repairs and the associated costs. The differences in the average repair cost and the repair rate per vehicle kilometre between the studied posted speed limits are not statistically significant (P-value > 0.45) (Paper III, Appendix).

4.4.4 Seasonal effects

Table 4.3 shows that the number of barrier repairs is higher during winter than during summer in all regions. This difference is highly significant (Pearson's Chi-squared statistic=63.834 on 1 df) (Paper III, Appendix). The difference can be explained by darkness and road conditions

in wintertime with slippery road surfaces and frequent snow removal activities, which lead to higher barrier collision risks.

Table 4.3 *Barrier repairs and associated costs for roadside and road median barriers during different seasons, regardless of road type, barrier type and speed limit*

	Seasons					
	Summer 15th April and 14th October			Winter 15th October - 14th April		
Regions	Number of repairs	%	Average cost per repair (SEK/Rep)	Number of repairs	%	Average cost per repair (SEK/Rep)
Northern	36	32	13 100	76	68	12 200
Central	164	41	16 800	238	59	15 400
Western	286	42	11 200	397	58	11 400
South-Eastern	160	38	23 300	262	62	21 200

Table 4.3 also shows that, to some extent, the average cost per repair is higher during summer than winter in all regions. Barrier damage from collisions seems to be greater during the summer. This is verified in Table 4.4, where the average number of replaced posts per repair in all regions is higher during summer than during winter. An explanation may be that lower speeds during winter, due to bad weather and road conditions, lead to lower impact forces at collisions with less damage to the barriers. However, the difference in the repair costs between the seasons is not statistically significant.

Table 4.4 *Average number of replaced posts for roadside and road median cable barriers, regardless of road type and speed limit*

	One year		Winter		Summer	
Regions	Number of repairs	Average replaced posts per repair	Number of repairs	Average replaced posts per repair	Number of repairs	Average replaced posts per repair
Northern	97	8.3	68	7.8	29	9.2
Central	341	9.6	218	8.5	123	11.4
Western	172	9.5	111	5.9	61	15
South-Eastern	348	9.5	218	8.2	130	11.7

4.4.5 Differences between the Regions

The repair costs per vehicle kilometre are higher in the Northern and Central Region than in the Western and South-Eastern Region (Table 4.2), regardless of barrier and road type. This difference is statistically significant (P-value = 0.0007) (Paper III, Appendix). The major factor contributing to this difference is that the number of repairs per vehicle kilometre in the Northern and Central Region is higher than in the Western and South-Eastern Region. The difference is statistically significant (P-value = 0.0001) (Paper III, Appendix). In other words, the risk for barrier damage is higher in the Northern and Central Region than in the Western and South-Eastern Region, despite the fact that traffic intensity is much higher in the Western and South-Eastern Region and repair policies are the same in all regions. The higher risk for

barrier damage in the Northern and Central Region could, among other things, be due to the long, cold, and snowy winters with slippery road conditions and, consequently, frequent snow removal activities. This is confirmed by Table 4.4, where the number of barrier repairs is higher during the winter than during the summer in all regions.

Differences in tendered and unit prices for barrier repairs between the regions are factors contributing to the differences in average cost per repair between the four regions. Higher tender and unit prices in the Central and Northern Region indicate poor competition within the road maintenance market.

Another factor contributing to a higher average repair costs per vehicle kilometre in the Northern and Central Region is that the majority of the roads in these regions are collision-free roads. As mentioned in section 4.4.2, the average repair cost per vehicle kilometre for barriers installed along collision-free roads is higher than for barriers installed along motorways and 4-lane roads (Table 4.2).

4.5 Conclusions and recommendations

Based on the results presented in this study, the following conclusions can be drawn:
- The repair rates and the average repair cost per vehicle kilometre for median cable barriers are higher than for median w-beam barriers, regardless of road type.
- From a purely repair cost perspective, the use of barriers with a stronger construction, such as w-beam barriers, is more cost effective for the road authorities. The repair rate for median barriers along motorways can probably be almost halved by using w-beam barriers instead of cable barriers.
- The repair rate and the average repair cost per vehicle kilometre for median barriers along collision-free roads are mostly higher than along motorways or 4-lane roads. The risk for barrier collisions along collision-free roads is higher than along other road types probably due to lower geometrical standards along collision-free roads.
- From a pure repair cost perspective, the use of barriers with stronger construction along collision-free roads and roads with low geometrical standards will be cost effective for road authorities, as the use of this barrier type will result in a reduced number of repairs and lower repair costs.
- Based on the information available from this study, it is not possible to describe how speed limits affect barrier repairs and the associated costs.
- The number of barrier repairs being higher during the winter than the summer is probably due to collisions caused by poor road conditions, slippery road surfaces, darkness and damage caused by snow ploughs. However, barrier damage is greater during the summer probably due to higher speeds.
- In the Northern and the Central regions, which are characterized by long and snowy winters, the repair rate and the average repair cost per vehicle kilometre for median barriers are higher than in the Western and South-Eastern regions.
- From a pure repair cost perspective, the use of barriers with a stronger construction in regions with long snowy winter seasons will be cost effective for the road authorities, as the number of barrier repairs will be reduced.

A recommendation to use a specific barrier type must not only be based on maintenance aspects. Several other important aspects need to be considered, e.g. investment costs and safety performance. Such aspects together with the results presented in this chapter were used to create a new approach to calculate and analyse life-cycle costs for road barriers. This approach is described in Chapter 6.

CHAPTER 5

ASSESSMENT OF INJURY RATES ASSOCCIATED WITH BARRIER COLLISIONS

Costs for injuries associated with road barrier collisions are a considerable part of the socio-economic costs. To estimate such costs for a particular barrier type, it is necessary to quantify collision and injury risks associated with the barrier in question. Unfortunately, it is often difficult to precisely quantify the injury risks associated with road barrier collisions because information regarding collisions, traffic conditions and road barrier types is often unavailable.

This chapter presents a study aimed at quantifying and comparing the rate of injuries (i.e., number of injuries per vehicle kilometre) associated with collisions with different barrier types. The injury rates obtained from this study were used to calculate the costs for injuries as a part of the socio-economical cost for road barriers. This study is unique in that barrier performance evaluations were based on actual collision data, consideration of post-impact collision data and an injury classification made by Swedish healthcare services.

Estimation of injury risks associated with barrier collisions based on standard crash tests, with the aim of evaluating barrier performance, was not used in this study. This was due to the fact that impact conditions, redirection criteria and occupant response parameters in the current crash tests are specified for rather unlikely crash scenarios. As examples, Thomson (1999) mentioned ignorance of the effects of secondary collisions (i.e., post-impact collisions), the choice of too small impact angels as well as conflicts between approaches predicting occupant injury risks in crash tests and actual barrier performance.

5.1 Injury risks associated with barrier collisions and influencing factors

In general, the use of road barriers is a very effective way to reduce road injuries and fatalities. Installation of median cable barriers on 13 m wide roads reduced the number of fatal crashes by almost 76% in Sweden during the period 1998 – 2009 (Carlsson 2009). Fatal and disabling cross-median collisions on highways in Washington State were reduced by 75% on highways by using median cable barriers (Ray et al. 2008). Another study showed that the number of fatal collisions reported by police on French highways with roadside barriers was 50% less than on roads without barriers (Martin et al. 2001).

Despite the effectiveness of reducing injuries, road barriers themselves may cause severe or fatal injuries by inflicting severe impact forces on vehicle occupants during a crash (Insurance Institute for Highway Safety 2008; Road and Traffic Authority 2004; Stigson 2009). The severity of an impact into a road barrier depends on the barrier's flexibility, impact angle and impact speed. Flexible systems, such as cable barriers, generally impose lower impact forces upon vehicles than other systems, since more of the impact energy is dissipated by deflection of the barrier (AASHTO 2006). Because the impact event occurs over a large lateral distance, the time of the impulse event is extended. With flexible barriers, the risk of post-impact collisions has to be considered. Thomson (1999) showed that 65% of the cases involving impacts with flexible barriers resulted in severe secondary collisions.

Impact speed is another factor affecting impact severity. According to Singelton et al. (2004), the injury risk is proportional to impact speed. It has been shown that a higher posted speed is associated with higher crash severity (Ydenius 2009).

The severity of a barrier impact also depends on the impact angel. Based on full-scale barrier crash tests, a study showed that the impact severity increased when the impact angel increased from 20° to 45° (Ydenius 2010). The most significant increase in injury risk occurred with concrete barriers. Based on this result, flexible or semi-rigid barrier systems showed potential for reducing injury severity. It is worth noting that Ydenius did not consider the risk for severe injuries due to secondary collisions. Bryden and Fortuniewicz (1986) showed that 25% of barrier collisions resulted in secondary collisions causing severe injuries. It has also been reported that 25% of all road median barrier collisions involve more than one collision and that severity increases with the number of collisions (Mak et al. 1986). Secondary collisions have been reported as the cause of more severe injuries than the initial impact with road barriers (Ray et al. 1986; Ray et al. 1987).

Furthermore, choosing a 45° impact angle by Ydenius as an initial barrier impact angle in barrier crash tests is to some extent unrealistic. A reconstruction of 81 accidents on European roads showed that 90% of the cases had an exit angle below 20° (i.e., the angle between the barrier and the travel line of the vehicle after the barrier collision) (Thomson et al. 2006). On a straight road with a barrier parallel to the edge line, the exit angle and the impact angle are almost equal. A factor affecting the impact angle is the lateral distance between the barrier and the edge line of the carriageway. The possible impact angle increases if a longer lateral distance is available for the vehicle to travel (Thomson et al. 2006).

The lateral distance between the road barrier and edge line of the carriageway also affects the risk of post-impact over-/under-rides which in turn affects barrier collision severity (Marzougui and McGinnis 2010).

5.2 Method

The analyses in this study were based on documented data associated with actual road barrier collisions for the period 2005-2008 in Sweden. The road segments studied included 640 km of road E4, located between Helsingborg and Knivsta, and 346 km of road E6, located between Rabbalshede and Vellinge.

The best way to compare road barrier performance is to use documented barrier collision data to calculate collision rates as described in NCHRP Report 490 (Ray et al. 2003). Collision rates are calculated by determining the number of collisions in a particular category and dividing it by the traffic work (i.e. vehicle kilometres travelled) along that road segment. In the present study, the analysis was based on the injury rates calculated by dividing the number of injuries in a specific injury category, by the traffic work during a four year period for the road segment equipped with a specific barrier type using the following equations:

$$RI_{bt,i} = \frac{NI_{bt,i}}{TATW_{bt}} \qquad (5.1)$$

$$TATW_{bt} = AADT_{bt} \bullet BL_{bt} \bullet NY \bullet 365 \qquad (5.2)$$

where

       RI = Injury rate measured in number of injuries per vehicle kilometre.

       NI = Number of injuries.

       bt = Barrier type.

       i = ISS-interval.

       TATW = Total traffic work3.

       AADT = Average annual daily traffic.

       BL = Barrier length.

       NY = Number of the years covered in the study

The lengths of barriers along the studied roads were measured on-site using a vehicle mounted digital distance meter, a Coralba Tripmeter®. This was necessary because records of the lengths of median barriers were limited and records for roadside barriers were unavailable. Information regarding AADT was obtained from a web-based database called AADT-Map containing information about traffic volume on Swedish roads. Collision data, such as location of the collision, posted speed, injury type, barrier type, cause of collision etc., was obtained from the Swedish Traffic Accident Data Acquisition (STRADA). In this data base, the injuries are classified either by the police or health care personal or by both. The police classify the injuries into four categories on-site: Fatal, severe, mild and no injuries (i.e., only property damage).

Healthcare services classify injuries according to Injury Severity Score Codes (ISS) into five ISS-intervals: 0 (unhurt), 1-3 (mild injury), 4-8 (moderate injury), 9-15 (severe injury) and 16 or higher (very severe or fatal injury).

Traffic safety analyses in Sweden are often based on accidents reported by the police because the number of accidents reported by healthcare services is limited due to the limited number of healthcare services connected to STRADA. It is well-known that injury classifications made by the police are less accurate than classifications made by the healthcare services, as the police have neither the qualifications nor the required tools to make diagnoses on-site. To minimize the possible effect of this divergence on this study, the injury classification made by healthcare services was used as a basis for analyses. Furthermore, the number of injuries in different categories reported only by the police was converted to the number of injuries in ISS-intervals. This result was used in equation 5.1 to calculate the injury rate for each ISS-interval.

For the statistical analysis, a method called Poisson regression analysis was used. Details about the statistical analysis can be found in paper IV.

5.3 Results

In STRADA, 1019 barrier collisions, involving 1529 persons, were found along the studied roads during the period 2005-2008 (Table 5.1). Among the collisions studied, 330 collisions, involving 495 persons, were reported both by police and healthcare services.

The results showed an over-classification of injury severity made by the police in Sweden. For example, among the injuries classified as severe by the police only 15% were in fact injuries with ISS $\geq$ 9. The number of injuries reported only by the police was converted to ISS-intervals and summarized with the number of injuries reported by healthcare services for the same ISS-intervals (Table 5.2). Detail about this conversion can be found in paper IV.

Table 5.1 *Data regarding the studied barriers and number of injured persons associated with barrier collisions for the period 2005-2008*

Barrier Type	Barrier Length (km)	Traffic work (100 Mvkm)	No Injuries	Mild Injuries	Severe Injuries	Fatal Injuries	0	1-3	4-8	9-15	16-
			Injury Classification made by the Police				Injury Classification made by the Healthcare (ISS-intervals)				
			Number of injuries								
W-beam	1439	321.38	73	476	96	11	73	226	30	5	13
Cable	1027	137.78	33	406	22	4	112	173	14	7	6
Concrete	117	41.57	12	67	9	0	4	41	1	1	0
Pipe	87	25.99	9	59	15	0	5	17	2	2	0
Sum	2670	526.74	127	1008	142	15	194	457	47	15	19

Table 5.2 *Number of injured persons associated with barrier collisions reported both by police and healthcare services after conversion to ISS-intervals*

Barrier Type	0	1 - 3	4 - 8	9 - 15	16 -
	ISS-interval				
W-beam	174	498	61	16	17
Cable	175	346	30	12	8
Concrete	18	77	4	2	0
Pipe	20	59	7	4	1
Sum	387	979	103	34	26

For injuries with ISS $\geq$ 1, a likelihood ratio test showed that the differences in injury rates between the barrier types were significant at 95% confidence interval (P-value < 0.001) (Table 5.3). The results also showed significant differences between the injury rates for different posted speed limits at 95% confidence interval (P-value < 0.001). The highest injury rate was found on roads with speed limit of 90 km/hr (Table 5.3).

Table 5.3 *Injury rates and confidence intervals for injuries associated with barrier collisions*

	Injury rate [a]	95% confidence interval	Injury rate	95% confidence interval	Injury rate	95% confidence interval
	Injuries with ISS $\geq$ 1		Injuries with ISS $\geq$ 4		Injuries with ISS $\geq$ 9	
Barrier type						
W-beam	2.09	1.77 - 2.47	0.29	0.21 - 0.39	0.11	0.07 - 0.17
Cable	3.82	3.10 - 4.69	0.41	0.27 - 0.60	0.19	0.11 - 0.31
Concrete	1.75	1.22 - 2.52	0.14	0.06 - 0.32	0.04	0.01 - 0.15
Pipe	2.44	1.59 - 3.72	0.39	0.19 - 0.81	0.07	0.02 - 0.31
Posted speed limits						
70	2.83	2.21 – 3.62	0.29	0.18 - 0.47	0.09	0.036 - 0.21
90	3.63	2.75 - 4.77	0.53	0.33 - 0.85	0.17	0.075 - 0.39
110	1.80	1.48 - 2.20	0.25	0.18 - 0.36	0.07	0.035 - 0.13
120	1.84	1.18 – 2.88	0.17	0.07 - 0.43	0.08	0.021 - 0.29

[a] The injury rates are presented in number of injuries per 100 million vehicle kilometre.

For injuries with ISS ≥ 4, the differences in injury rates between the barrier types were also statistically significant at 95% confidence interval (P-value = 0.041) (Table 5.3). The differences in injury rates between different posted speed limits were also significant at 95% confidence interval (P-value = 0.013). The highest injury rate was found on roads with speed limit of 90 km/hr (Table 5.3).

For injuries with ISS ≥ 9, the statistical analysis for the differences in injury rates between barrier types and posted speed limits were not statistically significant (P-value = 0.208) (Table 5.3). The limited number of barrier injuries with ISS ≥ 9 gave a poor statistical basis.

5.4 Discussion

5.4.1 Effect of barrier types

The results show that the rate of injuries with ISS ≥ 1 and ISS ≥ 4 was higher due to collisions with cable barriers than with other barrier types (Table 5.3). The second and the third highest injury rate were associated with pipe and w-beam barrier collisions, respectively. The lowest injury rate was observed for concrete barriers collision.

As an explanation, for the high rate of injuries due to collision with pipe barriers, it is worth noting that 70% of the pipe barrier collisions presented in this study were collisions with pipe barriers installed along highway bridges in urban regions with high traffic density, several connecting roads, and, consequently, a higher risk for barrier collisions and post-impact collisions. Furthermore, pipe barriers along bridges are distinguished by a strong construction due to its solid posts and additional longitudinal beams. Even though this type of pipe barrier constituted only 34% of the total studied pipe barrier length, collisions with them resulted in 75% of the injuries reported. It is also known that the pipe-beams often do not interact during the impact event due to a weak connection between them. The lower pipe-beam often falls to the ground during the impact (Lennart Wahlund, personal communication, 25 Oct. 2010). These facts might, to some extent, explain the high injury rate associated with pipe barrier collisions.

To find more explanations for the differences in injury rates between the studied barrier types, several post-impact events were studied. As for any automobile accident, barrier collisions are divided into three phases: Pre-impact, impact and post-impact. Post-impact events include all events that can occur during the post-impact phase. It should be observed that one or several events can occur during the post-impact phase. In this study the following post-impact events have been studied:

- Post-impact collisions, where the vehicle after the initial barrier collisions smashes into other vehicles, barriers or other obstacles,
- Redirection of vehicles, where the vehicle has crossed more than one lane after the initial barrier collision,
- Post-impact over-/under-rides, where the vehicle rides over or under a barrier; and
- Post-impact roll-overs, where the vehicle turns over after the initial barrier collision or after a post impact collision.

Post-impact collisions: The rates of barrier collisions resulting in post-impact collisions were to some extend higher on roads equipped with cable barriers and pipe barrier than with the

other barrier types (Table 5.4). This could be a possible explanation for the differences in the injury rates between the barrier types. As mentioned before, post-impact collisions cause more severe injuries than the initial impact with road barriers (Ray et al. 1986; Ray et al. 1987). It is also known that severity increases with the number of collisions (Mak et al. 1986).

The high rate of post-impact collisions along roads equipped with cable barriers could be due to the fact that median cable barriers in Sweden are often placed at the centre of the road median. With this placement, barrier collisions will occur with large impact angles and, consequently, large exit angles. Large exit angles normally increase the risk for post-impact collisions. On the other hand, w-beam and concrete barriers are often installed very close to the edge line of the carriageway. This way of placement contributes to small impact angles, and, consequently, small exit angles. Ydenius (2010) confirmed that the exit angles increased drastically for semi-rigid and flexible barriers when impact angles increased from 20° to 45°, while it remained almost the same for rigid systems.

Redirection of vehicle: After a barrier collision, the vehicle involved is almost always redirected. However, redirection occurs at different angels and along different lateral distances. In this study, the analysis of vehicle redirection events focused on barrier collisions where the vehicle involved crossed over more than one lane after being redirected back into traffic. This is because the longer the lateral distance, the higher the risk for other post-impact events.

Table 5.4 shows that the rate of barrier collisions, where the vehicles after impact crossed more than one lane, was highest on roads with cable and pipe barriers. This indicates that the vehicle travelled a long lateral distance after impact with cable or pipe barriers. This contributes to an increased risk for post-impact collisions.

Table 5.4 Post-impact events occurred immediately after the first impact

Barrier Type	Barrier collisions which resulted in post-impact collisions		Barrier collisions where the collided vehicle crossed more than one lane		Barrier collisions resulting in post-impact over-/ under-rides		Barrier collisions resulting in post-impact roll-over	
	Number of Collisions [a]	Collision rate [a]	Number of Collisions	Collision rate	Number of Collisions	Collision rate	Number of Collisions	Collisions rate
W-beam	45	0.14	94	0.29	7	0.04	48	0.15
Cable	25	0.18	73	0.50	19	0.14	47	0.34
Concrete	6	0.15	18	0.38	0	0	2	0.05
Pipe [b]	4	0.17	12	0.46	-	-	4	0.15

[a] Collision rates are presented in number of collisions per 100 million vehicle kilometre

[b] Pipe barriers did not exist as road median barriers along the studied road.

A combination of the cable barrier's flexibility and mechanical properties as well as driver behaviour might be an explanation for long lateral travel distances. Unlike other barrier types, cable barriers generally impose low impact forces on vehicles because the impact, energy is dissipated by barrier deflection (AASHTO 2006). It is therefore possible that the steering

systems often remain undamaged after a cable barrier collision. This allows the driver to instinctively redirect the vehicle back into traffic after the impact. Cable elasticity could impose an additional force, propelling the vehicle back into traffic. Consequently, the risk of post-impact collisions and post-impact roll-overs will increase.

In collisions with rigid or semi-rigid barriers, deflection and elasticity is limited and vehicle damage is usually so extensive that the drivers cannot steer the vehicle after the impact and the vehicle will only travel a short distance. This could explain the low rate of post-impact events caused by concrete and w-beam barriers (Table 5.4). Unfortunately, no scientific research confirming this has been found.

Post impact over-/under-rides: The collision rate for vehicles ending up in the opposite traffic lanes, due to over-/under-rides, was highest for cable barriers (Table 5.4). This high rate of over-/under-rides could be an explanation for the high injury rate observed on roads equipped with cable barriers.

One explanation for the high rate of over-/under-rides observed on roads equipped with cable barriers could be the placement of cable barriers. As mentioned before, cable barriers in Sweden are placed at the centre of the road median, while w-beam and concrete barriers are placed close to the edge line of the carriageway. Consequently, the impact angles will be larger on roads equipped with cable barrier than on roads equipped with w-beam and concrete barriers. A combination of high speed and large impact angle might increase the risk for over-/under-rides.

According to Marzougui and McGinnis (2010), placement of barriers at the road median centre or close to it increases the risk for over-/under-rides (Figure 5.1). Another disadvantage of the placement of barriers at the centre of the road median is that the snow heaps on the edges increase the risk for over-rides by decreasing the required height of median barriers (figure 5.2). Several incidents of this type were observed in Sweden during the last years.

It is also worth noting that w-beam barriers in Sweden are often installed on both sides of the road median. This double installation reduces the risk of the errant vehicle crossing the road median. Over-/under-rides due to collisions with concrete barriers were not found in this study. It is worth noting that heavy trucks were not involved in any of the over-rides.

Post-impact roll-overs: The highest rate of post-impact roll-overs occurred in collisions with cable barriers (Table 5.4). This high rate of roll-overs could partly be explained by the high rate of post-impact over-rides for cable barriers. The instinctive reaction of the drivers to redirect the vehicle after the impact might also increase the risk for roll-overs.

5.4.2 Effect of posted speed limits

The injury rate associated with barrier collisions, with ISS$\geq$ 1 and ISS $\geq$ 4 respectively was higher on roads with speed limits of 70 and 90 km/hr than roads with speed limits of 110 and 120 km/hr. This result is in contrast to previous studies which showed that the injury risk was proportional to impact speed (Singelton et al. 2004). To explain this divergence, it is worth noting that the roads with speed limits of 110 and 120 km/hr investigated in this study were mainly rural roads with high geometrical standard, such as smooth alignment, and good visibility. Whereas, roads with posted speed limits of 70 and 90 km/hr were mainly urban roads with high traffic density, several connecting roads and, consequently, a higher collision

risk, as mentioned in Chapter 4. The effect of posted speed limits on injury rates for each specific barrier type could not be investigated because separating data in this way gave an insignificant basis for statistical analysis.
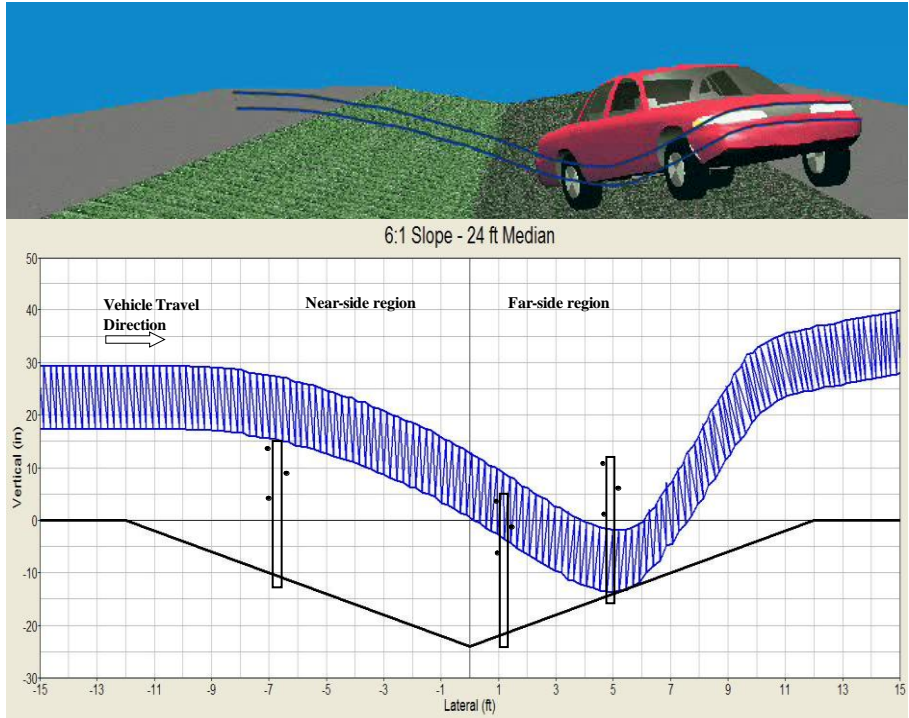

Figure 5.1 *Vehicle dynamics analysis made by Marzougui and McGinnis (2010) explaining the relation between barrier placement and risk for over-/under-rides*

Figure 5.2 *An over-ride incident in Sweden where the road median barrier has lost its function mainly due to the snow heaps*

5.4.3 Limitation and strength of the study

The high injury rate for cable barriers found in the present study is in contrast to the results of previous studies and the good reputation that cable barriers have (AASHTO 2006; Ray et al. 2008; Ydenius 2010). This divergence could be due to the use of injury classifications made by healthcare services and the consideration of injuries associated with post-impact events in the present study.

The effect of non-reported traffic accidents on the accuracy of traffic safety analyses is a well-known issue (Amoros et al. 2005; Elvik and Mysen 1999). A study of the barrier collisions and barrier repairs on the roads studied in 2006 showed that the number of reported barrier collisions in STRADA was only 17-31% of the number of reported barrier repairs, depending on the geographical region. The rate of reporting is usually highest for accidents involving fatal injuries, and lowest for accidents involving only property damage (Amoros et al. 2005), and, therefore, collisions with ISS = 0 were not considered in the analysis in this study.

Each barrier type examined in this study exists in many different designs. Even though this variation might affect the results, it was not considered in the study as segregation of variants would give an insignificant basis for statistical analyses. Collisions with more than one barrier type were excluded in this study as it was hard to conclude which barrier type contributed to the injuries.

5.5 Conclusions and recommendations

Based on the results presented in this chapter, the following conclusions can be drawn:
- The rate of injuries associated with barrier collisions in Sweden is higher on roads equipped with cable barriers than on roads equipped with the other barrier types studied.
- The rate of barrier collisions resulting in post-impact collisions, over-rides, roll-overs and collisions, where the vehicle crossed more than one lane after the initial barrier collision, is higher on roads equipped with cable barriers than on roads equipped with other barrier types. This high rate of post-impact events on roads equipped with cable barriers is probably due to the placement of cable barriers and their mechanical properties.
- The result of this study contrasts with previous evaluations, which indicated a higher performance level for cable barriers compared to other barrier types. This divergence might be explained by the use of actual documented collision data, consideration of injuries associated with post-impact events, and use of injury classifications made by healthcare services in this study.
- The injury rate associated with barrier collisions is higher on roads with speed limits of 70 and 90 km/hr than on roads with speed limits of 110 and 120 km/hr.

In order to re-evaluate the Swedish guidelines for placement of the median barriers, SRA is recommended to investigate the high rate of over-/under-rides and roll-overs due to collisions with cable barriers. SRA is also encouraged to use the injury classification system used by healthcare services for future barrier performance evaluations and other traffic safety analyses. For this reason, reporting injuries by healthcare services on a nationwide level is required.

Injury rates obtained in this study will be used in the next chapter to calculate accident costs as a part of a life-cycle cost analysis for barriers.

CHAPTER 6

LIFE-CYCLE COST ANALYSES FOR ROAD BARRIERS

Beside the criteria mentioned in Section 4.1, the initial cost for road barriers is a crucial factor affecting the selection of barrier type. When choosing between two barrier types, both fulfilling the same performance requirements, designers usually select the one with a lower initial cost. Life-cycle costs for barriers are seldom considered when selecting barrier types. This fact could be due to limited information regarding maintenance costs which obstruct an adequate consideration of maintenance aspects during the road planning and design process, as mentioned in Chapter 2. Another problem regarding calculating life-cycle costs, when selecting road barriers, is the limited information available regarding costs for injuries associated with barrier collisions.

This chapter presents a study aimed at implementing and evaluating an approach for analysing life-cycle costs for road barriers based on results presented in Chapters 4 and 5.

6.1 Method

The presented approach for analysis of life-cycle costs for road barriers is based on a method called "Life-cycle costing: using activity-based costing and Monte Carlo methods to manage future costs and risks" (Emblemsvåg 2003). For the present study, the method was modified for application within the road infrastructure sector through minor changes in some steps and exclusion of others. The study focused on Swedish conditions. To evaluate the presented approach for life-cycle cost analysis, a 100 km long road section with an AADT of 15000 vehicles was chosen along Road 45 in western Sweden. The road was in the planning and design process and designed as a four-lane road with a 1.5 meter wide, unpaved road median with a road barrier. The analyses were focused on road median barriers including w-beam barriers, cable barriers, and concrete barriers. The approach consisted of the following steps:

Step 1: Defining the scope of the approach, cost objects and cost components
In this step the scope of the approach was identified. This began by identifying the corresponding cost objects and cost components. The cost objects were specific barrier types. For each cost object, the cost components were investment, maintenance, and socio-economic costs.

The length of the life-cycle and the discount rate were also decided in this step. The life-cycle for road equipment, including road barriers, is 30 years in the SRA's calculations (Vägverket 2008b). A discount rate of 4%, which is recommended for all calculations in SRA, was used to discount all costs during the life-cycle to the first year of the barrier service life, which was 2009. The project descriptions for the chosen road segment were used to identify the traffic volume, the number of lanes, the length and placement of barrier and other circumstances.

Step 2: Identifying the activities
Each cost component was broken down into costs for the activities which generate it. Investment costs were broken down into cost for design, acquisition and installation activities

for barriers, barrier reflectors and earth supports/barrier ends. Maintenance costs were broken down into costs for maintenance activities, such as barrier repair, tension adjustment of cable barriers, reflector cleaning, scavenging earth supports and sweeping away settled sand and wastes along the paved road median. Finally, the socio-economic costs were broken down into costs for fatalities and injuries due to barrier collisions and traffic delay costs due to barrier collisions and maintenance activities.

Step 3: Identifying and quantifying the activity cost drivers

The cost drivers, such as machinery, man power, material, length of road, traffic volume, activity duration, rate of activity recurrence, etc., were identified and quantified in order to trace how cost drivers affect activity costs, cost components and cost objects. (Paper V, Appendix 1).

Step 4: Identifying the relation between cost drivers and activity costs

The relationships between activity costs and cost drivers were identified. The relationships were presented as mathematical functions in order to describe the influence of the cost drivers on activity costs, cost components and cost objects (Paper V, Appendix 2).

Step 5: Estimating the cost components for cost objects

The cost for each activity for each year of the barrier' service life was calculated using the equations mentioned in Step 4. These annual costs were discounted to the present value of the first year of the service life, namely year 2009, and summarized to obtain the total cost for the activity during the service life. The costs for these activities were summarized to obtain the total cost for each cost component identified in Step 1. Furthermore, the cost components were summarized to estimate the life-cycle cost for each cost object (i.e., barrier type).

Step 6: Modelling the uncertainties and running the Monte Carlo simulation

In this step uncertainties in the cost driver values were considered in the approach in order to reduce the future risks, as risks and uncertainties are closely linked (Emblemsvåg 2003; Markeset and Kumar 2001). For the presented life-cycle analyses approach, a Monte Carlo simulation was used to model uncertainties in order to reduce risks. This method is defined as the use of random sampling to treat problems, whether of a deterministic or probabilistic sort (Rubinstein 2008).

Modelling uncertainties started by selecting an uncertainty distribution for each cost driver (Paper V, Appendix 1). A normal or lognormal distribution was selected for cost drivers with rather certain mean values or when data was available to derive an adequate distribution. A triangular distribution was chosen for cost drivers, which were suspected of having a normal distribution but still had a rather large amount of uncertainty. A uniform distribution was chosen for cost drivers which were highly uncertain and had virtually no expected values. The uncertainty distributions were saved in a MS Excel® spreadsheet.

After modelling the uncertainty, the Monte Carlo simulation was run with 100 000 iterations to get a satisfactory level of confidence for the statistical analyses. A software programme called @RISK 5.5.1®, created in MS Excel®, was used for the Monte Carlo simulations. The results were presented in a frequency chart, showing the uncertainty

distribution of the life-cycle costs, and sensitivity charts for further analyses. The sensitivity charts were generated measuring the statistical response of the life-cycle cost, given the uncertainty in the cost drivers. The response was measured using the rank correlation method (Kendall 1962).

Step 7: Performing relevant analyses

In this step, an uncertainty analysis was conducted to ensure that, after all uncertain elements being included in Step 6, the barrier type which generated the lowest life-cycle cost was still the best alternative. For this analysis, the frequency chart was used.

The sensitivity charts created in Step 6 were studied to identify cost drivers with a marked influence on life-cycle costs. These cost drivers were further analysed in Step 8.

Step 8: Managing life-cycle cost

The aim of this step was to examine the possibility of further optimising the alternative with the lowest life-cycle cost. For example, through possible design changes or using a more efficient method to perform activities the cost drivers could be affected in such a way that the life-cycle costs will be reduced. In this step, focus was on those cost drivers which, according to the sensitivity charts, have a considerable effect on the life-cycle cost. For the studied road, this step is further described in section 6.2.3.

6.2 Results

6.2.1 Life-cycle cost

The calculation results show that concrete barriers generate the lowest life-cycle cost compared to cable and w-beam barriers (Table 6.1). This result is mainly due to the fact that concrete barriers generate the lowest maintenance and socio-economic costs among the barrier types studied. The underlying factor for this is that concrete barriers require limited maintenance, which in turn results in limited traffic disturbances and, consequently, lower socio-economic costs. However, concrete barriers generate the highest investment cost compared to other barrier types.

It is also worth noting that cable barriers generate the highest life-cycle cost, despite the low investment cost. This high life-cycle cost is due to higher maintenance and socio-economic costs.

6.2.2 Uncertainty and sensitivity analyses

Considering the uncertainties, the frequency chart shows that life-cycle costs for concrete barriers are still lower than for the other barrier types studied (Figure 6.1). Concrete barriers, with a lower mean value for life-cycle cost and a distribution closer to the mean value, are therefore more advantageous than w-beam and cable barriers.

Table 6.1 *Life-cycle costs for the studied barriers during 30 years*

| Cost components | Activities | Barrier types | | |
		Concrete	W-beam	Cable
Investment costs (1000 SEK)	Design	5	5	5
	Barrier acquisition and installation	98 013	45 192	19 231
	Reflector acquisition and installation	251	290	290
	Acquisition and installation for earth supports/end terminals	2 615	140	1 800
Sum		**100 885**	**45 628**	**21 326**
Maintenance cost (1000 SEK)	Barrier repair		11 082	27 534
	Reflector cleaning	4 492	4 492	4 492
	Tension adjustment			1 778
	Sweeping	1 480		
	Earth support flushing			1 728
Sum		**5 972**	**15 575**	**35 532**
Socio-economic costs (1000 SEK)	Traffic delay cost: barrier repair		1 216	2 734
	Traffic delay cost: reflector cleaning	2 848	2 848	2 848
	Traffic delay cost: tension adjustment			1 086
	Traffic delay cost: sweeping	470		
	Traffic delay cost: earth support flushing			1 661
	Traffic delay cost: fatal collisions	377	738	691
	Traffic delay cost: severe collisions	754	675	1 021
	Traffic delay cost: collisions involving mild injuries	702	604	952
	Traffic delay cost: collisions involving property damages	89	122	303
	Cost for fatal injuries	64 749	126 800	118 706
	Cost for severe injuries	2 406	2 155	3 258
	Cost for mild injuries	36 440	31 365	49 404
	Cost for property damage	325	447	1 105
Sum		**109 159**	**166 971**	**183 769**
Life-cycle costs during 30 years (1000 SEK)		**216 016**	**228 173**	**240 627**

Note: 1 SEK ≈ 0.1 EUR
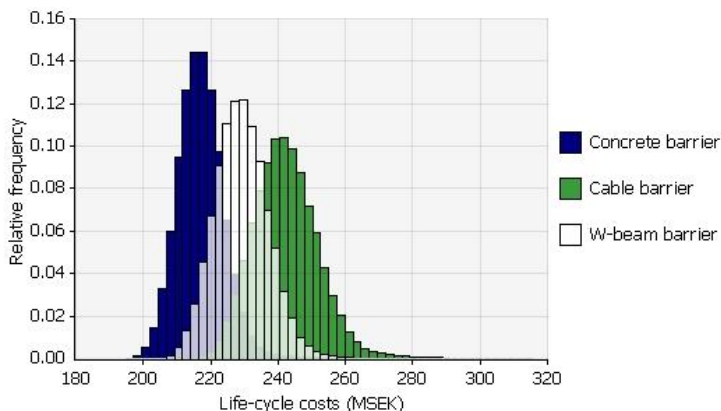
Figure 6.1 *Frequency chart describing the distribution of life-cycle costs for studied barriers*

The sensitivity charts show several cost drivers, which considerably affect the life-cycle costs (Figures 6.2-6.4). The larger the rank correlation coefficient, the greater the influence on life-cycle costs. A positive correlation coefficient in this case indicates that the cost driver has an increasing effect on the life-cycle costs (i.e., any increase in the value of the cost driver results in increased life-cycle costs). Cost drivers with a rank correlation coefficient higher than 0.05 or lower than -0.05, were chosen for further studies, as only those cost drivers have substantial influence on life-cycle costs. Since sensitivity charts are generated using statistical information, random errors occur. These errors are negligible for cost drivers with a rank correlation coefficient higher than 0.05 or lower than -0.05.
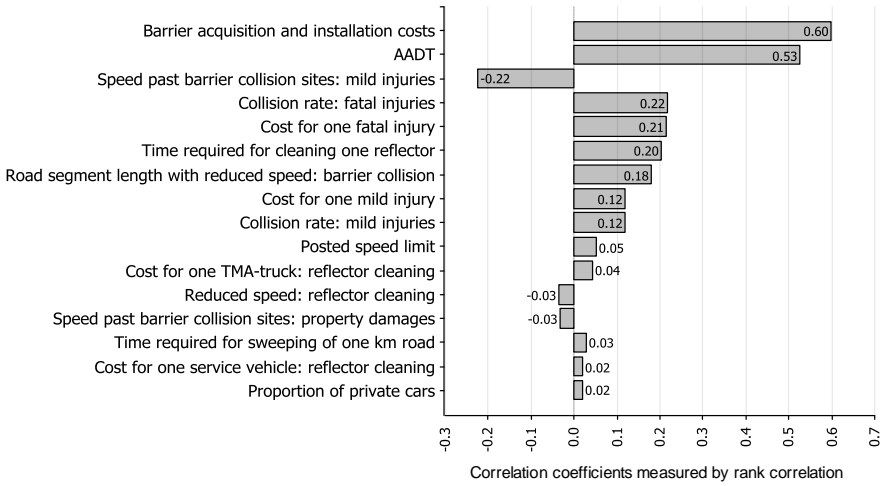

Figure 6.2 *Sensitivity chart for cost drivers affecting life-cycle costs for concrete barriers*
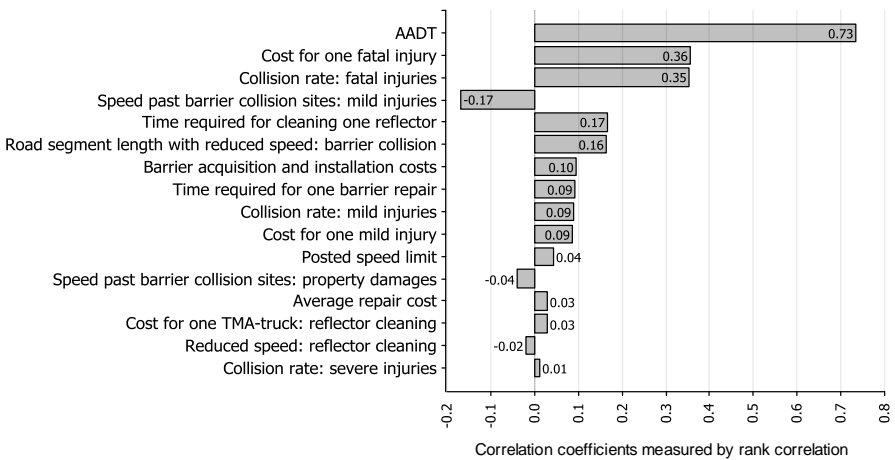

Figure 6.3 *Sensitivity chart for cost drivers affecting life-cycle costs for w-beam barriers*
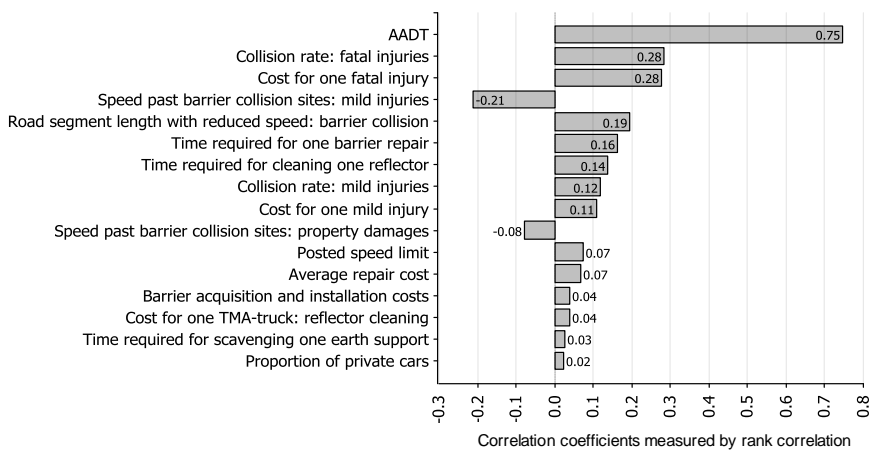
Figure 6.4 Sensitivity chart for cost drivers affecting life-cycle costs for cable barriers

6.2.3 Managing life-cycle costs

As mentioned in Step 8 in Section 6.1, this step usually focuses on the alternative which generates the lowest life-cycle cost. However, the limited differences in life-cycle costs between the barrier types for the studied road segment gives a reason not to eliminate the possibility of having cable or w-beam barriers as an optimal alternative. It is therefore necessary to consider all the three barrier types in this step. Each cost driver was analysed separately as follows.

Annual average daily traffic: For this cost driver an increasing effect on the life-cycle costs for the studied barrier types is observed (Figures 6.2-6.4). According to the project description for the studied road, there is a greater risk for AADT to be higher than 15000 vehicles than lower. The higher the AADT compared to the forecast value, the greater the difference in life-cycle costs between the barriers. In this case, concrete barriers should be preferred, as the life-cycle costs for concrete barriers are less sensitive for changes in AADT compared to the other road barriers (Figure 6.5).

Barrier acquisition and installation costs: This cost driver shows an increasing effect on the life-cycle costs for the studied barrier types (Figures 6.2-6.4). The effect of changes in barrier acquisition and installation costs on life-cycle costs is much more crucial for concrete barriers than for w-beam and cable barriers (Paper V, Appendix 3). This divergence is due to the fact that the acquisition and installation costs per metre for concrete barriers are approximately five times higher than for cable barriers and two times higher than for w-beam barriers (Paper V, Appendix 3). The high production cost for concrete barriers, the limited number of concrete barrier manufacturers in Sweden as well as the limited use of this barrier could explain its high acquisition cost. Reducing acquisition costs is difficult using current production methods. For w-beam and cable barriers, prices are already relatively low due to a highly competitive market. The low prices for cable barriers could be due to the producers' marketing policy; namely lower initial prices are compensated by higher spare part prices (Karim 2008). Such a marketing policy gives a reason to believe that future repair costs for cable barriers will

increase. Barrier installation costs might be reduced by using more efficient installation methods. Still, a reduction in installation costs would not drastically affect life-cycle costs, since they only constitute a small part of investment costs compared to barrier acquisition costs.
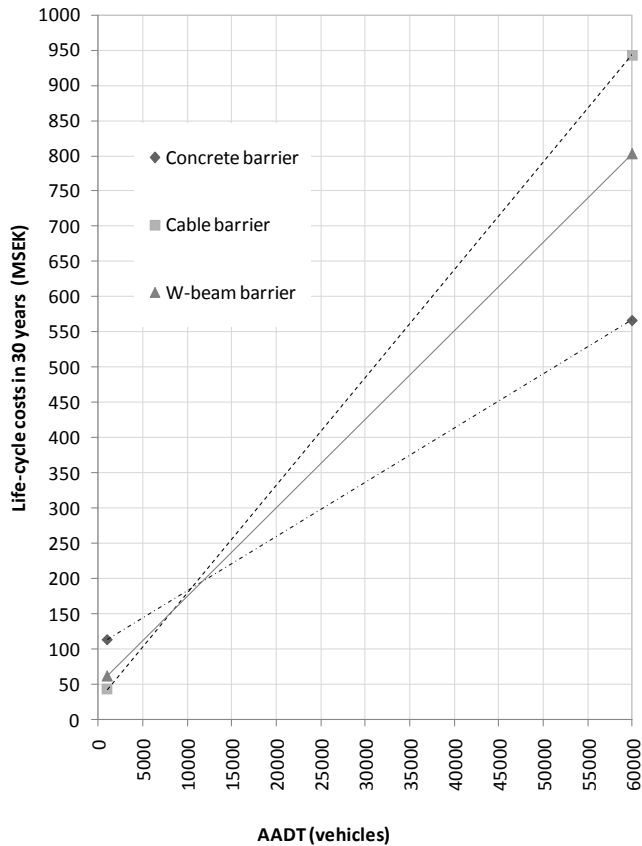

Figure 6.5 *Effect of AADT on life-cycle costs for the studied barrier types*

Speed past barrier collision sites involving mild injuries: This cost driver has a decreasing effect on the life-cycle costs for the studied barriers (Figures 6.2-6.4). The higher the speed past a collision site, the less travel time, and, consequently, social-economical costs and life-cycle costs will decrease. In general, the speed past barrier collisions sites depends on many factors, such as the degree to which the vehicles involved disrupt traffic, road users' behaviour, AADT and the time when the collision occurs. With the current limited knowledge of these factors, it is very difficult to estimate an average value for this cost driver without extensive field studies. It is also difficult to forecast future values. It is, therefore, seldom possible for a road designer to reduce life-cycle costs by choosing a design that permits higher speeds past an accident or working site. However, the sensitivity of the life-cycle costs to

changes in this cost driver is slightly higher for cable barriers than for the other barrier types (Paper V, Appendix 3).

Collision rate for barrier collisions involving fatal injuries: An increasing effect on the life-cycle costs for the studied barrier types is observed for this cost driver (Figures 6.2-6.4). With a limited knowledge regarding this cost driver, it is hard to forecast how this rate develops over the barrier's service life. As road designers do not have any control over this cost driver, it can not be used by them to reduce the life-cycle costs. However, the life-cycle cost for concrete barriers is less sensitive to changes in this cost driver compared to the other barrier types studied. Concrete barriers are, therefore, preferred in order to minimize the effect of any possible increase in this cost driver on life-cycle costs.

Cost for one fatal injury: This cost driver shows an increasing effect on life-cycle costs (Figures 6.2-6.4). In Sweden, the cost for one fatal injury has increased from 4.2 MSEK in 1986 to 22.3 MSEK in 2006. This trend will probably continue in the future. Concrete barriers are, therefore, preferred, as the life-cycle cost for concrete barriers is less sensitive to changes in the cost for fatal injuries compared to the other studied barrier types (Paper V, Appendix 3).

Time required for cleaning one reflector: This cost driver has an increasing effect on life-cycle costs for the studied barrier types (Figures 6.2-6.4). The time required for cleaning one reflector is uncertain due to insufficient documentation. The number of reflector cleanings during one year differs between contract areas. Some maintenance contracts include biannual reflector cleaning as a basic contract post. Additional cleaning can be ordered by SRA as a supplemental post. Other contracts have all reflector cleaning activities as a supplemental post. Consequently, sometimes reflectors are not cleaned due to insufficient maintenance funds.

According to the maintenance contractors consulted for this study, reflectors for w-beam and concrete barrier are seldom cleaned, despite being a contract requirement. These reflectors are placed at the side of the barriers and are assumed to be self-cleaning through water turbulence generated by traffic during rainy days. However, this assumption has not been scientifically verified. For cable barriers, reflectors are usually mounted on top of the posts, and are considered and treated as roadside reflector posts. If it is true that the self-cleaning effect makes reflector cleaning unnecessary, this contract post can be omitted for w-beam and concrete barriers. This means that the life-cycle costs in Table 6.1 can be further reduced by approximately 7.3 MSEK for w-beam and concrete barriers.

Length of the road segment with reduced speed after barrier collisions: For this cost driver an increasing effect on the life-cycle costs is observed (Figures 6.2-6.4). This length depends on several factors such as AADT, severity of the collision, time of the collision, the degree to which the vehicles involved disturb traffic after the collision as well as the time required for towing and rescuing actions and if these actions caused a total traffic stop. Data regarding the influence of these factors on the length of the road segment with reduced speed is very limited. It is also difficult to forecast how this cost driver will develop during a barrier's life-cycle, and, consequently, very difficult for designers to influence this cost driver. However, the life-cycle cost for concrete barriers is less sensitive to changes in this cost driver

(Paper V, Appendix 3). Concrete barriers should, therefore, be preferred to reduce the effect on the life-cycle costs of any possible increase in this cost driver.

Collision rate for barrier collisions involving mild injuries: This cost driver has an increasing effect on life-cycle costs (Figures 6.2-6.4). However, road designer can hardly use this cost driver to reduce life-cycle costs, as it is very difficult to analyze which influence design activities will have on the cost driver. Based on current knowledge, it is also difficult to forecast how this rate will develop during a barrier's life-cycle. Concrete barriers should be preferred in order to minimize the effect of any possible increase in this cost driver on life-cycle costs, as the life-cycle cost for concrete barriers is less sensitive for changes in this cost driver (Paper V, Appendix 3).

Cost for one mild injury: An increasing effect on life-cycle costs is observed for this cost driver (Figures 6.2-6.4). The cost for a mild injury has increased continuously from 40,000 SEK in 1986 to 199,000 SEK in 2006. This trend will probably continue in the future and if so, concrete or w-beam barriers are preferred because their life-cycle costs are less sensitive to changes in this cost driver than the life-cycle cost for cable barriers (Paper V, Appendix 3).

Posted speed limit: This cost driver shows an increasing effect on life-cycle costs (Figures 6.2-6.4). However, reducing the posted speed in order to reduce life-cycle costs for the studied barrier types is a doubtful choice for a road designer because such a reduction will negatively affect other aspects. It is also difficult to forecast speed limit changes during the life-cycle. However, in 2009 the posted limits were increased along several highway segments in Sweden. If this trend continues in the future, concrete barriers should be chosen, because the life-cycle cost for concrete barriers is less sensitive to increases in posted speed compared to the other barrier types studied (Paper V, Appendix 3).

Speed past barrier collision sites involving property damage: A decreasing effect on life-cycle costs for this cost driver is observed (Figures 6.2-6.4). The higher the speed past a collision site, the less travel time, and consequently, the lower the socio-economic costs and life-cycle costs. As mentioned before, the speed past barrier collision sites depends on many factors. With the current limited knowledge regarding the influence of these factors, it is difficult to estimate values for this cost driver, and to evaluate how road designers could influence this cost driver and, consequently, the life-cycle costs. However, the sensitivity of the life-cycle costs for changes in this cost driver is slightly higher for cable barriers than for the other barrier types studied (Paper V, Appendix 3).

Time required for one barrier repair: According to Figures 6.3 and 6.4, this cost driver has an increasing effect on the life-cycle costs for cable and w-beam barriers by affecting the socio-economic costs associated with traffic delays during barrier repairs. This cost driver has a greater effect on the life-cycle cost for cable barriers than for w-beam barriers (Paper V, Appendix 3). This divergence might be explained by the fact that the barrier repairs rate (i.e., number of repairs per vehicle kilometre) for cable barriers is twice as high as for w-beam barriers (Chapter 4).

Barrier repair time can be reduced by using more efficient repair methods. If possible, minor damages to barriers should be repaired at the same occasion, thus reducing the time for establishing traffic management measures, which constitute a great part of the barrier repair time. However, during recent years, the time needed to set up traffic management measures has increased as these measures have become more advanced due to more rigorous safety requirements for repair crews. This trend will be even more evident in the future. To eliminate the risk of substantial increases in life-cycle costs due to any possible increase in the time required for barrier repairs, concrete barriers are preferred, because they seldom require repairs (Chapter 4).

Average repair costs: This cost driver has an increasing effect on the life-cycle costs for cable and w-beam barriers (Figures 6.3 and 6.4). The life-cycle cost for cable barriers is more sensitive to changes in repair costs (Paper V, Appendix 3). However, this cost driver has a negligible effect on the life-cycle cost for concrete barriers, because they seldom require repairs (Chapter 4).

By using more efficient repair methods, repair costs can be reduced. However, the repair costs will probably increase in the future because demands for more advanced traffic management measures will increase the installation time for traffic arrangement as well as the total repair time. To eliminate the risk of substantial increase in the life-cycle costs due to any possible increase in the average repair costs, concrete barriers are preferred for the studied road.

6.3 Discussion

For the studied road segment with an AADT of 15000 vehicles, concrete barriers are obviously the optimal choice for decision makers as they, despite their high investment costs, generate the lowest life-cycle cost compared to w-beam and cable barriers. This difference is mainly due to the low maintenance and socio-economic costs associated with concrete barriers (Table 6.1). In Sweden, the repair rate is also lower for concrete barriers than for the other barrier types studied (Chapter 4). Less maintenance will reduce maintenance costs as well as socio-economic costs due to less traffic disturbances and, consequently, lower traffic delay costs. Concrete barriers also give a lower injury rate (i.e., number of injuries per vehicle kilometre) (Chapter 5). This low injury rate reduces socio-economic costs directly through lower costs for fatalities and injuries and indirectly through fewer traffic disturbances. It is worth noting that the low injury rate for concrete barriers, determined in Chapter 5, is based on a limited statistical basis. Although, the study covered all concrete barriers installed along highways in Sweden, the use of this barrier type is very limited compared to cable and w-beam barriers.

The life-cycle cost for concrete barriers remains the lowest after including the uncertainties described in Step 6, in Section 6.1. According to the cost managing efforts mentioned in Section 6.2.3, concrete barriers should be selected in order to reduce the effect of any possible increase in the value of the cost drivers that have an increasing effect on life-cycle costs. However, it is very difficult to further reduce life-cycle costs for the studied barrier types. Most of the cost drivers, which influence the life-cycle costs, can only to a small extent be influenced by design activities.

The presented approach for analysis of life-cycle costs shows a potential to increase efficiency in the road infrastructure sector by using a more efficient road design process. The

results show that road components which generate low investment costs are not necessarily optimal when considering long-term benefits and costs for road authorities and society. Consequently, it is of great value to use life-cycle costs analyses as a decision basis. However, for some reasons, such as aesthetics, the choice could be the alternative which does not give the lowest life-cycle cost. Even in such cases, life-cycle cost analyses are important to show the consequences of such choices.

The presented approach for life-cycle cost analyses can be characterized by the possibilities to:

- Include the influence of future risks and uncertainties on life-cycle costs;
- Identify cost drivers with a crucial effect on life-cycle costs; and
- Reduce life-cycle costs through improvements in the road design process and use of more efficient maintenance measures.

As in any other approach to life-cycle cost analyses, some simplifications were made in the presented approach. For example, repair costs, repair rates, and injury rates associated with barrier collisions were assumed to have linear correlations to traffic work (i.e., vehicle kilometres travelled), as no better models were available (Chapters 4 and 5). The influence of traffic queues on socio-economic costs was ignored.

Costs due to delays in transports of goods should have been considered in the presented life-cycle cost analyses as a part of the socio-economic costs. Unfortunately, these costs were not possible to calculate because of insufficient data regarding the type of goods and costs for production delays. The studied road is used by Volvo and SAAB automobile manufacturers for their just-in-time transports. Disturbance in traffic on this road results in costly production disturbances. Even if it is not possible to calculate the cost for these production disturbances, some estimations can be made. In this case, concrete barriers will result in fewer traffic disturbances because of limited maintenance needs. Road designers must weigh the use of other barrier types, with the possibility of future traffic disturbances and consequently production losses, against the higher additional investment cost for concrete barriers.

A successful implementation of life-cycle cost analyses in the road design and planning process depends upon the availability of reliable data. In this study, the most time-consuming process was data collection. For example, collection and analyses of data regarding costs for barrier repairs and injuries associated with barrier collisions required two years of work. The data regarding variables, such as road type, speed and barrier placement, had to be collected from many different sources, often non-digital. The current methods used by SRA for collecting, storing and managing data do not suite implementation of life-cycle cost analyses. If collection of data for calculation of life-cycle cost analyses for one road component on one road segment required such extensive work, it will be a tremendous task to cover road components in general.

Difficulties in obtaining data could obviously be a decisive obstacle for implementation of approaches for life-cycle cost analyses in the planning and design process. Another obstacle could be that the funds for road construction and maintenance are separated in Sweden as in many other countries, although the source is the same (Chapter 3). Consequently, an all-embracing perspective, including maintenance aspects, seldom exists during the planning and design process.

With the current system of data management, life-cycle cost calculations will be a difficult, costly and time-consuming process. Limited resources for the planning and design process will make complete life-cycle cost calculations for each particular road object almost impossible. A possible solution could be to have life-cycle cost aspects considered in road design manuals from the onset to ensure a systematic consideration of life-cycle cost aspects during the planning and design process. However, the presented study also shows that each road object has its own unique characteristics. Therefore, if possible, life-cycle costs should be calculated individually for each road object in order to reflect reality and avoid generalisation as much as possible. Because of this, the results presented in this Chapter regarding road barriers must not be overgeneralised for selection of barriers on other roads.

The risk for sub-optimisation has to be considered when using the presented approach for life-cycle cost analyses on a particular road object. For example, by selecting concrete barriers, SRA saves approximately 820 000 SEK/year, that is 24.6 MSEK over 30 years for a 100 km road segment. However, by using cable barriers, 79.6 MSEK in investment costs can be saved. This sum could be used to make another 373 km of roads safer by installing median cable barriers. Each life lost in traffic is estimated to costs approximately 22 MSEK for Swedish society. The choice is then between selecting concrete barriers and saving 24.6 MSEK over 30 years or selecting cable barriers and saving funds to make another 373 km roads safer. With a limited budget for traffic safety improvements, cable barriers might be a better choice, despite higher maintenance and socio-economic costs compared to other barrier types. A consequence of this is that more resources must be available for maintenance measures.

6.4 Conclusions and recommendations

Based on the results presented in this chapter the following conclusions can be drawn:

- The presented life-cycle cost analysis approach indicates a potential to increase efficiency in the road infrastructure sector by using a more efficient design process. Road authorities are, therefore, encouraged to consider life-cycle cost analyses in the road planning and design process.
- By modelling uncertainties, life-cycle cost analyses make it possible to identify and analyse the influencing factors crucial for minimizing life-cycle costs.
- Road components with low investment costs might not be the best option, if maintenance and socio-economic aspects are taken into account.
- Collection of data to carry out a life-cycle cost analysis is a difficult and time-consuming process. However, this fact does not mean that consideration of life-cycle cost aspects in the road planning and design process is an impossible task.

To ensure a systematic implementation of life-cycle cost analyses during the road planning and design process, road authorities must supply road designers with relevant data. For this reason, a systematic data collection process is required regarding costs and other influencing factors, which are necessary for life-cycle cost analyses. Road authorities must also create possibilities to correlate required data to each other, which currently are often stored in several different databases. For example, it should be possible to correlate maintenance costs for road barriers with data regarding road types, AADT, posted speeds, etc.

As the cost for traffic delays is a considerable part of the life-cycle costs for road barriers, the models used for calculation of these costs in the presented approach must be further developed to include the effect of traffic queues on traffic delay costs.

Bearing in mind the costs generated by the use of road barriers, it should be of interest for road authorities to compare life-cycle costs for roads with and without barriers. Such a comparison requires, among other things, a study of the costs generated by not using road barriers, such as costs due to decreased traffic safety. It also requires a study of the influence of road barriers on performance of other road maintenance measures, such as snow removal, mowing and pavement maintenance.

.

CHAPTER 7

CONCLUDING SUMMARY

Based on the results of this PhD project, the following conclusions can be drawn:

- To manage costs, road authorities have often focused on eliminating costs after they are incurred (i.e., reactive cost management) instead of eliminating costs in the commitment stages (i.e., proactive cost management).
- In many cases, the use of reactive cost management reduced maintenance costs, yet in other cases, it resulted in impaired maintenance standards and quality. This impairment is mainly due to the focusing on reducing personnel, recurring rate of maintenance activities as well as prioritizing some maintenance measures before others.
- In almost all efforts towards efficient maintenance, road authorities have ignored improvement potentials that exist during the planning and design phase. This might be one of the crucial factors underlying the failure of some efforts towards efficient maintenance.
- Although insufficient consideration of maintenance aspects during road planning and design is a well-known issue for road authorities and other concerned actors, the underlying causes and consequences have not been studied adequately. This fact is confirmed by the limited amount of literature on the subject found in this study.
- Insufficient consideration of maintenance aspects during the road planning and design process is due to a complex combination of problems related to insufficient consulting, insufficient knowledge regarding maintenance, regulation without maintainability consideration, inadequate planning and design activities, inadequate organisation and demands from other authorities.
- The repair rate and the average repair cost per vehicle kilometre for median cable barriers is higher than for median w-beam barriers, regardless of road type.
- From a purely repair cost perspective, the use of barriers with a stronger construction, such as w-beam barriers, is more cost effective for road authorities. The repair rate for median barriers along motorways can probably be almost halved by using w-beam barriers instead of cable barriers.
- The repair rate and average repair cost per vehicle kilometre for median barriers along collision-free roads is usually higher than along motorways or 4-lane roads. The risk for barrier damage along collision-free roads is higher than along other road types, probably due to inferior geometrical standards along collision-free roads.
- From a purely repair cost perspective, the use of barriers with a stronger construction along collision-free roads and roads with low geometrical standards will be cost effective for road authorities because this will result in a reduced number of repairs and repair costs.
- The number of barrier repairs is higher during winter than summer, probably due to poor road conditions, slippery road surfaces, darkness and damage caused by snow ploughs. However, damage to barriers is greater during the summer.
- In SRA's Northern and the Central regions, which are characterized by long and snowy winters, the repair rate and the average repair cost per vehicle kilometre for median barriers is higher than in the Western and South-Eastern regions.

- From a purely repair cost perspective, the use of barriers with a stronger construction in regions with long snowy winter seasons will be cost effective as the number of barrier repairs will be reduced.
- The rate of injuries associated with barrier collisions in Sweden is higher on roads equipped with cable barriers than on roads equipped with the other barrier types studied.
- The rate of barrier collisions resulting in post-impact collisions, over-rides, roll-overs and collisions, where the vehicle crossed more than one lane after the initial barrier collision, is higher on roads equipped with cable barriers than on roads equipped with the other barrier types studied. This high rate of post-impact events on roads equipped with cable barriers is probably due to the placement of cable barriers and their mechanical properties.
- The results of this study contrast with previous evaluations, which indicated a higher performance level for cable barriers compared to other barrier types. This divergence might be explained by the use of actual documented collision data, consideration of injuries associated with post-impact events, and use of injury classifications made by healthcare services in this study.
- The injury rate associated with barrier collisions is higher on roads with speed limits of 70 and 90 km/hr than on roads with speed limits of 110 and 120 km/hr. This can be explained by a higher risk of collision along these roads.
- The presented life-cycle cost analysis approach indicates a potential to increase efficiency in the road infrastructure sector by using a more efficient design process. Road authorities are, therefore, encouraged to consider life-cycle cost analyses in the road planning and design process.
- By modelling uncertainties, life-cycle cost analyses make it possible to identify and analyse the influencing factors crucial for minimizing life-cycle costs.
- Road components with low investment costs might not be the best option, if maintenance and socio-economic aspects are taken into account.
- Collection of data to carry out a life-cycle cost analysis is a difficult and time-consuming process. However, this fact does not mean that consideration of life-cycle cost aspects in the road planning and design process is an impossible task.

CHAPTER 8

RECOMMENDATIONS AND FUTURE STUDIES

8.1 Recommendations for road authorities

Based on the results of this PhD project several recommendations were formulated. For an adequate consideration of maintenance aspects during the road planning and design process, road authorities are recommended to:

- Establish well-defined long-term goals for maintenance, and develop methods to evaluate the fulfilment of these goals;
- Develop well-structured systems for experience exchange and consulting among actors involved in maintenance activities and in the planning and design process;
- Increase knowledge regarding road maintenance among actors involved in the planning and design process;
- Develop a systematic evaluation process with clear guidelines for the examination of completed road projects to ensure adequate consideration of maintenance as part of a quality assurance system;
- Add maintainability in the planning and design related guidelines, regulations and other documents;
- Create guidelines and requirements for future maintenance considerations, which should be incorporated into procurement of requests for quotations and other purchasing related documents; and
- Create incentives for consultants to consider maintainability aspects during the planning and design process to a sufficient extent.

To ensure a systematic implementation of life-cycle cost analyses during the road planning and design process, road authorities are encouraged to:

- Create a systematic data collection regarding the input variables included in the life-cycle cost analyses;
- Create an appropriate platform to connect data regarding the input variables which are obtained from in different data sources. Such a platform is necessary to avoid manual handling of data. For example, the maintenance cost for road barriers should be connected to data regarding road type, AADT, posted speed limits, etc; and
- Supply all the design involved actors with required data for calculations.

For more adequate evaluation of road barrier performance and performance of other traffic safety measures the road authorities are recommended to:

- Use injury classifications which are made by healthcare services;
- Encourage reporting of traffic injuries by healthcare services on a nationwide level; and

Re-evaluation of the Swedish guidelines for road barriers placement is recommended. Life-cycle cost analyses should be considered in these guidelines as a basis for selection of barrier types.

8.2 Future studies

To ensure a sufficient re-evaluation The following future studies regarding road barrier performance are proposed:

- Investigation into the high rate of over-/under-rides and roll-overs indicated in this PhD project due to collisions with cable barriers;
- Investigation into how barrier placement, in relation to the edge line of the carriageway, influences the frequency of barrier collisions, severity of associated injuries, post-impact events and associated repair costs;
- Estimation of correction factors for under-reporting of barrier collisions resulting in property damage which are not reported by healthcare services; and
- Investigation into the low injury rate indicated in this PhD project due to collisions with concrete barriers.

The following subjects are proposed for future studies regarding the presented approach of life-cycle costs analyses for road barriers:

- Development of a user-friendly and computer-based version of the presented approach for analyses of life-cycle costs for road barriers; and
- Estimation of the effect of traffic queues, due to barrier collisions and barrier maintenance measures, on traffic delay costs.

An interesting application of the presented approach for life-cycle cost analyses is to compare life-cycle costs between roads with road barriers and roads without road barriers. Such a comparison requires a complementary addition to the presented study by:

- Studies of costs which can be generated by not using road barriers, such as costs for decreased traffic safety: and
- Studies of the effect of road barriers on performance of other maintenance measures, such as mowing, snow removal and pavement maintenance.

BIBLIOGRAPHY

AASHTO. (2006). "Roadside Design Guide." AASHTO, USA, Washington, D.C.

Adams, T., and Kang, M. (2006). "Considerations for Establishing a Pavement Preservation Program." *Transportation Research Board 85th annual meeting*, USA, Washington D.C.

Amoros, E., Martin, J. L., and Laumon, B. (2005). "Under-reporting of road crash casualties in France." *Accident Analysis and Prevention*, 2006 (38), pp. 627-637.

Arnek, M. (2002). "Empirical Essays on Procurement and Regulation." Ph.D. thesis, Uppsala University, Sweden, Uppsala.

Arnek, M., Hellsvik, L., and Trollius, M. (2007). "En svensk modell för offentlig-privat samverkan vid infrastrukturinvesteringar: rapport framtagen av en för Banverket, VTI och Vägverket gemensam arbetsgrupp." [Towards a Swedish model for PPP infrastructure projects]. *Report No. 588*, Swedish National Road and Transport Research Institute, Sweden, Linköping (in Swedish).

Bajaj, A., Gransberg, D. D., and Grenz, M. D. (2002). "Parametric Estimating for Design Costs." *AACE International Transactions*, USA, Morgantown, pp. 81-86.

Baltzer, S. (2007). "Long Term Performance-based Maintenance Contracts in Denmark." Nordic (3), pp.10-11.

Bryden, J. E., and Fortuniewicz, J. S. (1986). "Traffic Barrier Performance Related to Vehicle Size and Type." *Transportation Research Record: Journal of the Transportation Research Board,* (1065), pp. 69-78.

Carlsson, A. (2009). "Uppföljning av mötesfria vägar: slutrapport." [Evaluation of 2+1 Roads: final report]. *Report No. 636*, Swedish National Road and Transport Research Institute, Sweden, Linköping (in Swedish).

Carlsson, A., and Brüde, U. (2005). "Uppföljning mötesfria vägar: halvårsrapport 2004:1." [Evaluation of 2+1 Roads: half-year report 2004:1]. *Report No. 19:2005*, Swedish National Road and Transport Research Institute, Sweden, Linköping (in Swedish).

Carlsson, A., and Brüde, U. (2006). "Uppföljning mötesfria vägar: halvårsrapport 2004:2." [Evaluation of 2+1 Roads: half-year report 2004:2]. *Report No. 47-2005*, Swedish National Road and Transport Research Institute, Sweden, Linköping (in Swedish).

Carpenter, B., Fekpe, E., and Gopalakrishna, G. (2003). "Performance-Based Contracting for the Highway Construction Industry." Battelle, Washington D.C., <http://transportationsolutions.info/FinalReportFeb4th2003.pdf>, accessed 10th January 2009.

Elvik, R., and Mysen, A. B. (1999). "Incomplete accident reporting: meta-analysis of studies made in 13 countries." *Transportation Research Record: Journal of the Transportation Research Board*, 1999, (1665), pp. 133-140.

Emblemsvåg, J. (2003). "Life cycle costing: using activity-based costing and Monte Carlo methods to manage future costs and risks." John Wiley & Sons, Inc., USA, New Jersey.

European Commission. (2004). "Resource Book on PPP Case Studies." European Commission, Belgium, Brussels, <http://ec.europa.eu/regional_policy/sources/docgener/guides/pppresourcebook.pdf>, accessed 15th January 2009.

European Committee for Standardization. (1998). "EN 1317-2, Road restraint systems - Part 2: Performance classes, impact test acceptance criteria and test methods for safety barriers." European Commission, Belgium, Brussels

European Committee for Standardization. (2000). "Road equipment CEN/TC 226." European Commission, Belgium, Brussels

Freer-Hewish, R. J. (1986). "How design, construction and maintenance inter-relationship affect total life performance of roads." *15th ARRB conference, part 3, p. 293-313*.

Gaffeny, J. A., and Gane, P. C. (1970). "Highway design with maintenance in mind." *Roads and road construction*, 48, (576), pp. 300-308.

Gahm, G. (2008). "Blir bevarandet av vägkapitalet nedprioriterat?." [Is the preservation of road assessment low prioritized?]. *ViaNordica*, Helsinki (in Swedish).

Goldkuhl, G., and Röstlinger, A. (1998). "Förändringsanalys." [Change analysis]. Studentlitteratur, Sweden, Lund (in Swedish).

Gransberg, D. D., and Molenaar, K. R. (2004). "Life-Cycle Cost Award Algorithms for Design/Build Highway Pavement Projects." *The Journal of Infrastructure Systems*, 10, (167), pp. 167-175.

Holmvik, N., and Wallin, H. (2007). "Användning av livscykelanalys och livscykelkostnad för vägkonstruktion inom Norden." [The use of life-cycle analyses and life-cycle costs for road infrastructure in the Nordic countries]. M. Sc. thesis, Lund Institute of Technology, Sweden, Lund (in Swedish).

Huvstig, A. (1998). "Whole life Costing." The World Road Association (PIARC), Concrete Roads Committee, Malaysia, Kuala Lumpur.

Huvstig, A. (2004). "Economic Models as Basis for Investment Decision." *10th International Symposium on Concrete Roads,* , Turkey, Istanbul.

Insurance Institute for Highway Safety (2008). "Fatality Facts 2008 Roadside Hazards" Insurance Institute for Highway Safety,<http://www.gov.mu/portal/goc/cso/ei750/road.pdf>, accessed 5th March 2010.

Karim, H. (2008). "Improved Road Design for Future Maintenance - Analysis of Road Barrier Repair Costs." Licentiate thesis, Royal Institute of Technology, Sweden, Stockholm.

Karim, H., and Magnusson, R. (2006). "Vägprojektering för minskade drift-och underhållkostnader - Brister och möjligheter." [Road design for lower maintenance costs - Problems and possibilities]. *Rep. No. 2006:1*, Dalarna University, Sweden, Borlänge (in Swedish).

Kendall, M. G. (1962). "Rank Correlation Methods." Hafner publishing company, USA, New York.

Liljegren, E. (2003). "Contracting out road maintenance. A study on quality, transaction costs and learning organization." Ph.D. thesis, The Swedish Royal Institute of Technology, Sweden Stockholm (in Swedish).

Mak, K. K., Sicking, D. L., and H.E. Ross, J. (1986). "Real-World impact conditions for ran-off-the road accidents." *Transportation Research Record: Journal of the Transportation Research Board*, (1065), pp. 45-55.

Markeset, T., and Kumar, U. (2001). "R&B and risk-analysis tools in product design, to reduce life-cycle cost and improve attractiveness." *Annual reliability and maintainability symposium,* USA, Philadelphia.

Martin, J. L., Derrien, Y., Bloch, P., and Boissier, G. (2001). "Severity of run-off-crashes whether motorway hard shoulders are equipped with a guardrail or not." *Traffic Safety on three Continents*, Moscow, Russia.

Marzougui, D., and McGinnis, R. (2010). "NHCHPR Project 22-25: Development of Guidance for the Selection, Use, and Maintenance of Cable Barrier Systems." *Presented on the mid-year meeting for Transport research Board, committe AFB20*, USA, Napa CA.

Mattingly, S. P., and Ma, Z. J. (2002). "Selecting a guardrail end terminal for high snowfall regions." *Cold Regions Engineering Cold: Regions Impacts on Transportation and Infrastructure*, USA, Anchorage, AK, pp. 267-277.

Neuzil, D., and Peet, J. S. (1970). "Flat embankment slope versus guardrail: comparative economy and safety." *Transportation Research Record: Journal of the Transportation Research Board*, 306, pp. 10-24.

Nilsson, J., Ihs, A., Sjögren, L., Wiman, L. G., and Wågberg, L. (2006). "Performance Contracting. Summary of Knowledge and Recommendations for Further Research." *Rep No. 650*, Swedish National Road and Transport Research Institute, Sweden, Linköping (in Swedish).

Olsson, U. (1983). "Projektering med hänsyn till drift och underhåll." [Infrastructure design with regard to maintenance and operation]. *Report No.1983:25*, Construction Research Council, Sweden, Stockholm (in Swedish).

Olsson, U. (2002). "Generalized Linear Models: An Applied Approach." Studentlitteratur, Sweden, Lund.

Prarche, S. (2007). "Infrastructure management and the use of public private partnerships." *CSCE annual general meeting and conference*, Canada, Yellowknife.

Queiroz, C. (2007). "Public–Private Partnerships in Highways in Transition Economies - Recent Experience and Future Prospects." *Transportation Research Record: Journal of the Transportation Research Board*, (1996), pp. 34-40.

Ray, M. H., Michie, J. D., and Hargrave, M. (1986). "Events that produce occupant injury in longitudinal barrier accidents." *Transportation Research Record: Journal of the Transportation Research Board*, (1065), pp. 19-31.

Ray, M. H., Michie, J. D., Hunter, W., and Stutts, J. (1987). "An analysis of the risk of occupant injury in second collisions." *Transportation Research Record: Journal of the Transportation Research Board*, (1133), pp. 17-22.

Ray, M. H., Silvestri, C., Conron, C. E., and Albin, R. B. (2008). "Assessment of Fatality Risk in Collisions with Cable Median Barriers in the State of Washington." *WIT Transactions on Information and Communication*, 39, pp. 245-255.

Ray, M. H., Weir, J., and Hopp, J. (2003). "In-Service Performance of Traffic Barriers." *NCHRP Report 490*, Transportation Research Board, USA, Washington, D.C.

Road and Traffic Authority. (2004). "Fatal Roadside Object Study." *Report No. 04.060*, Road and Traffic Authority, Australia, Sydney

Rubinstein, Y. N. (2008). "Simulation and the Monte Carlo Method." John Wiley & Sons, USA, New York.

Singelton, M., Qin, H., and Luan, J. (2004). "Factors associated with higher levels of injury severity in occupants of motor vehicles that were severely damaged in traffic crashes in Kentucky." *Traffic Injury Prevention*, 5, (2), pp. 144-150.

Stenbeck, T. (2004). "Incentives to Innovations in Road and Rail Maintenance ", Licentiate Thesis, Royal institute of Technology, Sweden, Stockholm.

Stenbeck, T. (2006). "Effects of Outsourcing and Performance-Based Contracting on Innovations." *Transportation Research Record*, (1948), pp. 3-8.

Stenbeck, T. (2007). "Promoting Innovation in Transportation Infrastructure Maintenance." Ph.D. thesis, Royal Institute of Technology, Sweden, Stockholm.

Stigson. (2009). "Variation in crash severity depending on different vehicle types and objects as collision partner." *International Journal of Crashworthiness*, 14, (6), pp. 613-622.

Thomson, R. (1999). "Roadside Safety Design Philosophies: Are They Working?" *Traffic Safety on Two Continents*, Sweden, Malmö.

Thomson, R., Fagerlind, H., Martinez, A., Amenguel, A., Naing, C., Hill, J., Hoschopf, H., Dupré, G., Bisson, O., Kelkka, M., Van der Horst, R., and Garcia, J. (2006). "European Best Practice for Roadside Design: Guidelines for Roadside Infrastructure on New and Existing Roads, final report." The European Union Road Federation, Belgium, Brussels

Thorsman, H., and Magnusson, Y. (2004). "Thorsman & Magnusson Projekt 04: Mötsfria 2+1 väg." [Torsman & Magnusson Project 04: Collision-free roads]. MSc thesis, Dalarna University, Sweden, Borlänge (in Swedish).

Trochim, W. (1989). "Outcome pattern matching and program theory." Evaluation and Program Planning, 12, pp. 355-366.

Trost, J. (2005). "Kvalitativa intervjuer." [Qualitative interviews]. Studentlitteratur, Lund (in Swedish).

United Nation. (1998). "Public-Private Partnership - A New Concept for Infrastructure Development." *Publication ECE/TRADE/226*, France, Rogerville

Vägverket. (2004a). "Processbeskrivning: Bygga." [Process description: Construction] *Publication 2004:94*, Swedish Road Administration, Sweden, Borlänge (in Swedish).

Vägverket. (2004b). "Processbeskrivning: Genomföra Upphandling." [Process description: Procurement]. *Publication 2004:41*, Swedish Road Administration, Sweden, Borlänge (in Swedish).

Vägverket. (2004c). "Processbeskrivning: Överlämna." [Process description: Consignment]. *Publication 2004:95*, Swedish Road Administration, Sweden, Borlänge (in Swedish).

Vägverket. (2004d). "Processbeskrivning: Upprätta Arbetsplan." [Process description: Work plan]. *Publication 2004:92*, Swedish Road Administration, Sweden, Borlänge (in Swedish).

Vägverket. (2004e). "Processbeskrivning: Upprätta Bygghandling." [Process description: Construction Documents]. *Publication 2004:93*, Swedish Road Administration (in Swedish).

Vägverket. (2004f). "Processbeskrivning: Upprätta Förstudie." [Process description: Feasibility]. *Publication 2004:90*, Swedish Road Administration, Sweden, Borlänge (in Swedish).

Vägverket. (2004g). "Processbeskrivning: Upprätta Vägutredning." [Process description: Raod Survey]. *Publication 2004:91*, Swedish Road Administration, Sweden, Borlänge (in Swedish).

Vägverket. (2004h). "Vägar och Gators Utformningar 2004." [Road Design Manual]. *Publication 2004:80*, Swedish Road Administration (in Swedish).

Vägverket. (2007). "Strategisk plan 2008-2017" [The Swedish Road Administration´s Focus 2008 - 2017]. *Publication* 2007:37, Swedish Road Administration (In Swedish)

Vägverket. (2008a). "Funktions- och standarbeskrivning drift - FSB." [Function and standard description for road operation] *Publication 2008:54*, Swedish Road Administration (In Swedish).

Vägverket. (2008b). "Vägverkets samhällsekonomiska kalkylvärden." [Socio-economic values for Swedish Road Administration]. *Publication 2008:67*, Swedish Road Administration Borlänge, Sweden (in Swedish).

Wolford, D., and Sicking, D. L. (1997). "Guardrail Need: Embankments and Culverts." *Transportation Research Record: Journal of the Transportation Research Board*, (1599), pp. 48-59.

World Bank. (2002). "Toolkit for Public-Private Partnership in Highways." <http://rru.worldbank.org/Toolkits/PartnershipsHighways/>, accessed 25th April 2009.

Ydenius, A. (2009). "Frontal crash severity in different road environments measured in real-world crashes." *International Journal of Crashworthiness*, 14, (6), pp. 525-532.

Ydenius, A. (2010). "Integration of Car and Road Infrastructure Design." Ph.D. thesis, Karolinska Institutet, Sweden, Stockholm.

Ydrevik, K. (2009). "Performance-based pavement maintenance - Theory and Practice." *Transportforum*, Sweden, Linköping (in Swedish).

Yin, R. K. (2003). "Case Study Research: Design and Method." SAGE Publications, USA, California.

Zietlow, G. (2004). "Implementing Performance-based Road Management and Maintenance Contracts in Developing Countries - An Instrument of German Technical Cooperation." <http://www.performance-based-road-contracts.com/>, accessed 10th January 2009.

Zietlow, G. (2008). "Cutting Costs and Improving Quality through Performance-Based Road Management and Maintenance Contracts - The Latin American and OECD Experiences." *Regional Seminar on Performance-Based Management and Maintenance Contracts*, Tanzania.

Österberg, R. (2003). "Contracting out Public Services - An evaluation of the public consequences of opening up routine road maintenance to competition." Doctoral thesis, The Swedish Royal Institute of Technology, Stockholm, Sweden.

DEFINITIONS

Swedish Road Administration (SRA): The Swedish Road Administration is the national authority that was assigned responsibility to oversee the entire Swedish national road transport system until 1st April 2010. After this date, Swedish Traffic Administration (STA) is assigned this task.

Collision-free roads: Collision-free roads are a specific category of three-lane roads, consisting of two lanes in one direction and a single lane in the opposite direction, alternating every few kilometres. The opposite directions are separated with road barriers, mainly steel cable barriers, to prevent cross-over collisions (Vägverket 2004h). In Sweden, the collision-free roads are also called 2+1 roads.

Road equipment: The European committee for standardisation (European Committee for Standardization 2000) has divided road equipment into the following groups:
- Road restraint systems, e.g. crash barriers, safety fences and guardrails;
- Horizontal signs, e.g. road markings;
- Vertical signs, e.g. road signs and anti-glare systems;
- Traffic control equipment, e.g. traffic signs;
- Noise protection devices, noise barriers; and
- Parking meters and automatic car park ticket dispensers.

STRADA: The Swedish Traffic Accident Data Acquisition (STRADA) information system is a coordinated national registration of traffic accidents and traffic injuries run by the police and the health care authorities. This information system concerns the whole road transport system.

ISS: The Injury Severity Score Codes (ISS) is an anatomical scoring system providing an overall score for patients with multiple injuries. Each injury is assigned an Abbreviated Injury Scale (AIS) score, allocated to one of six body regions (head, face, chest, abdomen, extremities, and external). Only the highest AIS score in each body region is used. The three most severely injured body regions have their score squared and added together to produce the ISS score for a person. Healthcare services classify injuries associated with traffic accidents in five ISS-intervals: 0 (considered as unhurt), 1-3 (considered as mild injury), 4-8 (considered as moderate injury), 9-15 (considered as severe injury) and 16 or higher (considered as very severe or fatal injury).

Annual Average Daily Traffic Map: The Annual Average Daily Traffic Map (AADT-Map) is a web-based database containing information about roads administered by the SRA. In this application, the Swedish road network is categorized into homogeneous sections. For each section, the traffic volume is measured regularly.

The Swedish National Road Database: The Swedish National Road Database (NVDB) is a nationwide road database, containing up-to-date information regarding the Swedish road transport system.

ENCLOSURES (PAPER I-V)