RAILWAY SAFETY

- Risks and Economics

Johan Bäckman

Doctoral thesis
Traffic and Transport Planning
Errata
In this electronic version the changes in the errata have been incorporated. The text is therefore not exactly the same as in the printed version.

Printing instructions
The layout of the thesis is made for two-sided printing. Some pages are therefore left blank intentionally.

Cover: Lovisa Bäckman, 2002
To Anna

the flower fairy of my life
Foreword

In the long term planning of infrastructure investments in 1996, I had the opportunity to assist in the review of the economic analyses made by the rail and road authorities. The coordinating authority was the Swedish Institute for Transport and Communications Analysis (SIKA). The review of the cost-benefit calculations made by the Swedish National Rail Administration (NRA), led to questions about the economic aspects of its rules and arrangements relating to safety. Significant research potential was identified and a research project was formulated and financed by The Swedish Transport and Communications Research Board (KFB). The National Rail administration has financed 25% of the total costs.

During this work, I have received help from many different people. Analysing economic aspects of railway safety requires an inter-disciplinary approach. It is necessary to use economic theories and statistical methods, as well as risk analysis techniques. In addition, technical knowledge of the railway system is necessary. The fact that the subject involves several different disciplines has made it necessary to seek assistance from various sources.

I would like to acknowledge the help of Hans Ring, head of the Safety Department at NRA, who has helped me to get in contact with the right persons since 1998 and has given many valuable comments on drafts of the different working papers. Lars-Göran Mattson, at the Royal Institute of Technology (KTH), supervisor in the first half of the project, gave valuable help and encouragement. Karl-Lennart Bång at KTH has been supervisor during the second half of the project and has given valuable comments on various drafts.

In addition, a number of people have been of great help in various parts of the project. Ulf Persson, at the Institute of Health and Economics (IHE), was a valuable resource for the risk valuation project; his discussion and review of my drafts were of great help. Many thanks to Professor Michel Jones-Lee and Professor Graham Loomes who helped during the data analysis phase of the risk valuation project. I spent two months at the University of Newcastle and we had many interesting discussions. Anders Lundström, previously working at the Swedish Rail Inspectorate, assisted with data in the radio-block study. The discussions and encouragement were highly valued. Hans Thegström, also at the Rail Inspectorate, has been very helpful in providing information for the analysis of passenger train derailments. There is a long list of people who have assisted in various parts of the work, to whom I am very grateful.

Finally, my thanks go to my family, my lovely wife Anna, for all encouragement and support, to my daughter Lovisa, who has painted all the lovely covers of my reports, and to my son Ludvig, whose mere existence increased the pressure on finishing this thesis.

Johan Bäckman

Stockholm, April 2002
Abstract

Safety analysis is a process involving several techniques. The purpose of this thesis is to test and develop methods suitable for the safety analysis of railway risks and railway safety measures. Safety analysis is a process comprising problem identification, risk estimation, valuation of safety and economic analysis. The main steps are described in separate chapters, each of which includes a discussion of the methods and a review of previous research, followed by the contribution of this author. Although the safety analysis procedure described can be used for analysing railway safety, it has such general foundations that it can be used wherever safety is important and wherever safety measures are evaluated. It combines cost benefit analysis with criteria for the distribution and the absolute levels of risk.

Risks are estimated with both statistical and risk analysis methods. Historical data on railway accidents are analysed and statistical models fitted to describe trends in accident rates and consequences. A risk analysis model is developed using fault tree and event tree techniques, together with Monte Carlo simulation, to calculate risks for passenger train derailments. The results are compared with the statistical analysis of historical data.

People’s valuation of safety in different contexts is analysed, with relative values estimated in a willingness-to-pay study. A combination of focus groups and individual questionnaires is used. Two different methods are used to estimate the value of safety and the results are compared. Comparisons are also made with other studies.

Different approaches for safety analysis and methods for economic analysis of safety are reviewed. Cost-benefit analysis as a decision criterion is discussed and a study on the economic effects of a traffic control system is presented.

There are several results of the work. Historical data shows a decrease in the accident rate. The average consequence of each accident has not changed over time. The risk analysis model produces comparable results and enables analysis of various safety measures. The valuation study shows that people prefer the prevention of small-scale accidents over the prevention of larger, catastrophic accidents. There are only small differences in the valuation of safety in different contexts.
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1. Introduction

1.1 Background

Between 1970 and 1980, there were 14 serious railway accidents with multiple fatalities in Sweden. Several accidents were caused by drivers passing signals at danger, and these might have been prevented by a train control system. These accidents caused a lot of media attention and debate in the beginning of the ’80s, which led to the decision to install Automatic Train Control, ATC.

After a head-on train collision in Lerum in November 1987, with 9 fatalities, the rules regulating maintenance work on signal equipment were changed. The accident was caused by a fault in the signal equipment: two cables had been switched incorrectly. The underlying cause was the time pressure on the maintenance workers, which led to the fault not being detected. Since that accident, more time has been given to the inspection of completed work. In general, this increases safety, but can also lead to longer delays.

The decision to install ATC and the new rule regulating maintenance work can serve as examples of the way decisions on safety have been made in the railway sector. Actual accidents have stepped up the demand for higher safety and new safety rules have been formulated to prevent specific types of events occurring again. The decisions have been partly based on informal judgements and the process can be described as deterministic, because the risks have been judged solely on the basis of the possible consequences. The problem is that this approach can lead to a demand for huge investment to prevent events with very low probabilities.

The same approach can also be found in other countries. In 1987, there was a fire at King’s Cross station on the London Underground, with 31 fatalities and many people seriously injured. In December 1988, two trains collided at Clapham Junction with 35 fatalities and many seriously injured. The investigations and judicial inquiries following these accidents resulted in several recommendations and new laws for increased safety. However, many of the recommended measures overlapped, were uneconomical or unnecessary in other ways.

British Rail compiled a list of the cost per life saved for each of the 250 projects recommended following the accidents. The first 12 measures have very low costs, as low as £10,000 per life saved. At project 155, the costs have risen to about £1 million per life saved. After that, there is a fairly sharp rise in costs, so that, at project 210, the costs are approaching £10 billion per life saved.1

There are also other examples where the investment costs are low but the safety measures lead to other effects. In April 1990 there was a passenger train derailment in Sköldinge. The train was only allowed to travel at 40 km/h because of speed restrictions when passing points. This was given by the signals and the Automatic train control system (ATC). However, an ATC transponder 2 was failing and when the driver received the information on the failure he immediately cancelled the braking induced by the ATC-system and increased speed to 126 km/h. When passing the point the train derailed. Two passengers were killed and several injured.

1 Ford, 1992, p. 652
2 A transponder is an electronic plate mounted between the rails sending information to the train. There are several variants and they can give information on location, speed, signal aspects etc. The transponders are often mounted in groups of three or four.
The accident led to a change in the ATC-system. After receiving an erratic signal from the system, the driver now have to reduce speed below 80 km/h and maintain that speed until a correct signal is received from the ATC-system. This will eventually happen when the next transponder-group is passed. The distance between the transponder-groups varies from a few metres to several kilometres. This of course has effects on the traffic and it can lead to delays. The investment costs were small in comparison with the possible safety effects and the effects on the traffic.

Priorities will always have to be established and the decision-makers will have to decide upon the resources available for safety and then choose between different safety projects. It is evident that society cannot afford every conceivable safety project. Still, society finds it hard to accept high risks from public transport, and there is a constant search for ever safer operations.

This calls for a general approach for analysing railway safety. There is a need for procedures and models that combine safety issues and other effects, and that can deal with economic aspects as well as inputs that are more subjective. This thesis provides knowledge about methods for analysing railway safety.

1.2 Safety analysis procedure

The analysis of railway safety and selection of safety measures is a process involving various steps. Normally it starts with the identification of a problem. Potential solutions are then identified and analysed. When it comes to making a decision, factors other than cost are also taken into account. These steps are somewhat obvious.

The steps in a safety analysis are described below. The procedure includes analysis of economic aspects of safety and deals with the distributional effects of risks. The procedure described has such general foundations that it is not only applicable to railway contexts, but also to the analysis of other types of infrastructure project. The procedure is applicable wherever safety is important. It can be illustrated as in the following diagram.
1.2.1 Problem identification

The occurrence of accidents has traditionally been the primary source in the risk identification process. Railway accidents do and will occur and it is a natural reaction to seek their causes. “What happened?” “Why?” and “What was the problem?” are questions that are normally posed. Accidents will therefore continue to be a “source” of problem identification. This is especially true for rare accidents with unique sequences of events leading to them. An example is the Lerum accident mentioned above, where the combination of time pressure and incorrect inspection of the maintenance work led to a terrible head-on collision of two passenger trains.

Problems can also be identified when new or existing systems are the subject of risk analysis. There are numerous techniques for risk identification, many involving checklists of some kind, as well as group discussions with key people in the organisation, other experts, etc. The purpose of these methods is to explore every possible combination of factors that can lead to accidents or other events with unwanted consequences. They can identify and describe previously unknown, yet possible hazards, and possible chains of events leading to an accident or a system failure.

However, the problems identified need not be component failures, such as the collapse of wheel bearings leading to derailments, or other engineering factors. They may also be risks perceived by people. Even if no accident has occurred, the fact that people express fear or
perceive risks may constitute grounds for safety analysis. Surveys often reveal that the prime risk that rail passengers are concerned about is that of being attacked or harassed in public places, such as station areas, platforms or on trains. Other concerns often expressed are the risks perceived when trains pass platforms at high speed. This “visible” risk concerns people.

Risk analysis methods can be used at this stage, in the way described above, as a source of problem identification, or as a tool or support to describe hazards, chains of events and the possible underlying causes.

1.2.2 Identification of options

The next step in the process is to identify and describe different options for solving the problem. When the problem is identified through an accident, the selection of appropriate safety measures might be relatively straightforward. When the whole system is under review and the safety performance is analysed, a wide range of options might be available for the reduction of risk.

The identification and description of options is an important step that is often overlooked. Economic theory prescribes that the option (or safety measure) in question must be compared with something, often called a base case. Specifying the base case is just as important as describing the options under investigation. It can, but definitely does not have to be the status quo. “Doing nothing” might not be a real option. The base case should then be the “budget” alternative, the measure that has to be taken, regardless of any other considerations.

Consider, for example, the building of a new airport. In order to solve the transport needs to and from the airport, the building of a new railway line is considered. The rail option could be compared with a (low-cost) base case in which transport is provided by bus (if possible). The effects of the rail alternative should then be compared with the bus case. Failure to identify and describe the alternative options will produce misleading comparisons, and the true benefit for society will not be identified.

1.2.3 Estimating probabilities and consequences; calculating risk level

The third step is to analyse current safety levels and the possible improvements with the various options. It includes both qualitative and quantitative methods and is therefore a two-step phase. The common mistake is to start by quantifying the most obvious effects and then forget other important factors. The way to avoid this is first to list all the effects and decide whether they are beneficial or detrimental to the options considered, giving a broad picture of the options.

The second step is then to quantify the effects. There is a variety of methods for quantitative risk analysis and some are reviewed in this thesis. Examples will be given of both statistical methods and what are referred to as risk analysis methods. It is often not possible to quantify all the effects, as is the case with for example environmental impact. The qualitative description of these effects can be listed together with the quantification of those effects where this is feasible in the report. This will provide an overview and help the decision-maker to evaluate the options.

If the focus were solely on the risks, the analysis could end here and a decision be taken on the appropriate selection of safety measures. However, this would neglect the fact that many safety measures have other effects, costs as well as benefits. Consider for example the installation of ATC and Line Block. These systems have a significant impact on operations; they lead to improved efficiency and competitiveness of the railway system. It is therefore
necessary to include the operational effects in the analysis and weigh the safety effects against these other costs and effects.

One way of explicitly weighing different types of effects is to use Cost Benefit Analysis, CBA. With this method, the societal effects of a project are quantified and given a common value. Normally, the effects are assigned monetary values. In this way, the investment costs of, for example, a safety measure can be compared with the value people put on safety. This value can be estimated with different methods. It is often carelessly expressed as the value of life or the Value Of a Statistical Life (VOSL), but should be seen as a measure of the amount of resources that ordinary citizens would like to spend for a given risk reduction. In the standard analysis, the number of lives saved in a safety project is then multiplied with this value (VOSL), giving the total value of the safety effects. Corresponding values are also used for injuries.

One fundamental premise of CBA is the so-called Hicks-Kaldor criterion. It stipulates that a measure, or an investment, should be implemented if the total benefits aggregated over the affected population outweigh the total costs. If the benefits and costs are unequally distributed, the possibility of compensating those at loss justifies the measure, even if the compensation never takes place. The projects with, for example, the best benefit-cost ratio should be implemented first. The principal goal of CBA is thus to maximise the social economic profit by comparing all benefits with all costs.

However, the direct valuation approach and the use of CBA will not provide answers to all the questions about what measures should and should not be implemented. The distribution of risk is also important. Situations in which many people can benefit greatly from an activity that presents small risks to the community still cannot be accepted if a few people, or specified individuals, are exposed to very large risks. Clearly, if a person is killed because of an activity, it is not possible to compensate him or her. The conclusion is that the Hicks-Kaldor criterion does not hold for risks with potentially lethal consequences. This leads to the next step in the safety analysis process.

1.2.4 Weighing against risk criteria

The solution to the problem of unequally distributed risks is the combination of CBA with the use of safety criteria. The criteria set limits for the risk that can be accepted for an activity. When the total risk of the system has been estimated, it can be compared with the criteria for unacceptable risk. These criteria can be designed in different ways and it is common to use different levels of criteria for risks to individuals and for risks to society as a whole. It is also possible to use different levels for existing and new activities.

The question to be posed in this step is: “Are the risks at unacceptably high levels?” If so, a decision should be taken to reduce the risks. If not, the process can continue with a valuation of the safety effects and of all the other costs and effects. The criteria for unacceptable risk levels will in this way set limits for the cost-benefit analysis. It will function as a boundary within which the CBA can rank different options.

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3 There has been a lot of debate on the benefits and drawbacks of the method over the years. Used in its most basic form, CBA provides a way of comparing different effects. It is more a way of systematically dealing with various types of effects than anything else. In its more elaborate form, it is based on sophisticated economic theory and claims to give the correct ratio of costs and effects, and the possibility to rank different societal projects. This thesis will not deal with this discussion. The use of the method here is somewhere between the extremes.

4 There are other economic measures that could be used that are not dealt with here.
1.2.5 Qualitative and quantitative description of all effects

Analysing safety risks and the effects of safety measures for the railway system is a demanding and information-intensive activity. One of the prominent properties of the railway system is the inter-dependency of many train movements. Trains meeting on single-track lines, connections for passengers at larger stations, driver schedules and differences in train speed are all examples of properties that are combined in train timetables. Disruptions are not restored as easily as on the road network.

One implication of this is that the impacts of changes in infrastructure, rolling stock or safety regulations might be difficult to grasp and analyse. The data needed for in-depth analysis might not be available. Simulations might be needed to identify the impacts on operations.

1.2.6 Valuation of all the effects

In order to make different types of effects comparable, a common denominator must be assigned. Some costs and effects have a market value, such as investment and material costs of accidents. It is therefore convenient to assign monetary values to the effects that do not have a market value, such as safety, in order to make all effects comparable.

There is a long tradition in the road sector of using an estimated value of the prevention of a road fatality. This value is calculated as the average sum of the material costs of an accident and a value of life per se. The material costs are for healthcare, net loss of production value, damage to property and administration. The “human value”, or value of life per se, has been estimated using “willingness to pay” methods. The average valuation is then used in the economic analysis of road safety measures.

Furthermore, effects that are only seen after 20 years must be made comparable with immediate costs. It is necessary to discount effects spread out over time. This demands an interest rate as well as a time horizon. In most industrialised countries, there are official values for interest rates and time horizons that should be used in the calculations in order to permit comparisons with other societal projects. Calculating the present value of costs and benefits is a part of the valuation of effects and is demonstrated further in section 5.3.

1.2.7 Economic evaluation

There are several possible approaches when making decisions about safety. In this thesis an approach is proposed in which risk levels and benefits of safety measures are explicitly analysed. The benefits and costs are valued and the decision maker is allowed to make trade-offs between them. This is done by combining risk criteria with cost-benefit analysis. The necessary conditions for making sound decisions about safety are created. Safety effects can be compared with other effects and the distribution of risk is controlled.

In the CBA, all costs and benefits are put together in a one-dimensional measure. The present values of the benefits are compared with the present value of the costs. If the present value of the benefits exceeds the present value of the costs, the measure should be implemented. In real world situations, this is a simplification. The costs of all beneficial projects normally exceed the financial resources available for investment. There is always a financial budget constraint.

It is also important to realise that this approach implies that there are measures that can be taken to prevent some accidents occurring, but that they should not be taken because the benefit does not outweigh the costs. There are examples of safety rules that produce (small) safety effects but also have other effects/costs that are very large in relation to the actual benefit. These safety rules could be questioned.
1.2.8 Decisions

The CBA is seldom the only evidence in the decision process. In infrastructure investment and planning environmental impacts are important. For all investments over a specified size, the law requires a description of the environmental effects, an environmental impact assessment (EIA). This describes the effects on wildlife, landscape, etc. There are several effects described in an environmental impact assessment that currently cannot be valued and included in a cost-benefit analysis. The decision-maker has to consider these effects together with the economic aspects. There can also be other motives for the decision taken, not present in any of the material on which the decision is based.

It is, of course, just as possible that the decision can be “do nothing”, not to install the safety system or whatever is being considered, as it is to install the system or, more generally, to proceed with the option considered.

1.2.9 Evaluation

Every decision process should contain an element of evaluation. This ensures that the decision taken is implemented in the way intended by the decision-maker. Risk analysis methods can be used for this in the safety analysis. This leads us back to the start of the process.

1.3 Description of the thesis

1.3.1 Objectives and scope

The aim of this thesis is to develop and provide information on methods for analysing railway safety. A systematic approach to safety analysis is outlined and a procedure described. The thesis focus on methods for calculating risk levels, distributional aspects of risk, economic valuation of risk reductions and economic analysis of safety measures. These areas are often neglected when rail safety measures are analysed. In particular, the following general questions are posed.

<table>
<thead>
<tr>
<th>Question</th>
<th>Answered in chapter</th>
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<tbody>
<tr>
<td>Which methods can be used for modelling risks in the railway system?</td>
<td>2</td>
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<tr>
<td>What are the actual risk levels of the Swedish railway system?</td>
<td>2</td>
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<tr>
<td>How reliable are the databases currently in use?</td>
<td>2</td>
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<tr>
<td>How should risk criteria be implemented and incorporated when railway</td>
<td>3</td>
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<tr>
<td>safety measures are evaluated?</td>
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<tr>
<td>What is the value of railway safety? Road traffic risks have been valued</td>
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<td>systematically in economic analyses. Should the same values be used when</td>
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<tr>
<td>rail safety is analysed?</td>
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<tr>
<td>Economic aspects are important when safety is discussed. How should</td>
<td>5</td>
</tr>
<tr>
<td>economic evaluations of safety be carried out?</td>
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1.3.2 Methods

A number of different methods can be used when conducting a safety analysis. The aim of this thesis is to review some methods that are suitable when analysing railway safety. Each step in the procedure (Figure 1) requires different methods and, for the convenience of the reader, each chapter starts with a section on the methods associated with that step. This means that the next chapter, dealing with the problem of estimating risk levels, will describe and employ both traditional statistical methods and risk analysis methods, such as fault tree analysis. These methods will be reviewed before the current project’s development work is described.

1.3.3 Definitions and terminology

A number of terms and labels are used and it is necessary, in order to avoid confusion, to clarify the definitions used in this thesis.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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| Risk           | Risk is usually defined as a combination of two factors. The first is the probability that a certain type of incident will occur and the second is the effects of that incident. Together, these factors constitute the risk.  
  **Comment** This is not to say that risk has not been defined in other ways. Risk has, for example, been defined as the magnitude of the maximum negative consequence and sometimes as only the probability of a negative consequence. This demonstrates the need for explicitly defining the terminology. Throughout this thesis, risk is defined as the combination of probability and consequence.5 |
| Safety         | Safety is defined as absence of risk. Because we can have different risk levels, we can also have different safety levels. Increased safety is equal to decrease in risk.                                           |
| Risk analysis  | The term “risk analysis” denotes a process ranging from the description of the system to an evaluation of the possible means of reducing risk.  
  **Comment** Several different types of methods can be used in a risk analysis. These can be statistical methods or what in the thesis is referred to as “risk analysis methods”. It is important to recognise that risk analysis is a process in which “risk analysis methods” can be used. |

5 The study of the radio-block system focused on estimating the probabilities of railway accidents. No attention was paid to the possible consequences, as this was not possible using the data available. The risks of the system were therefore not estimated, even though the conclusion that the system reduces risks was drawn.
Safety analysis

The term “Safety analysis” is used as a label for a procedure for analysing safety. The steps in the procedure are built of various models for analysing risk levels, effects of safety measures, economic effects etc.

Comment The procedure has a broader perspective than a traditional risk analysis and is therefore given a distinctive name. The procedure described encompasses steps not normally included in a risk analysis. Note that risk analysis methods can be used when conducting a safety analysis.

Risk analysis methods

Various types of methods for estimating risk levels other than statistical methods.

Comment Examples of risk analysis methods are Fault Tree Analysis, Failure Mode and Effects Analysis, Monte Carlo Simulation, Event Tree Analysis, etc.

Estimated risk

Calculated risk level, based on empirical material.

Comment Risks can be estimated through statistical analysis or other quantitative or qualitative methods. There is always some degree of uncertainty associated with estimates of risk, but, in contrast to subjective risk, estimated risk is based on some empirical material handled according to established methods.

Subjective risk

The risks perceived by people.

Comment Subjective risk, or perceived risk, is affected by personal values and conceptual frameworks. The way people perceive risks has been the subject of extensive social science research. For example, a psychometric model was developed in the late 1970s. It included nine risk dimensions explaining differences in individuals’ perceptions of risk.\(^6\)

Individual risk

The risk exposure of each individual.

Comment A typical example is the risk faced by a train passenger.

Collective risk

The risk to which a group of people or society as a whole is exposed.

Comment An example is the risk faced by people living near a chemical plant, or a railway line where trains carrying dangerous goods pass.

Accident

A non-intended event with harmful consequences.

Incident

A non-intended event with no harmful consequences.

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<th>Table 1 Definitions used in the thesis.</th>
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\(^6\) Reviewed in Sjöberg, 1996
1.3.4 Layout

The basic layout of the thesis follows the steps in the safety analysis procedure. Each chapter starts with a review of the methods used. This is then followed by a small literature review that shows what has been done in other studies. Finally, the studies carried out in the current project are described.

**Procedure**

1. Problem identification
2. Description of alternatives
3. Estimating probabilities and consequences, calculate risk level
4. Compare risk level with criteria
   - Acceptable risk level?
5. Qualitative and Quantitative description of all other effects
6. Valuation of risk reductions and other effects
7. Economic analysis
8. Decision
9. Implementation and evaluation

**Chapter**

**Chapter 2. Estimating risk levels**
Includes both statistical methods and risk analysis methods. Reviews previous research and describes three studies conducted: a statistical analysis of the safety effects of ATC and Line block, a statistical analysis of fatal train accidents on the Swedish network and development of a risk analysis model for passenger train derailments.

**Chapter 3. Risk criteria**
Reviews the international use of risk criteria, current research and possible applications of criteria in safety analysis.

**Chapter 4. Valuing safety**
Describes methods for finding a value to put on railway safety and risk reduction for rail passengers. Describes a study of the valuation of risk in different contexts, where rail safety is compared to road, tunnel and fire safety.

**Chapter 5. Economic analysis and decision criteria**
Basic principles for CBA analysis as well as aspects of using CBA as a decision criterion are discussed. Previous research on and economic analyses of rail safety measures are reviewed. An economic analysis of a traffic control system for regional lines has been conducted and is described.

Figure 2 Layout of the thesis.
2. Estimating risk levels

2.1 Introduction

In the third step of a safety analysis, the probabilities and the consequences are estimated and the risk level calculated. This can be done with different methods. The two main categories are statistical methods and risk analysis methods. These are not completely different. Using risk analysis methods normally includes the use of some statistical methods as well. Nevertheless, it is convenient to separate the two as the term “risk analysis methods” includes a variety of methods whose prominent features are not statistical.

The two categories of methods are first described in section 2.2. Previous research is reviewed in section 2.3 and the author’s contribution is presented in sections 2.4-2.6. The three studies are

1. A statistical analysis of the safety effects of ATC and Line-block
2. A statistical analysis of fatal train accidents on the Swedish network

2.2 Methods

2.2.1 Statistical methods

Statistical methods are used in the transport sector to produce estimates of accident rates and consequences using several measures. The use of statistical methods is common in the road sector, where there is a large number of accidents every year and it is possible to calculate reliable estimates of accident rates and average consequences.

There is one main problem when it comes to using statistical methods to analyse railway safety: the lack of data. With the exception of level crossing accidents, few accidents occur and it is difficult to get reliable estimates of, for example, the expected number of fatalities per year. One possible way of solving this problem would be to report incidents in detail and to use this data for statistical analysis. Unfortunately, the railway sector does not have the same tradition of reporting incidents as the airline sector.

There are however possibilities. Statistical hypothesis tests can often be conducted with relatively sparse data, as exemplified in the analysis of ATC and Line-block (section 2.4). This study compared the accident risks between railway lines with ATC and line block and lines with manual train dispatching. The method and the experience acquired from the study are discussed on page 46.

It is rewarding to separate the accident rate from the expected consequences once an accident has occurred. The accident rate can be expressed as the number of accidents for some given unit of measure. Normally, in the transport sector, the distance travelled is used and the accident rate is for example, expressed as the number of accidents per billion train kilometres. The consequences can be measured by the number of fatalities or injuries per accident.

It is sometimes possible to fit statistical probability distributions to the data in order to get more accurate descriptions of accident risks. For example, in both road and rail accidents, the numbers of fatalities per accident show a skew pattern where the most probable outcome is

\(^7\) Automatic Train Control ATC, and Line block are automatic train control systems. See also Appendix 1.
one or a few fatalities, but with some small probability there might be a serious accident with
many fatalities. A theoretical probability distribution may then provide a better understanding
of the risks. When fitting a theoretical probability distribution to empirical data, the following
steps are usual8.

1. Consider arguments in favour of specific distributions.
2. If no such arguments exist, analyse the possible values of the variable and restrict the
   review of distributions accordingly.
3. Choose one or several distributions with the correct range of values from a catalogue of
   theoretical distributions.
4. Estimate the parameters of the distribution(s).
5. Choose one of the distributions by reviewing the goodness-of-fit measured by the chi-
   square test or some other test.

This process is greatly simplified by the use of statistical data packages such as Bestfit. These
types of programmes help in displaying the data, fitting theoretical probability distributions,
calculating test statistics and ranging the possible distributions according to the test-results.
An example of this type of analysis is reviewed in section 2.3.1.3. In this thesis, several
probability distributions are used or referred to; a list of those used is provided in Appendix 3,
together with explanations and descriptions.

Another possibility is to model trends with regression models. These might be linear,
exponential or have any other form. The number of accidents has for example fallen over
time. There has been a constant strive for safer railways, many safety measures have been
implemented and, in some countries, automatic train protection systems have been installed.
This has of course had an influence on the number of accidents per year. Furthermore, the
number of fatalities per accident might also have changed. More crashworthy rolling stock
has been developed and old stock phased out and replaced. It is then possible to use statistical
models to describe these trends.

There are arguments for using statistical models instead of, for example, point estimates such
as mean number of accidents per year. If the accident rate has changed over time, then the
calculated average number of fatalities might be a bad indicator of the situation today. If
projections are considered, it is necessary to study the trends in the accident rate and the
number of fatalities per accident. This has been done by Evans9 and in a new study presented
in section 2.5.

We now turn to a description of risk analysis methods before we review the use of statistical
methods in previous research.

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8 Evans and Verlander, 1996, p. 185
9 Evans, 2002
2.2.2 Risk analysis methods

2.2.2.1 Introduction

Several methods are associated with the term “risk analysis“. There are also different ways of using these methods. In the following table, examples of methods are divided into groups depending on the type of objects they are designed to analyse: 1) technical systems, 2) organisational risks and 3) human reliability.

<table>
<thead>
<tr>
<th>Method</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Technical systems</td>
<td></td>
</tr>
<tr>
<td>Fault tree analysis – FTA</td>
<td>Analysis of the causes of a given incident</td>
</tr>
<tr>
<td>Event tree analysis – ETA</td>
<td>Analysis of alternative consequences of a given event</td>
</tr>
<tr>
<td>Failure modes and effects analysis – FMEA</td>
<td>Analysis of faults of technical components</td>
</tr>
<tr>
<td>Hazard and operability study – HAZOP</td>
<td>Analysis of possible risks/disruptions in processes</td>
</tr>
<tr>
<td>Maximum credible accident – MCA</td>
<td>Analysis of worst possible consequences</td>
</tr>
<tr>
<td>2. Organisational risks</td>
<td></td>
</tr>
<tr>
<td>Management oversight and risk tree – MORT</td>
<td>Organisational demands are compared with actual organisation</td>
</tr>
<tr>
<td>Administrative safety analysis</td>
<td>Organisational conditions are judged according to a form</td>
</tr>
<tr>
<td>3. Human reliability</td>
<td></td>
</tr>
<tr>
<td>Work safety analysis</td>
<td>Working conditions are analysed</td>
</tr>
<tr>
<td>Action error analysis – AEA</td>
<td>Analysis of dangerous divergences from pre-specified working procedures</td>
</tr>
<tr>
<td>Human reliability analysis – HRA</td>
<td>Analysis of human inclination to act erratically during certain working tasks.</td>
</tr>
</tbody>
</table>

Table 2. From Lindberg, Thedéen et al., 1993

The methods listed here can also be used in different ways. The first three steps in the safety analysis are qualitative. Describing the system, identifying the hazards and specifying the generic causes and modelling the risks are of a qualitative nature. In many cases, a preliminary analysis may be sufficient and the correct measures identified without the use of quantitative methods. In other cases, a detailed hazard analysis might be required. This can include quantitative methods for estimating accident rates, for example. In some cases, the data is sufficient for inductive statistical analysis and in other cases the data must be generated, giving a deductive analysis.

The list in Table 2 contains examples of the methods used in risk analysis and there are many variants that are not described here\(^\text{10}\). The first two methods in the table above have been used in the present project.

\(^{10}\) For a review of different risk analysis methods, see for example Rausand, 1991
2.2.2.2 The fault tree method

Fault tree analysis is a deductive method. It is a tool for identifying the causes and the combination of causes that leads to a hazardous event. Fault trees are illustrated graphically through a number of symbols. When the method was developed, there was no consensus on the rules for designing fault trees and the method was classified as something of an art. There is now agreement on the basic rules of fault tree construction. We start by describing the basic idea and then return to the rules.

2.2.2.2.1 The structure and the symbols of fault trees.

The symbols that are used in fault trees are listed on the next page. Fault tree construction starts with a hazardous event and the purpose is to model the causes of this event. We call this hazardous event the “top event”. Through various logic gates, this top event is connected to different possible faults on a middle level. At the bottom of the fault tree are the basic initiating causes that can be assigned probabilities. Fault trees are constructed in the following way.

Fault Tree 1. Example of a fault tree with an OR-gate.

The causes can be assigned probabilities and a calculation of the fault tree top event probability made. We will return to the quantitative calculations later. In the example above, the top event occurs if either Cause A or Cause B occurs. We have another case if the hazardous event occurs only if both A and B occur at the same time. An example could be the event that a hospital’s electrical power supply is disrupted. For this to happen, the external power supply has to be off, and the internal power generator has to be malfunctioning. This can be illustrated with an “AND”- gate in the following way:

Fault Tree 2 Example of a fault tree with an AND-gate
It is also possible to assign an ordering of the causes, so that one must occur before the other in order for the top event to occur. This can be included by adding an ellipse to the right of the gate. The condition is then written in the ellipse. It is also possible to give such conditions even if there is only one cause below the unwanted event. For the top event to occur, the condition must be fulfilled.

The trees can be relatively extensive, and some elements can recur in several places in the tree. It is therefore possible to split the trees into smaller units and link them through in and out gates. This is illustrated later. Symbols commonly used in fault trees are given in Table 3.
Primary event symbols

<table>
<thead>
<tr>
<th>Primary event</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base event</td>
<td>A basic fault requiring no further development.</td>
</tr>
<tr>
<td>Conditioning event</td>
<td>Specific conditions or restrictions that apply to a logic gate.</td>
</tr>
<tr>
<td>Undeveloped event</td>
<td>An event that is not developed further.</td>
</tr>
</tbody>
</table>

Intermediary event symbols

<table>
<thead>
<tr>
<th>Intermediate event</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intermediate event</td>
<td>An event that occurs as a result of antecedent causes.</td>
</tr>
</tbody>
</table>

Gate symbols

<table>
<thead>
<tr>
<th>Gate symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>And</td>
<td>Event occurs if all inputs occur.</td>
</tr>
<tr>
<td>Or</td>
<td>Event occurs if at least one of the inputs occurs.</td>
</tr>
<tr>
<td>Exclusive OR</td>
<td>Event occurs if exactly one of the inputs occurs.</td>
</tr>
</tbody>
</table>

Transfer symbols

<table>
<thead>
<tr>
<th>Transfer symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfer in</td>
<td>The tree is further developed at the corresponding TRANSFER OUT.</td>
</tr>
<tr>
<td>Transfer out</td>
<td>The tree is a portion of a larger tree and connected to the corresponding TRANSFER IN.</td>
</tr>
</tbody>
</table>

Table 3. Symbols used in fault trees. Table adapted from Vesely, Goldberg et al., 1981, p. IV-3

It is necessary to define the system that is analysed carefully. Delimitations are necessary both externally and internally. A radiator is a part of a heating system with several possible delimitations. We can limit the analysis to a specific radiator, to the heating system of the
house, or to the power supply network in the town. The delimitation chosen depends on what function of the system we want to analyse. If one of the rooms in the house is too cold, an analysis of the radiator in that room might suffice. In other cases, the boundary has to be drawn higher up in the system.

Furthermore, it is necessary to have internal limits. In an analysis of the causes of derailments with passenger trains, there are a number of immediate and sufficient causes for a train to derail. One of these could be a track fault. An example could be a broken rail or faults with points. For the systems analyst it might be sufficient to model track faults, or in a more detailed analysis, faults with points as a cause of derailments. It is necessary to limit the level of detail, because it is not always possible to get into all the details that are possible with a system like a set of points. Suppose that there is a failure in the motor that shifts the position of the points, should we analyse the main components in the motor, or should we analyse the material in the components?

A systems analyst is interested in the general groups of failures that can occur and has the set of points as the highest level of detail. The design engineers that construct the set of points have it as the external boundary and the material in the motor as the internal boundary. In other words, the choice of external and internal boundaries depends on the perspective.

In order to decide how various effects relate to each other, it is possible to separate failure mechanisms, failure modes and failure effects. Different failure mechanisms lead to failure modes that have different failure effects. Even here, the perspective is important. What is a failure mechanism for the systems analyst might well be a failure effect for the design engineer.

**2.2.2.2 Basic principles of fault tree construction**

When analysing a system, its boundaries must first be defined. When that is done, a failure mode can be chosen. This failure mode is the top event of the fault tree. The task is then to find the immediate and necessary events, failure modes or failure mechanisms that lead to the top event. These are then analysed in turn until the internal boundary is reached. There are five rules for this process.

---

1. The descriptions in the event boxes should be written as failures.
2. If the event is caused by a component, classify as a state of component, it not classify as state of system.
3. No miracles - if the normal functioning of a component prescribes a certain sequence of events, assume the component works normally.
4. Finish every level. All gates should be completed before continuing with the next level.
5. No gate to gate. A gate should not be connected directly to another gate. All inputs to a gate should be a correctly described fault.

---


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2.2.2.3 Quantitative analysis of fault trees

There are a number of techniques for performing a quantitative analysis of fault trees. Every fault tree can be described with a set of Boolean formulae. By so doing, it is possible to perform qualitative and quantitative analyses. There is a set of rules for this. We here look at how the two basic gates in fault trees can be described with Boolean algebra.

The "OR"-gate can be represented in mathematical terms by the union of two events and can be replaced with a plus-sign with Boolean algebra. If we have a situation like the one in Fault Tree 1, then the event will occur if either A or B occurs. The probability of the top event is then the probability of A plus the probability of B.

When looking at the example in Fault Tree 2, the "AND"-gate corresponds to the union of two events and can be replaced with a multiplication sign with Boolean algebra. For the top event to occur, both A and B must occur at the same time. The probability of the top event will then be the product of the probability for A and the probability for B.

Below is given a table of a number of mathematical rules and their corresponding Boolean algebraic formulations. We will only comment briefly on a couple of the rules here. The first rules, 1a–3b, correspond to the rules of ordinary algebra and are not discussed here.

<table>
<thead>
<tr>
<th>Rule</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>X \cap Y = Y \cap X</td>
</tr>
<tr>
<td>1b</td>
<td>X \cup Y = Y \cup X</td>
</tr>
<tr>
<td>2a</td>
<td>X \cap (Y \cup Z) = (X \cap Y) \cup Z</td>
</tr>
<tr>
<td>2b</td>
<td>X \cup (Y \cup Z) = (X \cup Y) \cup Z</td>
</tr>
<tr>
<td>3a</td>
<td>X \cap (Y \cup Z) = (X \cup Y) \cap (X \cup Z)</td>
</tr>
<tr>
<td>3b</td>
<td>X \cup (Y \cap Z) = (X \cup Y) \cap (X \cap Z)</td>
</tr>
<tr>
<td>4a</td>
<td>X \cap X = X</td>
</tr>
<tr>
<td>4b</td>
<td>X \cup X = X</td>
</tr>
<tr>
<td>5a</td>
<td>X \cap (X \cup Y) = X</td>
</tr>
<tr>
<td>5b</td>
<td>X \cup (X \cap Y) = X</td>
</tr>
<tr>
<td>6a</td>
<td>X \cap X' = \phi</td>
</tr>
<tr>
<td>6b</td>
<td>X \cup X' = \Omega = 1</td>
</tr>
<tr>
<td>6c</td>
<td>(X')' = X</td>
</tr>
</tbody>
</table>

Table 5. Rules for qualitative and quantitative analysis of fault trees, adapted from Fault Tree Handbook Vesely, Goldberg et al., 1981, p. VII-2. See also Ang and Tang, 1975, chapter 2

Rule 4a shows that there are differences between Boolean algebra and conventional algebra. According to rule 4a, the intersection of X and X = X. Translated to conventional algebra we would get X*X=XX=X^2. However, in Boolean algebra we get something else. This is apparent if in a Venn-diagram we draw two identical sets that have all events in common. The same difference holds for rule 4b. These rules can be applied when the same event occurs on several places in the fault tree. When translating the fault tree to Boolean formulae, the event will appear several times. Rules 4a and b then state that we can reduce the formula so that the
event only occurs once. Rule 5a, the rule of absorption, states that the intersection of X and [the union of X and Y] is X.

Figure 3. Venn diagram for the intersection of X and [the union of X and Y]
The Union of X and Y is the area covered by both X and Y. The intersection of X and this union is the area that X has in common with the union, which is the total area. As shown in the Venn diagram above, it is the area covered by X. Rule 5b similarly states that the union of X and [the intersection of X and Y] is X. This can easily be understood from the Venn diagram below.

Figure 4. Venn diagram for the union of X and [the intersection of X and Y]
The intersection is in this case the area X and Y have in common, marked grey in the diagram. The total area of X and the grey area is of course X.

2.2.2.2.4 **Cut sets and minimal cut sets**

Technical systems can fail in a number of ways. Failures can be caused by single component faults or combinations of component faults or faults of different sub-systems. Every single way a system can fail is called a “cut set”. It is defined as a collection of events such that the system fails or, in fault tree terms, the top event occurs.

There is often a large number of such combinations that can lead to a system failure. It is therefore interesting to find the single component faults or combinations of events that are both necessary and sufficient for the top event to occur. These types of events or combinations of events are called “minimal cut sets”. Their properties are such that if one of the events does not occur, the top event does not occur. Minimal cut sets are calculated with the rules given in Table 5. Through formulating the tree in terms of the mathematical rules given, it is possible to reduce the tree and calculate the minimal cut sets by complementary addition and substitutions. This can however be very time consuming if the fault trees are extensive. There are now functions for calculating the minimal cut sets in fault tree software available on the market.

The benefits of the fault tree method are that it is simple to use, that it is easy to communicate the results of the analysis and that many of the problems in the system are discovered during
the construction of the tree. Further descriptions of the method can be found in a handbook from the U.S. Nuclear Regulatory Commission\textsuperscript{11}.

### 2.2.2.3 The event tree method

Event tree analysis is an inductive method that enables a structured description of the possible consequences of an accident. The purpose is to describe the possible scenarios that can follow an initiating event and to calculate the probabilities for the possible consequences. Event trees consist of a number of graphical symbols showing the chain of events in chronological order. The tree branches off at “failure/success” ports, typically depending on whether the different safety systems succeed or not. Given for example a derailment with a passenger train, there are very different consequences depending on whether or not the carriages overturn, whether there is a fire or not, etc. It is possible with the event tree method to describe all possible scenarios and calculate probabilities for these. The principle is explained in the example below.

Event trees always follows a time line (from left to right) and contain a number of nodes where the tree branches off. Every path ends in a final event where the consequences are described. In the example there are 8 final events and every sequence of events, or path, is called a scenario. Performing event tree analysis demands information. At every node, a probability is assigned to the branches. Further, an estimate of the consequences of each scenario is needed. In the example above, we need to estimate the consequences in all eight scenarios and insert estimates in the consequences column (Fatalities per event).

The construction of event trees follows a number of steps.

1. Choice of the initiating cause. This is an important step in the analysis. As for fault tree analysis, the choice depends on the purpose of the analysis and on the perspective.

2. Construction of the event tree. Event trees can be drawn both horizontally and vertically. In this thesis, the first alternative is chosen. The event tree shows a number of events in a chronological order. The events are described in a top row. Under this row is drawn a tree structure and at each event the tree splits off into one or several branches. Each branch is assigned a probability and the total probability of each node is always 1.

\textsuperscript{11} Vesely, Goldberg et al., 1981.

---

<table>
<thead>
<tr>
<th>Probability of derailment</th>
<th>Do the cars overturn?</th>
<th>Collision with other train?</th>
<th>Is there a fire?</th>
<th>Path probability</th>
<th>Train kilometres per year</th>
<th>Events per year</th>
<th>Fatalities per event</th>
<th>Fatalities per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.65E-07</td>
<td>1.00E-04</td>
<td>1.00E-04</td>
<td>0.01</td>
<td>4.65E-17</td>
<td>2.85E-09</td>
<td>4.00E+01</td>
<td>1.14E-07</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.60E-15</td>
<td>2.83E-07</td>
<td>2.00E+01</td>
<td>5.65E-06</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.99</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.00E+00</td>
<td></td>
<td>0.01</td>
<td>4.64E-13</td>
<td>2.85E-05</td>
<td>2.00E+01</td>
<td>5.71E-04</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.99</td>
<td>4.60E-11</td>
<td>2.82E-03</td>
<td>9.33E+00</td>
<td>2.64E-02</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.9999</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.00E-05</td>
<td></td>
<td>0.01</td>
<td>4.64E-14</td>
<td>2.85E-06</td>
<td>2.00E+01</td>
<td>5.71E-05</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.99</td>
<td>4.60E-12</td>
<td>2.82E-04</td>
<td>9.33E+00</td>
<td>2.64E-03</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.9999</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.00E+00</td>
<td></td>
<td>0.01</td>
<td>4.64E-09</td>
<td>2.85E-01</td>
<td>9.33E+00</td>
<td>2.66E+00</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.99</td>
<td>4.60E-07</td>
<td>2.82E+01</td>
<td>1.33E-02</td>
<td>3.77E-01</td>
<td></td>
</tr>
</tbody>
</table>

Event tree 1. Simplified example of event tree. Please observe that the figures are only set to serve as an example and are not based on any statistical estimates.

Event trees always follows a time line (from left to right) and contain a number of nodes where the tree branches off. Every path ends in a final event where the consequences are described. In the example there are 8 final events and every sequence of events, or path, is called a scenario. Performing event tree analysis demands information. At every node, a probability is assigned to the branches. Further, an estimate of the consequences of each scenario is needed. In the example above, we need to estimate the consequences in all eight scenarios and insert estimates in the consequences column (Fatalities per event).
3. Description of scenario consequences. Every scenario can have unique consequences and these should be described uniformly. In the example, the number of fatalities has been chosen as a measure of the consequences. It is of course possible to choose other measures.

4. Calculation of probabilities. The quantitative analysis of the event tree is performed by calculating the path probabilities, multiplying with the consequences and adding together the consequences (if possible) to a measure of the expected harm. The path probabilities are reached through multiplying the probabilities given in each branch.

Event trees give a clear picture of the possible consequences of a given top event, an accident or an incident. The method is often used together with fault tree analysis and these are among the most common methods for analysing technical systems.

2.2.2.4 Monte Carlo simulation as a method

Monte Carlo simulation is a method for making repeated calculations using randomly generated values in specified probability distributions. When modelling train derailments, for example, a number of variables give input to the calculations. A “traditional” analysis uses point estimates of the different probabilities. An example would be using the frequency $3.4 \times 10^{-6}$ per train kilometre, as an estimate of the number of derailments due to lateral distortion of the tracks. Instead of using point estimates, the variables can be replaced with probability distributions. There is a large number of different probability distributions that can be used. In the example above, the point estimate of the frequency of derailment due to lateral distortion of the tracks could be replaced with a Poisson distribution with the expected value $3.4 \times 10^{-6}$.

For each calculation, a value is randomly selected in each input variable. The value of the output variable is calculated and recorded. In the next iteration, new values are generated for the input variables. The process is repeated a selected number of times, for example 500 or 1000 iterations, and for each iteration the value of the output variable is recorded. This is illustrated in the figure below with two normal distributions and the simple model $U = A + B$. 
The output variable will thus be a random variable and the resulting distribution can be analysed.

### 2.2.2.4.1 Variation and uncertainty

When constructing a model, it is important to separate variables with known variability from variables whose value is uncertain. When variation and uncertainty are not separated, a measure of the total uncertainty is calculated. It is then not possible to see how much of the variation in the output variables depends on natural variation in the input variables and how that depends on uncertainty. On the other hand, if the model separates the variation from uncertainty, and we find that the variation in the output variable is largely dependent on uncertainty, then we can draw the conclusion that further studies could reduce uncertainty and thereby also reduce the variation in the studied variable (the output variable). If, on the other hand, the variation in output largely depends on natural variation in the input variables, then there is not much we can do about it.

There are two methods for separating variation and uncertainty.

1. Calculate variation and simulate uncertainty. It might be possible to calculate the variation directly if we have input parameters with known variability. For the uncertain variables, probability distributions are assigned and values are generated randomly in a simulation.

2. Simulate both variation and uncertainty. It is possible to simulate both variation and uncertainty. This is done through multiple simulations. The variables with known variation are changed in each iteration. The uncertain parameters are changed between the simulations. Normally, the uncertain parameters are simulated in a first step and the values stored in a table. The values for each simulation are then picked from this table, one by one.
By using the second method, the results of the multiple simulations can be studied and it is possible to study the effects of the uncertain parameters separately. The second method is more demanding but it might be easier when the models are complex.

### 2.2.2.4.2 Fitting probability distributions

When the model structure is ready, it is time to assign probability distributions to the input variables. The selection of probability distributions could be done from expert judgements or by fitting theoretical distributions to data. There are a number of possible methods for fitting probability distributions to data and there is also software that automatically fits a number of distributions and lists these according to a test of how well the distribution describes data.

Vose gives a number of questions to answer before fitting a probability distribution:\(^\text{12}\)

1. Is the variable continuous or discrete?
2. Is it necessary to fit a probability distribution or can data be used directly?
3. Does the variation of the distribution follow the variation of the variable?
4. Is the variable independent of other variables in the model?
5. Is there a theoretical probability distribution that is known to describe this type of variable?

The parameters in a distribution can be estimated with different methods. Normally, Maximum Likelihood Estimators are used. There are also other measures on how well a distribution follows a data material. A Goodness-of-Fit test (GOF) can be defined as:

“A goodness-of-fit test is a statistical test on how well our data supports an assumption on the distribution of a population or a random variable. The test shows how well a fitted distribution follows data.”\(^\text{13}\)

Examples of goodness-of-fit tests are the Chi-squared test, Kolmogorov-Sminov (K-S) and Anderson-Darling (A-D). These test statistics are often calculated in software such as Bestfit. The chi-square test is described here. It can be used for ranking different possible probability distributions.

The Chi-squared test measures how well an expected frequency of a fitted distribution resembles the observed frequency in data. The data are separated into classes, as in a histogram, and the frequencies of the classes are calculated. These frequencies are then compared with the frequencies in the fitted distribution. The Chi-squared test statistic is calculated from

$$\chi^2 = \sum_i \frac{(O_i - E_i)^2}{E_i}$$\(^\text{(1)}\)

where

- \(O_i\) is the observed frequency of class \(i\) and
- \(E_i\) is the expected frequency of values from the probability distribution that falls in class \(i\).

From this follows that the smaller the test statistic, the better the distribution fits the data. The problem with this test is that the results are dependent on the number of classes used in separating the material. The test might give different results if we change the number of

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\(^{12}\) Vose, 2000.

\(^{13}\) Aczel, 1996, p. 669.
classes or how the classes are assigned, for example. The Chi-squared test is best for discrete variables but can also be used for fitting continuous probability distributions.

2.2.2.4.3 Simulation and analysis

How simulation is performed is not discussed in this thesis. It is highly dependent on the software used and there are several programmes available. With such software as @Risk, from Palisade, simulation is relatively straightforward. The programme generates large amounts of data and gives tools for analysing the output.

It is important to review the output and analyse whether the model produces credible results. Are the distributions of the output variables sensible? If there are there any unexpected shifts in the curves, it might depend on how the input variables are related. The distributions of the input variables might have been truncated, i.e. restricted to a specific interval so that the tails of the distributions are “cut off”. This might give peculiar results.

Furthermore, it is important to ensure that the model is evenly disaggregated. If one variable has an very big influence on the output variables, it is advisable to consider if this part of the model should be further refined and disaggregated.

2.2.2.4.4 Summary

The Monte Carlo simulation method provides a powerful tool for analysing uncertainty and variability. The risks can be described with ordinary probability curves and non-statisticians can easily understand these. More important, the distributions of the input variables do not have to be approximated, correlations and dependencies can easily be modelled, the mathematical calculations are simple and changes can easily be made. However, there are also some drawbacks.

The tails of the resulting distributions are relatively sensitive to the input variables. The simulation technique does not distinguish between uncertainty and variability. It treats all probability distributions as variables with known variability. This might be misleading. Nevertheless, there are methods for separating variability and uncertainty and these have been described here.
2.3 Previous research

2.3.1 Statistical methods

2.3.1.1 Transport of dangerous goods

In a broad Swedish research project on the risks of dangerous goods transport, both statistical methods and risk analysis methods were used. The project was led by the Swedish Road and Transport Research Institute (VTI)\(^{14}\). The probabilities of accidents were estimated in separate studies for rail and road transport of dangerous goods. The project is somewhat unique in that it attempts to work through all the aspects of dangerous goods transport.

The probabilities of accidents were estimated through statistical analysis\(^{15}\). The work considered differences in rolling stock, number of axles per railway car and track standard. The accident probabilities for each class were expressed as a function of a measure of risk exposure. The number of axle kilometres was used as the exposure measure for derailments and the number of train kilometres for collisions.

There was of course a lack of data on dangerous goods accidents. This made the use of accident data for all goods transport necessary. In this way, the probability of dangerous goods accidents could be estimated in an indirect manner. The probability of a derailment with a four-axle wagon is calculated to be between \(3 \times 10^{-9}\) and \(8 \times 10^{-9}\) per axle kilometre, depending on the track standard. The probability that a tank wagon will be damaged in a collision when placed at random in the train is calculated to be \(1.6 \times 10^{-9}\) per axle kilometre. This is calculated from an average risk of a collision on \(6 \times 10^{-8}\) per train kilometre.

The probability that a tank wagon will be damaged and leak, given that an accident occurs, was also calculated. The data was somewhat unreliable and the results are not reviewed here.

2.3.1.2 Statistical analysis of derailments, collisions and fires

Estimating the probabilities of railway accidents was the purpose of a graduate project at the Department of Mathematical Statistics in Lund, Sweden\(^{16}\). In risk analysis, the possible accidents, their causes and consequences are modelled and probabilities are assigned to the parameters in order to estimate the total risk of the system. These analyses have often been made by different consulting companies and different estimates of probabilities of accident causes and consequences have been used. In an attempt to find statistically sound estimates, Sparre made a thorough review of official railway accident statistics from 1985 to 1995.

The study focused on derailments, collisions between two trains, or trains and other objects, and fires on trains. The study is unique in terms of the degree of detail as 24 parameters were studied for derailments, 16 parameters for collisions and eight for fires. The accident reports for 431 derailments, 141 collisions and 113 fires were studied. For the derailments, Sparre calculated the accident probabilities and confidence intervals using Poisson regression. The derailment frequencies are given in the table below.

\(^{14}\) The project is summarised in Lindberg and Morén, 1994
\(^{15}\) Fredén, 1994
\(^{16}\) Sparre, 1995
The probability of a passenger train derailment on track type B appears to be higher than the probability of derailment on track type C. However, Sparre calculated confidence intervals for the estimates and these show that these two estimates are not significantly different from each other. The collision frequencies for passenger trains and cargo trains are given in the following table. First select a row, then a column.

<table>
<thead>
<tr>
<th>Type of track</th>
<th>Passenger train</th>
<th>Cargo train</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$3.4 \times 10^{-8}$</td>
<td>$2.9 \times 10^{-8}$</td>
</tr>
<tr>
<td>B</td>
<td>$2.9 \times 10^{-7}$</td>
<td>$1.1 \times 10^{-6}$</td>
</tr>
<tr>
<td>C</td>
<td>$2.8 \times 10^{-7}$</td>
<td>$3.2 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

Table 6. Derailment frequencies, from Sparre, 1995, p. 56.

<table>
<thead>
<tr>
<th>Type of collision</th>
<th>Passenger train</th>
<th>Freight train</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger train</td>
<td>$6.5 \times 10^{-9}$</td>
<td></td>
</tr>
<tr>
<td>Freight train</td>
<td>$5.1 \times 10^{-9}$</td>
<td>$- \times 10^{-9}$</td>
</tr>
<tr>
<td>Other trackbound vehicle</td>
<td>$24.4 \times 10^{-9}$</td>
<td>$64.2 \times 10^{-9}$</td>
</tr>
<tr>
<td>Other object</td>
<td>$71.5 \times 10^{-9}$</td>
<td>$58.9 \times 10^{-9}$</td>
</tr>
<tr>
<td>Heavy object</td>
<td>$39.0 \times 10^{-9}$</td>
<td>$53.5 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

Table 7. Collision frequencies, from Sparre, 1995, p. 57.

Among the general conclusions we can note that an improved track standard leads to a lower probability of derailments, that collisions seldom lead to the train or single vehicle spreading far from the tracks, and that half the fires on passenger trains start in the locomotive, whereas most of the fires on freight trains start in wagons.

**2.3.1.3 Automatic systems for train protection – the British case**

The costs and effects of Automatic Train Protection (ATP) have been discussed publicly in Britain since the mid-1980s, when British Rail declared that the cost of installing network-wide ATP was too high to be justified by the safety benefits. In November 1988, British Rail changed its view and decided to install ATP across the network over a period of 10 years. This decision was reinforced by the recommendations of a report on the train collision at Clapham Junction. The report was written by Sir Anthony Hidden in 1989 for the Department of Transport. British Rail was advised to install ATP on the whole network within five years. Hidden also recommended that British Rail should make economic analyses of ATP "so that a financial value can be put on safety".

The British Rail report that followed stated that there were more cost-effective ways of saving lives. The Health and Safety Commission, now part of the Health and Safety Executive (HSE), also advised the Secretary of State that there were other investments that would be more cost-effective, that would save more lives and lead to fewer injuries. The Secretary of

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17 British Railway Board, 1994
State accepted this and released the successor to the British Rail infrastructure division, Railtrack, from the obligation of installing network-wide ATP\textsuperscript{18}.

The authors of the report, Evans and Verlander, used accident inquiry reports for the period 1968-1993 to estimate the \textit{probabilities} and \textit{consequences} of ATP-preventable accidents. As it happened, the average number of fatalities in ATP-preventable accidents was quite low compared with the average number of fatalities per accident for the whole database. Evans and Verlander argued that there was no reason to believe that the consequences of, for example, collisions would be less severe if the accident could have been prevented with ATP. They therefore used the whole data set to estimate the consequences. The frequency of ATP-preventable accidents per year multiplied by the average number of fatalities per accident gives the expected number of ATP-preventable fatalities per year. Using the whole data set to estimate the consequences rendered an estimate of 3.66 ATP-preventable fatalities per year. The 95\% confidence interval was calculated to be 1.44 to 5.89 fatalities per year. This interval is fairly wide and reflects the fact that the consequences range from one to 49 fatalities in a single accident.

Evans and Verlander also found a theoretical probability distribution that gave an almost perfect fit with the material. The distribution is called a logarithmic series distribution, has a long tail to the right, and therefore permits accidents with a larger number of fatalities than have occurred so far. From this it was also possible to conclude that the estimated mean number of fatalities per year would not be affected, even if a larger accident were included in the sample.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{Histograms of ATP-relevant accidents and a logarithmic series distribution, from Evans and Verlander, 1996, p. 187.}
\end{figure}

Evans and Verlander calculated what are called fatality-equivalents. These are based on the number of injuries multiplied by some factor that weighs the damage caused by a serious

\textsuperscript{18} Evans and Verlander, 1996, p. 110.
injury, for example, against a fatality. The expected number of serious injuries multiplied by
the factor is added to the expected number of fatalities and the sum is the fatality-equivalents.
They assumed that the injuries follow the pattern of the fatalities and estimated the number of
fatality-equivalents at 5.5 per year. With this estimated number of possible fatalities that could
be prevented by the network-wide installation of ATP, they reached a cost per life-equivalent
saved of about £11 million. The HSE has adopted the value of £2 million per life-equivalent
saved, which means that network-wide installation of ATP undoubtedly exceeds this value.

Evans also proposed that the assessment of a project should include a comparison of
individual risks with the acceptable risk levels stated by the HSE. The individuals who could
obtain the largest reduction in risks are train drivers. However, at present, their risk does not
exceed the threshold specified by the HSE. Regular commuters also run low risks. This
criterion will therefore not demand the installation of ATP19.

The calculations referred to above were made for the British Rail version of Automatic Train
Protection. The outcome of the discussions between the HSE and Railtrack was that versions
of ATP cheaper than the BR ATP are available and that it might be possible to install only
parts of the system and not the full version of the BR ATP20.

As a result of the Train Protection Strategy adopted by Railtrack following the Hidden report,
mentioned in the introduction, and the acceptance by the HSE that the full BR ATP version
was not cost-beneficial, a Driver Remainder Appliance was evaluated21. The risks were
estimated with risk analysis methods and the evaluation is therefore described in section 2.3.2.

The Train Protection and Warning System (TPWS) has thereafter been the object of two
separate studies. British Rail Research carried out a study in 199522, using a database of
signals passed at danger (SPADs) during the years 1985-1992. The main finding was that
TPWS would have prevented around 68% of the fatality-equivalents that a full ATP would
have prevented23.

In a report to the British Railway Inspectorate (HMRI), WS Atkins assessed the safety effects
of TPWS and made a cost benefit analysis of the installation of the system24. Atkins arrived at
a similar figure but by a different method. They found that TPWS could prevent around 65%
of the fatalities that a full ATP could prevent.

Following the accident at Ladbroke Grove on October 5, 1999, the Deputy Prime Minister
requested an investigation of the consequences of SPADs. The work was undertaken by Sir
David Davies and a report was presented in February 200025. Sir Davies did not make any
advanced statistical calculations. The report instead contains a general comparison of the
effects of the various train protection systems available. These are the Driver Remainder
Appliance (DRA) and three versions of TPWS and ETCS. There are few references to the
costs of the systems.

20 [Health and Safety Executive, 1996 #1540, Appendix 12b]
23 A fatality equivalent is defined as a weighted compound of a fatality, a serious injury and a light injury. A
fatality equivalent is around 1.5 fatalities. The underlying rationale is that for every rail fatality there will
inevitably be some injuries. In this way fatalities and injuries are handled together.
2.3.1.4 Speeds of trains in fatal accidents

Professor Evans of University College London carried out an extension to the study mentioned above, where the speeds of trains in fatal accidents were analysed. He collected information on the impact speed of trains in fatal accidents between 1967 and 1999\textsuperscript{26}. The impact speed in the case of head-on collisions is defined as the sum of the speed of the trains involved. For a rear-end collision, the impact speed is calculated as the difference between the trains’ speeds. The impact speed for derailments is the speed when derailing.

One of the arguments for modelling speed is the introduction of high-speed trains. If the consequences depend upon the impact speed, and there is an increase in average speed over time, then this must be incorporated in any analysis of accident risks. On the other hand, if there is no change in speed over time, then there is no case for incorporating the speed in the models. Clearly, if the average speed does not change over time, then there is no need to revise the expected number of fatalities, even if there is a relationship between speed and consequence. The expected number of fatalities will remain constant over time (\textit{ceteris paribus}).

The first hypothesis was therefore that a higher impact speed leads to more fatalities. The relationship was tested with least square linear regression and the regression line was forced through the origin. Common sense tells us that if the impact speed is zero then the consequences should also be zero. This means that any relationship must necessarily start at the origin. The second hypothesis was that there is a change in the impact speed over time.

There were two main conclusions from the study. The first was that there is a relationship between impact speed and the number of fatalities. The second was that there is no change in impact speed over time. This leads to the conclusion that there is no case for including speed when modelling railway accidents. The first conclusion drew upon a regression of the number of fatalities as a function of impact speed. The material is given in the plot below.

\textsuperscript{26} Evans and Verlander, 1996.
Looking at the data more closely shows that different conclusions can be reached if collisions are separated from derailments. Some derailments were followed by a collision. These are here treated as collisions. Evans finds that the relationship between impact speed and mean fatalities is \( \text{Fatalities} = 0.064 \times \text{Speed} \). When calculating the regression for the collisions, almost the same relationship is found, \( \text{Fatalities(Collisions)} = 0.060 \times \text{Speed(Collisions)} \). But there is also an upward trend in impact speed over time that is statistically significant. This means that there is a case for including speed when modelling collisions.

The derailments-only dataset shows that there is also a positive relationship between speed and number of fatalities here. The ‘problem’ is that there is no trend; the speed does not change over time. In fact, it is the inclusion of the Hatfield accident in October 2000 that pushed the regression line upwards. Before this inclusion, derailments showed a significant downward trend over time. This would also have led to the conclusion that speed should be modelled. However, the inclusion of the Hatfield accident withdraws that argument.

This article is a good illustration of the importance of correct data material and to the fact that railway accidents occur very seldom, which often leads to a lower reliability of statistical inferences.

### 2.3.1.5 Fitting statistical models to accident data

Evans studied accidents in Great Britain and based his calculations on a 34-year dataset containing 77 fatal accidents and 308 fatalities. This dataset was also used in the studies reviewed above. In order to model the trend in the accident rate, Evans proposed a model where \( \lambda \) is the accident rate, expressed as the number of accidents per billion train kilometres. In the model, \( \lambda \) is supposed to be a function of time, expressed as
\[ \lambda(t) = e^{\beta t} \]

where \( \alpha \) is the intercept, giving the accident rate in year 0, and \( \beta \) the coefficient, giving the annual proportional change in accident rate\(^{27} \). It would also be possible to use a model where \( \lambda(t) = \alpha \beta^t \)

In this case, the estimate of \( \beta \) must be a value <1 in order to have a decreasing trend.

Evans used the first model, and estimated the parameters with software called General Linear Interactive Models, GLIM. He found a decrease in the accident rate over time of 4.9% per year. He calculated the average accident rate for 5-year periods, and the data is plotted together with the estimated trend in the figure below.

![Graph showing the trend in fatal accidents per billion train kilometres (Great Britain 1967-2000) together with the fitted trend.](image)

From Evans, 2002, p. 17

The number of fatalities per accident was also analysed, and Evans found no change over time and therefore concluded that the mean number of fatalities per accident is a correct measure. Based on the trend and the average number of fatalities per accident, Evans estimated the expected number of fatalities for the year 2000 to be 4.93.

In Evans’ paper, an interesting comparison is made with the expected number of fatalities per year calculated by Railtrack, which has developed a risk analysis model described in the next section. Railtrack estimates the expected number of fatalities to be 11.3: a difference of 6.4 fatalities per year. There is an argument that low frequency accidents with serious consequences might occur and that any statistical estimate based on historical data will

\(^{27} \) Evans, 2002, p. 4
underestimate risks because these types of accidents occur so seldom that they have not occurred during the period covered by data.

Based on British traffic levels, the British accident data and the estimate from Railtrack, Evans calculated that it would require an accident with an accident rate of once every 42 years and 270 fatalities for the risk analysis model to be correct. Evans concludes that this is not credible and that the statistical estimate based on historical data is to be preferred\(^{28}\).

### 2.3.2 Risk analysis methods

In a report from 1993, Lindberg and Olsson investigated the actual use and the feasibility of using risk analysis methods in the railway sector\(^{29}\). They found that, apart from analyses of level crossings and the transport of dangerous goods, risk analysis methods have not been used frequently in this area. The already low risk levels for rail passengers were seen as an explanation for the lack of risk analyses. The authors found that the strongest argument in favour of using risk analysis methods in the rail context is that they give the decision-maker the chance to deal with risk and uncertainty in a more systematic and consistent way.

There has been some work done since Lindberg and Olsson’s literature review was written, and some of that research is discussed here.

#### 2.3.2.1 Consequences of accidents involving dangerous goods

In section 2.3.1.1, where research on the transport of dangerous goods is reviewed, a Swedish research project on the risks is described. Both statistical and risk analysis methods were used. The different consequence scenarios were modelled with separate event trees for the various substances studied\(^{30}\). The consequences connected to each scenario were based on dispersion estimates, calculated with a computerised dispersion model, and the location of the accident, in a city or in a small village.

6 event trees were constructed for railway transport and 10 trees for road transport. The event trees had between 3 and 6 levels, each level having two or three branches, giving up to 44 scenarios. A probability was calculated for each scenario and from this an average consequence for each substance was calculated.

The analysis showed that accidents involving ammonia and liquefied petroleum gas (LPG) gave the most serious consequences. The expected number of fatalities in an ammonia accident was 0.34 for a railway accident in a city\(^{31}\). Another finding was that the consequences did not differ much between railway and road accidents.

#### 2.3.2.2 Fault tree analysis of level crossing accidents

Shariari attempted to use fault trees to analyse level crossing accidents\(^{32}\). Based on statistics for 126 level crossing accidents in the western region of Sweden during a period of five years, parameters such as driver behaviour, car, infrastructural and environmental status were modelled. Shariari reached the conclusion that fault tree techniques can be used as a means of modelling level crossing accidents, but he also proposed that more extensive and co-ordinated

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\(^{28}\) Evans, 2002, p. 23  
\(^{29}\) Lindberg and Olsson, 1991.  
\(^{30}\) Helmersson, 1994  
\(^{31}\) Helmersson, 1994, p. 39  
\(^{32}\) Shariari, 1991
accident reports could enable the necessary degree of detailed analysis of causes and consequences.

2.3.2.3 The Swedish National Rail Administration Manual on tunnel safety

A more recent use of risk analysis methods is applied in the manual for evaluating tunnel safety produced by the Swedish National Rail Administration. In this manual, fault tree and event tree techniques are used extensively. Both qualitative and quantitative methods are used, the total risk is estimated and different risk-reducing measures for different situations are proposed. The final statement in the manual is that the most effective risk-reducing measures relate to construction, equipment and train crew, and that measures in the tunnels have much less effect on levels of risk and the possible course of events.

2.3.2.4 Human Reliability in the use of Driver Reminder Appliances

In a report to Railtrack, the consulting company Arthur D Little analysed human reliability in the use of Driver Reminder Appliances (DRA). A DRA is a device for reminding the driver to check the signal aspect before starting away from a signal, either after a stop on a station or after a restrictive signal on the line. Two versions were evaluated, passive and active DRA (PDRA and ADRA).

The passive appliance is basically a button that the driver has to push manually when arriving at a red signal. The button then has to be released before the train can depart. The success of the system then depends upon that the driver remembers to push the button when a restrictive signal is reached and that he does not release the button before he or she has checked the signal aspect again. The active version differs in that the appliance is activated automatically when a restrictive aspect is received. However, this version also depends upon that the driver checks the signal aspect before releasing the button and departing.

The primary data source for estimating probabilities of SPADs is the rail industry’s SPAD database. The underlying factors leading to SPADs must however be studied with other methods, as there is little information on these in the database. AD Little used a technique called HEART, Human Reliability Assessment and Reduction Technique. This is a two-step process starting with defining generic tasks and assigning nominal probabilities to these. The error producing conditions (EPC) are then identified and the effect on the probabilities calculated. AD Little used HEART in combination with Human Hazard and Operability analysis for identifying the factors that influence the probabilities of human error.

The study showed that the main source of unreliability was the possibility of overriding/suppressing or not using the DRA, regardless of the DRA version (passive or active). Furthermore, the active DRA required a response to both yellow and red signal aspects. The ratio between red and yellow signals is 1:10. The fact that the same response is required for two different signal aspects lowers the effectiveness at red signals. This was also a contributing EPC for the active DRA.

The effectiveness of the DRA in its different versions was calculated and found to be 50%-53% for PDRA, 51% for ADRA at running signals and 68% for ADRA at platform signals. The greater effectiveness of ADRA at running signals is partly attributed to the fact that the

33 Shariari, 1991, p. 75-59
34 Banverket, 1997b
35 Banverket, 1997b, Appendix 5, p. 47
driver does not have any other tasks that affect the operation of the DRA. The study is not reviewed further here, but serves as an example of the use of risk analysis methods in the railway sector. The evaluation of DRA also comprised a cost benefit analysis, reviewed in section 5.4.2.3.4 on page 158.

2.3.2.5 Risk analysis of flank protection

In a project for the Swedish National Rail Administration, risks of different flank protection measures were studied\(^{37}\). Flank protection refers to the various ways the routes of trains are protected. In a network, train movements are interdependent. Meetings, overtakings and station stops have, for obvious reasons, to be scheduled. There are, for example, several possible ways of allowing two trains to meet at a station. For all meetings, in virtually all rail systems, there is a requirement that train routes should have flank protection. This requirement can be implemented in three basic ways: through trap points, diverting the train from a route that would lead to a collision, through signals stopping trains from entering the route, or through derailers derailing a train that is about to enter the route, or through a combination of these. Given these ‘tools’, there are three main options for trains meeting at a single-track station.

2.3.2.5.1 Basic principles of setting train routes

Not simultaneous station entrance

No flank protection is provided if the overlap behind main signals is shorter than a specified safety zone. The trains are then not allowed to enter the station simultaneously. One train must first enter and come to a standstill, before the next train can pass the station.

Simultaneous station entrance with safety zones

Flank protection is provided if the overlaps are long enough. The overlap must be longer than the required safety zones. In this case, simultaneous station entrance can be allowed.

Simultaneous station entrance with trap points

Flank protection is provided if the trains can be diverted from the conflict route by trap points. A trap point is any point that leads the train from a route that would lead to a collision if the train passes a signal at danger. This provides the highest safety level. The principle is illustrated in the figure below.

![Figure 9. Simultaneous station entrance with flank protection through trap points](image)

Timetable constructors have to ensure that meetings are possible, creating time windows on the station for each train. Train dispatchers set the routes for the trains on a day-to-day or minute-to-minute basis. On a station with dozens of tracks, hundreds of points and signals, the setting of train routes is automated.

\(^{37}\) Alonso, 2000
2.3.2.5.2 Risks

What is clear from the above is that there are several options, but these also imply varying levels of risk. There are also other factors contributing to the complexity. Points might be self-normalising, reducing the flexibility for the train dispatcher. Points might be in the wrong position, signals might show the wrong aspect, train drivers might misread or misinterpret signals, the overlap may have a different length, and trains travel at different speeds and have different braking distances. All this affects the risks of the rail system.

Alonso identified 9 different possible flank protection measures. In the study, flank protection refers to measures to protect trains from head-on, rear-end and side-on collisions. The possible measures are:

1. Trap point
2. Tongue of point in protective position
3. Derailer
4. Main signal
5. Main ground signal
6. Shunting ground signal
7. Stop light, technically controlled
8. Fixed barrier (on track under construction)
9. Buffer stop

List 1. Flank protection measures, from Alonso, 2000, p. 10.

One of the purposes of the study was also to evaluate the possibilities of a method for risk analysis developed by Railtrack. The method can be described as a structured process for evaluating risks in the rail system. There are seven steps in the process.

1. Identification of hazards
2. Causal analysis
3. Consequences analysis
4. Loss analysis
5. Options analysis
6. Impact analysis
7. Demonstration of ALARP and compliance.


Alonso worked through steps 1, 2, 3 and 5. The identification of hazards was made with a risk analysis method called HAZOP. The principle behind HAZOP is to study the ideal intended operation of a system and the possible deviations from this. The following hazardous events were identified:

1. Speeding
2. Driver loses control over train
3. Driver disregards signal
4. Driver does not apply breaks
5. Driver does not stop before signal
6. Train hits derailer
7. Procedural disruptions
8. Miscommunication between driver and train dispatcher
9. Signal misplaced: problem for driver to view signal
10. Time pressure
11. Driver misreads signal / reads the wrong signal.

List 3. Hazardous events identified in HAZOP study of flank protection measures. Alonso, 2000

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38 Railtrack, 2000b, 2000a
The causal analysis was restricted to flank protection measures 4, 5, 6 and 7. These were the signals. The causes were analysed using fault trees. Two databases, administered by the Swedish Railway Inspectorate, were used to provide input for the quantitative analysis. Two cases were studied, with or without Automatic Train Control ATC. The consequences were analysed with event trees.

Alonso found the best flank protection measures to be long overlap, tongue of point in protective position, derailler when train speed can be assumed to be low, trap point with short overlap, and fixed barrier.\(^{39}\)

### 2.3.2.6 Railtrack Layout Risk Method (LRM)

Railtrack has developed a tool for analysing the design and layout of junctions.\(^{40}\) It is a simulation tool that analyses the risks of different layouts at junctions by simulating operations. It is not a network model in the traditional meaning, and it is not possible to use the model for capacity analysis or timetable calculations.

The model makes risk calculations based on train service patterns, conflicts between trains, signal positions, train speeds, passenger train loading and probabilities of Signals Passed At Danger (SPAD). It calculates the potential risks from collisions and does not consider derailments, for example.

The model is built in Microsoft Excel and uses several input sheets for all the variables. A list of all input parameters is listed on the next page. The principal steps in the calculations are:

1. Time window for conflict to occur
2. Frequency of conflict
3. Frequency of collision
4. Fatalities due to collision

These four steps are reviewed in the following subsections.

#### 2.3.2.6.1 The conflicts – calculating time windows

A conflict is defined as the occurrence of two trains, arriving on different routes at the same track location, given no protection from signalling arrangements. It is operationalised through the concept of a time window. “A time window is an interval of time such that trains arriving on conflicting routes within the time window would collide if one train was not held by a signal at danger.”

A collision occurs when one train passes a signal at danger. The LRM model considers three different types of conflicts, head-on, converging and crossing. A converging conflict occurs when a train may enter a track section already occupied by a train, with the possibility of a rear-end collision. A crossing conflict occurs when two train paths cross.

A conflict cannot occur if there are interlocking, flank protection or trap points that would always divert the train from the conflict. When calculating the probability of a conflict, the usual position of the points, the relative numbers of trains moving through the points and whether the points are self-normalising are considered.

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\(^{39}\) Alonso, 2000, p.11  
\(^{40}\) Railtrack, 1999
For each conflict, a time window is calculated. The time window is the length of time during which a collision can occur and it is of course different for head-on, converging and crossing conflicts. The calculations are based on the distance from the SPAD signal to the potential accident point, the length of the conflict zone, the probability of a SPAD and the probability that a route is set.

### 2.3.2.6.2 Frequency of conflict

The traffic can be modelled with two different methods. The “Random Method” assumes no accurate timetable and the arrival of trains to the junction are uniformly distributed over the modelled time. In the “Timetable Bias Method”, a timetable and punctuality data are entered into the model. The arrival of trains at a junction is then modelled with Monte Carlo simulation using the timetable and punctuality data entered.

It is possible to compare the methods. If risks are higher with the timetable method, this is an indication that the timetable itself introduces a potential for conflicts. There is then a need to review the causes of the difference.

The probability of a route being set is dependent upon the priority of different services. A passenger train is given a higher priority than a freight train. For example, given that the two trains arrive simultaneously at their respective signals, the probability that the passenger train is given a set route is 0.9 and for the freight train 0.141. This affects the consequences, as it is significant whether a freight train hits the side of a passenger train or vice versa.

### 2.3.2.6.3 Frequency of collision

Behind the model is the assumption that a SPAD precedes every collision. It is not possible to have a collision if there has been no SPAD. Of course, not all SPADs lead to a collision and the level of risk as a result of a SPAD is dependent upon the track layout. Furthermore, the probability of a SPAD is in the first place dependent upon the placement and choice of signalling equipment, amongst other things.

The probability of a SPAD is calculated from historical data. Two different types of signals are modelled: platform starter signals and signals protecting a junction. The historical data provides information on the probabilities of SPADs for platform starters and non-platform starters. The overlap is the distance from the signal to a potential collision point. The overlap provides a protection in the event of a SPAD. The driver might see the signal too late, for various reasons, and pass it, despite applying the brakes, but will not pass the overlap. Furthermore, a movement up to the signal is only allowed if the overlap is unoccupied and other movements prevented from entering it.

In the model, the probability that a SPAD train passes the overlap is calculated. The probability is calculated from the average SPAD-intensities, given from historical data, the length of the overlap and the speed of the trains.

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41 The figures are taken from the manual Railtrack, 1999, p. 41
2.3.2.6.4 Calculating the consequences

The consequence model has been developed for Railtrack by a consultancy company, WS Atkins. The model calculates the consequences of head-on, rear-end and side-on collisions. The calculations are based on:

1. Speed of SPAD train and scheduled train
2. Types of train involved
3. Number of carriages
4. Passenger loading
5. Number of cab staff

This part of the model is not reviewed further here.

2.3.2.6.5 Pros and cons

The model can be used to compare different layouts at a specific location. It cannot be used to compare risk levels of different layouts at different locations with different traffic and train services. The model is a bottom-up model, calculating the total risk level from the various input variables. There is an inherent uncertainty in this approach and the absolute risk level calculated should not be used in comparisons with other safety measures. However, the method can be used as a tool for comparing the relative difference in risk of layouts and indicating where changes are likely to have a positive effect on the level of risk.

2.3.2.7 The Railtrack Safety Risk Model (SRM)

Railtrack has developed a risk analysis model for the British network using fault trees and event trees. It encompasses derailments, collisions and fires. It is a way of describing the risks in the whole network: a network-wide model instead of a train movement focused model. Its purpose is to provide risk assessments, identify hazardous events, failures and their contribution to the risks, and to assist in the analysis of safety measures. The general design of the model is described in Figure 10.

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42 Symons and Dennis, 2000, p. 2
Railtrack put a lot of effort into ensuring that they did not miss any hazards in the system. They made a thorough review of previous hazard identification studies and made a full list of the hazardous events and the precursors. In the model, 110 hazardous events are represented,
together defining the risks on Railtrack-controlled infrastructure. The model is currently set up for the entire British network, and so the results are not applicable to any specific line in the network.

Passenger loadings and train speeds are included in the model, along with secondary effects such as fires, collisions with line-side structures, buildings or trains on adjacent tracks. The model quantifies risk to the following groups:

- passengers on trains and on stations
- railway staff on trains, at stations and working on the track
- members of the public.

The third group includes people crossing the tracks at level crossings as well as trespassers entering the track area without legitimate purpose. Railtrack uses “equivalent fatalities” to measure harm: a compound of fatalities and injuries, where 10 major injuries or 200 minor injuries equals one fatality. Railtrack estimates the following risks with the model.

<table>
<thead>
<tr>
<th>Accident category</th>
<th>Risk (equivalent fatalities / year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train accidents</td>
<td>24.4</td>
</tr>
<tr>
<td>Movement accidents (excluding trespassers)</td>
<td>24.8</td>
</tr>
<tr>
<td>Non-movement accidents (excluding trespassers)</td>
<td>27.5</td>
</tr>
<tr>
<td>Trespassers</td>
<td>61.2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>138.0</strong></td>
</tr>
</tbody>
</table>

Table 8. Total risk by accident category, from Railtrack, 2001, p. 7.

Railtrack analyses the risk profile and finds that the largest risk contribution comes from “adult trespassers struck/crushed while on the RCI” with 47.2 equivalent fatalities per year. This is followed by “passenger slips, trips and falls” (11.1 equivalent fatalities/year) and “passenger train collision with road vehicle on level crossings” (6.18 fatalities/year). Derailments with passenger trains are estimated to give 4.36 equivalent fatalities per year. In section 2.6, a model for passenger train derailments is developed. It uses the same approach as Railtrack’s Safety Risk Model. Railtrack’s derailment model is therefore reviewed in a little more detail.

### 2.3.2.7.1 The Railtrack SRM derailment model

The Railtrack Safety and Standards directorate has kindly provided the fault tree for passenger train derailments. The fault tree has been used as a basis for the development of a risk analysis model in the current project. In the Railtrack model for passenger train derailments, six top events feed into six different event trees. The top events are:

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43 Railtrack, 2001, p. 1
44 RCI = Railtrack controlled infrastructure
45 The safety and standards directorate was a department within Railtrack. In year 2001 it was separated from Railtrack, the infrastructure holder, and now form the independent body “Railway safety”, but is still owned by Railtrack PLC, a shareholding company.
46 Based on the fault trees in the model. Personal communication Symons, 2000.
TE1. Fast passenger train derailment on Open track
TE2. Fast passenger train derailment in station
TE3. Passenger train derailment slow speed
TE4. Passenger train derailment in single track tunnel
TE5. Passenger train derailment in twin track tunnel
TE6. Passenger train derailment on underbridge

List 4. Top events in Railtrack's safety risk model for passenger train derailments

This is an ambitious level of detail that requires a lot of data in order to be meaningful. This quantity of data is not available in Sweden. The factors that influence derailment consequences and exist before or just at the moment of derailment are:

1. the speed of the train
2. the location of the derailment
3. the type of carriages
4. the number of passengers on the train.

List 5. Factors influencing the consequences of derailments

Railtrack has modelled the first factor by making separate fault trees for derailments at high speed and derailments at low speed. The data for the probabilities of the different underlying causes are the same, but the number of derailments, or actually the probability of an accident, are separated into two parts by a simple probability. 95% of derailments on open track are set to occur at high speed and 5% at low speed.

The probability of a derailment at a stations, on open track, or in a tunnel is set in a similar manner. 95% of the derailments occur on open track, 3% at a station, 0.6% in twin-track tunnels and 1.4% in single-track tunnels.

The probability of a wheel failure, for example, is normally independent of where on the line the failure occurs. The same goes for axle failure due to overheated bearings. The probabilities of these types of faults, i.e. rolling stock faults, are independent of where the failure occurs. Other faults are more specific. The probability of a broken rail is lower in a tunnel than on open track. Lateral distortion of the tracks or problems with snow and ice do not occur in tunnels. Therefore, the probabilities of track faults in tunnels are different from the probabilities of track faults on open track.

The fault tree for passenger train derailments can be seen as consisting of different parts. The event “rolling stock fault” feeds into five of the six mentioned fault trees in the SRM. The “track fault” tree also feeds into several of the six trees. The whole fault tree can therefore be broken down into a limited number of separate parts and these can be modelled in more detail.

This type of model can be used to analyse and describe risks in the railway network and to identify factors that contribute to the overall level of risk. It is also a tool to calculate the average level of risk and will give results different from those of a statistical analysis based on data from ten or fifteen years. This is because it is possible in a risk analysis model to describe very unlikely accidents that have serious consequences and the way this type of event contributes to the overall risk level. We now turn to the work done within the present project.
2.4 Safety effects of Line-block and ATC

2.4.1 Introduction
This doctoral project has included an economic evaluation of a traffic control system called Radioblock, which can be described as a low-cost alternative to traditional automatic line block signalling. The economic aspects of the system are described in section 5.5 and a technical description of the systems is given in Appendix 1.

In order to estimate the safety impact of this system, a comparison of the lines equipped with Automatic Traffic Control Systems, ATCS, and those without was undertaken. This part of the study has been described in a separate working report47. The Swedish Railway Inspectorate’s JAS database was used48. This contains data on 2408 incidents and accidents from 1989 onwards. This information was correlated with a suitable measure of exposure in the form of the traffic volume on the two kinds of line, data on which was collected from the Swedish State Railways (SJ) TRACK database for the period from 1991 until November 199749.

JAS does not contain all accidents that have occurred. This will be illustrated in section 2.5.2, where the risks of passenger train derailments are analysed. There are formal criteria that apply to the JAS database. All accidents where there are fatalities or injuries to passengers or railway staff, or where the material costs exceed SEK 1 million, must be reported to JAS. If there is no loss of human health and the material costs are lower, then there is no requirement to report the accident or incident to JAS. However, there are accidents that do not meet the requirement that have been reported in JAS. There is therefore a lack of consistency.

This was not identified as a big problem when the Radioblock study was conducted. In a subsequent project, data was collected from several sources. This showed that JAS cannot be used as a reliable source of information when studying accident rates, for example. However, it has not been possible to re-do the analysis and calculations, and so the study is presented here as it is.

2.4.2 Correlating data – three problems
The Railway Inspectorate has used a system of its own for classifying and labelling lines and different track sections. This system did not correspond to that used by the National Rail Administration (NRA) or SJ50. It was therefore necessary to assign some common denominator to accident locations on different lines or sections, and the system used by the NRA and SJ was chosen. This uses numbers to label every part of the railway system, which, in 1997, consisted of 217 different track sections. A specific track number was then added to the information for every accident in the JAS database. It was possible to do this automatically in part.

A second problem was that SJ changed the labelling system between 1994 and 1995. The work started with seven files containing data on train- and vehicle-kilometres operated each year on every track section, one file each for the years from 1991 to 1997. The file for 1997 contained information for 217 track sections, whereas that for 1991 only had 162 track

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47 Johansson, 1998a
48 Swedish Railway Inspectorate, 1989 -
49 SJ - The Swedish State Railways, 1997
50 The JAS database has been updated since the study was made and now contains information on track numbers corresponding to the system used by the Rail Administration.
sections. Only 89 track sections were labelled similarly for the whole period 1991–1997. The reason for this was that between 1994 and 1995 several track sections were divided into two or more sections with new numbers. Furthermore, some sections had simply been renumbered and new tracks had been built.

This caused more problems and work than was first expected. In order not to lose information, it was decided to use the actual labelling system given in the file for 1997. The track sections that had been split had new train-kilometre figures assigned to them, based on the assumption that traffic was homogenous along the “old” track sections, the figures for which were divided according to the length of the “new” sections. This resulted in a list of figures for train-kilometres and vehicle-kilometres run on 191 track sections for the years 1991–1997.

The possible errors produced by this procedure were diminished in the following analysis. All track sections with the same traffic control system (manual or automatic) were added and the total train-kilometres operated calculated. This means that many of the track sections that were split in the data collection phase were added together again because the traffic control system was the same on the “new” track parts. (The split track sections that had different traffic control systems were of course added to their corresponding groups.) Whilst there are possible errors produced because of the assumptions made, this procedure got closer to the real values than with any other.

The third problem that had to be addressed was that signalling systems are different on different track sections and that there has been investment in signal technology during the period analysed: the situation today is different from that in 1991. Selecting all the accidents on a specific track section that has ATCS today will not give a correct result if the signal system was been installed during the sample period. Accidents that occurred before the system was installed would be wrongly labelled as accidents on tracks with ATCS.

Therefore, a list of the dates when ATCS was installed and became operational had to be compiled. The information on the signalling systems before 1991 was found in a book on infrastructure data from the Swedish Railway Club and information on changes to these systems after that year has been published in the Swedish journal TÅG. The list has been checked by Bengt Hultin, Anders Lundström and Christer Södergren at the Swedish Railway Inspectorate. Having compiled the list with the in-service dates of the signal systems for the various track sections, it was possible to get all the accidents right and avoid classifying any as ATCS accidents when the signal system was not in service until after the accident happened.

2.4.3 Finding relevant accidents

It was then possible to identify all the accidents that occurred on track sections with and without automatic signalling systems, respectively, and to sum the traffic in the two categories. This then gave a list of accidents of which many were unrelated to the signalling system. The search was therefore qualified and accidents categorised according to the list below were excluded.

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51 Aghult, Lind et al., 1999
52 Olson, 1998
Table 9. Types of accidents that were excluded from the dataset.

Accidents on double-track lines were also excluded mainly for reasons of comparability. The difference in traffic volume between double-track lines and small regional lines makes comparisons misleading. A search then gave the number of accidents given in the table below:
2.4.4 Statistical analysis

Correlating the accident and traffic data shows that there are about 0.21 accidents per million train kilometres on lines with automatic signalling systems and 0.44 on lines without. A simple statistical test was performed to see if there was a significant difference between lines with and without automatic signalling systems.

We can view the occurrence of accidents as a Poisson-distributed random variable. Poisson distributions are used to describe random variables that count the number of occurrences in a specified interval of time. Traffic volume is a continuous variable and we can view the traffic on the selected track sections as a specified interval of a continuous variable. The conditions for a Poisson distribution are therefore fulfilled. Most importantly, the probability that two accidents will occur at the same time in a given very small interval is close to zero and the accidents are independent, meaning that the probability of an accident for a given interval is not changed if an accident happens in another interval prior to the first specified. Furthermore, the probability of an event is proportional to the length of the interval and independent of where the interval starts\(^\text{53}\).

The data is then defined as two samples from different populations. We will make a comparison between the samples to test the difference between the probabilities or proportions of the variable. The sample sizes are the numbers of train kilometres and the number of accidents is the observed variable.

\[
M \in Po(25 \cdot \rho_m) \quad \sigma_m^2 = 25 \cdot \rho_m \\
S \in Po(189 \cdot \rho_s) \quad \sigma_s^2 = 189 \cdot \rho_s
\]

\[n_1 = 25 \quad \text{traffic volume, in million train kilometres, on tracks without automatic signalling systems}
\]

\[x_1 = 11 \quad \text{the number of observed accidents on tracks without automatic signalling systems}
\]

\[n_2 = 189 \quad \text{traffic volume, in million train kilometres, on tracks with automatic signalling systems}
\]

\[x_2 = 40 \quad \text{the number of observed accidents on tracks with automatic signalling systems}
\]

\[
\hat{\rho}_m = \frac{x_1}{n_1} = \frac{11}{25} \approx 0.44 \\
\hat{\rho}_s = \frac{x_2}{n_2} = \frac{40}{189} \approx 0.21
\]

\[\Rightarrow D = \hat{\rho}_m - \hat{\rho}_s = 0.44 - 0.21 = 0.23 \quad (2)
\]

\[
\sigma_D = \sqrt{\frac{\rho_m}{n_1} + \frac{\rho_s}{n_2}} = \sqrt{\frac{0.44}{25} + \frac{0.21}{189}} = 0.137 \quad (3)
\]

\(^{53}\) It would also be possible to use a Negative Binomial Distribution, see Appendix 3.
Let us test the following hypotheses:

\[ H_0 : \rho_m - \rho_s = 0 \]

\[ H_1 : \rho_m - \rho_s > 0 \]

with the risk level \( \alpha = 5\% \)

The number of accidents in both cases is sufficiently large to make an approximation of the Poisson distribution to a normal standard distribution. The test statistic will then be approximately normally distributed, with the mean 0 and the variance 1. The test statistic is given by the formula

\[ r = \frac{\hat{D} - D}{\sigma_D} \in N(0,1) \quad (4) \]

The decision rule is given by

\[ \alpha = 5\% \quad \rho_m - \rho_s > 0 \Rightarrow \text{Reject } H_0 \text{ when } r > \lambda_{0.05} \]

\[ \lambda_{0.05} = 1.6449 \]

\[ r = \frac{\hat{D} - D}{\sigma_D} = \frac{0.23 - 0}{0.137} = 1.68 \quad (5) \]

\[ r = 1.68 > \lambda_{0.05} = 1.6449 \quad (6) \]

\[ \therefore H_0 \text{ is rejected with the risk level } 5\% \]

This means that we can demonstrate, to a 95\% confidence level, that lines without automatic signalling systems have a higher frequency of accidents than lines with such systems. It is not possible to assess the magnitude of the differences, as the data is far too limited. However, the estimated difference of 0.23 accidents per million train kilometres can serve as a rough approximation of difference in accident frequency.

### 2.4.5 Discussion

No remarks have so far been made on the number of injuries in the data. It is also of course difficult to make any definite statements on that. However, it is worth noting that the high number of injuries on lines with automatic train control systems (see Table 10) is due to one major accident in Älvsjö, south of Stockholm, in April 1994, when 13 persons were injured. Major accidents will happen and the fact that we have not seen one on the lines without automatic signalling systems might be explained by the relatively low traffic volume on them. It is also possible that the difference in train occupancy could explain the difference in the number of injured. The most heavily laden train on the pilot line carried at most about 55 people at the same time. This is certainly not the case in the Stockholm area. If all conditions were equal, it is possible that a similar accident could have occurred on lines without automatic traffic control systems. Whether this is true or not can only be decided by a broader study on the subject.
Another feature of the radio block system is that it gives the possibility of blocking parts of lines when maintenance is carried out. The Railway Inspectorate has shown that most accidents today happen during line maintenance\textsuperscript{54}. With traditional automatic line block signalling, the maintenance staff use a cable connected to the rails that closes the track circuit. This marks the section as occupied and the interlocked signalling stops trains from entering the section.

In the Radioblock system, this is done through a special terminal connected to the service radio. This terminal blocks the track section in the interlocked signalling system, hindering trains from entering the section\textsuperscript{55}. That the system increases safety compared to the manual train dispatching system is obvious, but whether the safety level of this system is the same as for the ATCS system is impossible to tell, as we only have one pilot installation. In the evaluation of the Radioblock system, the safety effects were represented with a “+” in the cost-benefit analysis. This is described in section 5.5.6.

\textsuperscript{54} Lundström, 1997
\textsuperscript{55} Banverket, 1996, p. 44
2.5 Fatal accidents on the Swedish rail network

2.5.1 Estimating fatality risks using official statistics

The official statistics were collected by the state-owned operator SJ. Each year since 1938, SJ has published a leaflet with the title “Traffic safety”\textsuperscript{56}. It contains data on the number of derailments, collisions and fires, amongst other things. There is also data on the number of passenger, railway staff and bystander fatalities.

There are several problems when using these data for analysing railway risks. First, the data on fatalities are aggregated. It is not possible to find the number of passenger fatalities in derailments. Passenger fatalities are aggregated to a single figure, as is the number of derailments. However, the problems do not end here.

There have been criteria for the inclusion of accidents in the statistical data. For rail accidents such as derailments and collisions, the criterion was a minimum level for material costs. For a long time, the minimum level was 10,000 French Francs. If a rail accident led to costs over the given level, it was included in the data, if not, it was left out. However, this figure has been changed a couple of times, most recently at the beginning of the 1990s, when it was altered to 10,000 Euros, which is a value around ten times higher. This of course led to a radical decrease in the number of reported accidents. Different figures can be found for the same year, depending on the minimum level used. With the old level, there were 171 derailments in 1990; with the new, there were only 39. It is therefore not meaningful to use the data on the number of accidents for the whole period 1938 to 2000. We can however look at a period when the definition did not change.

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\textsuperscript{56} SJ - Stab Trafiksäkerhet, 1938-1996
In the diagram, the number of accidents per million train kilometres is plotted. The number of derailments and collisions have been aggregated into five-year periods, as has the traffic volume. The frequency is then calculated as the number of accidents divided by the traffic volume for each period.

There is a U-shaped trend in the diagram. It is probable that the initial decrease in the number of reported accidents reflects a real decrease. However, the data show an increase at the end of the period. This increase reflects inflation. The minimum level was not changed until the beginning of the 1990s and inflation in the 1980s led to increasing material costs, and, therefore, more accidents being reported. This did not necessarily reflect a real increase in the number of accidents.

We do not have the same problem with fatalities. The definition of a fatality has not been susceptible to the same definitional problems. The diagram below shows the number of passenger, railway staff and other fatalities. “Other” is bystanders, persons walking on the tracks, passengers jumping off trains, etc.

![Total number of fatalities per year](image)

Figure 12. Total number of fatalities per year, based on Swedish official statistics.

It is possible to look at the passenger fatalities separately. The actual number of fatalities each year shows large variation. A moving average has been calculated, with a period of 5 years. The moving average of passenger fatalities is shown below in comparison with the graph of traffic volume for each year.
Figure 13. Traffic volume and moving average of passenger fatalities.

It is apparent that there are some specific accidents that affect the shape of the curve. There were for example 48 passenger fatalities in 1956 and that year alone gives the first peak on the curve of moving averages. It is interesting to note that there is a constant decrease in the number of fatalities, and that there seems to be a significantly lower level since the introduction of ATC at the beginning of the ’80s. The installation of ATC started in 1980 and most of the network was equipped by 1985.

We can study the relation between passenger fatalities and traffic volume separately, by plotting the number of fatalities as a function of traffic volume.

Figure 14. Plot of passenger fatalities as a function of traffic volume. Sweden 1960-1999.
It is not necessary to force a regression line through the material. A simple Pearson correlation gives a value of 0.521. The correlation is significantly different from zero, although it is not very strong. The corresponding figures for railway staff and “others” are 0.321 and 0.841. It is interesting to note that the correlation is strongest between traffic volume and other fatalities.

We will now continue with a look at the material in BOR.

### 2.5.2 Estimating fatality risks using BOR

#### 2.5.2.1 Introduction

A new accident database, called BOR, has been created within this project. The purposes of BOR have been twofold. The first aim was to collect information on derailments of passenger trains in Sweden for the period 1985-1999. This would enable correct estimates of accident frequencies and probabilities of the generic causes of passenger train derailments. The estimates were needed in a risk analysis model developed within the project. The information was collected mainly from the accident databases in service during the period.

The second aim was to collect information on train accidents in general to enable estimates of the consequences of different accident scenarios. Therefore, information on train accidents between 1960 and 2000 was collected. The aim was to find all train accidents with passenger or railway staff fatalities. A wide range of sources was used in order to find all accidents.

Initially the information was kept in two separate databases, one for passenger train derailments and one for the time series of train accidents with fatalities. In order to simplify analysis, the two were merged into one database called BOR. BOR contains both accidents and incidents, including all derailments between 1985 and 1999, and the list of train accidents from 1960 onwards. Extra funding from the NRA has enabled further data collection, and therefore all passenger train collisions and fires on passenger trains between 1985 and 1999 have been added to the database. The total number of reports is around 1000. The collisions have been studied and the information checked. The data on fires in passenger trains are included in the database, but have not been analysed yet. The information has to be verified, causes coded, etc. The fire data is therefore not discussed further in this thesis.

BOR contains:

- 473 derailments or collisions out of which 350 occurred after 01/01/85.
- Out of 473 train accidents: 267 accidents with passenger trains.
- Out of 267 passenger train accidents: 41 accidents with passenger or railway staff fatalities.

#### 2.5.2.2 Data sources

Before 1988, Swedish State Railways (SJ) was the main operator on the Swedish network. In 1988, the company was divided into an infrastructure authority, the Swedish National Rail Administration (Banverket, NRA) and the profit-maximising company SJ, owned by the state but now acting in a competitive market including other operators. As part of this transition, the Railway Inspectorate was also created to investigate of accidents on the Swedish network.
There are three databases currently running in Sweden, operated by the NRA, the Railway Inspectorate and SJ. The NRA has a computerised system called BIS, containing different modules, e.g. for track information and for accident reporting. There are accident reports from 1988 onwards.

The benefit of BIS is that relatively detailed information on the track properties of the scene of an accident can easily be found; the drawback is that the track information may not be correct. The reason for this is that, when an accident is reported, the reporting officer must enter a command to import the track information into the accident report. If this is not done, the accident report will not contain the track information. If changes are made on the line, the new information is entered into the system. When viewing the accident report later, the track information provided will then be the actual status of the line, not the track status at the time of the accident.

The second database, called JAS, is administered by the Railway Inspectorate and contains information from 1989 onwards. There are some formal criteria for the accidents that must be reported into the database. There should either be fatalities or injuries, or material costs of at least SEK 1 million (corresponding to about Euro 120 000). There are other accidents reported in JAS that do not meet the criteria, and there are accidents that do meet the criteria, but which are not reported in the database. There is therefore a lack of consistency in the reporting procedures.

The third database, called INCIDENT is run by the State Railways, SJ. SJ has been reporting accidents since the nineteenth century, but the computerised database started in February 1995. The first report is from 7th July 1995. However, the database was closed in December 1997 and the reporting continued at the Safety Department, whose database is called Incident SJ/SÄ. In this report, the two are treated as one and called INCIDENT.

Other data sources have also been used in this study. Between 1994 and 1998, the Railway Inspectorate administrated a database called HÅR (the Event Register, author’s translation.). The goal was to collect information on all accidents as well as incidents. The database contains 4035 reports, and has been used in recent studies in the belief that it contains all accidents during the period, a claim that is commented on in a later section.

In 1995, Sparre made a study on collisions, derailments and fires on the Swedish network for the years 1985 to 1994 based on accident reports from SJ. The data files produced have also been used in the database.

In order to ensure that all passenger train derailments, collisions and fires have been found, the central archive and the shelves of the safety department at SJ have also been searched, and this work was fruitful.
2.5.2.3 Derailments 1985-1999

BOR contains 120 passenger train derailments between 1985 and 1999. Of these, 106 involved trains with passengers on board. There is a definition problem to be aware of here. A passenger train is a train that has been classified so because it has been given a train number in a timetable. It is still a passenger train when the passengers have left the train and it is on its way to a scheduled night’s rest. However, on this trip, from the platform to a siding, it might be involved in a shunting accident. These accidents have been classified as passenger train accidents in the official databases, even though no passengers were involved. Furthermore, there might be passengers on board trains that have been classified as “service trains”, without having a proper train number according to any timetable.

In order to get around this, information has been added on the presence of passengers. The definition of a passenger train might then be “a train with passengers on board”. In this way, more correct estimates of the risks passengers face might be calculated. This also means that derailments occurring during shunting are included, as long as there were passengers on board.

A closer look at the material in the database, reveals that the number of derailments each year varies between 2 and 13, see Figure 15. The overall average is around 7 derailments/year.

![Figure 15 Total number of passenger train derailments each year 1985-1999, BOR.](image)

In order to illustrate the problems of using the statistical databases for analysis, a diagram of the accident reports in each of the databases was drawn. For each year, it shows how many reports are to be found in each of the databases, together with the total number of accidents in BOR. The framing bars in the diagram below correspond to the columns in Figure 15.
Figure 16. Number of accident reports in the separate databases used.
The diagram illustrates that using any of the databases in Sweden will give underestimates of the risks and the number of accidents. Even the database HÄR, which the Railway Inspectorate claimed should contain all events during the four years it was in service, does not contain all the passenger train derailments that occurred during that period. There are always a number of unrecorded cases. Nevertheless, BOR is closer to a true description of the number of passenger train derailments than the databases currently running.

2.5.2.4 Collisions 1985-2000

As an extension to the project, information on collisions with passenger trains between 1985 and 2000 was added to the database. This work was carried out during spring 2001. A short description of the material will follow.

By using the same data sources as previously, 129 passenger train collisions were found. However, there have been only 97 accidents with passengers on board. Information on passenger presence has been added for the collisions in the same way as for the derailments. If we look at the collisions in the data, we will find that they vary between 1 and 12 per year, with an average of a little over 6 collisions per year.

![Figure 17 Number of passenger train collisions per year between 1985 and 1999.](image)

The collisions have been separated into collisions with moving objects and collisions with non-moving objects. ‘Moving objects’ are vehicles (rail or road, including motorcycles and cars), people and anything else that can move. ‘Non-moving’ objects include trees fallen on the tracks, items placed on the tracks by vandals, buffer stops, etc.

The source of the information can be illustrated with a diagram, similar to the diagram given for derailments. The same point can be made here as there. The diagram below illustrates the problems the statistical analyst faces when using the information in the official databases.
Figure 18. Number of collisions in the source databases together with the number of collisions in BOR.
2.5.2.5 Train accidents 1960-2000

In order to enable estimates of the consequences of accidents, information on derailments and collisions from 1960 to 2000 was also collected. The goal was to find all collisions and derailments where there was at least one passenger or railway staff fatality. Different sources have been used to provide information to the database. First, the central archive of SJ has provided information for the years 1960-1963 and 1985-1991. The safety department of SJ has provided information for 1992-1995 and, of course, the databases mentioned above have been used.

However, in 1962 SJ was re-organised and responsibility for safety was moved, and so it has not been possible to find accident reports archived in a systematic way for the years 1964–1984. One former officer of the safety department sent his material to the central archive where it was found during the work. This material was unfortunately not complete.

It was obvious that BOR did not contain a complete list of all accidents with passenger fatalities. Therefore, a media archive search was ordered. One of the main newspapers in Sweden, Dagens Nyheter (DN), has administered an article archive since the beginning of the century. Initially it only contained articles from DN, but nowadays a separate company owns the archive and collects articles from all main newspapers in Sweden. The search gave information on some accidents not in the database. Unfortunately, even the newspaper archive had weeded out potentially useful material.

The safety department at SJ has published a leaflet containing accident statistics every year since 1938. In one table, the number of fatalities and injuries for different types of accidents is displayed. This information has been used as a key in the search for accidents, as it turned out that not all accidents were found in the initial search.

With the “key” on hand, a new search for accidents was made at the Royal Library in Stockholm, a reference library containing all published material in Sweden. With the belief that all major railway accidents are news of national interest, the front pages of every edition of DN for the 7 years from 1964 until 1970 was read. This took some time but some of the “missing” accidents were found.

The total number of fatalities reported in the database is 238. Out of these, 175 were passengers or train staff, killed in train movement accidents. Comparing the information in the database shows that nearly all train accidents with passenger fatalities 1960-2000 have been found. Finding all train accidents with railway staff is a little more complicated as some were reported as train accidents and some as work accidents. It is not always clear how specific accidents were treated when the material was aggregated for the official statistics. This is still under revision.

Further work with the database will be carried out. A complete list of all types of information in the database is listed in Appendix 2. For example, the presence of passengers on board is one type of information in the database. This information has been double-checked for the passenger train derailments 1985-1999 and can be relied upon. The causes of the derailments for the same period have also been triple-checked and can be judged as reliable.

During the work with BOR, accident reports, newspaper articles and other material have been collected and copied. This information is kept in binders, each entry in the database is given a number, and the corresponding reference can easily be found in the binder system.
2.5.2.6 Statistical analysis of fatal accidents using BOR

It is possible to use the data in BOR for estimating transport fatality risks, as described in the previous section. BOR provides a list of fatal train accidents on the Swedish network for the period 1960-2000. Whilst it has been created primarily for fatal passenger train accidents, fatal accidents with other train types have also been included. There are probably some train accidents with railway staff fatalities “only” that have not been found. This is due to the problems mentioned in the previous section. It is, as stated earlier, unfortunately not possible to use the official aggregated statistics to find the number railway staff fatalities in train movement accidents.

A list of all fatal accidents on the Swedish rail network is presented below. It contains all passenger fatalities and is the best list so far of accidents with railway staff fatalities “only”. It serves as a basis for the statistical analysis presented here. The statistical analysis follows the model developed by Professor Evans\(^57\), which was reviewed in section 2.3.1.5. By using the same approach, we are able to compare the results with British accident data.

<table>
<thead>
<tr>
<th>Date</th>
<th>Primary accident</th>
<th>Secondary accident</th>
<th>Place</th>
<th>Passenger fatalities</th>
<th>Railway staff fatalities</th>
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</thead>
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<td>28/01/60</td>
<td>Collision</td>
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<td>1</td>
<td></td>
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<td>Collision</td>
<td>Stora Juna</td>
<td>0</td>
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<td></td>
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<td>Collision</td>
<td>Jonsered - Lerum</td>
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<td>0</td>
<td></td>
</tr>
<tr>
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<td>Levelcrossing</td>
<td>Derailment</td>
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<td>0</td>
</tr>
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<td></td>
</tr>
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<td>0</td>
<td></td>
</tr>
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<tr>
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</tr>
<tr>
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<td>Collision</td>
<td>Holmsveden - Kilafors</td>
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\(^{57}\) Evans, 2002
<table>
<thead>
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<th>Fatalities</th>
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<tr>
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</table>


By way of explanation there are, for example, accidents at level crossings included in the data. These level crossing accidents have led to passenger or railway staff fatalities. Common for all these except one is that they led to a derailment following the collision. The data can be aggregated for each year and for 10-year periods. The table below gives the traffic volume and the yearly accident figures, together with yearly aggregates of the number of fatal accidents and of fatalities. The traffic volume is the sum of the passenger train and freight train mileage per year.
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| 1960-1969  | 1.188          | 16                              | 49                        | 13.5                                | 3.1                     |
| 1970-1979  | 1.047          | 17                              | 81                        | 16.2                                | 4.8                     |
| 1980-1989  | 1.070          | 9                               | 41                        | 8.4                                 | 4.6                     |
| 1990-1999  | 0.999          | 2                               | 4                         | 2.0                                 | 2.0                     |

| 1960-1999  | 4.304          | 44                              | 175                       | 10.2                                | 3.98                    |

It is apparent from the 10-year aggregation of accidents per billion train kilometres, that there is a downward trend in the accident frequency. It is therefore not meaningful to use a mean frequency for the whole period. It is however possible to fit a trend model to the material. There are several possible models. All trend models calculate the expected frequency as a function of time. The downward trend would require a negative slope in any model. However, it would not be possible to use a linear model, as that would eventually give a negative frequency, which is impossible. An exponential model would be preferable. Even so, there are several possibilities.

In section 2.3.1.5, two different exponential models were described. The model adopted here is the one pointed out by Evans. It is preferable as it gives the annual change in accident rate directly. Based on the data, we can estimate parameters in the model and plot 10-year average accident rates together with the trend. The trend parameters are estimated using Microsoft Excel.

Figure 19. Number of fatal accidents per billion train kilometres and estimated trend, 1960-1999.

The analysis gives an estimate of $\beta$, the annual change in accident rate, of $-6.4\%$. This can be compared with the results in Great Britain, where the estimated annual change is $-4.9\%$. Based on the Swedish data, it is possible to estimate the average accident rate for the present 5-year period 2000-2004. On this basis, we get an estimate of on average 1.92 fatal accidents per billion train kilometre.

Turning now to the number of fatalities per accident, the calculated average for the whole period 1960-1999 is 3.98, and with a T-test we get a 95% confidence interval of [2.7; 5.1]. This can be compared directly with the British figure of 4.0 fatalities per accident. Professor Evans performed a linear regression on the British data and found a small, insignificant downward trend in the number of fatalities per accident. He therefore concluded that the number of fatalities per accident was constant over time. It would therefore not be necessary to use anything other than the average for the whole period.

When analysing the Swedish data, we also find a very small and insignificant decrease in the number of fatalities per accident. The number of fatalities per accident can therefore be regarded as constant over time. Below is a plot of the number of fatalities per accident in the 44 accidents dataset.
2.5.2.6.1 Predicting the expected number of fatalities for the next five year period

Based on the estimates, we are now in a position to predict the number of fatalities each year for the coming 5-year period. Given that the accident frequency is 1.92 fatal accidents per billion train kilometres, and that we have around 110 million train kilometres per year, we can expect 0.21 fatal accidents per year. Assuming that the number of fatalities per accident is 3.98, as estimated above, we can expect $0.21 \times 3.98 = 0.84$ fatalities per year in train movement accidents.

2.5.2.6.2 Fatal derailments

If we look at a subset, such as the derailments only, we see that there were only 10 fatal derailments during the period. The total number of fatalities in these derailments was 32. The average number of fatalities per derailment is then 3.2. When we analysed the whole dataset, we found a downward trend in the accident frequency. When we look at derailments only, the same trend is not found. The number of fatal derailments per billion train kilometres is plotted in the diagram below, showing five-year averages.
It is not obvious from the plot that there is a trend in the material. We can start by calculating the average number of fatal derailments per billion train kilometres. There were, as stated above, 10 fatal derailments. The traffic volume for the period 1960-1999 was 4.3 billion train kilometres, giving an estimate of 2.32 accidents per billion train kilometres. This figure is probably an overestimate.

It is possible to fit a trend to the material by calculating 10-year averages. Through this procedure, a trend is estimated and a prediction for the coming 5-year period is made.

The estimated average number of fatal derailments for the period 2000-2004 is 1.4 per billion train kilometres. The R-squared is very low, only 16% of the variation in the material is explained by the regression. However, the figure calculated seems more convincing, and corresponds better to the proportional share of derailments in the total number of train
accidents. There were 44 accidents in total and 10 of these were derailments, giving a share of 10/44 = 23%. If we compare the estimated accident rates, we get a share of 1.4/1.92 = 73%. This difference seems a little too big, but there are great uncertainties in the estimates and we can use the figure estimated for derailments as an example. It is also possible that the share of derailments as a proportion of total number of accidents has increased while the share of collisions has decreased. This could be because the investment in automatic train control systems might have reduced the risks of collisions more than it has reduced the risk of derailments.

Using the estimate of 1.4 fatal accidents per billion train kilometres, we can calculate the expected number of fatalities in derailments each year. The product of the accident rate, 1.38, and the expected traffic volume, 0.11 billion train kilometres per year, is the number of fatal accidents per year: 1.4x0.11 = 0.154. The expected number of fatalities in each fatal derailment is 3.2, giving an expected number of fatalities of 0.154x3.2 = 0.5 fatalities per year.

2.5.3 Summary

The official statistics have serious drawbacks that appear when statistical analysis is attempted. The definitions have changed over time. Fatalities have been reported with some accuracy and there is a downward trend in the material. There are some uncertainties regarding the classification of passenger fatalities and other fatalities. By using the database BOR, these pitfalls are avoided.

BOR contains 44 fatal train traffic accidents for the period 1960-1999. This material has been analysed with statistical methods. The accident rate and the number of fatalities per accident have been studied separately. Together they enable calculations of the expected number of fatalities per year.

However, there is a downward trend in the accident rate. The accident rate has fallen by around 6.4% per year in the period 1960-1999. The analysis shows that the expected accident rate for the 5-year period 2000-2004 is 1.92 fatal accidents per billion train kilometres.

The number of fatalities per accident has remained fairly constant at 3.98 fatalities per accident and there is no trend in the data. Together with the traffic production of 0.11 billion train kilometres per year, we get an estimate of the expected number of fatalities per year: 0.84 passenger and railway staff fatalities per year for the period 2000-2004.

When looking at derailments only, we find that the expected accident rate is 1.4 fatal derailments per billion train kilometres. The number of fatalities per fatal derailment is 3.2. Given a traffic production of 110 million kilometres per year, we get an estimated average number of fatalities per year of 0.5 for the period 2000-2004.
2.6 Passenger train derailments on the Swedish network 1985-1999

2.6.1 Introduction

The number of passenger train derailments per year in Sweden has been at a low level for the last fifteen years. Swedish State Railways (SJ) began an investment programme for the installation of Automatic Train Control (ATC) in 1980. The reason for this was a number of serious multiple-fatality accidents in the 70s that raised demands for increased safety. ATC lowered the number of serious accidents dramatically and there has only been a few accidents of any kind since. Nevertheless, closer studies of the risks in the railway system are justified. There is a decrease in the number of fatal train accidents, which can be seen in Figure 19. The trend is not that clear for fatal passenger train derailments, as given in Figure 21.

Passenger train derailments on the Swedish network have been studied in the last part of this doctoral project and the work is reported for the first time in this thesis. The purpose was to develop a model of the risks in the railway system that could provide a better understanding of the risks, assist in risk assessments and simplify the analysis of various safety measures. Furthermore, the type of model developed can provide information on the risk profile of the rail system and help identify the main sources of risk.

In this project, fault tree and event tree methods have been used. The approach adopted by Railtrack (described in section 2.3.2.7) is developed in the model and the author has had access to the fault trees developed by Railtrack. These have been adapted to fit Swedish conditions, with both extensions and simplifications. The relatively small numbers of accidents that have occurred on the Swedish network have made some simplifications necessary. Furthermore, differences in the network and operational principles give rise to differences in the accident outcome and this has made extensions necessary.

The fault trees produce estimates of the accident frequencies and these estimates feed into event trees, where each type of accident scenario is described. In the event trees, a series of questions is posed, answered with yes or no at assigned probabilities, each answer giving at least two new branches. This means that the model grows exponentially; the number of scenarios doubles for each step. Simplifications are necessary to keep the model manageable, for practical reasons the number of branches cannot be unlimited, but there is a minimum number of levels and branches required if the model is to describe reality. The level of detail in the event trees is a matter of choice.

This type of model is very data intensive and the model described here is no an exception. The Swedish statistical databases on the other hand are quite modest in the level of detail given. The reason for focusing on passenger train derailments was the belief that passenger train derailments would be reported to the current accident databases to a higher degree than other types of accidents, giving better estimates of, for example, the number of derailments each year. This assumption was wrong, as described in section 2.5.2.3. The coverage of the separate databases turned out to be relatively unreliable, even for such rare and serious events as passenger train derailments. This demanded extensive data collection that consumed a great deal of time in the project.

The fault tree model is fed with estimates of accident frequencies based on statistics for passenger train derailments on the Swedish network between 1985 and 1999. In order to get a reliable list of all derailments, several databases that were in use during the relevant period have been employed. The information collected has been merged and all data analysed. In this way a more or less complete list of passenger train derailments during the period has been
established. The data has been stored in a new database called BOR, which was developed within the current project. This is described in detail in section 2.5.2 and in Appendix 2. However, in order to estimate the consequences we need more information.

A derailment leads to a chain of events that results in final consequences. The events are, for example, carriages overturning, fires breaking out, etc. There are numerous possible chains, all leading to a separate consequence. The model has to be fed with estimates of the consequences for each of the possible chains of events.

The various consequences have been estimated from statistics on train accidents over 40 years. A search was been made for all accidents with passenger or railway staff fatalities between 1960 and 2000, and the information was stored in BOR, which is the only database in Sweden with such a long time horizon. With the information in BOR, it is possible to get a more reliable perspective on, for example, the consequences when passenger carriages overturn.

### 2.6.2 Purpose and issues

The purpose is to develop a model that assists in risk assessments, provides knowledge about the risks in the rail system, and simplifies the analysis of safety measures. The aim of the model is also to provide risk estimates that can be utilised in the safety analysis procedure described in section 1.2. The development of the model is an illustration of the possible use of risk analysis methods for estimating the risks in the railway system. By building a new database on train accidents, a platform for future risk analysis is established.

As mentioned above, the methods and the model developed are here applied to passenger train derailments on the Swedish network. The methods are however applicable to all sorts of risk in the railway system, and the focus on passenger train derailments only serves as an example of the application.

The general questions posed are:

1. How many passenger train derailments occur every year?
2. What are the generic causes of these accidents?
3. How many lives are lost each year in passenger train derailments?
4. What is the contribution of rare but severe, large accidents to the average number of fatalities in passenger train derailments?
5. What parameters influence the consequences and how can these be modelled and estimated?

The safety analysis procedure prescribes that the qualitative work is carried out before the quantitative. This includes specifying the model and describing generic causes of the risks. Then the model is fed with data from BOR. For reasons of readability, the specification of the model and the data for the different parameters are described together. However, we will start with reviewing the methods specific to this project.

### 2.6.3 Methods

Some of the important parameters that have to be handled when modelling passenger train derailments are hard to estimate. It is for example difficult to find the probability that a derailment will be followed by a collision with a train passing on an adjacent track. These types of events are extremely rare. Nevertheless, they are still possible. By using risk analysis methods, several benefits can be obtained. The use of fault trees and event trees gives a
rational structure to the problem. A rational treatment of parameters with low and uncertain probabilities is also needed.

Fault trees and event trees give a framework for including all parameters, but the basic problem of estimating probabilities of events that have not yet occurred is not solved. A possible solution to this is to include uncertainty and variability in the model. This can be done by using Monte Carlo simulation, combined in this model with fault and event trees, and applied to passenger train derailments. This enables several important functions, such as for example a more elaborate way of modelling speed. For a description of the methods, see section 2.2.2.

2.6.3.1 Software used

There are powerful programmes specifically for constructing fault trees. Railtrack has used a programme suite including the “Fault tree+” software. Such packages are relatively expensive and require special additions to enable Monte Carlo simulations. In this project, a cheaper solution has been chosen where the fault and event trees are constructed in Microsoft Excel for Windows. An add-in from Palisade called “@Risk” makes specifications of probability distributions and simulations simple and quick. Diagrams and correlations have been calculated with this software. Because the fault and event trees are constructed in Excel, they do not have the same graphical layout as described in section 2.2.2.2, but the principle is the same. In this thesis, the fault trees are built with “Faultrease”, a programme designed for the purpose. The programme also has some limited computational capabilities, which have not been utilised. All computations have been done in Excel, but the fault trees illustrated have been built in Faultrease.

2.6.4 Modelling Passenger Train Derailments

2.6.4.1 Risk factors

Many parameters have to be taken into account when modelling passenger train derailments. Some generalisations and simplifications normally have to be made. However, the problem is of a general scientific nature. What parameters influence the variable we are studying? Should the time of day be included in the model? Is the time of year relevant? Is the driver’s age or sex relevant to the model? Parameters that probably are relevant to passenger train derailments are listed below.

1. The probability of the generic causes of a passenger train derailment.
2. The speed of the train when it derails.
3. The location of the derailment: open track / station / tunnel, etc
4. The type of train and passenger carriages.
5. The probability that passenger carriages overturn.
6. The number of people on the train.
7. The probability that another train, passing on an adjacent track, hits the derailed train.
8. The probability of dangerous goods being released.

The general question is how we decide the correct set of parameters to include in our study. The normal procedure is to start with a set of parameters that from some subjective view seems subjectively reasonable. The scientist’s knowledge of the subject influences their choice. When the choice is made and the model set up, simplifications can be made based on analysis of the model. The procedure is, then, to start with a rather large number of parameters and reduce them to a manageable number.
The selection of the parameters to exclude can be based on explicit calculations. By testing the parameters’ importance or contribution to the overall results from the model, it is possible to find those that have little influence. The quality of the estimates and the background data can also influence the selection. We would like to construct a model that gives the best description of reality with as few and as reliable parameters as possible.

The model is described and the selection of parameters discussed below. The layout of the fault and the event trees is also described. A full version of the fault trees can be found in Appendix 4. For a review of the fault and event tree method, see page 14 - 20.

### 2.6.4.2 The fault trees

#### 2.6.4.2.1 Modelling location

In order to model location, separate fault trees can be constructed and each top event then represents the derailments at a specific location type. In the Railtrack Safety Risk Model, location was modelled in 6 separate fault trees. Railtrack made separate fault trees for derailments at fast and slow speed on open track. It was possible, and also necessary, to bring down the number of fault trees in order to get a manageable model. The top events in the model developed are:

- **TE1.** Passenger train derailment on open track
- **TE2.** Passenger train derailment at a station
- **TE3.** Passenger train derailment in a tunnel.

The difference to Railtrack’s model is that derailments in tunnels are modelled in one fault tree and that speed is modelled with probability distributions in the Monte Carlo simulation. The probabilities calculated in the fault trees feed into the event trees together with the average number of passenger train kilometres run per year. From the three top events and the average traffic volume, the overall number of passenger train derailments per year is also calculated. This is illustrated below, with the top events in the fault trees.

![Fault tree 3. Fault tree with the top events in the derailment model.](image-url)
Passenger train derailments on open track are then modelled in the following fault tree.

Fault tree 4. Frequency of passenger train derailment on open track

The top event is developed into derailments due to track faults, rolling stock faults and erratic behaviour. These three categories are the same in the fault tree for derailments at stations. This can be seen from the fault tree below.

Fault tree 5. Frequency of passenger train derailments at stations.

The probability of a derailment at a station due to track faults, the left branch in Fault tree 5, is calculated as the product of the probability of track faults and an estimate that a derailment will occur at a station (given under the circle). This estimate is calculated from data in BOR. During the period 1985-1999 there were 39 derailments on open track, 66 at stations and 1 in a tunnel. This gives a probability of a derailment at a station of 66/106 = 0.63. Similarly, the probability of a derailment on open track due to track faults is calculated to be 39/106≈0.37, which is the probability given in the left branch of Fault tree 4. The total probability is of course 0.63+0.37 = 1. The probability of derailments due to track faults is thus divided into a
probability of derailment on open track and a probability of derailment at stations. Derailments due to erratic behaviour are handled in the same way.

The attentive reader will already have noted that the probabilities for rolling stock faults do not add up to 1. The figures in the fault trees are 0.36+0.63=0.99. This is because we have a small probability of rolling stock faults leading to derailments in tunnels. This is modelled in the following fault tree.


The probability that a rolling stock fault will lead to a derailment in a tunnel and not on open track is then 0.01. Observe that this figure is not calculated from the data in BOR\textsuperscript{58}. There was one derailment in a tunnel, and the cause was a structural failure, where a 30 kg stone block had fallen from the tunnel roof, causing the train to derail. The figure 0.01 is an estimate of the probability calculated from the proportion of the total length of all Swedish tunnels compared to the total network length. This is an approximation. Calculating a better estimate would require information on the traffic volume per tunnel kilometre compared to the traffic production on open track and adjustment for a possible difference in probability due to better tracks in tunnels. For example, some rolling stock faults such as axle failures are not discovered until the train passes a point, and there are few points in tunnels. Such factors affect the distribution of rolling stock faults between open track and tunnels.

Track and structural faults are indeed possible in tunnels. However, the probability of a lateral distortion of the track in a tunnel is in most cases zero, and other possible track faults such as broken rails, etc., have lower probabilities than on open track. The probabilities of track faults in tunnels should therefore be calculated separately: using the figures for track faults on open track will give an overestimate of the risks.

As stated above, there has only been one passenger train derailment in a tunnel since 1985. There are therefore reasons to question the reliability of any estimates of tunnel risks produced by the model, but this part of the model has been included for completeness. This can be reviewed in a future project. The contribution of the tunnel model to the overall risk estimates is small.

We now turn to the parameters that form the base of the analysis: the generic causes.

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\textsuperscript{58} It might be natural to assume that the figure is calculated from the number of derailments in tunnels divided by the total number of derailments; 1/106 \approx 0.01. This is not the case!
2.6.4.2.2 Generic causes

The generic causes are at the bottom of the fault tree, and are assigned values based on statistical analysis of the 106 passenger train derailments used in the study. As described on page 45, we can view the occurrence of accidents as a Poisson-distributed random variable. In the same way, we can treat the generic causes of passenger train derailments as Poisson-distributed random variables. The Poisson distribution counts the number of independent events in an interval of time. Instead of time, we chose another continuous variable: the train kilometres run. The probability that two events with the same generic cause will occur in the same interval is zero when the interval is very small. Furthermore, the generic causes can be viewed as independent events and the number of events is proportionate to the size of the interval. The conditions for a Poisson distribution are fulfilled.

The generic causes in the fault tree have therefore been assigned Poisson distributions. The estimated frequencies of the generic causes are set as the expected means of the distributions. The frequencies are listed in a table in Appendix 6. The number of derailments per billion train kilometres has been chosen as a measure of frequency. This gives nominal figures that are more easily handled in the model. When the frequencies are transferred to the event trees, they are given as number of derailments per train kilometre.

One property of the Poisson distribution is that the variance is equal to the expected mean. It is therefore not necessary to calculate the variance separately. Adding Poisson distributions is easy as the sum of two distributions has the expected mean of the sum of the two expected means of the added distributions. It is therefore easy to aggregate the causes into the top events and to the total number of passenger train derailments. There are 86 Poisson distributions in the fault tree model, representing the generic causes. The fault tree for track faults is shown below. The figures are estimated from data in BOR.
Fault tree 7. Passenger train derailment due to faults on rails and track support structures. PTD is short for Passenger Train Derailment. Gtkm is the abbreviation for 1,000 million trainkilometres.

All fault trees in the model can be found in Appendix 4. The fault tree for derailments in tunnels has been greatly simplified due to lack of data. As described in the previous section, there are reasons to believe that track faults are rarer in tunnels than on open track. The model for the track and structural faults is therefore separated from the fault trees for open track. There are no data in BOR to feed the tunnel fault tree with information, but it is included for the completeness of the model. The Swedish NRA’s handbook on tunnel safety, described in section 2.3.2.3, provides a way of estimating risks in tunnels and the fault trees in the model developed here can be refined along those lines. For the purposes of this project, the simplified tunnel fault trees are satisfactory.
2.6.4.3 The event trees

The number of accident scenarios is 92, reduced from an initial 348 due to the need for simplification. This process is described at the end of this section, in the discussion on omitted parameters. The three event trees in the model are initiated with the probabilities calculated in the fault trees. In each branch, probabilities have been assigned either as point estimates or as probability distributions. The path probability, that is the probability of each scenario, is calculated from the derailment probability, the average number of train kilometres run per year and all the probabilities given in each scenario.

The estimates of the consequences are then fed in at the end of the model. It is evident that all of the possible series of events that could happen in one accident have not actually happened. It is therefore difficult to give separate estimates of each type of accident or scenario. The problem has been solved by using seven levels of severity, to which each accident scenario has been assigned. This means that we only have seven types of consequences, which is of course a simplification. However, the purpose of the study is to test the methods and verify the design of the model, and this can be achieved with the chosen method for assigning consequences. We can also see the influence of the consequence parameters by the use of the Monte Carlo method.

The number of fatalities per year is calculated from the probabilities of each type of scenario and the consequence. The numbers of fatalities are then added in all event trees and together these give the total number of fatalities per year in passenger train derailments. The main principle is described on page 20.

Number of scenarios: 24

Number of fatalities: 0.42

Event tree 2. Derailments on open track.
Event Tree 2 displays the consequence model for passenger train derailments on open track. The nominal values in the event tree are the expected values in the distributions and the number of fatalities is reached through standard recalculation. The outcome of the simulation is not necessarily the same as the outcome of the standard calculation given above. We will now discuss the various parameters that influence the results. One parameter that is not included in the figure above is derailment speed, although it has a big influence on the consequences. There are three event trees in the model, one for each location type, and these are given in Appendix 5.

2.6.4.3.1 Modelling speed

In the section on statistical analysis, page 29, a study of the speed of trains in fatal collisions and derailments was reviewed (section 2.3.1.4). The number of fatalities per accident was modelled as a function of the impact speed. The relationships were not very strong, especially not for derailments. The argument for including speed in the model required a relationship between the number of fatalities and the speed together with a change in the derailment speed over time. In the study, a relationship between speed and number of fatalities was found, but the change in impact speed over time was somewhat uncertain, at least for derailments.

The model developed here includes derailment speed. The reason for this is that speed affects the consequences in several ways. Derailment speed is used in the model as a factor influencing the expected values and variances of the consequences assigned to the various scenarios. Furthermore, speed is used to influence the probability that carriages will overturn in a derailment. These relationships are discussed below under their respective headings.

The derailment speed, i.e. the speed of the train when it derails, is modelled with a probability distribution that is different depending on the location of the derailment. The speed distributions have been fitted using the Bestfit software from the data on the derailments in BOR. A standard chi-squared test was used as a tool for choosing a distribution. Unfortunately, it has not been possible to find the derailment speed for all 106 derailments and the analysis is based on just 82. These are separated into those occurring at stations and those on open track. The number of derailments in each group is limited and this affects the p-value of the distribution fit. None of the fits is significant. Nevertheless, for reasons given above, we have reason to believe that derailment speed follows a distribution, even though its shape so far is unknown. A distribution has therefore to be chosen that gives a reasonable fit to the data and has the properties required. It cannot for obvious reasons be a distribution with a maximum value lower than the maximum speed that trains travel on the Swedish network, and it cannot be a distribution giving negative values.

A normal distribution was chosen for derailments on open track and in tunnels. The expected value in the normal distribution, for derailment speed on open track and in tunnels, was 56 km/h and the standard deviation 38 km/h. However, this distribution gives negative values in the left tail and it therefore has to be truncated at zero. The maximum allowed speed on the Swedish network is 200 km per hour and therefore the distribution is also truncated at 200 km/h. This also changes the expected value. Instead of 56 km/hour, it is 62 km/hour. The distribution is illustrated in Figure 23.
For derailments at stations, a lognormal distribution was selected. The expected value for the derailment speed at stations was 32 km/h and the standard deviation 16 km/h. This distribution is slightly skewed and has a long tail to the right, which reflects the fact that derailment speeds at stations have a more concentrated distribution with a few exceptions where the speed is relatively high. Note that the distributions do not represent the line speeds of trains on the Swedish network. Instead, it is the distribution of speeds at the moment of derailment. Often the driver applies the brakes when he discovers the danger and the speed is therefore somewhat reduced.

Figure 24 Probability distribution for derailment speed at stations.
These distributions are used in the event trees and feed into the estimates of the consequences and the probabilities that carriages will overturn, discussed next.

2.6.4.3.2 Overturning carriages

The most important factor influencing the consequences of a derailment is whether the carriages remain upright or they overturn. Fortunately, accidents with overturning carriages are rare, but they sometimes occur. In BOR, there are 14 derailments with passenger or railway staff fatalities during the period 1960-1999. Carriages overturned in 12 of the 14 fatal derailments. This implies that there is a relationship between the probability that carriages overturn and the consequences.

Another way of looking at it is to analyse the derailments between 1985 and 1999. As previously stated, BOR contains all known derailments 1985-1999 involving passenger trains. There were 106 passenger train derailments with passengers onboard during the period. In five of these cases, carriages have overturned. This gives an estimate of the proportion of cases where carriages overturn. It is worth noting that in these five accidents, the speeds were 70, 70, 86, 100 and 126 km/h. When we look at all 18 passenger train derailments in BOR, where carriages have overturned, we find that the lowest registered derailment speed is 60 km/h. The correlation with derailment speed is 0.551.

There therefore seems to be a case for including the probability of overturning carriages in the model and to let speed affect the probability. This is modelled in the event tree. The fact that the probability of overturning carriages increases with speed can also be seen in the following cumulative diagram, Figure 25, based on 35 derailments with speeds over 60 km/h:

![Overturning carriages chart](image)

Figure 25. Chart of number of derailments with overturning carriages for derailment speeds higher than 60 km/h. ‘Yes’ represents derailments with overturning carriages.

59 10 of these are “pure” derailments and 4 are derailments as a result of a collision with road vehicles at level crossings.
It is conceivable that the probability of carriages overturning can be described as a random variable following a cumulative distribution. If the derailment speed is under 60 km/h, the probability is very low. Correspondingly, if the derailment speed is over 150 km/h, the probability is rather high, but still less than 1. Based on the actual outcome, as described in Figure 25, a cumulative distribution function has been assigned to the variable for overturning carriages. The distribution is illustrated in Figure 26 below.

![Figure 26. Probability of overturning carriages as a function of derailment speed.](image)

In the event trees, it is assumed that the probability of overturning carriages in a derailment follows a normal distribution. It is modelled with the following cumulative distribution function:

\[
F(DS) = P(S \leq DS) \ ; \ S \in \mathcal{N}(\text{Speed}, \ SD)
\]

Where:
- \(F(DS)\) is the cumulative distribution function giving the probability that carriages will overturn at a given derailment speed;
- \(DS\) is the derailment speed;
- \(S\) is the random variable for overturning carriages given a certain speed;
- \(\text{Speed}\) is the expected value of the random variable \(S\);
- \(SD\) is the standard deviation for the random variable \(S\).

The derailment speed is given by the probability distribution described in the previous section. The parameters of \(S\) are given in the following table:

<table>
<thead>
<tr>
<th></th>
<th>Speed</th>
<th>Standard Deviation SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Track</td>
<td>130</td>
<td>30</td>
</tr>
<tr>
<td>Tunnels</td>
<td>130</td>
<td>30</td>
</tr>
<tr>
<td>Stations</td>
<td>90</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 13. Parameters of the distribution functions for overturning carriages.

It is understood from the table that the distribution function for overturning carriages differs depending on whether or not a derailment occurs at a station. The reason for this is the
numbers of points that can make the consequences more severe at relatively low speed. A train derailing on points at a station at 80 km/h has a higher probability of its carriages overturning than a train derailing on plain line at 80 km/h. Furthermore, points are designed for different speeds. The standard set of points in Sweden allows a maximum speed of 40 km/h. These are mainly found at stations. Other points are designed for speeds up to 100 km/h and above.

When the figures in the table above were determined, several values were tested. In fact, uniform distributions were assigned to both Speed and SD. The limits for Speed were 80–150 km/h, for the SD, 15-50 km/h. Simulations were run, and a sensitivity analysis carried out. The span of the total number of passenger fatalities was relatively large. With a low mean and high standard deviation, the curve had a flatter shape giving a higher probability of carriages overturning. In fact, this probability then rose to around 0.3, that is, an excessively high probability. By narrowing the possible span for the mean and the standard deviation, a more convincing probability distribution was received.

The standard β-coefficients were calculated by multivariate stepwise regressions. The expected value of the function for overturning carriages had little effect in explaining the output. The β-coefficient was –0.1. For the standard deviation, the coefficient was of the same size but positive, 0.1. Removing these from the regression changed the R-squared from 0.72 to 0.7. The R-squared indicates how much of the variation is explained by the regression. Normally a higher figure is desirable, but here we are only interested in the change of the strength when the two parameters are removed. Based on this analysis, the decision was made to set the mean speed and the standard deviation according to the figures given in Table 13.

One aspect that is important to remember is that the probability that carriages will overturn will be different for derailments on open track and at stations because of the differences in expected derailment speed. As stated in the previous section, speed follows two different probability distributions depending on the location of the derailment. The expected value for the derailment speed on open track is estimated to be 62 km/h. This implies that it is only when the speed is above 60 km/h, at the right tail of the distribution, that there is a probability of carriages overturning. This is illustrated in the following diagram, where the cumulative distribution function for the probability of overturning carriages is set against the inverse cumulative probability distribution for derailment speed, on open track.

---

60 Recall that the distribution was truncated, giving an expected value that differs from the mode.
Figure 27. Diagram for derailment speed and probability of carriages overturning; derailment on open track.

The corresponding diagram for stations is a little different. The speed distribution is shifted to the left and this implies that the probability of carriages overturning is smaller.

Figure 28. Diagram for derailment speed and probability of carriages overturning; derailment at a station.

2.6.4.3.3 The number of tracks on the line

The total length of the Swedish network is 11,159 km, 8475 km of which is regularly used by passenger trains. Of this, 1450 km has double or multiple tracks\footnote{Banverket, 1997a, p. 95}. In other words, 83% of the network used by passenger trains has single-track lines, and 17% double-track lines. However, the traffic volume is more intense on the double-track lines.
The probabilities of a derailment on a single-track line and a double track line respectively depend upon the distribution of train traffic on the different line types. Unfortunately, there are no official figures for the number of passenger train kilometres operated on single track or double track lines, so that they have to be calculated.

SJ has provided raw data in a large file containing nearly 200,000 entries with information on traffic volume for the period 1991-1999 by track section and train type. The reason for choosing the limited period of 1991-1999 is the fact that SJ only has data files with sufficient detail for that period. This is not a problem here, because the information will only serve as a tool for estimating the distribution of the traffic on double- and single-track lines.

SJ and the NRA have not yet managed to harmonise their descriptions of the Swedish rail network. They use their own labels for track sections and have separate numbering. Some work has been done, but there are still separate lists of numbered track sections and even though some labels are the same, there are still differences. Furthermore, both SJ and the NRA have the habit of reorganising their systems every second year. This is a headache for all railway researchers and means that information from the NRA on track standards could not be co-ordinated with information on the traffic volumes from SJ.

Fortunately, a list including track data was set up in a previous project. It contains information on when line-block and ATC became operational, but also on the opening dates of double-track sections of the Swedish network. It was connected to the data file from SJ and the information on traffic production was filtered.

The total passenger train volume for 1991–1999 is 564 million train-kilometres. However, it was not possible to use all of the information because of differences in the numbering of the lines, the way the network is sectioned, etc. Around 10 out of 215 lines were excluded and the passenger train traffic on the remaining lines was 511 million train-kilometres. Of this figure, 268 million train-kilometres were on double-track lines and 243 million train-kilometres on single-track lines. These figures are not exact: there have been changes in the network, new double-track lines have been built, etc, but they give the best estimate available. The figures can be seen as aggregates for the period (1991-1999).

Assuming that the probability of a derailment is independent of the track standard, this implies that 52.5% of derailments occur on double track and 47.5% on single-track lines. This assumption does of course not hold. Sparre performed Poisson regressions on the number of passenger train derailments on different types of track. He divided tracks into three types, and the derailment probabilities are displayed in the table below.

<table>
<thead>
<tr>
<th>Track type</th>
<th>Accident probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Continuous-welded track with concrete sleepers</td>
<td>3.4x10^-8</td>
</tr>
<tr>
<td>B. Continuous-welded track with wooden sleepers</td>
<td>2.9x10^-7</td>
</tr>
<tr>
<td>C. Jointed track</td>
<td>2.8x10^-7</td>
</tr>
</tbody>
</table>

Table 14. Derailment probabilities depending on track standard. From Sparre, 1995, p. 40

As we can see, there is a difference in the probability of a derailment depending upon the track standard. The main difference is between category A and B/C: B and C are on a similar level. One could expect that B would be lower than C, but Sparre shows that this is dependent upon the limited number of derailments, giving large confidence intervals for the quota of the probabilities for A and C. The probability that a derailment should occur on a line with track
type B or C is between 8 and 9 times higher than on a line with track type A. Even if it were possible to recalculate the figures, it is unlikely that figures very different from Sparre’s would be obtained. We are here merely interested in the relative difference, which might deviate from the figure given. If accidents that occurred on one of the track types were reported in a higher degree to SJ, the figures would be biased, although this seems somewhat unlikely. Given that the proportion of unrecorded cases are on a similar level for all track types, we can assume that the calculated relative figure is satisfactorily accurate.

We can assume that all double-track lines have track type A. The problem is to find the distribution of track standard on single-track lines. As we lack detailed information on this, we can assume that 50% of all single-track lines have track standard B. We can now calculate the probability that a derailment will occur on a double- or a single-track line respectively. The probability is given by the formula

\[
P(T) = \frac{D(T)}{D(1) + D(2)}
\]

where:

\( P(T) \) is the probability that a derailment will occur on a line with \( T \) tracks;

\( D(T) \) is the expected number of derailments from a unit number of train-kilometres run on a line with \( T \) tracks. \( D(T) \) is calculated from

\[
D(T) = \frac{TKM(T)}{TKM(TOT)} \left( P(TSA) \cdot \frac{D(A)}{D(A)} + P(TSB) \cdot \frac{D(B)}{D(A)} \right)
\]

where:

\( TKM(T) \) is the number of train-kilometres run on lines with \( T \) tracks;

\( TKM(TOT) \) is the total number of train kilometres run;

\( P(TSA) \) is the probability of track standard A;

\( D(A) \) is the number of derailments per train-kilometre run on track standard A;

and similarly

\( P(TSB) \) is the probability of track standard B;

\( D(B) \) is the number of derailments per train-kilometre run on track standard B.

Replacing with the figures above we will have

\[
D(1) = \frac{247}{511} \left( 0.5 \cdot \frac{3.4 \times 10^{-8}}{3.4 \times 10^{-8}} + 0.5 \cdot \frac{2.9 \times 10^{-7}}{3.4 \times 10^{-8}} \right) = 2.27
\]

\[
D(2) = \frac{268}{511} \left( 1 \cdot \frac{3.4 \times 10^{-8}}{3.4 \times 10^{-8}} + 0 \cdot \frac{2.9 \times 10^{-7}}{3.4 \times 10^{-8}} \right) = 0.52
\]
\[
P(1) = \frac{2.27}{2.27 + 0.52} = 0.81 \quad (11)
\]
\[
P(2) = \frac{0.52}{2.27 + 0.52} = 0.19 \quad (12)
\]

From this little exercise we now have the probabilities that a derailment occurred on a single track or on a double-track line, given the current distribution of the traffic production on the two line types.

These two figures now feed into the event tree.

### 2.6.4.3.4 Blocking of adjacent tracks

If a derailment occurs on a double-track line, there is a probability that the train will block the adjacent track. There is then a risk of collisions with trains passing on that track. This probability is of course small, but the consequences could be severe should it happen, especially if the passenger carriages have overturned in the derailment. Some support can be found in BOR when making judgements about this probability.

The derailment spread is the distance from the track centre to a derailed carriage. BOR contains information on spread for some of the derailments between 1985 and 1999. In 13 cases, the spread was more than one metre. This means that some of the carriages moved at least one metre away from the track, which means they could impinge upon the adjacent track’s space. However, in five of these cases, the carriages overturned. This gives 8 out of 106 derailments as a lower limit for the probability that the carriages will move away from the track when derailing. 51 derailments lack information on the spread, and 45 derailments have the spread set to one metre, i.e. the train, or one or more carriages, moved a small distance from the track centre, but remained predominantly on the line and did not leave the railway corridor.

We can here draw upon the benefits of using the Monte Carlo simulation method by substituting an educated guess with a probability distribution. Instead of a single figure, we will use the possibilities to model the uncertainty. As we do not know anything about the distribution of the parameter, we will utilise triangle distributions for the case where the carriages remain upright. The triangle distribution specifies the minimum, most probable and maximum values the variable can take. In this case, the parameters are set to 0.01, 0.05 and 0.2. The distribution is thus skewed.
Figure 29. Triangle diagram for the probability that a derailed train will not affect the clearance for adjacent tracks.

The lack of data for these estimates is a weak point in the calculation of the results. However, it is better to set low figures and include the scenario in the model than to exclude the scenario altogether due to lack of data. For the purpose of this project, the described method is sufficient. Further work should aim at detailed studies of these parameters.

In the case where carriages overturn, the probability is set to 0.5. The reason for this is that if the carriages fall over they will most certainly block the adjacent track if they fall towards it. If they fall away from the adjacent track, they will most certainly not block it. The probability that the cars will fall to the right or the left side if they overturn is equal\textsuperscript{62}.

2.6.4.3.5 Collision with a train following the derailment.

There are two possibilities here. Either the derailed train can be hit by a train running on the same track, or it can be hit by a train passing on an adjacent track. The second scenario happened in the tragic accident at Great Heck, near Selby, Great Britain, on the 28\textsuperscript{th} February 2001. A Land Rover with a car trailer left the M62 and went down an embankment and onto the tracks. It was hit by a southbound express passenger train that derailed. The train continued, staying in line and upright, until it reached a series of points where it was diverted into the path of a north-bound freight train. The collision with the freight train was unavoidable. The time span from when the Land Rover went onto the tracks to the collision with the freight train was around 60 seconds\textsuperscript{63}.

In such cases, the probabilities are very small and it is of course very hard to find any statistical support for the probabilities chosen.

\textsuperscript{62} The author has not found any arguments for believing anything else.

\textsuperscript{63} Health and Safety Executive, 2001
It is here assumed that the first type of scenario, where a derailed train is hit by another train travelling on the same track, is less likely than the second scenario. The line block system will detect all trains that occupy a specific section of a line and set the signals to stop for following trains. This also means that a derailed train will continue to occupy the line section and all signals will remain red until the derailed train is removed. This holds as long as the derailed train short-circuits the track circuit. In order not to do that, all carriages would have to leave the track with all axles. Furthermore, a standard procedure when this occurs would be to short circuit the track circuit manually, as is standard procedure when maintenance is carried out. This would have to be not done, but, furthermore, the only thing that required for the short-circuit is that the rails are connected in some way, which could be by an overturned carriage as well as an axle. It is very unlikely that the track circuit would not be short-circuited and so this scenario is not considered in this model64.

This parameter is, like overturning carriages, modelled with a triangle distribution. The means of the distributions are set conservatively low and with a difference of one degree. The probability that a derailed train will be hit by a train passing on an adjacent track is set to 1 in 100, and the probability that a derailed train will be hit by a train going on the same track section is set to 1 in 1000. This means that this will happen on average once in 139 years. The highest and the lowest possible values are set to one degree over and under the mean respectively, giving symmetrical distributions.

### 2.6.4.3.6 Probability of a fire following a derailment or collision

The combination of derailment or collision and fire is serious. Throughout history, a number of examples have shown that the consequences are without doubt more severe when a fire is involved. As with the previous section, it is hard to find statistical material supporting any specific probability estimate for fires following a derailment or collision. There was no fire in any of the 106 derailments used in the model.

The probability of a fire following a derailment, or a combined derailment and collision, is represented by a triangle distribution with the most probable value 0.025 for the derailments and 0.05 for the combined accidents. The minimum and maximum values are given in the table below.

<table>
<thead>
<tr>
<th>Type of accident</th>
<th>Min</th>
<th>Mode</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Derailment only</td>
<td>0.0005</td>
<td>0.025</td>
<td>0.05</td>
</tr>
<tr>
<td>Derailment + Collision</td>
<td>0.001</td>
<td>0.05</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 15. Values specifying triangle probability distributions for fire following derailment or combined accident derailment + collision.

It is worth underlining that the probabilities are chosen as conservative estimates and the purpose is to estimate the influence of the parameters on the average number of fatalities.

---

64 On the 29th June 1990, a freight train dropped an empty tank wagon between Vännäs and Degermyr, Sweden. The wagon derailed and went of the track, coming to a stand-still close to the track, but did not closing the track circuit. A passenger train then collided with the tank car. This type of event can and does occur.
2.6.4.3.7 Other factors not in the model

2.6.4.3.7.1 Release of dangerous goods following a combined derailment and collision
Passenger trains do not carry dangerous goods in Sweden. A single passenger train derailment cannot therefore lead to the release of dangerous goods. There is a (very) small possibility that a derailed passenger train could be hit by another train. There is also a small possibility that the colliding train could be carrying dangerous goods. Furthermore, the dangerous goods in that collision could be released with some small probability. The consequences of such an accident could be very severe, although it is very unlikely that all these circumstances would occur together. It is not possible to make any well-founded statements on the magnitude of the probability of this scenario.

The scenario was, however, initially included in the model. The number of branches in the event trees was 348. A simple sensitivity analysis was made and the effect these rare events had on the average number of fatalities per year was very small. For example, increasing the number of fatalities in these accidents by ten times only increased the average number of fatalities per year on the third decimal. Therefore, with a confident belief that the model would not give misleading results, and with the aim of simplifying the model and reducing the number of branches in the event trees, the release of dangerous goods was excluded from the model.

2.6.4.3.7.2 Evacuation procedures on trains and in tunnels
There are several measures that are taken in order to reduce the consequences should accidents occur. Such arrangements are common in tunnels, e.g. signs showing the shortest escape routes, emergency lamps helping passengers to find their way out, special paths or escape tunnels parallel to the train tunnel, etc. Trains can also be prepared for evacuation with the possibility of escape through the windows, with special training programmes for staff on arranging evacuation, etc.

The number and quality of these types of arrangements can of course vary and this affects the consequences of possible accidents. In the initial version of the event tree for tunnels, two more steps were added, modelling the quality of the evacuation procedures. The questions posed were “High quality of evacuation procedures on trains: Yes/No” and “High quality of evacuation procedures in tunnels: Yes/No”. In order to simplify the event tree and reduce the number of branches, these two were excluded. In a complete analysis, they should be included, but within the present project simplifications are necessary. After excluding these, the number of branches in the tunnel event tree was reduced from 144 to 36.

2.6.4.3.7.3 Types of carriage and numbers of passengers on board
Different types of carriage might give different levels of safety. This can theoretically be modelled, but it requires information not available to this project. BOR contains information on the type of train and carriage for some, but not all derailments. Given the lack of data, the assumption has been made that the consequences on average are the same independent of the type of carriage. The same assumption is made for the number of passengers on board. In the end, the average consequence will be the one calculated in the risk analysis model.

It deserves to be pointed out that it is not a limitation of the method that has led to the decision not to model these factors. It is merely a matter of lack of information. The information could be gathered, but it would demand more time and resources than available here.
2.6.4.3.7.4 Collision with buildings in station areas
There is also a possibility that a derailed train will collide with a station building. This happened for example in a derailment in Cologne, Germany 06/02/00. One of the carriages was almost wrapped around a station building and the accident caused the loss of 9 lives.

Photo 1. Train crash in Brühl, Germany, 2000-02-06

It is obvious that the consequences of such incidents are more serious than a “normal” derailment. Nevertheless, it was decided to exclude this scenario from the model. The problems of finding any support or evidence for a judgement on the probability of the scenario led to the decision. In a full model, the scenario should be included.

2.6.4.3.8 Seven classes of consequences

It is impossible to make individual estimates of the consequences of all of the 124 different scenarios in the event trees. In order to simplify the process, seven levels of severity have been constructed. These are listed below. For each of the levels a probability distribution has been assigned. This is because even within each scenario, the numbers of causalities can show variation, and this variation can be described in the model.

It would be most straightforward to assume that the number of fatalities follows a Poisson distribution. The Poisson distribution counts the number of occurrences in a short interval of time. What is important for the distribution to hold is the smallness of \( p \), that is the occurrences of the studied variable, relative to the largeness of the population \( N \), which in this case would be the number of derailments. Furthermore, the Poisson distribution has a tail to the right when \( p \) is 5 or less. We have reason to assume that the consequences would follow a skewed distribution with a long tail to the right. It then seems that it would be correct to use the Poisson distribution for the severity levels.

However, when we have \( p \geq 10 \) the Poisson distribution gets close to the shape of the normal distribution. Furthermore, it is discrete and cannot handle units less than 1. In the model, it is necessary to allow for consequences that are described as 0.5 fatalities. This should be interpreted as 1 fatality every second derailment with the scenario specified. In order to solve this, a continuous distribution is needed, and a lognormal distribution has been chosen for the consequences of the different scenarios in this model. This distribution is typically used for describing incomes, which are necessarily skewed with a long tail to the right. The lognormal distribution counts quantities that are a product of a large number of other quantities. The number of fatalities could be seen as a quantity that is the product of the number of derailments. For a description of the lognormal distribution, see Appendix 3.

As an illustration, a distribution for one of the severity levels is displayed in the figure below.
The standard deviation of the distribution is set to be 50% of the expected value. This is somewhat arbitrary but there is a reason. By using a fixed proportion of the standard deviation relative to the mean, the distribution for the consequences will have the same shape irrespective of severity level.

In the model, the consequences are influenced by the derailment speed. There is a positive relation between the consequences and the speed, as was demonstrated in an article by Professor Evans, reviewed on page 29. This is handled by letting the expected values of the consequence distributions be a function of the derailment speed. When derailment speed is high, the consequences are thereby worse.

There is also evidence that the standard deviation will increase when the derailment speed increases. As we have let the consequences be influenced by the speed, and we have set the standard deviation as a proportion of the mean, we will have this effect in the model. The same then holds for the rare but potentially serious accidents. For these accidents there is a possible spread in the consequences from only light injuries to multiple fatalities, which is then reflected in the model. The model can easily be changed should evidence for specific distributions, means or standard deviations for the separate severity levels appear.

The consequences in the different locations are assumed similar, ceteris paribus, i.e. at the same derailment speed. The assumption has here been made that the consequences should on average be at roughly the same level, given similar scenarios and identical derailment speed, for the derailments on open track and at stations, and somewhat more severe for derailments in tunnels. It should be remembered that two different speeds are simulated, one for derailments on open track and in tunnels, and one for derailments at stations. The reason for this was that the derailment speed differed between these types of locations.

65 Evans, 2001
This means that a derailment at a station, where the speed is 60 km/h, the train does not affect the platform space and does not hinder trains passing on adjacent tracks, its carriages remain standing, etc., should on average have the same consequences as a derailment on open track given similar circumstances regarding derailment speed, etc. For a similar derailment that occurs in a tunnel, the consequences are assumed to be more severe.

The lower derailment speed at stations does influence the consequences, in three classes. The basic assumption for the expected number of fatalities given a certain derailment speed is the same for derailments on open track and derailments at stations. The difference in speed gives different expected numbers of fatalities for each severity level and derailment location, as shown in the table below.

<table>
<thead>
<tr>
<th>Severity level</th>
<th>OPEN TRACK</th>
<th>STATION</th>
<th>TUNNEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Below medium</td>
<td>0.1</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Medium</td>
<td>5.0</td>
<td>2.5</td>
<td>5.0</td>
</tr>
<tr>
<td>Serious</td>
<td>7.0</td>
<td>3.5</td>
<td>7.0</td>
</tr>
<tr>
<td>Very serious</td>
<td>10.0</td>
<td>5.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Catastrophy</td>
<td>18.0</td>
<td>9.0</td>
<td>18.0</td>
</tr>
</tbody>
</table>

Table 16. Levels of severity and expected values of number of fatalities per accident

The figures above are the expected values of the probability distributions that represent each severity level for each location. Note that the number of fatalities per accident is less than one for the severity levels “Below medium” and “Light”. The values are the expected values of the consequence distributions and not physical outcomes.

The relationship between speed and consequences is assumed linear. The slope of the line is given in the table above. The relationship is then given by the distribution

\[ C(\text{Severity level}) \sim \logN(\text{Average Consequence} \times \beta \times \text{Speed} , (\text{Average Consequence} \times \beta \times \text{Speed} / 2) ) \]

where:

- \( C(\text{Severity level}) \) is the distribution of the consequences for each severity level;
- \( \beta \) is the slope of the curve;
- Speed is the simulated speed, controlled by the distribution for the derailment speed.

In this way, it is possible to let the speed directly influence the consequences by letting both the expected mean and the standard deviation be linearly adjusted by the derailment speed. Adjusting the slope of the line is a way of calibrating this part of the model. Note that when the speed is below average the consequences will also be less severe. The bounds of the relationships have not been investigated, but the distribution of the speed sets natural limits to the effect on the consequences.

As an example, consider the medium severity level for open track. The expected speed is 60 km/h and the expected number of fatalities for this severity level is 1. If the derailment speed should instead be 120 km/h, then the expected number of fatalities would increase to

\[ E(\text{Fatalities}) = 1 \times 0.017 \times 120 = 2.04 \]

As illustrated in Figure 30, 95% of the distribution will fall between 0.35 and 2.26 fatalities for this severity level.
2.6.5 Results

With the model set up, we are ready to make simulations. The model has of course been tested along the way. The possibility of correlating input data with output data has proved useful for discovering anomalies in the model. During the development phase, some of the parameters were given limited ranges and this gave peculiar results. This could be solved by extending the range or assigning a different probability distribution, for example. In the early versions, the relationship between speed and overturning carriages was modelled with a linear relationship. This was later replaced with the probability distribution described.

The calculated mean number of passenger train derailments is a little higher than the average number of derailments reported in BOR. There are 106 passenger train derailments, with passengers on board, reported in BOR for 15 years. This gives an average of 7.07 passenger train derailments per year, with a standard deviation of 3.04. The average number of derailments per year is calculated to be 7.09 in the model and the standard deviation is 0.69. By performing a one-sample t-test on the statistical material the probability of having more than 8 passenger train derailments is calculated to be 13%. The corresponding figure calculated by the risk analysis model is 9.1%. The distribution of the number of derailments is showed in the diagram below.

Figure 31. Distribution of overall numbers of passenger train derailments per year.
The shape of the histogram appears to follow a normal distribution curve. In a strict sense, the material does not have a normal distribution. Fitting a curve to the data does not give a significant fit. The P-value of a chi-squared test is 0. This is because we have a very large dataset of 10,000 values for each output variable. No test will prove significant because we will always have some deviations from the expected value and this will make the test insignificant. Reducing the number of iterations to 100 and running the fit will give several distributions that fit relatively well to the material, with for example an R-squared of 0.98 for a lognormal distribution.

![Normal distribution plot and histogram](image)

Figure 32. Normal distribution plot and histogram of overall numbers of passenger train derailments per year. However, plotting a normal distribution over the histogram, as is done above, shows that the fit is relatively close. It is therefore assumed that that the normal distribution can serve as an approximation for describing the number of passenger train derailments per year. It is apparent that the result follows the material in BOR.
No specific analysis has been made on the probabilities of causes that have not yet led to an accident. Entering estimated frequencies of such generic causes, as “Coupling failures” would directly change the results of the model. In this project, these parameters have been assigned a zero frequency. The in-depth analysis of these parameters is outside the scope of this project. An analysis of the derailments reported in BOR shows that 52 out of 86 possible causes did not lead to a derailment. Changing the frequency of these from 0 to 1 per billion train kilometres would raise the expected number of passenger train derailments per year by around 40%. This is more or less hypothetical but can serve as an upper limit for the expected number of passenger train derailments per year.

As we saw in Fault tree 3 on page 68, the overall number of derailments per year is calculated from derailments on open track, at stations and in tunnels. The probabilities of these are displayed in the table below.

<table>
<thead>
<tr>
<th>Outputs</th>
<th>PT derailments on open track</th>
<th>PT derailments at stations</th>
<th>PT derailment in tunnels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>27.93</td>
<td>47.88</td>
<td>0.06</td>
</tr>
<tr>
<td>Maximum</td>
<td>55.99</td>
<td>95.76</td>
<td>6.14</td>
</tr>
<tr>
<td>Mean</td>
<td>39.82</td>
<td>68.10</td>
<td>1.20</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>3.87</td>
<td>6.61</td>
<td>1.01</td>
</tr>
</tbody>
</table>

Table 17. Descriptive statistics for derailment probabilities per billion train kilometres for different locations.

As we can see, there is a spread in the calculated probabilities, reflecting the tails of the distributions of the input variables. When we come to the output of the event trees, the calculated number of fatalities, we will get somewhat different results. The total number of fatalities per year is calculated to be 0.78, with a rather large standard deviation of 0.68. The maximum calculated value is 10.4 fatalities. This variable has a different shape to that of the number of derailments per year.
Figure 33. Histogram of the total number of fatalities per year

As with the output of the overall number of passenger train derailments per year, it is not possible to fit a curve in a strict sense. Nevertheless, we can still argue in a similar manner that a certain distribution function can serve as an approximation for describing the data. The distribution above is skewed and appears to follow a lognormal distribution curve. This can be seen from the following figure.
A property of the lognormal distribution is that all values are >0. Furthermore, the lognormal distribution has a long tail to the right, which allows for a low probability outcome with many fatalities. The distribution can serve as an approximation of the expected number of fatalities per year. Normally the number of fatalities will be lower than the calculated average. However, the model includes the rare but serious, multiple-fatality accidents. Therefore, the occurrence of a serious derailment with more than 10 fatalities would not change the results of the model significantly.

The expected numbers of fatalities per year are a little higher on open track than at stations. The figures are 0.40 for open track and 0.37 at stations. The contribution from derailments in tunnels is very modest, only 0.004. This is of course because of the weighting at the top of the event trees that assigns only 1% of the derailments to tunnels. We are now ready to look at the causes and the relationships between input and output variables.

A common method for analysing the sensitivity of outputs to changes in input variables is to use multiple regression. The regression can explain some of the variation in the output.
variable, but not all. Part of the variation is unexplained and referred to as an error term. It can be viewed as the variation around the regression line. The problem is normally to decide what parameters to include in the regression and which parameters to exclude. There are several methods for this and that commonly used is stepwise regression. This allows for evaluation and re-evaluation of a parameter’s contribution to explaining the variation of the output variable. The significance of every variable is evaluated at every stage.

This can also be done using a multivariate method, which is a way of analysing multiple parameters simultaneously. In multivariate regression, a set of parameters, or input variables, is treated as one variable, described with \( X=(X_1,X_2,X_3,\ldots,X_k) \) where \( k \) is an integer. We call these variables vectors.

The strength of the regression is tested with the coefficient of determination, denoted by \( R^2 \). This coefficient measures the proportion of the total variation that is explained by the regression, that is by the parameters included in the regression. In this way, the R-squared measures how well the regression as a whole describes the material.

The contribution of the separate parameters is given by their coefficients. It is also possible to test the significance of individual parameters. It is thus also possible to test if a parameter should be included in the regression. The slope parameters are then tested with the hypothesis that they are not zero, using a t-test.

Differences in uncertainty between variables can distort comparisons greatly. A certain change in one variable can have a much bigger effect than a comparable change in a variable with a large standard deviation. The solution is to normalise the b coefficients. In @Risk, these are calculated from the formula \( \text{output change} / \text{output standard deviation} / \text{input change} / \text{input standard deviation} \). This means that they are standardised by the standard deviation of both the input data and the output data.

When we look at the overall number of passenger train derailments per year, the contribution of the separate parameters follows the calculated probabilities, for obvious reasons. The cause giving the largest contribution is where a set of points is not in the correct position, this is detected, but the driver does not check the position of the points properly, and, when passing the points, the train derails. This is the most common cause in the analysed dataset and for obvious reasons it has an effect on the regression.
Figure 35. Regression sensitivities for overall numbers of passenger train derailments, displaying $b$ coefficients in the regression for the input variables.

The variables in the figure are explained from top to bottom in the following table.
<table>
<thead>
<tr>
<th>Label</th>
<th>Explanation – Generic cause</th>
<th>Standardised b Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Point not in correct position</td>
<td>Derailment due to incorrect train movements on S&amp;C - Point not in correct position, detected - Incorrect control by driver.</td>
<td>0.406</td>
</tr>
<tr>
<td>Other rolling stock faults</td>
<td>Rolling stock faults – Other causes</td>
<td>0.258</td>
</tr>
<tr>
<td>3. Movement of Points under t…</td>
<td>Incorrect train movements – Other driver/train crew error at S&amp;C - Movement of Points under train, due to train crew errors</td>
<td>0.257</td>
</tr>
<tr>
<td>4. Defective S&amp;C</td>
<td>Derailment due to faults on S&amp;C - Defective S&amp;C</td>
<td>0.255</td>
</tr>
<tr>
<td>6. Uncategorized SPAD which are…</td>
<td>Incorrect train movements – Signals passed at danger – SPAD due to driver errors.</td>
<td>0.220</td>
</tr>
<tr>
<td>7. Running into snow/ice</td>
<td>Running into obstructions - Running into snow/ice</td>
<td>0.219</td>
</tr>
<tr>
<td>Shunter errors</td>
<td>Incorrect train movements - Shunter errors</td>
<td>0.215</td>
</tr>
<tr>
<td>Axle failure due to other…</td>
<td>Rolling stock faults – Axle failure leading to passenger train derailments – Axle failure due to other causes.</td>
<td>0.202</td>
</tr>
<tr>
<td>8. Other track faults…</td>
<td>Track faults – Other track faults leading to passenger train derailments.</td>
<td>0.197</td>
</tr>
<tr>
<td>9. Buckled rail due to heat…</td>
<td>Track faults - Buckled rail leading to passenger train derailments – Buckled rail due to heat expansion.</td>
<td>0.190</td>
</tr>
<tr>
<td>Running into track locks…</td>
<td>Running into obstructions – Running into track locks or brake shoes.</td>
<td>0.173</td>
</tr>
<tr>
<td>10. Point not in correct position</td>
<td>Faults on S&amp;C - Points not in correct position – not detected - Points not in correct position due to other/unknown causes.</td>
<td>0.170</td>
</tr>
<tr>
<td>11. Broken rail</td>
<td>Track faults - Broken rail</td>
<td>0.168</td>
</tr>
<tr>
<td>12. Driver disregards signal…</td>
<td>Incorrect train movements – Signals passed at danger – SPAD due to disregard.</td>
<td>0.167</td>
</tr>
<tr>
<td>15. Overspeeding</td>
<td>Speeding on S&amp;C.</td>
<td>0.146</td>
</tr>
<tr>
<td>16. Miscellaneous unknown causes</td>
<td>Miscellaneous unknown causes.</td>
<td>0.146</td>
</tr>
</tbody>
</table>

Table 18 Explanation of regression parameters in Figure 35.

The R² for the regression is 0.90 when 26 out of 75 parameters are included. Not all of the parameters in the regression are listed in the graph above. With stepwise regression, the parameters selected are the ones that give the highest explanatory power. It would be possible to use fewer parameters but that would lower the R².
When we look at the total number of fatalities per year we have to be somewhat cautious. The derailment speed is a dominant parameter in the model, it affects the consequences and the probability that carriages will overturn. In other words, these are correlated, so we will therefore have problems if we try to calculate a regression and include both speed and these variables. This is called multicollinearity and is a problem permeating all multiple regressions where the variables are not truly independent.

The problem can be solved by adding a correlation matrix to the model or by excluding either speed or the consequence variables from the regression. It seems straightforward to exclude speed. When this is done, we can calculate multiple regressions and calculate sensitivities. We will start by having a look at the variables in the event trees. The consequence variables are not included. Below is a tornado diagram for a multiple regression with the number of fatalities in derailments on open track as the response and the parameters in the event tree as independent input variables.

![Tornado diagram](image)

Figure 36. Standardised b coefficients in multiple regressions for overall numbers of fatalities per year, for passenger train derailments on open track.

As we can see, the variable “overturning carriages” is dominant in the regression. The $R^2$ is 73% and most of the explanatory power comes from this single parameter. The $R^2$ is low because the consequence variables are not included. If we include these, we will have a much higher $R^2$. The regression will then explain 89% of the variation. Observe that in none of these figures are the speed variables included, as that would be a form of double counting, or using the terminology introduced above, would give multicollinearity. A similar pattern is found for the expected number of fatalities in derailments at stations.

We can also look at the influence of the different severity levels.
Regression sensitivity for expected number of fatalities per year

<table>
<thead>
<tr>
<th>Consequence Level</th>
<th>Std b Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST Very Serious</td>
<td>0.452</td>
</tr>
<tr>
<td>OT Serious</td>
<td>0.304</td>
</tr>
<tr>
<td>ST Below medium</td>
<td>0.102</td>
</tr>
<tr>
<td>OT Below medium</td>
<td>0.096</td>
</tr>
<tr>
<td>ST Light</td>
<td>0.095</td>
</tr>
<tr>
<td>ST Medium</td>
<td>0.093</td>
</tr>
<tr>
<td>OT Medium</td>
<td>0.092</td>
</tr>
<tr>
<td>OT Light</td>
<td>0.091</td>
</tr>
<tr>
<td>OT Very serious</td>
<td>0.083</td>
</tr>
<tr>
<td>ST Catastrophy</td>
<td>0.059</td>
</tr>
<tr>
<td>TU Catastrophy</td>
<td>0.031</td>
</tr>
</tbody>
</table>

Figure 37. Standardised b coefficients in multiple regression for total number of fatalities per year, only consequence variables included. ST stands for station and OT for Open track.

We can therefore see that the serious, low-frequency, multiple-fatality accidents have a large effect on the overall number of fatalities. We can also aggregate the total number of fatalities in the serious accidents. It then turns out that 44% of the expected number of fatalities results from the serious accidents with 5 or more fatalities. This figure can be compared to the figure reached by Railtrack, whose model calculates that these types of accidents give a 63% contribution to the overall number of fatalities.

2.6.6 Comparison of results with other models

We can also compare the expected number of fatalities per million train kilometres. The expected number of fatalities per year in British passenger train derailments is 4.63. The total number of passenger train kilometres produced is 250 million per year. This gives an average of 0.01852 fatalities per million train kilometres.

The figure reached in the present project is 0.78 fatalities per year. With around 65 million passenger train kilometres per year, we can expect 0.012 fatalities per million train kilometres. The figures are relatively similar and give some support for the present model. It also gives a rough indication that the assignment of severity levels in the present model gives acceptable results.

It is also interesting to compare the results of the model with the statistical estimate presented in section 2.5.2.6.2 on page 62. The expected number of fatalities per year from derailments was estimated to be 0.5. The corresponding figure estimated with the risk analysis model is 0.78. These figures are not completely comparable. This is because the figure estimated with historical data was a prognosis for the period 2000-2004. The figure estimated with the risk analysis model was a mean for the period 1985-1999.
However, by using the trend estimated in section 2.5.2.6.2, it is possible to estimate the mean number of fatalities per year for the period 1985-1999. This has been done and the figure reached was 0.58 fatalities per year. The difference between the estimates is then 0.78 - 0.58 = 0.20 fatalities per year. The question is then whether this difference is motivated or if any of the models are giving unreliable estimates. There is a possibility that accidents with very low frequency but high consequences have not been captured with the statistical method used, simply because some very rare accidents have not occurred during the period covered by the dataset. In this case, a statistical calculation of for example the sample mean would not be a reliable estimator of the true mean.

In Great Britain, Railtrack has estimated the expected number of fatalities in train accidents to be 11.3 per year. Evans has compared this with an estimate based on historical data and found that the latter was preferred. We can now make the same comparison by using the same type of calculation66.

Assume the probability of a non-occurrence of an accident to be at least 0.5. If the occurrence of this type of accident can be described as a Poisson process with the mean rate $\lambda$, per billion train kilometres, then the probability of non-occurrence in $k$ billion train kilometres is $e^{-\lambda k}$.

We can then calculate the maximum value of $\lambda$, given that the probability of non-occurrence $\geq 0.5$, and the traffic production $k$, by $\lambda = -\ln(0.5)/k$.

In Sweden, the total passenger train traffic in the period 1960-1999 was approximately 2.5 billion train-kilometres. The maximum probability of $\lambda$ would then be $-\ln(0.5)/2.5 = 0.27$. This equals 1 accident in 3.6 billion train kilometres. With a traffic volume of 70 million train kilometres per year, it corresponds to a frequency of once in 51 years. The difference between the estimate from the risk analysis model and the statistical estimate is 0.78 – 0.58 = 0.20 fatalities per year. Assume that this type of derailment occurs with the frequency once in 51 years. The models would then give equal estimates of the expected number of fatalities, if there are 51 x 0.20 = 10 fatalities in the derailment.

We are now in a position to ask if this type of accident could occur. The risk analysis model gives an estimate of the risk that differs from a statistical estimate based on historical data. There is a small probability that we will have a derailment with 10 fatalities or more. If we trust estimates based on historical data, we can conclude that the risk analysis model provides somewhat high although still credible estimates of risks.

---

66 The calculations follows the method developed by Evans, 2002, p. 22
2.6.7 Using the model

Once the model is set up, it is possible to carry out analyses of safety measures. For example, the effect of reducing the number of passenger train derailments due to improper control of points by the driver, when the points have detected that the tongue is not in the correct position, could be discussed. If the probability of this cause could somehow be reduced by 50%, the number of passenger train derailments could well fall from 7.03 to 6.53 per year, and the expected number of fatalities from 0.78 to 0.73. In other words, it would be a very small difference.

If by some safety measure the probability that carriages overturn in an accident could be reduced by 50%, then the same reduction in expected number of fatalities would occur. The safety impact would thus be a reduction in the expected number of fatalities of around 6%. We assume that the measure would not change the number of derailments.

The model allows us to analyse safety measures and find their possible effects relatively easily. Often a measure can have an effect both on the probability of the causes and on the consequences. The problem is normally to estimate the change in accident probability or the change in the other variables in the model. However, with the Monte Carlo simulation method it is possible to give ranges for the change in the variables. It is also possible to use discrete values with separate probabilities for the change, or simply to let the change in probability take separate values in a sequence of simulations and in this way get a series of results that can be compared. It is not within the scope of this project to take this further and the analysis will therefore necessarily stop here.

2.6.8 Summary

This project set out with the aim of constructing a risk analysis model for passenger train derailments that enables risk assessments, provides knowledge on the risks in the rail system and simplifies the analysis of safety measures. The aim was also to carry out a detailed analysis of the generic causes of derailments and of the parameters influencing the consequences, and to calculate the expected annual consequences. The model servers also as a description of how risk analysis methods can be used for analysing railway safety. The model uses fault trees and event trees in combination with Monte Carlo simulation, which makes it possible to study the variability of the input variables and to model the uncertainty surrounding some of the estimates.

To achieve the purpose it was necessary to collect information on derailments on the Swedish network. The official databases currently in service are not sufficiently reliable. Therefore, information on derailments has been collected from several data sources and merged into a new database called BOR. A great deal of time and effort has been made to find the causes of the derailments and to check the information for various important parameters.

Furthermore, in order to estimate the consequences of different types of accidents, a time series of all train accidents with passenger fatalities from 1960 to 2000 has been set up. There are official statistics giving the total number of fatalities in different types of accidents, but the information is aggregated and detailed information on each accident has not been available before BOR. With the information in BOR, it is possible to find those train accidents where passenger carriages have overturned and find support for judgements on the consequences of different types of accidents. The number of train accidents with passenger fatalities is still limited. If we select a specific accident type, we will only have a handful of accidents to study. It is therefore not possible to make any statistical inference, but it still
gives knowledge on different accidents and provides some support for expert judgements on the consequences.

The model contains three fault trees, one for each type of location modelled: open track, stations and tunnels. At the base of the fault trees are the generic causes and from these the derailment probabilities are calculated. The top events in the fault trees feed into three separate event trees, where the consequences are modelled. Each accident scenario ends with an estimate of the consequences and the expected number of fatalities is calculated. The total number of fatalities is then aggregated from all accident scenarios.

With the Monte Carlo simulation method, it has been possible to model the influence of speed on various parameters. Speed affects the expected number of fatalities for each scenario. It also influences the probability that carriages will overturn in a derailment. It has been possible to study the effect and relationships of these parameters, and the method provides a powerful way of finding convincing evidence for the limits of the probabilities assigned. It has for example been possible to study the relationship between speed and the probability of carriages overturning in a series of simulations and thus assign a credible probability distribution describing the relationship and the variability. The approach chosen therefore differs from the one adopted by Railtrack. Railtrack developed separate fault and event trees for low-speed and high-speed derailments. By the use of Monte Carlo simulation, a smaller and more concise model could be developed and the derailment speed is modelled in a more credible way.

The total number of passenger train derailments was calculated to be a little over seven per year. The number of passenger train derailments follows a normal distribution and the standard deviation is only 0.67. This means that there is only a 7% chance that there will be more than 8 derailments per year. It is possible to model the expected number of fatalities per year with a lognormal distribution. The lognormal distribution has a long tail to the right. The major part of the outcome of a random variable that follows a lognormal distribution is relatively concentrated. However, the distribution does allow for rare outcomes with high consequences. The mean of the simulations was 0.78 fatalities per year and the standard deviation was 0.68.

The risk analysis model is a powerful tool for estimating the effects of various safety measures. In itself, it does not contain any tools for estimating the possible change in the input variables to the model. However, if a given safety measure is estimated to give a certain reduction in any of the input variables, it is possible to find the overall safety effect.

It is also possible to carry out backwards analysis. Instead of hypothesising about the change in input variables, it is possible to see if a safety measure is worthwhile. It is possible to find the safety effect of eliminating a certain accident cause. This effect can then be compared with the costs or necessary changes and this may indicate whether or not the measure should be implemented, or if further analysis is required.

The data collection phase of the project took a great deal of time and effort. The final phases, in which the model was developed and tested, were a little shorter than planned. The result is that some aspects could have been further elaborated, for example, the design of the event trees for derailments in tunnels. Still, the model gives credible estimates of risks and provides a better understanding of them. It can function as a tool for estimating the effects of various safety measures.
3. Risk criteria

3.1 Introduction

The Hicks-Kaldor criterion is the underlying principle of Cost Benefit Analysis. It requires that those who suffer as a result of a societal project could be compensated, allowing the project to be justified if those who gain can compensate those who lose and still be better off. The Hicks-Kaldor criterion stipulates that this is true even if no compensation is given. Many societal projects have these properties; the benefits outweigh the costs and compensation could be given. The exception is when there are fatal risks.

The risks of a societal activity can be unfairly distributed. Aeroplane pilots, train drivers, miners, or personnel at nuclear power stations may face considerably higher risks in their everyday lives than the average person. Still, we need transport as well as energy and mining products.

With fatal risks, it is not be possible to compensate the person who loses out as they are likely to be dead. Some sort of regulation is therefore required to ensure that the risks are not unfairly distributed. Clearly, many societal projects entail risks of fatal accidents, and yet they are necessary. The solution is to ensure that no specific group or individual has an disproportionately high risk compared to the average citizen that benefits from the project. This can be done by using risk criteria that set limits to the risks to which specific groups or individuals are exposed. Two forms of criteria are discussed.

Individual risk criteria relate to the risk which specific individuals are exposed to. This, for example, can be expressed as the risk for a hypothetical person who lives within a specified area (near to a chemical or other industrial plant), or as the risk to a specific person irrespective of geographical location (for example, a train driver). Collective risk criteria, on the other hand, relate to the risks experienced by groups of people or society as a whole. Typical collective risks are those from transport activities, or nuclear plants that can threaten a whole region. There are two common ways of expressing these risks, namely as the number of fatalities per year, sometimes referred to as Potential Loss of Life (PLL), and as so-called Frequency/Number curves (FN curves). Sometimes, the term societal risk is used, normally referring to this second way of expressing collective risk67.

FN curves show the relationship between the number of fatalities (N) in an event and the accumulated frequency of events with the consequence of N fatalities. In this way, they show the probability of accidents with varying degrees of severity of consequences. It is important to stress that the FN curve shows the accumulated number of events. The diagram has double logarithmic scales.

67 For an example, see Railtrack, 2001.
According to the curve in Figure 38, the frequency of accidents with 10 or more fatalities is $10^{-5}$ per year or, in other words, the activity will result in one accident with 10 fatalities every 10,000 years. Because the curve shows the accumulated number of accidents, it is possible to calculate the total expected number of fatalities per year in accidents of a given size. The expected number of fatalities per year in 10 fatality accidents is 0.0001, according to the diagram. Furthermore, we can see that the number of expected fatalities per year in 100 fatality accidents is the same, $100 \times 10^{-6} = 0.0001$.

In this way, the FN curve contains more information than the more common way of expressing risk, as a single number for the average number of fatalities per year. The total number of fatal large-scale accidents is always smaller than the total number of fatal small-scale accidents. This means that the curve always slopes downwards to the right.

As we have seen, risks can be both defined and presented in different ways. We have the difference between individual and collective risk. We now turn to the way criteria for levels of risk can be designed and how they should be implemented.

Individual and collective risk criteria are formulated in different ways. Individual risk criteria are often specified as a single number. “The risk of being victimised in a fatal accident for an individual living within a specified distance from an industrial plant should not be more than $10^{-6}$ per year”. This is exemplified in Figure 39 below, where a lower level is also marked where the risks are so low that they are negligible or “acceptable”.

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**Figure 38.** Example of an FN curve, from Davidsson, Lindgren et al., 1997, p. 3-9
Collective risk criteria are often presented in the form of a line in an FN curve, exemplified below. An FN curve expresses the relationship between the yearly frequency of accidents of a size larger or equal to N and this size N. Both the x and the y-axis are logarithmic.

Two criterion lines are shown in Figure 40. The upper line is the criterion line for unacceptable risks. Should the risk curve at any point be above this line, measures must be taken to reduce the risks. The lower line shows the level at which risks are so low that they are in principle negligible. Risk levels between the lines are tolerable, but the risks should be judged according to a rule and reduced if this is found to be justified. This terminology is used throughout this thesis. The curve between the criterion lines is an example of an FN curve, in this case for the Channel Tunnel.
Different slopes can be chosen for the criterion lines. The criterion line in Figure 40 has a slope of $-1$. This means that the acceptable frequency of accidents with 10 or more fatalities is $10^5$ per year and the acceptable frequency of accidents with 100 fatalities is $10^6$ per year. The expected number of fatalities in large-scale accidents, with 100 fatalities per accident, will be the same as the expected number of persons killed in accidents with 10 fatalities per accident.

A steeper slope could, of course, be chosen, for example $-2$. This would imply an aversion to large-scale accidents. In the example above, it would mean that the we would find an accident with 10 fatalities every 10,000 years, giving an expected number of fatalities of $10^4$ per year, just as unacceptable as an accident with 100 fatalities every 10,000,000 years, giving an expected number of fatalities of $10^5$ per year. We will now look at the international use of risk criteria.

### 3.2 International use of risk criteria

The Netherlands has a long tradition of analysing risks and has conducted relatively extensive research on risks and uncertainty. They have an officially approved policy that distinguishes between individual risk and collective risk and between risks from existing and new activities. For individual risk, the level of unacceptable risk from existing activities or industries is chosen from the frequency of death from natural causes. This frequency is lowest for 14-year-old girls and is 1 in 10,000 years or $10^{-5}$ per year. When it comes to individual risk from new activities, the policy states that new industrial activity will not be allowed if the total individual risk increases by more than 10%. This gives a level for unacceptable risk of 1 in a million years for a new industrial activity or $10^{-6}$ per year. The levels for collective risk are expressed in an FN-diagram. The criterion line gives a maximum tolerable frequency of $10^{-5}$ accidents per year for accidents with 10 fatalities, for example. The line has a slope of $-2$ indicating that a higher weight is given to large-scale catastrophic accidents. The Netherlands does not use criteria for negligible risks.

This is somewhat similar to the policy in Britain. HSE in Britain has two levels of individual risk depending on whether the activity already exists or is new. The level for unacceptable risks from existing activities is taken from the risk level for harbour workers and is set at 1 in 1,000 years. The argument for this still fairly high risk is that the person exposed in some way benefits from the activity. The level for unacceptable risk from new activities is set somewhat arbitrarily at 1 in 10,000 years and the figures that have been chosen have gained public acceptance in Britain. There is one study of people’s attitudes towards risks and towards unacceptable risk levels for third parties near airports that indicate that the chosen risk level of 1 in 10,000 years is in accordance with people’s preferences.

Risks above the criterion level are not accepted under any circumstances. The risks must be reduced or the activity must be stopped. Great Britain also uses a level for negligible risks and this is set at $10^6$. Risks below the negligible level are so low that no risk-reducing measures are needed. In between there is an area in which the risks must be reduced, to As Low As Reasonably Practicable: the ALARP principle. Great Britain also uses criteria for collective risk in a similar way to the Netherlands.

A Swedish study of the valuation of risk contains an extensive review of the international use of risk criteria. The common approach is to use criteria for individual risk. Normally, the level is between $10^{-5}$ and $10^{-6}$. Some countries also use criteria for collective or societal risk.

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68 Davidsson, Lindgren et al., 1997, p. 5-35
69 Evans, 1997b
70 Davidsson, Lindgren et al., 1997
as in, for example, the Netherlands, Great Britain, Hong Kong and Switzerland. There are also some other differences in the use of the criteria. The following table shows the different levels used for individual risk.

<table>
<thead>
<tr>
<th>Authority and application</th>
<th>Maximum tolerable risk/year</th>
<th>Negligible risk/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Netherlands – new plants</td>
<td>$10^{-6}$</td>
<td>Not applied</td>
</tr>
<tr>
<td>The Netherlands – established plants or combined new plants</td>
<td>$10^{-5}$</td>
<td>Not applied</td>
</tr>
<tr>
<td>Health and Safety Executive, Great Britain – existing industries</td>
<td>$10^{-4}$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Health and Safety Executive, Great Britain – new nuclear plants</td>
<td>$10^{-5}$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Health and Safety Executive, Great Britain – existing dangerous goods transport</td>
<td>$10^{-4}$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Health and Safety Executive, Great Britain – new housing areas near existing plants</td>
<td>$10^{-5}$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Hong Kong – new plants</td>
<td>$10^{-5}$</td>
<td>Not used</td>
</tr>
<tr>
<td>The Department of Planning, New South Wales, Australia – new plants and housing</td>
<td>$10^{-6}$</td>
<td>Not used</td>
</tr>
<tr>
<td>Santa Barbara County, California, USA – new plants</td>
<td>$10^{-5}$</td>
<td>$10^{-6}$</td>
</tr>
</tbody>
</table>


As can be seen, different levels are applied depending on whether the activity is new or already exists. More stringent demands are set for new hazardous activities. The following table lists the use of official criteria for collective risk.

<table>
<thead>
<tr>
<th>Authority and application</th>
<th>Slope of the FN curve</th>
<th>Maximum tolerable risk/year</th>
<th>Negligible risk/year</th>
<th>Limit for maximum N</th>
</tr>
</thead>
<tbody>
<tr>
<td>VROM, the Netherlands – new plants</td>
<td>-2</td>
<td>$10^{-3}$</td>
<td>Not applied</td>
<td></td>
</tr>
<tr>
<td>Hong Kong – new plants</td>
<td>-1</td>
<td>$10^{-5}$ (for N=1)*</td>
<td>$10^{-5}$ (for N=1)</td>
<td>1000</td>
</tr>
<tr>
<td>Health and Safety Executive, Great Britain – existing harbours</td>
<td>-1</td>
<td>$10^{-1}$ (for N=1)</td>
<td>$10^{-4}$ (for N=1)</td>
<td></td>
</tr>
<tr>
<td>Santa Barbara County, California, USA – on-site risk</td>
<td>-2</td>
<td>$10^{-1}$ (for N=1)</td>
<td>$10^{-3}$ (for N=1)</td>
<td></td>
</tr>
<tr>
<td>Santa Barbara County, California, USA – off-site risk</td>
<td>-2</td>
<td>$10^{-1}$ (for N=1)</td>
<td>$10^{-5}$ (for N=1)</td>
<td></td>
</tr>
<tr>
<td>Störfall Verordnung, Switzerland</td>
<td>-2</td>
<td>$10^{-1}$ (for N=1)</td>
<td>$10^{-7}$ (for N=10)</td>
<td>1000</td>
</tr>
</tbody>
</table>

* This criterion is valid only for N>1

3.3 The problems involved in using FN criterion lines

In a paper, Evans and Verlander have pointed out some of the problems involved in using FN criterion lines for judging the tolerability of different risk levels\textsuperscript{71}. The main conclusion they draw is that FN criterion lines produce inconsistent results and do not always give the same answer in different situations that are similar in every relevant aspect. They instead propose a rule for minimising the expected disutility of accidents. This discussion is reviewed here and the proposed approach to judging risks is adopted in the procedure for evaluating railway safety. We first discuss the problems of FN criterion lines and then the difference compared with the expected disutility criteria. This section is based on the paper by Evans and Verlander.

3.3.1 FN criterion lines

Consider a system that can be judged as just tolerable. This can be written as

$$v = \max_n \left[ \frac{F(n)}{C(n)} \right] = 1,$$

where

- $n$ is the number of fatalities,
- $F(n)$ is the function defining the FN curve for the system studied and
- $C(n)$ is the function defining the FN criterion line.

Consider now a specific system that consists of two subsystems with FN curves, $F_1(n)$ and $F_2(n)$, respectively. The FN curve for the combined system is

$$F(n) = F_1(n) + F_2(n)$$

If each subsystem is just tolerable, consistency requires that the combined system must be judged as just tolerable as well. This can also be expressed as the following condition:

If $v_1=1$ and $v_2=1$, then $v = 1$.

For illustrative purposes, Evans and Verlander use simplified descriptions of the two subsystems. Subsystem 1 has 0.1 accidents per year with 10 fatalities. Subsystem 2 has 0.01 accidents per year with 100 fatalities per accident. The mean number of fatalities per year in each subsystem is then the same, that is, $0.1 \times 10 = 0.01 \times 100 = 1$ fatality per year. The FN criteria for the subsystems are assumed to be expressed as straight lines in a log-log diagram. The lines are defined by the functions

$$\log C_i(n) = \alpha - \beta \log(n)$$

It is now assumed that the equation for the FN criterion line has a slope of $-1$ and an intercept of 1 (on the logarithmic scale). The first part of this assumption implies that $\beta = 1$, while the second part can be rewritten as

$$C_i(1) = 1$$

Hence,

$$0 = \log C_i(1) = \alpha - \log(1)$$

and thus $\alpha = 0$.

So $C_i(n) = e^{-\log(n)} = 1/n$

\(\text{---}\)

\textsuperscript{71} Evans and Verlander, 1997
It follows immediately that for these criterion lines and with the fatality rates as above,
\[ v_1 = v_2 = 1 \quad (20) \]
and so both subsystems are in fact just tolerable. For the combined system, the criterion line is
\[ C(n) = C_1(n) + C_2(n) = \frac{1}{n} + \frac{1}{n} = \frac{2}{n} \quad (21) \]
So, for the combined system
\[ v = \max_n \left\{ \frac{F(n)}{C(n)} \right\} = \max_n \left\{ \frac{F_1(n) + F_2(n)}{C_1(n) + C_2(n)} \right\} = \max_n \left\{ \frac{[F_1(n) + F_2(n)]u}{2} \right\} \quad (22) \]
With the figures in the example above, it follows that
\[ v = \frac{[0.1 + 0.01] \times 10}{2} = 0.55 \quad (23) \]
This implies that \( v_1 = 1 \) and \( v_2 = 1 \), but that \( v \neq 1 \) and the condition is therefore not fulfilled. The conclusion is that FN-lines cannot be used as a decision-making rule for judging the tolerability of risk. They are still a useful way of illustrating the risks of systems, but they should not be used as a prescriptive tool.

### 3.3.2 Expected disutility

Evans and Verlander propose an alternative way of comparing risks with pre-specified standards. It is based on the Expected Utility Theorem for decision-making under uncertainty, which prescribes that the expected utility of a choice is the sum of the possible outcomes multiplied by the probability of each outcome. In the case with two outcomes, A and B, this can be written as
\[ U = p u(A) + (1-p) u(B) \quad \text{where} \quad (24) \]
p is the probability of outcome A and \( 1-p \) is therefore the probability of outcome B
\( u(A) \) is the utility of outcome A and \( u(B) \) is the utility of outcome B.

From this, Evans and Verlander derive the disutility per unit time for a given system. It is
\[ U = \sum_n u(n) f(n) \quad \text{where} \quad (25) \]
u(n) is the disutility of an accident with \( n \) fatalities and
\( f(n) \) is the mean frequency of accidents with exactly \( n \) fatalities.

One possible way to calculate \( u(n) \) would be to set \( u(n)=n \). The number of fatalities then describes the disutility of an accident. An alternative way could be to represent \( u(n) \) by
\[ u(n) = n^\beta \quad \text{where} \quad (26) \]
\( \beta \) is a parameter that corresponds to the slope of the FN criterion line. If \( \beta=1 \), \( u(n) \) reduces to \( u(n)=n \) We can then write (6) as
\[ U = \sum_n n^\beta f(n) \quad (27) \]
In this way the disutility of the system can be calculated and, if a value of \( \beta \) greater than 1 is chosen, large accidents are given extra weight and the calculated disutility of the system is higher. In order to judge the tolerability of the system using this method we need to compare \( U \) with some standard or threshold \( U_t \). If \( U \) exceeds \( U_t \) the risks of the system are intolerable.
$U_i$ can be compared with the intercept of the FN-criterion line. It sets a level for the intolerability line. This approach does not produce inconsistent results in the way that FN criterion lines do. The proof can be found in the article by Evans and Verlander.

One way of illustrating this approach could be to use a cumulative chart with the number of fatalities, $n$, on the x-axis and the cumulative disutility per year on the y-axis. The curve in the diagram is used for illustrative purposes. It is based on a logarithmic series distribution fitted to the railway accident statistics from Great Britain (discussed on p. 28). The cumulative disutility function is defined as

$$U(n) = \sum_{k=1}^{n} k^\beta f(k)$$  

(28)

with $\beta = 1$

When $n \to \infty$, then (9) approaches (8).

Figure 41. Cumulative disutility for accidents of size $n$ with threshold $U_i$.

A horizontal line could illustrate the threshold $U_i$. The risks (or disutility) are intolerable if the curve cuts the threshold line. The criterion can be formulated in the following way:

If the whole cumulative disutility curve is below the threshold line then the risks are tolerable.

The threshold value in the diagram is set to $U_i = 13$, as an example, and the curve reaches a value of approximately 14, which implies that the risks of the system are intolerable. In this example, the value of the parameter $\beta$ was 1. However, other values could be adopted. This will, of course, affect the shape of the curve and the decisions that are made. Consider, for example, two systems with the same number of expected fatalities per year. In the first system, there are 100 single fatality accidents per year. The other system has only one accident per year but with 100 fatalities. If we chose $\beta > 1$, we give priority to risk-reducing measures for the second system.

In order to use this approach in safety analyses of transport systems, the parameter $\beta$ and the threshold value $U_i$ must be decided. We will here attempt to use this approach for analysing the data from the risk analysis of passenger train derailments.
3.4 Expected disutility of passenger train derailments

We can compare the results of the analysis of passenger train derailments with a criterion for individual risks. We will then need to set a value for $U_t$. The estimated frequency of accidents of given sizes will then be aggregated and the expected disutility calculated. Using the simplification of letting the disutility of an accident be the number of fatalities, we will have an aggregated disutility that is equal to the expected number of fatalities per year. This is illustrated in the diagram below. However, let us first discuss a possible level of $U_t$.

It is possible to estimate a level for $U_t$ from individual risk criteria. There are no officially approved criteria in Sweden. The use of individual risk criteria in a selection of countries was listed in a study by the Rescuing Authority\(^72\). The intolerable level was set between $10^{-4}$ and $10^{-6}$. The report ends with a proposal to use the level $10^{-5}$ per year as a criterion for intolerable individual risks\(^73\), and this level is used here.

We also need a definition of an average passenger. The average passenger journey in Sweden was 58 kilometres in 1998, and the total number of passenger kilometres was 7144 million. However, we cannot calculate the total number of kilometres a typical rail passenger travels per year from this. We will therefore assume that a rail commuter typically travels 60 kilometres to work one-way. Calculated for 40 weeks of work per year this gives 24,000 kilometres per year. Dividing the criterion for intolerable risk by the total number of kilometres travelled per year will give the criterion for intolerable risk per kilometre travelled. This would be $0.00001/24,000 = 4.19 \times 10^{-10}$. Multiplying this with the total number of passenger miles travelled gives a total of 2.98 fatalities per year. We will use this figure here as the threshold value $U_t$. We can then illustrate the situation in the following diagram.

![Cumulative disutility from passenger train derailments with criterion line based on the individual risk criterion.](image)

We can see that the line is well below the criterion line. They are not fully comparable, as we have only calculated the cumulative disutility from derailments. The criterion line holds for the aggregated disutility from both derailments, collisions and fires. It is therefore an open question whether the railway system falls below this line. It is worth noting that the current individual risk criterion in Great Britain is $10^{-4}$ for the intolerable level and $10^{-6}$ as the broadly

\(^{72}\) Davidsson, Lindgren et al., 1997, p. 5-35

\(^{73}\) Davidsson, Lindgren et al., 1997, p. 8-13
acceptable level. The level $10^{-5}$ is set as a benchmark. A change in the individual risk criterion from $10^{-5}$ to $10^{-4}$ would raise the criterion line from 2.98 to 29.8 and it is obvious that we will fall well below this even with the collisions and fires included.

### 3.5 Summary

We will conclude this section here. It is apparent that the conclusions we draw depend upon the chosen level of the criterion for intolerable risks. If we choose $10^{-5}$ as the critical level, we will have reason to analyse the absolute risk levels further. The risks to which passengers are exposed might be above the criterion line. To find out if this is the case, we will need to carry out similar analyses for collisions as has been done for passenger train derailments. If we choose $10^{-4}$ as the critical level, the risks are well below the criterion line. Even so, further safety measures could be taken if their benefits outweigh the costs. This could be decided in economic cost benefit analysis. However, in order to enable economic cost-benefit analyses we also need an economic value for saving a statistical life. This is discussed in the next section.

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74 Railtrack, 2000b, p. D18
4. Valuing safety

4.1 Introduction

A common approach when evaluating societal projects is to use cost benefit analysis. The principle of cost benefit analysis is to measure and value the benefits and the costs of a project. If the present value of the benefits exceeds the present value of the costs, the project is profitable. The economic analysis is then based on the premise that the valuation of societal projects should, as far as possible, reflect the values the affected population puts on the effects. It is the individual’s willingness to pay, aggregated over the whole affected population, that constitutes the value of the project. This approach has gained acceptance in most industrialised countries and is used when new roads, railways or other infrastructure projects are evaluated. There is a long tradition in Sweden of using cost benefit analysis for the evaluation of projects in the road sector, such that it has been incorporated into the computer models used.

When a project has an impact on people’s health and safety, it must be measured and valued in some way. The National Road Administration has used standardised average values of safety for almost as long as they have used cost benefit analysis systematically. This average value is normally calculated as the sum of the average material costs of an accident, loss of production value and a value of safety per se. It is this value of safety that is the focus of this report.

In recent years, the National Rail Administration (NRA) has also started to use cost benefit analysis when evaluating its projects. There has, however, been a reluctance to use the valuation of safety estimated for the road context in the analysis of rail projects. The official policy of rail administrations around the world, not only in Sweden, has been that rail travel must be safe and that “safety is beyond price”. The search for even safer railways has led to the costs of safety measures per life saved normally being many times higher than the officially approved road safety value.

As part of this project, a study of people’s safety preferences was conducted. The aim was to see if there is any support for using a higher valuation of safety in the rail context than in the road context, and to study the people’s perceptions of different types of risk and their preferences for the prioritisation of safety investment. People’s perceptions of risk have been the object of research for many years. Psychologists have developed special “psychometric” models to explain the strength of people’s preferences and their behaviour in different situations. The possibility that differences in attitude to different risks carries over into differences in the valuation of safety measures, aimed at reducing those risks, has rarely been studied, however. In other words, it is possible that people might value a risk reduction in one context more than a comparable risk reduction in another.

A total of 38 group interviews were conducted. A combination of discussions and individual questionnaires were used to elicit the respondents’ preferences and attitudes to risk in different contexts. In the questionnaire, two different methods were used for estimating the strength of the respondents’ preferences. The results of the two methods are compared in this report. One of the methods was developed in a British study by Jones-Lee, Loomes et al.

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75 For a review of different approaches to valuing safety, see Jones-Lee, 1989, p. 3-30, Persson, 1992, Viscusi, 1993
76 Jones-Lee, Beattie et al., 2000
Professors Jones-Lee and Loomes carried out a study of differences in risk valuation between the Underground and road in 1995, on behalf of London Underground Ltd\textsuperscript{77}. The hypotheses was that people valued a risk reduction on Underground journeys more than a comparable risk reduction on road journeys. This would imply differentiated values of safety depending on the context. Their study showed that the willingness to pay (WTP) for preventing the loss of a statistical life on the Underground was about 20\% higher than the road equivalent\textsuperscript{78}. This study, here called the Underground study, was followed by a larger project commissioned by the Health and Safety Executive (HSE), together with the Department of Transport, the Home office and HM Treasury. The aim was to estimate “a ‘tariff’ of WTP-based values of safety for a number of contexts, namely: roads and public transport modes; fires; hazardous substances in the workplace; nuclear power; genetically modified organisms; and sport and leisure”\textsuperscript{79}. This rather ambitious aim had to be cut down for various reasons to the following contexts: rail, domestic fires and fires in public places.

This HSE study, conducted during 1998, improved on the methods of the Underground study. The questions developed for making trade-offs between safety in different contexts have also been used in the present study. This has enabled comparisons with the results obtained in the HSE study. However, the results presented here do not validate the results of the methods used in Great Britain. Problems with the methods used, are identified and discussed later.

\subsection{4.1.1 Measuring the value of safety}

Several different methods have been developed to measure the value of safety. There is a widespread and confusing use of different labels for different methods and the terminology is not very clear. It is therefore necessary to define the terminology used in this thesis. This section deals with some of the terminology but it is not an attempt to make a complete classification of all different methods\textsuperscript{80}.

Contingent valuation is a method for finding a monetary value of safety. In contingent valuation studies, respondents are asked how much they would be willing to pay for, for example, a small reduction in risk. The contingent valuation method is therefore often called a “willingness to pay”-method. There are also other variants of contingent valuation. The respondent can be asked to state freely the maximum price they are willing to pay. We call this “Open CV”. Alternatively, they can be asked whether a specified benefit is worth a given price. This question can be answered with “Yes” or “No” and is therefore called “Binary CV”.

There are other variants but they all have in common that they try to obtain a “direct connection” between a specified benefit and the cost for the individual\textsuperscript{81}. Contingent Valuation methods have been used to estimate values of road safety\textsuperscript{82}.

There are other methods that use non-monetary measures of safety benefits. These methods try to estimate a relative value of safety through comparisons of different risks, safety equipment, etc. Examples of these methods are “Risk–Risk Analysis” (RR), “Standard Gamble” (SG) or “Equivalence Questions”.

\begin{itemize}
  \item \textsuperscript{77} Jones-Lee and Loomes, 1995
  \item \textsuperscript{78} In the article from 1995, an Underground premium of 50\% was presented. This figure has since been revised due to new methods of aggregating the results.
  \item \textsuperscript{79} Jones-Lee, Beattie et al., 2000, p. 5
  \item \textsuperscript{80} For a review of different methods, see for example Jones-Lee, 1989 or Brooks, 1991, where further references can be found.
  \item \textsuperscript{81} Ivehammar, 1996, p. 19-44
  \item \textsuperscript{82} For an account of valuation of risks in different countries, see Elvik, 1995, ETSC (European Transport Safety Council), 1997
\end{itemize}
Risk-Risk analysis is a method where the risks are measured not in monetary terms but in terms of other risks. The respondents are asked to compare the risks of catching an illness, getting cancer or being injured or killed in an Underground accident, with for example the risk of dying in a car accident. This can be done in several ways. What is common is that it is “real” risk levels that are used as a starting or reference point in the questions. There are benefits of using the risk of fatal road accidents as a yardstick. This risk is well known to people. Road fatalities are one of the most common causes of premature death in industrialised countries and furthermore the deaths are often immediate, which simplifies the analysis.

In Standard Gamble, two alternatives are compared. One has a certain outcome, the other has a given probability p of a fully healthy life and a probability 1-p of death. In a series of questions, p is varied until the respondent is has no preference between the alternatives. The main benefit of this approach is that it handles uncertainty in a direct and clear way. The drawback is that respondents can find it difficult to rate the alternatives and give rational and consistent answers.

“Equivalence Questions” has no reference to probabilities, risks or uncertainty. It is a straightforward way of asking the respondents to choose between two alternatives with certain outcomes. The respondents are asked to chose between one safety measure that prevents X fatal accidents and another measure in a different context where X±Y fatalities can be prevented.

In the present study, Risk-Risk and Equivalence Questions have been used. The Risk-Risk questions were developed within the project, whilst the Equivalence Questions were developed and used in Great Britain. It is therefore possible to make interesting comparisons with the results of the British studies.

4.1.2 Problems when estimating the value of safety

Jones-Lee, Loomes et al. have demonstrated the problems of asking people for their willingness to pay for marginal risk reductions when the initial risk is already very low. People have great difficulty in understanding and handling the risk concepts used and they are not able to differentiate between different levels or changes in risk levels. The questions are difficult enough to demand considered answers. This can be difficult to achieve using, for example, mail-back surveys. Jones-Lee, Loomes et al. therefore used combinations of focus groups and questionnaires and found that a feasible approach.

Because of the aforementioned problems, it is also problematic to use direct methods such as revealed preference or contingent valuation to estimate people’s preferences. An indirect method that relates the value of a safety measure in one context to the value of a comparable safety measure in another context can be applied, thus reaching relative values. There are today officially approved values of safety for use in road safety analysis, which provide a yardstick for the value of safety in other contexts.

There are three main issues for the comparison of safety in different contexts. These relate to what will be referred to as strategic bias, “confounding by scale” and base-line risk effect. The first term, “strategic bias”, is used to denote the tendency for respondents to give answers that...
they think, in some way, would benefit themselves. A strategic bias is for instance seen when respondents that have a relatively high car mileage and seldom use public transport tend to value road safety higher than public transport safety. People have differing travel patterns, use different transport modes and travel differing distances, which makes it necessary to test whether these factors influence the results.

As stated earlier, the valuation of societal projects should, as far as possible, reflect the values the affected population put on the impacts. Different people and groups of people have different values. It is the sum of the value all individuals put on the impacts that should be compared with the costs of the project. The average Stockholm citizen would normally use the metro to a larger extent than would someone living on the countryside. They might have different values for Underground safety. If the government funds an Underground safety measure, then it is the value that the whole population put on the effects that should be used. To calculate this it is necessary to control for the differences between groups and to calculate a value based on the proportions of people in the various groups.

Large accidents often evoke unpleasant feelings throughout society, and the media often devotes a great deal of attention to them. It has sometimes been argued that the prevention of these accidents should be valued proportionately higher than the prevention of single fatality accidents. This has commonly been called a “scale effect”. The research in Great Britain has shown that this effect does not exist to the extent that was presumed. People do not value the prevention of large-scale accidents proportionately more than the prevention of small-scale accidents, per life saved.

However, it is a fact that road accidents tend to have few fatalities in each accident and, for example, railway accidents can be relatively serious, with many fatalities. This can affect the respondent’s valuation of safety in the different contexts. The second term, “confounding by scale”, refers to the problems that arise when the respondents are unable to separate the scale and the context when answering the questions. The respondents might value, for example, railway safety higher than road safety, because railway accidents tend to involve more fatalities than road accidents. Therefore, this “confounding by scale” effect must be tested for and controlled.

The third term, “base-line risk effect” relates to the fact that the initial risks differ between, for example, different transport modes. The probability of a fatal accident is several times higher for a 100km trip by road than a 100km trip by railway. It is possible that this fact influences respondents’ answers.

The standard willingness-to-pay theories predict that the value of a good should decrease when increasing amounts of this good are provided. Weinstein et al. have shown that utility theory predicts a higher valuation of safety when the base-line risk is high. The valuation is then not only dependent upon the change in risk but also on the initial risk level86. Clearly, if you have a very large quantity of a specified product, let us say chocolate bars, then the value to you of yet another bar is very low, whereas if you are offered any other candy product, your willingness to pay for this might be relatively high, provided that you have very little of this product. Similarly, safety measures aimed at activities where the risks are relatively low (you have “a lot of safety”), such as railway transports, should receive lower value than safety measures aimed at activities where the risks are higher, such as road transport.

There are several empirical studies that support these theoretical predictions87. However, the issue is not uncomplicated: other studies point to a reversed relationship. In some studies the

86 Weinstein, Shepard et al., 1980
87 Horowitz and Carson, 1993; Savage, 1993; VanHoutven, 1997; Covey, 2001
respondents were valuing safety measures in terms of the risk reduction in proportion to the actual size of the problem. A safety measure that prevented 900 out of a 1000 deaths from a disease per year were given a higher value than a measure that prevented 900 out of 10000 deaths per year. This result points to a decreasing value of safety when the base-line risk is increased, which is contrary to the prediction of the theories.

There are also other patterns. In the extension to the British study, Covey found that the respondents mistakenly believed that they would benefit more from a safety programme that targeted a higher base-line risk than from a programme that addressed an area with lower base-line risk, even though the nominal risk reductions were the same\textsuperscript{88}. These types of misperceptions have to be addressed and handled in the data collection phase. The different patterns that have been found point to the need to test whether the respondents are sensitive to differences in base-line risk.

Furthermore, there is a problem of dealing with altruism in people’s preferences for risk reductions. Two different forms of altruism have been discussed, and the effects on the willingness-to-pay approach depend on what form is encountered. “Pure” altruism refers to individual A’s inclusion of individual B’s utility. This means that individual A respects, or accepts individual B’s valuation of safety. “Safety focused” altruism refers to individual A’s valuation of the safety of individual B. If pure altruism is assumed, including the altruistic values would be a form of double counting\textsuperscript{89}. They should therefore not be included. If, on the other hand, “safety focused” altruism is assumed, then the altruistic component should be included\textsuperscript{90}. In this study, “pure” altruism is assumed and the issue is not addressed further.

An attempt to validate the results is also made. The answers to the equivalence questions are compared to the answers to the risk-risk questions, both on an aggregated and individual level.

4.2 State of the art and piloting

This study builds upon an earlier study conducted within this project\textsuperscript{91} and on the work done in Great Britain by Jones-Lee, Loomes et al\textsuperscript{92} in 1997-1998, regarding relativities in the valuation of risk. Their work included extensive piloting and testing of the various instruments used with the objective of ensuring robust and internally consistent results. A follow-up study was also conducted in Great Britain in January 2000\textsuperscript{93}. Some comparisons are made with the results of the follow-up study in section 4.5. A short review of the earlier pilot study and the work done in Great Britain in 1998 follows below.

4.2.1 The earlier pilot study

An earlier study within this project used a mail-back survey to explore the subject. The object was to evaluate some of the possible arguments for differentiating between safety programmes and test whether there were any grounds for using different values for preventing a fatality depending on the context. The study was conducted in Stockholm in 1998 and a non-random sample of 150 people received the questionnaires.

\textsuperscript{88} Jones-Lee and Loomes, 1999; Covey, 2001
\textsuperscript{89} Bergström, 1992
\textsuperscript{90} VanHoutven, 1997; Covey, 2001
\textsuperscript{91} Johansson, 1998c (The author’s bachelor name was Johansson.). The report is also reprinted in the licentiate thesis, Bäckman, 1999.
\textsuperscript{92} Jones-Lee and Loomes, 1999
\textsuperscript{93} Jones-Lee, Burton et al., 2000
The study used both closed-ended and open-ended questions in combination to collect information on the arguments that people might use when valuing different safety programmes. Dimensions such as degree of control or possibility of influencing the level of risk, degree of voluntariness of the risk, and responsibility for safety were studied. The respondents were asked to state whether they agreed or disagreed with statements describing properties of the dimensions in the different contexts. They were also asked questions on their attitudes to being involved in accidents in different contexts and the motivation for their answers in open-ended questions.

The results of the study were largely comparable to the findings of the London Underground study. The use of different arguments for differentiating between different risks was on the same level in Sweden as in Great Britain. This was somewhat encouraging and it also supported the belief that the following research could be made comparable. No attempt was made to estimate the magnitude of the difference in the respondents’ valuation of for example rail safety compared to road safety. There were apparent problems with the questions used for this and, furthermore, the sample was not a true random sample.

4.2.2 The British study

In the British study, the following four hazardous contexts were studied: road accidents, rail accidents, domestic fires and fires in public places. The methodology was developed in a series of three pilot studies preceding the main study. The work focused on the underlying factors in the decisions taken by respondents, initially concentrating on which of the “so-called ‘psychometric’ dimensions people would endorse as most important for differentiating between hazard contexts and prioritising safety expenditure” \(^94\). Up to 14 dimensions were tested in the first pilot study. These dimensions were translated into arguments for differentiating between the values of different safety programmes. The number of arguments was then reduced and a subset of the 14 was finally used in the main study. The procedure of the main study was as follows.

Introduced to the four hazard contexts, the respondents were asked to rate their chances of dying from each hazard. Factors influencing the risks were then discussed.

Four safety programmes, all preventing the same number of fatalities but in different contexts, were then presented and arguments for differentiating between them, and not treating them as equal, were discussed.

The respondents then answered two questionnaires, called “Safety Priorities Questionnaires” (SPQs). These were designed to ask the respondents about their arguments for prioritising and differentiating between the safety programmes. This led to a discussion and an exercise involving individual ranking of the safety programmes.

In the final step, the probability or strength of the difference between the safety programmes was estimated. The respondents were faced with a table where they were asked to choose between programmes that prevented a given number of fatalities in one context and a programme that prevented a given number of fatalities in another context. The number of deaths in the two contexts was then changed and the design of the question allowed the respondent to state when the programmes were of equal value. This type of questioning is called “Equivalence Questions”.

\(^{94}\) Jones-Lee and Loomes, 1999, p. 14
A more complete description can be found in the final report of the British study\(^95\). A form of the steps in the study described above is also carried through into the main study of the present project. The difference is that the focus is somewhat less on the underlying factors and arguments for prioritising.

4.2.3 Development work and piloting

It was decided at an early stage that a combination of focus groups and questionnaires should be used, a decision based on the positive experiences of this approach in the British studies. Several benefits were obtained by using this method. The group discussions allowed the participants to familiarise themselves with and evaluate different arguments for discriminating between different risks. In particular, the different properties and the differences between risks in different contexts were discussed. The participants were then helped by this discussion when answering the questionnaire. Many stated that it would not have been possible to answer the questionnaire without the preceding discussion.

The development of the questionnaire used in the present study started from the experiences and the findings of the pilot study reviewed above. Contact was made with Professor Jones-Lee and Professor Loomes. The project was presented and the questionnaire methods discussed at a meeting in April 1999. The types of equivalence questions developed in the British study were kindly provided by Jones-Lee and Loomes for use in this project, enabling comparison with the results of the British study.

The equivalence questions were refined, the design of the questions was modified slightly in order to enhance clarity, and a new form of risk-risk question was developed. This used grids\(^96\) to describe and illustrate risks. The respondents also stated their preferences using grids. The purpose of these questions was to test the two different types of methods used and hopefully to enable validation of the results.

The preliminary plan was to let a consulting company with experience of conducting group interviews collect the data. After discussing this with Jones-Lee and Loomes, the decision was taken not to engage any external consultants. Their experience of this was that it leads to an important loss of quality and control. The possibility that the author might influence the respondents towards a certain view was seen as of minor concern in comparison with the impact of the inability to clarify and help the respondents if consultants were used.

4.2.3.1 Pilot studies

12 group interviews were held to gain basic experience of group interviews, to explore the possibilities for the form of data collection, to test the influence of the discussions on the answers to the questionnaires, and to test out the questions in the questionnaires. This work therefore had different phases.

The first two groups had an exploratory character, where the discussions were open ended and not heavily moderated. General aspects of risks and hazards were discussed. This gave information on the aspects most likely to evolve in a discussion and on what aspects might not come to mind when thinking about risk. For example, it was obvious that the size of the risks concerned everybody, but that responsibility for safety was not an aspect that would normally come up in a discussion.

\(^{95}\) Jones-Lee and Loomes, 1999, Jones-Lee, Loomes et al., 1999

\(^{96}\) For an example, see Appendix 8, p. 249.
The following two groups were somewhat more moderated and more direct questions were posed to the group for discussion. Alterations were made to the questionnaire subsequent to every meeting in order to enhance clarity and workability. In this second phase it appeared that the pair-wise ranking questions used were not giving satisfactory results. In these questions, respondents were asked to rank the fear they perceived in a set of pair-wise choices of different accidents. The questions enabled respondents to state the strength of their preferences. The lack of internal consistency of the answers and the problems of correlating the answers to the other types of questions in the questionnaire led to the replacement of these questions with a simpler form of ranking questions.

The third pilot phase involved four groups. The questions to be used to moderate the discussion were refined and the variety of questions previously used was brought down to three themes around which the discussions evolved. In this third pilot phase, the workability of the ranking questions was tested. The respondents were first asked a quite straightforward question on the fear of four described accidents, all with the same number of fatalities and with the only difference being that they occurred in different contexts. They were also asked to motivate their rankings in an open-ended question. In a follow-up question, the respondents had to rank four separate safety programmes, described as aimed at preventing the accidents described. The respondents also had to motivate their rankings on this question.

In the fourth and final pilot phase, a random sample was used. During this phase, some internal inconsistencies in the risks presented to the respondents were discovered and changes had to be made to the risk-risk questions. The general design of the risk-risk questions remained unchanged but the values used were modified. Calculating the results also revealed that the respondents did not understand the equivalence questions correctly. In particular, it was clear that the respondents did not manage to disregard the baseline risks in different contexts. This led to a new way of introducing the questions. Certain clarifications had to be made and the focus on the effects of the different safety programmes was stressed much more heavily. The final version of the questionnaire can be found in Appendix 8.

4.3 The sample and procedure in the main study

A consulting company was used to recruit the respondents to the group interviews. A random sample of around 1000 persons was taken from a register of the Swedish population. The company interviewed the respondents in order to get a sample corresponding to the Swedish population with respect to sex, age and income. It was also instructed to try to ensure a gender balance in every group. Eight people were recruited for every group, but the average group size was six. As few as three and as many as nine also occurred. The company also recruited the respondents to the four groups in the fourth pilot phase.

26 group meetings were held. 16 of these were in Stockholm and 10 in Arvika. Arvika is a small municipality in the western part of Sweden with 26,500 inhabitants. A major railway line passes through it, connecting Stockholm with Oslo, the capital of Norway. There is some commuting to Karlstad, the nearest large town, 75 kilometres away, with many workplaces and a university. One of the purposes of choosing a smaller town was to ensure a wide distribution of travel patterns. In Stockholm, the average citizen is familiar with metro, bus and train travel. In Arvika, on the other hand, it is unusual to use public transport at all, and many people have never travelled by metro. The influence of these differences on the responses in the different samples has been tested.

Every group meeting lasted for around 90 minutes and started with a 30 minute discussion on various aspects of risk. After a short break for refreshments, the rest of the time was used for answering a questionnaire.
4.3.1 The discussions

Three main questions were posed to the participants in the discussions. These were:

1. What risks do you face in your daily life?
2. What are the differences between these risks
3. If you could reduce any of these risks, which would you choose?

The first question was answered quite easily and many different risks were discussed. The second question proved to be somewhat more difficult and there were some differences in the way different groups managed to answer it. As it was necessary for the groups to have a common set of arguments the discussions were not stopped until all relevant dimensions had been discussed. These were the differences in degree of control, voluntariness of the risks and differences in responsibility towards safety.

Typically the discussions also included risk profiles, differences in how risks are perceived, and the size of the risks. A very common answer to the last question was that the first risk participants wanted to reduce was that of being assaulted and the second was the general risk from traffic. This question was not put to all groups, as there was a shortage of time in some cases.

4.4 The questionnaire and the methods used

Four different contexts were studied. The questions concerned the risks of being killed in a railway accident, an accident on the metro, in a domestic fire or in a road accident. The first three contexts are all compared to the road context. The differences between the risks in the different contexts were discussed, as described in the previous section, before the respondents answered the questionnaire, in which the differences were approached in three different ways.

4.4.1 Ranking questions

The respondents were first asked to rank the contexts studied. The first question asked for the context to be ranked with respect to the fear it provokes. Four different accidents in four contexts were described, all alike, with the same number of fatalities in each accident, the only difference being the context. The respondents were asked which of the accidents they felt was worst and to rank that as 1, rank the second worst as 2, etc.

In a follow-up question, the respondents were asked to rank the accidents according to the order in which they would like to try to prevent them. The cost of preventing the accidents was equal and the respondents were told that it was not certain that all four accidents could be prevented. In addition to the text in the questionnaire, the respondents were told a story as an analogy, in order to summarise the discussions and show an explicit trade-off between different aspects of risk. The story was as follows.

_________________________________________________________

"Imagine a group of people heading for a nice weekend on an island just off the coast. They have loaded their sailing boat and are sitting in it at the quayside just before leaving, having some wine or bear whilst listening to the sea weather report on the radio. The report warns of gales and bad weather, but the group decides to leave anyway as they are just about on their way. When they have been sailing for an hour, they realise that they have forgot the sea map. They carry on, as they have sailed these waters a couple of times before. When they reach

______________________________

97 Risk profiles deal with the differences between, for example, risks associated with air travel that have low probability but serious consequences, and risks from playing football that have high probability but limited consequences.
more open water the weather changes quickly. Really bad weather makes the boat capsize and five people drown.

Another accident happens in a totally different context. Several commuters are on their way to work on a rural bus service. They are sitting there as usual, reading their newspapers, when suddenly the bus runs off the road and crashes into a cliff, killing five people.”

A short discussion around the two accidents and the differences between them followed, and the respondents were then told to think for themselves around the four accidents described in the first question and rank the order in which they would like to prevent them. This gave different answers and showed that the respondents were able to take account of aspects other than the dread factor.

These first two questions served as ice-breakers and were designed to summarise the discussion and allow the respondents to rehearse the arguments for differentiating between the contexts. They forced them to think about the differences and to draw conclusions on their preferences for the ranking of the contexts. This is a first step that precedes any decision about the intensity of an individual’s preferences and, by letting the respondents answer these questions separately, it allows the answers of the following questions to be checked.

### 4.4.2 Equivalence Questions

Two different methods were then used for estimating the strength of the relativities in the valuations. So-called ”Equivalence Questions”, previously used in a British study, were used in the questionnaire. The design was modified in order to enhance clarity. The use of the same type of equivalence “tables” enables interesting comparisons with the results from the British study. Questions were set up to compare safety programmes aimed at preventing fatalities in pair-wise comparisons of contexts, namely, rail v. road, metro v. road and fire v. road. The questions can be found in Appendix 8, questions 14-19.

The principle of the Equivalence Questions is that the respondents are asked to choose between a safety programme that prevents a given number of fatalities in one context and one that prevents a given number of fatalities in another context. The numbers of deaths in the two contexts are then changed and the design of the question allows the respondent to state when the safety programmes are of equal value. The focus in these questions is on the consequences and the respondents were explicitly asked to disregard the probabilities.

In a set of 19 choices, the number of fatalities in each context that could be prevented is systematically changed. Starting with, for example, 100 fatalities in railway accidents v. 15 fatalities in road accidents, the next choice is between 70 fatalities in railway accidents v. 15 fatalities in road accidents and then 50 fatalities in railway accidents v. 15 fatalities in road accidents. The numbers are changed so that the 10th choice is between 15 fatalities in railway accidents and 15 fatalities in road accidents. The figures are then reversed so that the number of preventable rail fatalities is constantly 15 and the road figure increases up to 100. The table is thus neutral and the respondents have an equal opportunity to give priority to both contexts. For each row, the respondents are asked to state whether they prefer the left or the right alternative or if they find it “hard to choose”. Respondents are able to state “hard to choose” for a series of the choices and so give a range where they find the alternatives “equal”.

The questions were then also set up to test if the respondents were sensitive to the scale of different accidents. The hypothesis was that the respondents do not want to give priority to safety programmes aimed at preventing large-scale accidents if the costs per life saved exceed the costs of safety measures preventing small-scale accidents, i.e. the scale of the accident is not a basis for differentiating between safety measures. Respondents here faced a choice
between, for example, preventing 100 fatalities in large-scale railway accidents v. 15 fatalities in small-scale railway accidents. The figures were also here mirrored around a choice of preventing 15 fatalities in large-scale railway accidents v. preventing 15 fatalities in small-scale railway accidents.

The benefit of these questions is that they isolate the context or the scale factor without being too fabricated. Secondly, the questions are not leading the respondents as they are neutral in their design and allow the possibility of giving just as much priority to one context as to the other. Thirdly, they give the strength of the respondents’ preferences for one context over the other and enable aggregation to a single measure of the population preference.

4.4.3 Risk-Risk questions

Furthermore, a kind of Risk-Risk question has been developed within the project. These questions display the risk levels more explicitly by using a grid to illustrate the risks. The risks for a given person who uses two different transport modes were marked in the grid and the respondents were asked to choose between safety equipment that reduces the risks for one transport mode and different equipment for the other mode, both giving the same risk reduction. In a follow-up question they were asked to mark in a grid the size of the risk reduction in the non-preferred context that would be of equal value as the risk reduction in the preferred context. Four sets of questions were set up comparing rail v. road in two sets of questions, followed by metro v. road and finally fire v. road.

The respondents are presented with the risks faced by a person who commutes a given distance to work by, for example, train and also uses a car and drives a given number of kilometres every year. The risks to which this person is exposed are described in a grid with 100,000 boxes. The respondent is asked to imagine that they are this person. They are then told that they are about to buy a piece of personal safety equipment that reduces the risk by an amount corresponding to three of the marked boxes. The equipment can be installed in one of the contexts and they are then asked to choose in which of the contexts they want to reduce the risks / install the equipment.

If the choice is between rail and road, and the respondent chooses rail, they then continue to a follow-up question where they are asked to mark in a grid the risk reduction in road transport necessary for the alternatives to be of equal value to them. If they choose road, they continue to another follow-up question where they can state the risk reduction needed in rail transport for the alternatives to be of equal value. In other words, each respondent only answers one of the two follow-up questions in the four sets of context comparisons. With this question structure, the respondents first face a direct choice between different safety measures and are then asked to state the strength of the relationship between them.

In the follow-up question the square net is enlarged, or blown-up, and only a fraction of the 100,000 squares are shown. These squares are shown 100 times larger in size and a smaller scale grid is superimposed, for two purposes: firstly to make it easier to mark the answers, and secondly to give the respondents the option of marking fractions of a square, each square corresponding to risk of 1 in 100,000.

This question also made it possible to vary the initial risks, and this was done for one of the contexts studied, namely rail. In the first of the rail-road questions, the initial risks were equal over a ten-year period. This equality was achieved through adjusting the road and rail mileages so that the differences in risks per kilometre were incorporated. In the following set of questions, the base-line risks were different. The risks from the road mileage were four times the risks from the rail mileage, calculated over a ten-year period.
The benefits of these questions are that they are explicit as regards the risk levels and that they give a clear picture of the risk reduction in the different options. Another benefit is that they can be analysed in the same way as the equivalence questions and this enables comparisons and validation of the results.

4.4.4 Methods for analysing the data

The analysis of the data includes aggregation and four different tests. The aggregation of the equivalence questions and the risk-risk questions to sample averages was done using a method developed in Great Britain by Jones-Lee, Loomes et al.98. This method meets a number of requirements that any aggregation method must meet. The procedure is as follows.

As described above, the design of the equivalence questions allows respondents to give a range within which their answer lies. In order to aggregate the results over the whole sample it is necessary to calculate a single figure for the respondents’ trade-off between the two contexts. This figure is calculated with a simple geometric method.

The respondents’ valuations of safety can be expressed in a diagram. The quantity, i.e. the number of lives saved, is set on the x-axis, and the value, or price on the y-axis. The price per unit (value per life saved) is then the slope $\beta$ of the line in the diagram. The difference in this study is that instead of using a monetary valuation on the number of lives that can be saved in one context, the “price” is expressed in terms of the number of lives that can be saved in another context.

However, because respondents can give a range, there will be two lines in the same diagram, from which a single line must be estimated. This is calculated as the line in the geometric centre of the two plotted lines. The slope $\beta$ of this line is the respondents’ valuation of safety in one context expressed in terms of safety in another context.

From this, an aggregated average value can be calculated. The most intuitive method would perhaps be to calculate the average value of the individual $\beta$-values. For reasons given in the paper by Jones-Lee, Loomes et al.99, this method will give a result that does not fulfil a number of reasonable requirements. Instead of calculating averages of the individuals’ $\beta$-values, the individuals’ highest ranked context is assigned the value “1” and the lowest ranked context a fraction of 1, calculated from the slope $\beta$.

The answers to the equivalence questions can be expressed as “prefer the prevention of 15 fatalities on rail over the prevention of 17 fatalities on the road”. The rail context is in this example the highest ranked context and given the value 1. The road context is given the value $15/17=0.88$. This is done for every individual. Assume for example that individual two prefers road to rail. They have answered that they “prefer the prevention of 20 fatalities on rail over the prevention of 15 fatalities on road”. For this individual, the road context is assigned the value 1 and the rail context $15/20=0.75$. The aggregated premium for context A over B is then calculated as the average value of context A over the average value of context B. In the example above, the value would be $(1+0.75)/(1+0.88)=0.93$. This should then be interpreted as a lower value; the value of rail safety is 7% lower than the value of road safety. A full description of the method for aggregating the results can be found in the technical report100.

98 This method is described in detail in the paper by Professor Jones-Lee, Loomes et al (Jones-Lee, Loomes et al., 1998). It can also be found in the technical report on the risk valuation study presented here.(Bäckman, 2000)
99 Jones-Lee, Loomes et al., 1998
100 Bäckman, 2000
The answers to the risk-risk questions can also be interpreted as the willingness to pay for safety in one context expressed in terms of safety in another context. This means that the risk-risk questions can be calculated with the same method as the equivalence questions. The difference is that the respondents can only give one relation between the contexts, not a range, and it is therefore not necessary to make any geometric calculations to get a single value for each respondent.

The first test is to see if there is a strategic bias in the individual answers to the equivalence questions. The purpose of this is to test the hypothesis that the respondents have given answers that they believe in some way would benefit them or their household. If this is true, respondents with a high public transport mileage and a relatively low road mileage will tend to give higher priority to public transport safety than to road safety. To test this, the individual premium is first calculated. For individual 1 in the example above, the individual premium would be 1/0.88=1.136. Every individual thus gets a single figure, their individual answer to how much more safety in one context is worth compared to safety in another context. This individual premium is used to make pair-wise correlations with the individual’s answers to the background questions, regarding, for example, public transport mileage, access to a car, etc. These correlations indicate if there are any strategic biases. If for example individuals with a high rail mileage tend to give a higher premium to rail safety than individuals with a low rail mileage, then there is a strategic bias.

The second test is to see if there is any effect of “confounding by scale”. Three equivalence questions were set up to estimate the effect of the scale of accidents. The general hypothesis is that respondents do not value the prevention of large-scale accidents proportionately higher than the prevention of a corresponding number of fatalities in small-scale accidents. It is possible that respondents that value rail safety higher than road safety do so, because, contrary to the hypothesis, they value the prevention of large-scale accidents proportionately higher than the prevention of small-scale accidents. This effect might not be discovered if we only look at the sample averages. It will therefore be necessary to correlate the individual answers to the scale questions with the individual answers to the context questions. This was done in a way similar to the test described above. The respondent’s individual premium is calculated for both the “rail v. road” context question and the “large rail v. small rail” scale question. If individuals that give a high premium to rail safety, compared to road safety, also give a high premium to preventing large rail accidents compared to preventing small rail accidents, and vice versa, then we will have a “confounding by scale” effect. This means that the respondents have not been able to separate the scale and context aspects in the equivalence questions.

The third test is to see if the respondents are sensitive to the differences in base-line risk. The fact that the average citizen has a higher probability of dying in a road accident than in a rail, metro or fire accident can affect the valuation of safety in the different contexts. The standard willingness-to-pay theories then predict that the willingness-to-pay for safety increases with increasing levels of base-line risk. As stated above, two of the risk-risk questions were set up to enable this test. Both these questions concerned rail safety versus road safety.

In the first of the risk-risk questions, the road and rail risks were equal. In the second, the road risks were four times higher than the rail risks, calculated over a ten-year period. The hypothesis was that respondents would give a higher premium to rail safety in the first question, where the risks are equal, than in the second where the rail risks are lower. The

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101 They compare a large-scale railway accident with many fatalities, with a small-scale road accident with only one or a few fatalities.
effect of the change in base-line risk is tested by calculating the individual premium in the two sets of questions. Regression analysis is then used to test the relationship between the individual answers to the first and the second sets of questions.

The fourth and final test is an attempt to validate the answers to the equivalence questions. This is done by comparing the individual answers to the “rail v. road” equivalence question with the answers to the “rail v. road” risk-risk question. The different types of questions can, as stated above, be calculated and aggregated with the same method. It is therefore possible to compare the individual answers to the different questions. If the respondents that prioritise rail over road in the equivalence questions also do so in the risk-risk questions, and vice versa, if the respondents that prioritise road over rail in the equivalence questions also do so in the risk-risk questions, then the results can be seen as confirmed. If on the other hand, the individuals change preference between the different types of questions, then we have reason to be worried. The causes of this change in preference must then be analysed.

The difference between the equivalence and the risk-risk questions is one of perspective. In the equivalence questions, the respondents were asked to state what they think, from their viewpoint, that the government should do. In the risk-risk questions, they were asked to state what they would do themselves if they had a specified travel pattern, other than their present one. In this way, they were asked to imagine that they in fact were someone else, or at least had a different travel pattern. This difference can influence the way the respondents’ reason when they answer the questions.

4.5 The results

4.5.1 Background data

Information on background data can be found in the technical report\textsuperscript{102}. The aim of finding respondents from all age groups, with an equal proportion of men and women, was achieved. The distribution of income was also satisfactory.

4.5.2 Ranking questions

The responses to the ranking questions revealed that domestic fires were perceived to be the worst type of accident 61% of the respondents. The least bad type of accident seemed to be road accidents with 45% ranking it as number four. In this analysis, the answers to the fourth pilot study have been included as there were no differences in the question or presentation of the questions up until this question. Both the columns and the rows sum to 100%. Analysis of the answers reveals the following.

\begin{table}
\centering
\begin{tabular}{|l|c|c|c|c|}
\hline
\textbf{Priority} & \textbf{Rail} & \textbf{Fire} & \textbf{Road} & \textbf{Underground} \\
\hline
First & 12.7\% & 60.3\% & 7.9\% & 19.1\% \\
Second & 23.8\% & 18.5\% & 22.8\% & 35.5\% \\
Third & 34.9\% & 14.3\% & 24.3\% & 26.5\% \\
Fourth & 28.6\% & 6.9\% & 45.0\% & 19.1\% \\
\hline
\textbf{N} & 189 & & & \\
\textbf{Missing} & 6 & & & \\
\hline
\end{tabular}
\caption{Answers to ranking question (Q11).}
\end{table}

\textsuperscript{102} B"ackman, 2000, Appendix 1
This result was somewhat overturned in the follow-up question where the respondents were asked about their priorities for preventing the accidents. The analysis is here based on the 166 respondents in the main study. The reason for this is that there was a major change in the way this question was presented between the fourth pilot phase and the main study. The actual texts give to the respondents were not changed, but in addition to the text the respondents were given an analogy, described on page 121. The analysis of the answers to this question shows the following.

<table>
<thead>
<tr>
<th>Priority</th>
<th>Rail</th>
<th>Fire</th>
<th>Road</th>
<th>Underground</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>21.7%</td>
<td>32.1%</td>
<td>16.4%</td>
<td>32.3%</td>
</tr>
<tr>
<td>Second</td>
<td>37.3%</td>
<td>12.6%</td>
<td>18.9%</td>
<td>31.7%</td>
</tr>
<tr>
<td>Third</td>
<td>24.8%</td>
<td>28.9%</td>
<td>23.3%</td>
<td>24.2%</td>
</tr>
<tr>
<td>Fourth</td>
<td>16.2%</td>
<td>26.4%</td>
<td>41.5%</td>
<td>11.8%</td>
</tr>
</tbody>
</table>

Table 22. Answer to ranking question (Q12).

As can be seen, highest priority is given to preventing metro accidents, followed by rail, fire and road accidents in that order. Another way of looking at the answers is to count the occurrence of the different orderings. There are 24 different possible orderings of the alternatives. If we group them into orderings preferring the prevention of public transport accidents over those on the road and fire accidents we find that 44% gave priority to preventing both metro and railway accidents over the others and that only 24% wanted to prevent both the road and the fire accident before the public transport accidents. The remaining 32% have other rankings not following the division made here.

If we now compare these figures with the British study, we find some differences. In the British study, respondents were asked to rank safety programs that all prevented 10 fatalities. The contexts studied were road, rail, domestic fire and fire in public places. The ranking was done at the end of a “Safety Priority Questionnaire”, aimed at eliciting what arguments the respondents found relevant when prioritising safety measures. The British study therefore was more open. The second ranking question in the present study is similar to the ranking question in the British study. The rankings in the British study were as follows.

<table>
<thead>
<tr>
<th>Priority</th>
<th>Road</th>
<th>Public Fire</th>
<th>Domestic fire</th>
<th>Rail</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>75.4%</td>
<td>31.5%</td>
<td>33.1%</td>
<td>17.7%</td>
</tr>
<tr>
<td>Second</td>
<td>12.3%</td>
<td>27.7%</td>
<td>24.6%</td>
<td>17.7%</td>
</tr>
<tr>
<td>Third</td>
<td>8.5%</td>
<td>35.4%</td>
<td>21.5%</td>
<td>30.0%</td>
</tr>
<tr>
<td>Fourth</td>
<td>3.9%</td>
<td>5.4%</td>
<td>20.8%</td>
<td>34.5%</td>
</tr>
</tbody>
</table>

Table 23. Ranking of safety programmes in British study. Only the columns sum to 100%.

The metro context was not included in the British study but the figures show both similarities and big differences. The priorities for domestic fires are broadly similar to the figures obtained in the present study, but in the British study the road context was given a very high priority with over 75% of the respondents selecting the road safety programme as their first choice. The explanation is that the base-line risk is influencing the answers. There is a strong correlation between base-line risk and household benefit in the British study. The respondents stated that they prioritised the road safety programme because they believed that their household would benefit from it more than from the other programmes. This implies that the respondents have made the mistake of thinking that, because the base-line risk is bigger in the
road context, the household would in some way have a bigger benefit of a risk reduction there even if the risk reduction is equal in size in another context.

This pattern was not found in the present study. It was stressed in the presentation of the question that the probability of different accidents was irrelevant and that the costs of the safety measures were the same irrespective of the context. Further, the respondents were asked to concentrate on weighing dread against other risk attributes such as the voluntariness of the risks, the degree of control and the distribution of responsibility for safety. In this way, the base-line risk did not influence the answers in the way it did in the British study. Another difference is that the British respondents were allowed to state two or more safety programmes as equal. This explains why only the columns and not the rows add up to 100%.

4.5.3 Equivalence questions

4.5.3.1 Context effects

The answers to the equivalence questions broadly follow the answers to the ranking questions. The aggregation of the equivalence questions gave the following result.

<table>
<thead>
<tr>
<th>Question</th>
<th>Contexts</th>
<th>Context premia</th>
<th>All answers</th>
<th>Interpreted included</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>Rail vs Road</td>
<td>1.03</td>
<td>1.02</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Underground vs Road</td>
<td>1.04</td>
<td>1.04</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Fire vs Road</td>
<td>0.99</td>
<td>0.99</td>
<td></td>
</tr>
</tbody>
</table>

Table 24. Answers to equivalence questions (Q14-16).

This means that the respondents’ value a risk reduction for metro travels 4% higher than a comparable risk reduction for their road travels. The corresponding railway value is 2% and the fire premium is 1%. These figures are calculated for the whole sample. The method of aggregating the results is described in section 4.4.4 and in the technical report, appendix 4.

There are two different figures for each context in the table above. The reason for this is the following. The answers to the questions can be put in to three categories. The first category contains the answers that are correct in all aspects. Some minor faults are allowed, but generally, the answers do not give any reason to doubt that the respondent has understood the question.

The second category contains the respondents whose answers for some reason are not completely inaccurate but raise doubts as to whether the respondent has understood the question. A typical example is a respondent who in a choice between safety programmes for rail or road always chooses road, even if this means that they prefer to save 15 lives on the roads rather than 100 lives in railway accidents. The reason that the answer has been put in this category is the belief that the respondent has not fully understood the implications of the choice he has made. This category also includes answers where the respondent appears to have chosen the wrong column when indicating their preferences have been included. Typically, some persons seem to have made the mistake of ticking “hard to choose” when they actually intended to prioritise the right-hand option. This was a problem of the design of the question and might have been prevented by a colour scheme or other devices that made the layout clearer.

The third category contains the answers that cannot be interpreted in any way. It is obvious that the respondent did not understand the question and that the answers cannot be used at all.
In such answers the respondent might, for example, have chosen 100 rail over 15 road, then 15 road over 70 rail, and then switched back, choosing 50 rail over 15 road. Other examples are where the respondents have only marked two or three rows in the tables.

The first category answers are totally correct or did not raise any doubts as to whether the respondent had understood the question. These answers correspond to the first column with “OK answers only” in Table 24. Around 10% of the 166 answers were omitted. These omitted answers correspond to the second and third categories described above. The second column contains both the first category answers and interpretations of the answers corresponding to the second category. In the technical report, Appendix 5, there is a complete list of the answers that have been omitted and/or interpreted and the reason given for each of them.

With the results aggregated, it appears that the respondents gave the highest premia to the metro context, followed by rail. The fire context receives a small negative premium, meaning that fire safety is valued somewhat lower than road safety per life saved. The ranking of the contexts differs slightly from the answers to the ranking questions, the difference being that in the ranking questions the road context was in a clear fourth place. The overall ranking there was metro, railway, fire and then road. This is seen easily if the percentage figures for ranks 1 and 2 are added for each context in Table 22. The ranks are then metro 64%, rail 59%, fire 44.7% and road only 35.3%.

A common pattern is that the figures in Table 24 are all very close to 1. There is almost no context factor. The differences between the contexts are so small that they can be judged of equal value. However, there are differences between groups in how they have answered the equivalence questions. The answers can also be considered in diagrammatic form. The diagram below shows the answers to question 14, railway v. road safety.

![Figure 43. Railway safety v. road safety, equivalence question 14.](image)

The diagram (Figure 43) should be read in the following way. The first column on the left shows the answers to the first row/choice in the equivalence question. On this row, the respondent could choose between preventing 15 fatalities in road accidents or 100 fatalities in
railway accidents. The white part of the bar shows the number of respondents that chose to prevent 100 fatalities in railway accidents. From bar no 10, where the choice was between 15 and 15, we find that about one third preferred to prevent 15 fatalities in railway accidents, one third found it hard to choose and one third preferred to prevent 15 fatalities in road accidents.

The aggregation of these answers gave a 2% premium for railway safety. The diagram is based on the answers of 154 respondents out of a total of 166 (interpreted answers are included). The diagram shows explicitly that a few respondents have answered that they prefer to prevent 15 fatalities in one context, rail or road, instead of preventing 100 fatalities in another context. In Appendix 7, diagrams for all equivalence questions, can be found.

4.5.3.2 Comparison with the British main study

It is interesting to make comparisons with the British study, which was somewhat different. There, a sample of the population in four towns was chosen. The towns were Bangor, Brighton, Newcastle and York. The total sample size was 130 respondents in the main study. The aggregation of the results showed the following.

<table>
<thead>
<tr>
<th>Contexts</th>
<th>Ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Railway v. Road</td>
<td>0.834</td>
</tr>
<tr>
<td>Domestic fires v. Road</td>
<td>0.926</td>
</tr>
<tr>
<td>Public fires v. Road</td>
<td>0.923</td>
</tr>
</tbody>
</table>

Table 25. Relative ratios for contexts, equivalence questions in the British main study.

The big difference is that in the British study, rail safety is valued lower than road safety. Both public fire and domestic fire safety also receive a lower priority than road safety. The results were lower than expected. It is believed that the rather low figure for rail safety is due to an under-representation of rail users in the sample chosen. Due to this, the HSE commissioned a follow-up study in the London area, as mentioned in the introduction.

The results of the follow-up study were clearly different from the results of the main study. A sample of 150 respondents was taken from three towns around London. The main difference from the sample in the main study was that in the follow-up study the research team required 40% of the respondents to be regular rail users. They then received the following results.

<table>
<thead>
<tr>
<th>Contexts</th>
<th>Ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Railway v. Road</td>
<td>1.003</td>
</tr>
<tr>
<td>Domestic fires v. Road</td>
<td>0.890</td>
</tr>
<tr>
<td>Public fires v. Road</td>
<td>0.960</td>
</tr>
</tbody>
</table>

Table 26. Relative ratios for contexts, equivalence questions in the British follow-up study, Jones-Lee, Burton et al., 2000, p. 15

It turns out that the average rail relativity is almost the same as the average figure obtained in the present study. This is somewhat remarkable. The British follow-up study was conducted around three months after the Ladbroke Grove accident, where 31 people lost their lives. In spite of this, the average premium is not affected. One possible interpretation of this is that the method provides robust results that are not affected by what happens to be on the media’s
agenda. In the group interviews, the Ladbroke Grove accident was discussed separately. We will return to the results of the follow-up study in the discussion of strategic bias.

The Underground context was not included in the British studies. If the results from the 1994 London Underground study are calculated in the same way as the results of the 1997 British study, a premium of around 20% is obtained. This is also a significantly different figure from both the one found in the present study and the results of the 1997 study (with the results presented in table 5 above). It must be noted that a different type of question was used in the Underground study. This was a much rougher instrument and the results are therefore not comparable. It is probable that the Underground premium in the British study would have been different if the type of equivalence tables used in the present study had been available. A later section of this report takes a closer look at the patterns beneath the aggregated averages.

### 4.5.3.3 Scale effects

Three questions were set up to test if respondents were sensitive to the scale or severity of the accidents in the contexts studied (see questions 17-19 in the questionnaire, Appendix 8). Typically, it is assumed that a higher premium would be given to large-scale accidents. The fear of multiple-fatality accidents is assumed to be higher. Media attention and political statements after large accidents can be seen as a sign of the extra weight that people give to the prevention of larger accidents. The respondents were faced with the same kind of tables as was used for the context questions. The choices were now between the prevention of a number of fatalities in, for example, large-scale metro accidents versus the prevention of a number of fatalities in small-scale metro accidents. The fatality figures were changed in the same manner as for the context questions. The aggregation of the answers gave the following results.

<table>
<thead>
<tr>
<th>Question</th>
<th>Contexts</th>
<th>OK answers only</th>
<th>Interpreted included</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>Large v. small Railway</td>
<td>0.96</td>
<td>0.97</td>
</tr>
<tr>
<td>19</td>
<td>Large v. small Metro</td>
<td>0.96</td>
<td>0.95</td>
</tr>
<tr>
<td>19</td>
<td>Large v. small Fire</td>
<td>0.98</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Table 27. Answers to equivalence questions on scale of accidents (Q17-19).

The figures are all very similar, giving a lower value to large-scale accidents. This means that the respondents want to give a higher value to the prevention of fatalities in small-scale accidents than to the prevention of large-scale accidents. As the figures in the two columns are so similar, the larger sample with the interpreted values is used in later sections.

### 4.5.4 Risk-risk questions

The answers to the risk-risk questions have been aggregated with the same method as used for the equivalence questions. The responses and the aggregated figures should therefore be comparable to the answers to the equivalence questions. There are however differences between the question types that prevent comparisons of all questions.

In the risk-risk questions, the base-line risk is different between the contexts compared, except for the first of the four sets of questions. This was in the first of the two sets of questions on railway safety versus road safety. The list below shows the displayed risk of a fatal accident of the contexts that were compared in the different questions.
Table 28. Difference in base-line risk between contexts in risk-risk questions.

It emerged that the differences in base-line risk influenced the answers of the risk-risk questions heavily. When calculated in a manner similar to the equivalence questions the following results are obtained.

Table 29 Aggregated context premia for risk-risk questions.

In the table above, four different figures are given for each question. The reason for this is the same as for the equivalence questions, that there are three different categories of answers (see page 128). The first column contains all the correct answers, i.e. those that did not raise any doubts as to whether the respondent had understood the question or not. The second column contains the same group, but omitting the respondents that gave such answers as for a risk reduction in the rail context to be of equal value to a 3 in 100,000 risk reduction for the road, the rail risks must be reduced to zero. These answers are judged as relatively extreme and it is interesting to see the difference in premia when these are omitted. The third and fourth columns contain the corresponding values including the answers that could be interpreted in some way.

The results are significantly lower than the answers to the equivalence questions except for the answers to questions 20-22 where the baseline risk was equal for rail and road travel. This proves that the baseline risk influences the answers and it also makes it difficult to compare the answers to the questions, except for the first set, question 20-22. There we can see that the answers are at the same level and, as it happens, the calculated premia for railway safety only differed by one percent from the answers to the equivalence questions on railway v. road safety. This could be interpreted as a validation of the results. However, the similarities of the answers to the different types of questions only hold on an aggregated level. The individual answers raise questions. It is, as we shall see, not possible to use the aggregated results of the risk-risk questions as a validation of the results from the equivalence questions.

Including the answers that have to be interpreted does not change the results significantly. The difference is only around 2%. Even the exclusion of the extreme answers does not change the value to any extent. The remaining analysis will use the interpreted sample, that is, the sample that corresponds to the third column above.
4.6 Underlying patterns and biases

4.6.1 Strategic bias in equivalence questions

The analysis of the equivalence questions against background data shows a significant strategic bias. The analysis started with an aggregation of the results for the Stockholm and the Arvika groups separately. This revealed differences that led to further questions. In order to test the strategic bias, each respondent’s individual premium in each question is calculated. How this is done is described on page 124. The strategic bias is then tested by calculating pair-wise correlations of the individual premia with the background variables. This shows the following results for the equivalence questions.

<table>
<thead>
<tr>
<th>Matching questions</th>
<th>Rail(Q14)</th>
<th>Metro (Q15)</th>
<th>Fire (Q16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>0.026</td>
<td>-0.001</td>
<td>-0.019</td>
</tr>
<tr>
<td></td>
<td>0.746</td>
<td>0.988</td>
<td>0.813</td>
</tr>
<tr>
<td>Sex</td>
<td>-0.042</td>
<td>-0.049</td>
<td>0.064</td>
</tr>
<tr>
<td></td>
<td>0.603</td>
<td>0.533</td>
<td>0.428</td>
</tr>
<tr>
<td>Car access</td>
<td>-0.195</td>
<td>-0.218</td>
<td>-0.099</td>
</tr>
<tr>
<td>0=No, 1=Yes</td>
<td>0.016</td>
<td>0.007</td>
<td>0.220</td>
</tr>
<tr>
<td>Road mileage</td>
<td>-0.169</td>
<td>-0.211</td>
<td>0.020</td>
</tr>
<tr>
<td></td>
<td>0.038</td>
<td>0.009</td>
<td>0.806</td>
</tr>
<tr>
<td>Public Transport mileage</td>
<td>0.268</td>
<td>0.247</td>
<td>0.132</td>
</tr>
<tr>
<td></td>
<td>0.001</td>
<td>0.002</td>
<td>0.102</td>
</tr>
<tr>
<td>Education</td>
<td>0.178</td>
<td>0.178</td>
<td>-0.042</td>
</tr>
<tr>
<td></td>
<td>0.029</td>
<td>0.03</td>
<td>0.608</td>
</tr>
<tr>
<td>Income</td>
<td>0.090</td>
<td>0.112</td>
<td>0.170</td>
</tr>
<tr>
<td></td>
<td>0.275</td>
<td>0.177</td>
<td>0.036</td>
</tr>
<tr>
<td>Trimmed respondents</td>
<td>24:3</td>
<td>7:6 , 24:3 , 27:3</td>
<td>6:3</td>
</tr>
</tbody>
</table>

Table 30 Pair-wise correlations (Pearson) of individual premia v. background variables, questions 14-16. The upper figure in the cells shows the correlation and the lower figure the p-value.

The analysis reveals a relationship between valuation and access to cars. If the respondent has access to a car, they then tend to give a relatively high value to road safety compared to safety in other contexts. We can see that this relationship holds for two of the three contexts. The same pattern is revealed when we look at public transport mileage, which is logical. Those travelling more by rail and metro value public transport safety higher than those that have a low public transport mileage. The relationship is reversed when we turn to road mileage. Those with a low road mileage tend to value railway and metro safety higher than those with high road mileage.

It is interesting to note that there does not seem to be any correlation to the background variables in the fire context. It could be expected that access to a car would influence the answers, as fire safety is compared to road safety in the question. This was however not the case. The only correlation that was found for the fire v. road contexts was with income. It is not clear whether this is a coincidence or reflects a real difference. What the reasons for this correlation could be is not clear.

The sample has been trimmed because, for example, one respondent’s answer totally overturned the relationship on the rail v. road question (Q14). Omitting this respondent gave...
the correlation above\textsuperscript{103}. The calculated p-values above show the value of a double-sided test that the correlation is not zero. Considering the valuations of respondents with different public transport mileage, we find the following pattern.

<table>
<thead>
<tr>
<th>Public transport in winter, km/week</th>
<th>Never use</th>
<th>&lt;50</th>
<th>50-250</th>
<th>&gt;250</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q14 Railway vs Road</td>
<td>0.942</td>
<td>1.003</td>
<td>1.046</td>
<td>1.147</td>
<td>0.019</td>
</tr>
<tr>
<td>Q15 Underground vs Road</td>
<td>0.924</td>
<td>0.994</td>
<td>1,150 (1,109)</td>
<td>1.121</td>
<td>0.102 (0.024)</td>
</tr>
<tr>
<td>Q16 Fire vs Road</td>
<td>0.961</td>
<td>0.988</td>
<td>0.973</td>
<td>1.095</td>
<td>---</td>
</tr>
</tbody>
</table>

Table 31. Public transport mileage and valuation in equivalence questions.

The p-values are for regressions of the individual premia with the public transport mileage as predictor. The value for Q15 is strongly affected by the answers of two respondents. The figures within parentheses are calculated with the answers of these two respondents omitted. The total number of respondents was around 155.

The conclusion that can be drawn from all this is that there is a strategic bias in the answers of the equivalence questions. The respondents have answered in a way that they thought would benefit them. The more public transport is used, the higher the valuation of public transport safety. Conversely, the higher the road mileage, the lower is the premium to public transport. This correlation was not found in the British main study even though it was expected. No significant correlation could be found with, for example, background variables on transport mileage or other information collected. As mentioned earlier, it is believed that the British main study sample had an under-representation of rail users. When the answers of the high rail users in the follow-up study was analysed, a different value was obtained. It then turned out that respondents who were travelling less than 200 miles per year had a relative valuation for rail over road safety of 0.933. The high rail users, travelling 1000 miles or more per year, had a relative valuation of 1.157\textsuperscript{104}. These figures fit very well into the pattern presented in Table 31.

4.6.2 Confounding by scale effect

When we looked at the aggregated averages of the answers to the scale questions, we saw that there was no scale effect. In fact, the respondents tended instead to value the prevention of small-scale accidents a little higher than the prevention of large-scale accidents. In this section, we will test if the respondents have been able to separate the scale and the context when answering the questions. It is a possibility that respondents mistakenly thought of a railway accident as a large catastrophe with many fatalities and have compared that to a smaller road accident with one or a few fatalities. The respondents were asked to consider a small railway accident with one or a few fatalities, and to compare that with a road accident with similar effects.

A correlation of the individual answers to the context and scale equivalence questions was calculated to test for the possibility that the respondents were unable to separate the scale and the context aspects. The respondents’ individual premium have been calculated in the same way as described earlier. The test has been made for both the rail, metro and fire context. We will start by considering the correlation of the answers to the context and the scale questions.

\textsuperscript{103} This respondent had given a very high value to railway safety and at the same time reported a rather high road mileage.

\textsuperscript{104} Jones-Lee, Burton et al., 2000, p. 15
As we can see, there is no significant correlation between the individual answers to the context and the scale questions\textsuperscript{105}. The values for the fire context were calculated after omitting one respondent whose answers had a very large influence on the results. The figures in parentheses were the results before trimming. In order to illustrate this, we can plot the answers to the rail context and rail scale questions.

\begin{table}
\centering
\begin{tabular}{|l|c|c|}
\hline
\textbf{Context} & \textbf{Correlation} & \textbf{P-value} \\
\hline
Rail & 0.128 & 0.114 \\
Underground & -0.052 & 0.526 \\
Fire & 0.075 (0.218) & 0.356 (0.007) \\
\hline
\end{tabular}
\caption{Correlations (Pearson) between context valuation and scale valuation.}
\end{table}

The spread in the results indicates that the respondents have been able to separate the scale and the context aspects when answering the equivalence questions. In other words, we do not have a confounding by scale effect. This holds for all three contexts studied.

\textsuperscript{105} The p-values are calculated for a two-tailed hypothesis test that the correlation is not zero.
4.6.3 Baseline risk effect in risk-risk questions

In the aggregated answers to the risk-risk questions (see Table 29) we could clearly see an effect of the baseline risk the respondents were facing. It is interesting to see whether this result was an effect of the design of the questions or whether it can be confirmed as a true reflection of the respondents’ preferences. This can be studied by comparing the answers to the first risk-risk question (Q20-22), where the baseline risks were equal for the two contexts, with the answers to the second set of questions (Q23-25), where the baseline road risks were four times the baseline rail risks (see Table 28).

For the convenience of the reader, we shall here refer to the first set of questions (Q20-22), where the risks were equal, as the “equal risk questions”. Questions 23-25 are referred to as the “different risk questions”. The structure of the two sets of questions was a simple choice between two pieces of safety equipment and then a follow-up question. The specific follow-up question depended upon the first choice, so that for example the follow-up question to Q20 was either Q21 or Q22. Each respondent was asked to answer only one of the follow-up questions for each of the four sets of risk-risk questions.

The respondents can be divided into two groups. One group chose road or rail in both Q20 and Q23. A second group changed its view, from rail to road, or vice versa. If we find that the group that did not change its view is sensitive to the change in baseline risk, then we can draw the conclusion that the baseline risk has an effect on the valuation of safety. If on the other hand the whole effect can be attributed to the answers of the respondents that changed view, then the same conclusion cannot be drawn.

96 respondents out of 149 did not change preference between the two sets of questions. If we perform a regression with the individual premium in the “equal risk questions” as predictor and the premium in the “different risk questions” as response, we get a strong correlation. The p-value of the regression is 0.000.

![Regression Plot](image)

**Figure 45.** Plot of respondents’ individual premia in the equal risk question against their individual premia in the different risk question. The baseline risk is different in the two questions. The plot includes only respondents that did not change preference between the two sets of questions.
Those that gave a high premium to railway safety in the “equal risk questions” also gave a high premium in the “different risk questions”. However, the slope is not only greater than one, but also greater than two. This is not what would be expected, and the explanation is that the maximum premium that can be given to, for example, railway safety is 6.67 on the “equal risk questions”, but three times as much in the “different risk questions”\(^{106}\). It therefore appears that the respondents who favoured railway safety in the “equal risk questions” took the opportunity to give an even higher premium to railway safety in the “different risk questions”. 17 of the 24 respondents that favoured rail in both questions actually gave a higher premium to rail in the “different risk questions”.

Another way of looking at it is to count the occurrence of higher premia on the “different risk questions” compared to the “equal risk questions” among those that did not change their view between the questions. Out of these 96 respondents, 39 actually gave a higher premium to rail when the baseline risk was lower for rail and higher for road. 30 respondents gave exactly the same premium in both questions and the remaining 27 gave a lower premium when the railway risks were lowered. These 27 were in some sense sensitive to the change in baseline risks.

Looking more closely at the respondents who favoured road safety in both questions, a regression on the answers of these respondents gives a slope less than\(^1\), meaning that on average they are sensitive to the change in baseline risk. The R-squared is relatively low, only 31.2%. The data is limited: the number of respondents included is only 72. However, there seems to be some relationship.

![Regression Plot](https://example.com/plot.png)

Figure 46. Plot of respondents’ individual premia in question 20 (rail v. road) against individual premia in question 23 (rail v. road). The baseline risk is different in the two questions. In this graph, only the respondents that preferred road to rail in both questions are included.

\(^{106}\) This is due to the difference in baseline risk, see Table 28. In questions 20-22 the respondent could state that a risk reduction of 20/100,000 for rail travel is equal to a risk reduction of 3/100,000 for road travel. The individual premium will then be \(20/3 = 6.67\). In questions 23-25 the corresponding value is \(60/3 = 20\).
There are thus several different patterns in the data. The change in baseline risk made 55 respondents, or 36% of the sample, change their view. 51 of these changed from rail in Q20 to road in Q23, and the remaining 4 changed in the other direction(!). The answers of these 55 respondents are the major explanation for the rather large change in valuation for the whole sample between the “equal risk questions” and the “different risk questions”. It is not clear whether the fact that they changed view is an effect of the design of the questions or if it reflects the respondents’ preferences.

When analysing the answers of the respondents that did not change view between the questions we found a positive relationship. The fact that some of the respondents gave a higher premium when the baseline risk for railway was lowered must be attributed to the design of the question. Looking at the respondents that favoured road in both, the baseline risk can be seen to have an effect. This is in accordance with the predictions of the economic theories. The correlation between the individual premia in the “equal risk questions” and the “different risk questions” for these groups is relatively strong: 0.558.

The conclusion is, with some reservations, that the change in baseline risk has an effect. This conclusion draws upon the fact that 36% changed view between the questions and that the regression analysis of the respondents that favoured road in both showed that they on average gave a lower premium for railway safety when the baseline risk for rail travel was lowered. A general feeling is that some of the respondents had problems deciding the size of the risk reduction needed for the respective equipment to be of equal value.

The rather straightforward choice between a risk reduction for road or rail is simple and comprehensible. It thus seems that the answers to the follow-up questions are somewhat random. Even though the question simplifies the choice of risk reduction to relativity between different equipment that is twice or three times as effective, the concept of risk reduction in itself is so difficult that the respondents have problems giving coherent answers. Further elaboration of the questions and experimental research is needed in this area.

As an extension to the British study, Mrs Covey, lecturer at the University of Durham, made an attempt at estimating the effects of baseline risk. The general conclusion of the study is that differences in base-line risk do affect the way people prioritise different safety programmes107.

4.6.4 Equivalence questions and baseline risk

There are also reasons to believe that the respondents gave answers to the equivalence questions based upon an inaccurate perception of the baseline risks. The respondents were told not to think of the probabilities of the different types of accidents, but rather to focus on the consequences and the contexts. Still it might be the case that their own perception of their risks influenced the answers. The answers to question 13, where the respondents were asked to state their own risks, have been used to calculate the respondents’ own perceived risk per kilometre travelled. The individual premia in question 14 have then been correlated with the calculated risks. No relationship was found.

It is thereby not proven that the respondents were uninfluenced by their perceived risks when answering the equivalence questions. One of the conclusions in the British study was that some respondents seemed to believe that if the baseline risks were higher the safety

107 Covey, 2001
programme might do better than just preventing the 10 fatalities stated in the question\textsuperscript{108}. This might be the case in the present study as well. Further research is needed.

4.6.5 Comparison of equivalence and risk-risk questions

The results of the equivalence and the risk-risk questions were, as we saw, on average the same. Both questions rendered a small premium for railway safety of 2-3\%. However, 33\% of the respondents changed their preference between the questions. This “swapping” was in both directions, that is, both from road over rail in the equivalence questions to rail over road in the risk-risk, and vice versa. In an attempt to find an explanation for this behaviour, the respondents were put into two groups depending on whether they had changed preference or not.

Out of the 166 respondents, 148 had given answers that were OK or could be interpreted. 23 of these were clearly changing from road in the equivalence question (Q14) to rail in the risk-risk question (Q20), and 26 respondents changed from rail in Q14 to road in Q20. In other words, 49 respondents (33\%) did change preference. 53 respondents, or 35\%, did not change preference between the two types of questions.

46 of the respondents (31\%) gave equal priority to the contexts in the equivalence question and these were put in the two different groups depending on their answer in question 12, where they were asked to rank the four contexts studied. The answers of these respondents could then be used in the analysis.

Correlations of the individual premia with background variables were calculated for the group of respondents that gave priority to rail, or road, on both questions and for the group that changed preference between the questions. These correlations are displayed in the table below.

<table>
<thead>
<tr>
<th>Railway vs road</th>
<th>Matching question (14)</th>
<th>Risk-risk question (20-22)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Not Changing</td>
<td>Changing</td>
</tr>
<tr>
<td>Car access</td>
<td>0.082</td>
<td>0.312</td>
</tr>
<tr>
<td>0=Yes, 1=No</td>
<td>0.489</td>
<td>0.008</td>
</tr>
<tr>
<td>Road mileage</td>
<td>-0.161</td>
<td>-0.169</td>
</tr>
<tr>
<td></td>
<td>0.167</td>
<td>0.166</td>
</tr>
<tr>
<td>Public Transport mileage</td>
<td>0.360</td>
<td>0.248</td>
</tr>
<tr>
<td></td>
<td>0.001</td>
<td>0.037</td>
</tr>
<tr>
<td>Education</td>
<td>0.244</td>
<td>0.138</td>
</tr>
<tr>
<td></td>
<td>0.036</td>
<td>0.251</td>
</tr>
<tr>
<td>Trimmed respondents</td>
<td>24:3</td>
<td></td>
</tr>
</tbody>
</table>

Table 33. Pair-wise correlations of individual premia with background variables for the respondents changing preference and for the respondents not changing preference.

The most obvious pattern is that the public transport mileage has influenced all respondents on the equivalence question but only the not-changing respondents on question 20. For the respondents that changed view, their own public transport mileage was not relevant when answering question 20, whereas it was when answering question 14. It therefore seems as if

\textsuperscript{108} Jones-Lee and Loomes, 1999, p. 22
50% of the respondents managed to imagine that they “were someone else, having the specified travel pattern” and 50% did not manage that.

It must be noted that the respondents were asked to answer the questions from different perspectives. When answering the equivalence questions they were asked to say what they preferred government to do. They were thus asked to put themselves in the position of the politicians. In the risk-risk questions, on the other hand, they were asked to say what they would do themselves, given that they had a specified travel pattern, normally different to their actual one. Given all of this, it can be fully rational to prefer railway safety over road safety, for example, in the equivalence questions, and then to go for road safety over railway safety in the risk-risk questions. As the analysis above shows, there are possible explanations to the choices made. The correlation analysis shows that both groups seem to have been influenced by their own travel patterns when answering the equivalence question (Q14). What seems to separate the groups is that the people who did not change preference in some way seem to have disregarded the request to imagine that they were someone else with another, specified, travel pattern. These respondents’ answers correlate to the respondents’ individual travel patterns, their public transport mileage in particular. The answers of the other group, that did change preference, do not show any correlation with their public transport mileage on the risk-risk question. It thus seems that they managed to imagine that they had another travel pattern, other than their own.

There are also some differences in the valuation between the group that did not change preference and the group that did. Starting with those that did not change preference, it turned out that they valued road and railway safety approximately equally in the equivalence questions and then gave a small premium to railway safety in the risk-risk questions. The group that did change had a small premium for railway safety in the equivalence questions but this turned into a lower value in the risk-risk questions.

<table>
<thead>
<tr>
<th>Question</th>
<th>Not changing</th>
<th>Changing</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>0.993</td>
<td>1.040</td>
</tr>
<tr>
<td>20-22</td>
<td>1.028</td>
<td>0.972</td>
</tr>
</tbody>
</table>

Table 34. Relative valuation of railway safety for respondents not changing and respondents changing preference.

The conclusion from this is that the risk-risk questions cannot be said to validate the results of the equivalence questions. When we look at the aggregated averages the model performs well and the results seem reasonable. However, when we look at how separate individuals have answered, patterns emerge that raise doubts about the performance of the instruments used. Further elaboration of the different instruments is needed.
4.7 Summary

The aim of this project was to study people’s relative valuation of risks in different contexts. The hypothesis was that people would perceive differences in such aspects as lack of control, voluntariness of risk, etc., and that this would lead to differences in valuations of safety. The aspects mentioned are predominant in certain contexts, such as railway or metro traffic, and there were indications these differences would lead to a relatively high valuation of rail or metro safety compared to, for example, road safety.

This subject is not an everyday issue for the ordinary citizen and difficult decisions had to be made when prioritising between different safety measures. The fact that the risk level differs from context to context also complicates the matter. Therefore, a method combining group interviews with individual questionnaires was chosen. A total of 38 group meetings were held. 12 of these meetings were pilot meetings before the main study. There were 166 respondents in the main study. Every meeting lasted for 90 minutes and started with a discussion on risk and differences between different contexts.

This study has shown that the valuation of safety does not differ very much between different contexts. Three hazard contexts were studied: railway risks, metro risks and risks from fires. The reference point in the comparisons was road risks. The differences in valuation between the contexts were less than 20% in all sub-samples. Only a small premium of a few percent favouring rail and metro, relative to road or fire, could be detected, on average for the whole sample.

Two different methods were used in the study to estimate relative values of safety in different contexts. These are both indirect stated preference methods. The first method uses something called “equivalence questions” to elicit the respondent’s valuation of safety. The main idea is to let the respondent match safety programmes with different effects and to state when the safety programmes are of equal value. The second method is called risk-risk analysis. This method involves more explicit descriptions of probabilities and consequences and allows the respondent to compare and value safety measures in different contexts.

The questions were set up to estimate context and scale effects and to enable several tests. Context effects refer to the differences in valuations of safety between different contexts. Scale effect refers to the differences in valuation depending on the size of the accident. Four different tests are performed in the report: of strategic bias, of confounding of scale and context aspects, of baseline risk effects, and an attempt to validate the results.

Apart from the general finding that the context and the scale effects were very small, the scale questions also showed that the respondents preferred the prevention of small-scale accidents over the prevention of large-scale accidents. Safety measures aimed at preventing small-scale accidents received a higher value than safety measures aimed at preventing large-scale accidents.

The results have also been compared to the results of two recent British studies. The equivalence questions used in the present study were developed in Britain by Jones-Lee, Loomes et al. In their main study, they found that railway safety was given a lower priority than road safety. The valuation of railway safety versus road safety in fact entails a lower value for railway safety. The explanation given so far is that the British main study sample probably did not contain a representative proportion of rail users. Therefore, the HSE commissioned a follow-up study where there was a higher proportion of regular rail users. In this study, the premia for rail safety relative to road safety were at the same level as in the
The present study. In other words, they also found that rail safety and road safety were valued equally on average.

The fact that different respondents have different road and public transport mileage, that they use different transport modes, does influence the answers to the equivalence questions. This is referred to in the report as a strategic bias in the answers. Typically, respondents with a higher public transport mileage tended to value rail and metro safety higher than those with a low mileage. A relationship with road mileage was also found and was negative in direction. Respondents with higher road mileage valued public transport safety lower than those with a low road mileage. This effect was statistically significant. Comparisons with the British follow-up study showed that the rail premia for regular users in Britain were almost exactly on the same level as for the regular rail users in the present study.

A second test was done to see if the respondents managed to separate the scale and context effects when answering the questions. The fact that, for example, railway accidents have potentially more serious consequences with more fatalities than the average road accident could influence the answers to the context questions. The possibility that a respondent thought of a large rail accident and compared that with a small road accident, and therefore gave a higher priority to rail safety than to road safety, had to be tested. This was done by comparing the individual answers to the scale and the context questions. No significant correlations could be found, implying that the respondents did manage to separate the scale from the context when answering the questions.

When it came to the risk-risk questions, a third test was done, and an effect due to the baseline risk was detected. The questions were set up with different baseline risk levels but with equal risk reductions. This proved to influence the answers significantly. To some extent, the rather large change in valuation can be attributed to the design of the questions. However, a careful analysis of the individual premia of the respondents revealed that they were indeed sensitive to the change in baseline risk and that this effect was significant. This can be interpreted as a decreasing marginal benefit of safety.

In an attempt to validate the findings, a comparison between the individual answers in the equivalence and the risk-risk questions was made. This showed that, on average, the premia given to railway safety in relation to road safety in the equivalence question and the risk-risk question were almost exactly the same. Further analysis revealed that 36% preferred either rail or road in both questions and 31% were indifferent in the equivalence question, giving equal priority to rail and road safety. The main problem is that 33% changed preference between the questions, in both directions: 18% changed from preferring rail in the equivalence questions to preferring road in the risk-risk questions; 15% changed in the opposite direction.

4.8 Discussion

There are two overall conclusions that can be drawn from this study. The first is that there is no support in the public’s preferences for valuing railway, metro or fire safety at two, three or four times the value of road safety, as is currently the practice. This study gives support for a small premium and, considering values from people who are high public transport consumers, gives a premium of around 10-15 percent for railway and metro safety. The highest value that could be supported for fire safety is around 10%.

It is possible that the tragic fire in Gothenburg last year, in which 63 young people were killed, affects the results of the questions. It is difficult to know exactly how big this effect is, but it is probable that the fire accidents would have received fairly high premia irrespective of
whether or not a fire accident had occurred. The effect is clear on the ranking questions but maybe not obvious on the equivalence and the risk-risk questions.

The second conclusion is that the results are subject to several biases. Differences in baseline risk have an effect. This could be seen clearly in the risk-risk questions and it also eventually influenced the answers on the equivalence questions. Further development work and experimental research on the effects of the baseline risk are needed.

There was a small strategic bias in the answers to the equivalence questions. This is what could be expected. The respondents also seem to have managed to separate the scale and the context aspects when answering the questions. This is encouraging and supports the use of the methods.

The attempt to validate the results, by using different methods and comparing the individual answers to the different types of questions, has raised more questions rather than validating the results. As stated in the summary, about one third of the respondents changed preference depending on the type of questions. In an attempt to find an explanation for this behaviour, the respondents were separated into a group that gave priority to rail, or road, on both questions and a group that changed preference between the questions. It emerged that both groups showed a strategic bias when answering the equivalence question. There is for example a correlation with the public transport mileage in both groups. There are also differences. The group that did not change preference also showed a strategic bias in the risk-risk question. There is a correlation with this group’s public transport mileage. The group that did change preference, on the other hand, seems to have found other arguments for their preferences than their personal public transport mileage. Typically for this group there is a significant correlation with educational level instead.

There are then two possible explanations. One is that the respondents that did not change preference might have failed to take account of the travel pattern they were asked to imagine they had. For the respondents that did change view this new situation clearly led to a change in preference. Another interpretation is that even though the respondents were asked to imagine that they had a specific travel pattern, this did not affect their preference. The correlation with their own travel pattern might be just a coincidence. This seems a little unlikely however, and it does not explain why 33% changed preference between the questions.

In spite of these problems, it is the view of the author that the overall achievements of the methodology used are promising and that it could be applied in future studies on valuation of safety in contexts other than the one that was the subject of this study. The effects of baseline risk must however be studied and further comparisons of the results of different methods must be made.
5. Economic analysis and decision criteria

5.1 Introduction
We have now reached step 7 in the safety analysis process described in section 1.2. With the safety analysis process described, we have estimated risks and calculated the effects of safety projects. It is now time to take a step back and get a perspective on possible approaches to making decisions on safety. We will then describe the direct valuation approach in more detail before reviewing previous research. The section ends with a description of an economic analysis of a train control system, called Radioblock, which uses radio-based signalling and communication.

5.2 Different approaches to decision making
What are the possible options for the decision-maker deciding in matters of safety? Which tools can he use when choosing how much money to spend on safety or what projects to choose? Jones-Lee has discussed the different possible approaches at some length. The following section relies upon his distinctions. He assumes that the decision-maker has access to estimates of the safety and other effects of a given project. Let us first have a brief look at the possible approaches before we review previous research. The possible approaches are:

1. The No analysis approach;
2. Informal judgements;
3. Safety standards;
4. Cost-effectiveness analysis;
5. Direct valuation of costs and benefits;
6. Decision analysis.

5.2.1 The "No analysis" approach
"Ignore the estimates on the grounds that safety effects are, for one reason or another, incommensurable with other costs and benefits of public sector projects."

The best argument for not using the “No analysis” approach is the examples described in the introduction to this thesis. Using this approach might lead to the undesirable effect of increasing instead of reducing risk when enforcing new safety rules. Estimates of safety and other effects must be taken into account when deciding upon a given project. Otherwise, the decision maker might end up in a situation similar to the one described.

5.2.2 Informal judgements
"Rely upon informal judgement in weighing safety effects against other costs and benefits."

Using informal judgements has the benefit of looking into all aspects of a specified project. It also puts the responsibility on the decision-maker. The problem is that informal judgements tend to be inconsistent. As we saw in the introduction, the implicit value of life differed between £10,000 and £10 billion for the different projects British Rail started after the Hidden

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109 Jones-Lee, 1989, p. 3-30
110 Jones-Lee, 1989, p. 3
111 Jones-Lee, 1989, p. 3
and Fenell reports. Other studies have shown similar results. The implication of this is that more lives could be saved if resources were used more effectively.

5.2.3 Safety standards

"Use safety standards or targets. This would involve the pre-specification of “acceptable” levels of risk in various contexts. Projects that failed to meet the safety standards would be rejected out of hand and those that met the standards would be accepted or rejected on basis of their other costs and benefits."\textsuperscript{112}

The use of safety standards normally involves no reference to the costs of meeting the standards. Pre-specified levels of safety have to be met without regard to the costs. Projects that fail to meet the standards should be rejected. This approach also has the problem of resulting in inconsistencies in the valuation of life. A decision to force different transport modes to meet a specified level of risk will result in different amounts of money spent per life saved.

5.2.4 Cost-effectiveness analysis

"Basically, cost-effectiveness analysis seeks to maximise the extent of achievement of a given goal or objective (such as safety improvement) within a predetermined budget or equivalently, to minimise the cost of achieving a particular goal."\textsuperscript{113}

Several aspects are not considered in this approach. The decision is reduced to analysis of a given goal and the resources needed to achieve this goal. The level of effectiveness has to be specified before the solution with the lowest costs is selected. Conversely, the maximum costs can be specified and the solution with the highest effectiveness selected.

The cost-effectiveness criterion is sometimes expressed as the ratio of the effectiveness to cost. It is the slope of a line drawn from the origin to a given point on the effectiveness-cost curve. This is illustrated in the diagram below.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{diagram}
\caption{Ratios of effectiveness to cost, from Quade, 1982, p. 209}
\end{figure}

\textsuperscript{112} Jones-Lee, 1989, p. 3
\textsuperscript{113} Jones-Lee, 1989, p. 3
It is apparent from the figure that programme 1 is preferable if the ratio is the sole criterion for the decision-maker. This holds if the decision-maker is not concerned about the absolute levels of effectiveness. However, if a minimum level of effectiveness, $E_1$, is required, then programme 1 is unsatisfactory. This is often the case.

Cost-effectiveness analysis might be appropriate whenever the goals to be maximised are specified and other effects can be ignored. The good thing is that the decision-maker does not have to put a price on a human life or compare the value of a life to other benefits, like time savings, or costs of infrastructure. Within a given budget the decision-maker only has to choose the project with the best (safety) effects. What cannot be achieved with cost-effectiveness analysis is a selection between different projects that have different types of benefits. This is true for most projects.

5.2.5 Direct valuation methods

"Define and estimate monetary values of safety improvement and costs of risk so that safety effects can be incorporated directly into standard procedures of economic appraisal, such as cost-benefit analysis or social welfare maximisation". ¹¹⁴

There are two ways of doing this. The most widespread is Cost Benefit Analysis (CBA). The approach uses direct valuation of the costs and benefits of different projects, and the basis for these valuations is people’s willingness to pay or individual valuation of the costs and benefits. If the present value of the benefits of a project exceeds the present value of the costs, the project should be carried out. This method has been adopted by the majority of the road administrations in the industrialised world as the method for evaluating and prioritising road investment. The method has the advantage that it gives guidelines to the decision-maker on which of a number of projects to choose, and it shows explicitly the trade-offs that have been made. There are some problems with the method and these problems are discussed in the next section (5.3).

The second way is the estimation of a social welfare or utility function. This is more of a theoretical product than a method used in everyday politics. The idea is to construct a utility function of society based on the utility functions of its citizens. The approach is utilitarian in that it only takes account of the effects of a decision. A great deal of work has been done in this area. However, social welfare functions as decision criteria are not discussed further here.

5.2.6 Decision analysis

"Essentially, this involves the identification of the decision-maker’s main objectives and priorities and the subsequent estimation of the structure and parameters of a so-called “multi-attribute utility function” for the decision-maker. The primary purpose of this approach is not so much to turn decision making into a formulaic mechanical procedure as to facilitate decisions concerning complex issues by providing the decision-maker with an ordered structure and framework within which to assemble and analyse a wide diversity of information." ¹¹⁵

The decision analysis approach is more of a framework for making decisions. It gives the decision-maker assistance to think and reason about the trade-offs of the benefits and costs in a structured way. What it does not do is to give guidance on what to do or what project to chose.

¹¹⁴ Jones-Lee, 1989, p. 3-4
¹¹⁵ Jones-Lee, 1989, p. 4
5.2.7 Discussion

Jones-Lee discards the first four approaches primarily because that they do not let the decision-maker weigh benefits and costs and make trade-offs between them. He therefore supports the cost benefit approach, but also concludes that a decision analysis approach has advantages when it comes to decisions about low-probability events with catastrophic effects.\textsuperscript{116}

Dubus argues for the need to compare the safety levels of different transport modes and that available resources should be used effectively\textsuperscript{117}. There is an optimal safety level, he argues, where the total costs of enhancing safety equal the total benefits, a point beyond which no further measures should be taken. CBA or cost-effectiveness analysis should be used to determine this point.

In the safety analysis process, the safety standards approach has been combined with CBA. This approach was argued for by Evans in 1994. He proposed a combination of CBA with safety standards or limits on the tolerable levels of risk to different individuals\textsuperscript{118}. The goal when using CBA as a decision criterion is to select the projects or safety measures that maximise the net benefit. There is no reference to the distribution of risk in this criterion. The purpose of combining CBA with safety standards, or risk criteria, is to ensure that the distribution of risk is acceptable.

There are other approaches, for example multi-criteria analysis and Position Analysis (PA). These are not discussed in this thesis. We will now look more closely at some aspects of using CBA as a decision criterion.

\textsuperscript{116} Jones-Lee, 1989, p. 29
\textsuperscript{117} Dubus, 1989, p. 298-325
\textsuperscript{118} Evans, 1994, p. 426-427
5.3 Cost benefit analysis as a decision criterion

When making a social cost benefit analysis, the present value of the benefits is compared with the present value of the costs. In theory, all effects should be included in the analysis. In practice, only a few are usually included. The Swedish National Road Administration has developed a model for calculating the effects of changes in the infrastructure. The model, called EVA, is computerised and uses road data, traffic forecasts, etc. It includes several modules for such tasks as estimating emissions, calculating traffic flows, etc. A list of possible effects of road projects is presented in the following table. The effects calculated with the model are given in bold type.

<table>
<thead>
<tr>
<th>Economic effects of traffic</th>
<th>Environmental and land-use effects</th>
<th>Other effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic safety</td>
<td>Noise</td>
<td>Industry</td>
</tr>
<tr>
<td>Travel times</td>
<td>Air pollution</td>
<td>Tourism</td>
</tr>
<tr>
<td>Comfort</td>
<td>Barrier effects</td>
<td>Other regional effects</td>
</tr>
<tr>
<td>Vehicle costs</td>
<td>Vibrations</td>
<td></td>
</tr>
<tr>
<td>Maintenance costs</td>
<td>Water protection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Environment protection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Recreation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Protection of cultural relics</td>
<td></td>
</tr>
<tr>
<td></td>
<td>General aspects of landscape and cities.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Development</td>
<td></td>
</tr>
</tbody>
</table>

Table 35. Effects of road projects, from Vägverket (The National Road Administration), 1996, section 1.11

As can be seen, several effects are not calculated in the model. These have to be estimated separately. The first reason for this is that it can be problematic to measure or estimate the size of the effect. Take for example effects on the general aspects of landscape. How can these be measured? It is obvious that it is difficult to measure this effect. To value the effect would of course be even harder. The same arguments hold for the effects on tourism, local industry, etc. These effects can be very important in specific cases, as well as decisive for the decision-maker deciding upon a new road scheme, for example. This problem is common for all cost-benefit analyses. It is problematic to set economic values on non-market commodities\(^\text{119}\). Willingness to pay methods have been used to estimate values for time savings, safety, etc. However, it has not been possible so far to estimate WTP-values for changes in recreation, vibrations, scenery, etc.

Considering investments on the railway, other factors have to be included in the analysis. The number of projects is smaller, each project having its own characteristics, making a systematic approach like the one used by the road administration much harder. However, there are parameters for the economic calculations that should have common ground, particularly the interest rate for discounting and the time horizon.

---

\(^{119}\) Quade, 1982, p. 215
In this section, step 7 in the safety analysis process is discussed. This presumes that the effects have been described and quantified, and a monetary value has been assigned to the effects that can be valued. In the final step before the decision, the valued effects are put together in a cost-benefit analysis. In order to make the effects and the costs comparable, they must be discounted to a common year. This is normally the year a safety measure, new railway line, new road, or whatever is the object of the analysis, comes into service.

The reason for discounting is that costs and benefits that are realised in the future have a lower value than the costs borne today. The reason is of course that the interest rate would give a return on the money if invested elsewhere. A future investment would therefore be valued lower. Correspondingly, a benefit that arises in ten years’ time will have a lower value than a benefit that is realised today. Discounting costs and effects can be done both in cost-effectiveness analysis and cost-benefit analysis. The principle of discounting is illustrated in the following figure.

![Discounting diagram]

The present value is discounted by the following formula. The amount $k$ accrues at the end of $t$ years at the interest rate $p$.

$$ PV = k * \frac{(1 + \frac{p}{100})^t - 1}{(1 + \frac{p}{100})^t * \frac{p}{100}} \quad (29) $$

Using a common interest rate and time horizon enables comparisons of different societal projects. Railway safety investment can then be compared with childcare or health insurance costs. The estimated values of the benefits and costs can then be put together in one-dimensional measures. This can be done in several ways.

### 5.3.1 Present Value

Perhaps the simplest way is to calculate the Present Value. This is simply the present value of the benefits minus the present value of the costs. If the net value is above 0, the project is admissible. It is important to realise that the interest rate plays a key role in the analysis. In infrastructure projects, the costs appear before the infrastructure comes into use, whereas the benefits arise during a period of maybe 60 years. The interest rate has a significant effect on the calculation of the present value of the benefits. A high interest rate makes the present value of the benefits smaller and whether a project is considered admissible or not can therefore depend on the interest rate\(^{120}\).

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\(^{120}\) For an example, see Rosen, 1988, p. 235
5.3.2 Internal rate of return

The internal rate of return is the discount rate that would make a project’s net present value equal to zero. This criterion could be useful if a project yields a stream of costs and benefits. The internal rate of return is the r that solves the following equation\(^{(121)}\):

\[
B_0 - C_0 + \frac{B_1 - C_1}{1 + r} + \ldots + \frac{B_T - C_T}{(1 + r)^T} = 0
\]  

(30)

where T is the number of periods (years).

The criterion then stipulates that a project is admissible if the internal rate of return exceeds the opportunity costs of the funds. If the project’s rate of return is 2% and the government could get 3% from investing the money elsewhere, then the project is not admissible.

5.3.3 Benefit-Cost ratio

It is also possible to calculate the benefit-cost ratio. This is done simply by the formula:

\[
BCR = \frac{Benefits}{Costs}
\]  

(31)

If the ratio is above zero, the benefits outweigh the costs and the project is beneficial. This criterion is equivalent to the present value criterion. However, there is a pitfall in the use of Benefit-Cost ratios. The conclusions rendered by the criterion might differ depending on the classification of costs and benefits. It is possible to classify a cost as a negative benefit. Take for example an investment in a new road that costs 5 million Euros. There are two effects, time savings and environmental impact (including noise, pollution, etc.). The time savings have a present value of 15 million Euros and the environmental impacts a value of 5 million Euros. If the environmental impact is considered a negative benefit, the benefit-cost ratio is \((15-5)/5=2\). If the environmental impact is considered a cost, then the ratio will be \(15/(5+5)=1.5\). In both cases, the project is admissible. However, if a choice is done between this road project, and another societal project with a benefit-cost ratio of 1.7, different conclusions will be reached depending on if the environmental impacts are considered negative benefits or costs.

This problem does not of course permeate all analyses. In a standard appraisal of road projects, where different projects are analysed and compared, the problem is avoided by treating the effects similarly in all projects. The comparisons will then be reliable. It is when different types of projects with different types of effects are compared that the problem may arise.

5.3.4 Net Benefit-Cost ratio

Another common measure is the Net benefit-cost ratio, calculated with the formula:

\[
Net\ \text{benefit\ -\ cost\ ratio} = \frac{Benefits - Costs}{Costs}
\]

If ratio is above 1, the project is beneficial and should be undertaken. The net benefit-cost ratio is also susceptible to the same classification problem as the benefit-cost ratio. By classifying costs as negative benefits, or \textit{vice versa}, different conclusions could be reached when compared with other projects.

\(^{(121)}\) Rosen, 1988, p. 236
There are other measures, or criteria, that could be used. One example is the first year return that focuses on the benefits in the first year. However, the review of criteria necessarily stops here.
5.4 Previous research

5.4.1 Cost-effectiveness analysis

5.4.1.1 Modal Comparisons

Ebrahim and Gailey carried out a cost-effectiveness analysis on the transport of radioactive waste. The study, called “The costs of transporting low level radioactive waste out of Port Hope Area, Ontario”, compared the costs of three different modes of transport: road, rail and inland waterway\textsuperscript{122}. Both the rail and the waterway options required the waste to be transported part of the way by road, from the origin to the nearest loading location, and vice versa at the destination, in order to reach the deposit site.

This led to the result that the road alternative was found to be the economically best option when the waste was to be transported less than 200 km. If the waste disposal site was located in the Great Lakes region, the inland waterway alternative should be chosen. In all other instances, the rail alternative was to be preferred. For long-distance transport rail was the most cost-effective and safest option. The authors also believed the rail alternative to be the most acceptable to public opinion due to its more stringent safety regulations.

5.4.1.2 Nuclear waste transport by rail

B. Spraggins has written about the transport of spent nuclear fuel by train in the U.S.A. In particular, he has discussed the question of whether to use regular or dedicated trains, i.e. should spent nuclear fuel be transported in separate trains or should the wagons carrying the waste be mixed in ordinary freight trains\textsuperscript{123}? This question was addressed in the Hazardous Materials Transportation Uniform Act of 1990.

There are advantages to using dedicated trains, such as that the consignment can be monitored, or even escorted, it can choose the route so that it only uses high-standard tracks and/or avoid population centres, etc. However, there are disadvantages as well, for example higher operating costs, a higher train frequency increasing the risks of crossing accidents, etc.

In the paper, there are no cost estimates or analyses of the total economic effects but the issue deserves to be mentioned. In the U.S.A., the question has been one of liability. The railway companies have felt that they do not have enough liability protection if an accident happens whilst nuclear waste is being transported in regular trains. It has therefore been demanded that these consignments use dedicated trains.

5.4.1.3 Development of a cost-effective automatic train protection system

In Japan the high-speed train called the Tokaido Shinkansen has accomplished 30 years of service without a single accident involving a fatality. The Shinkansen also has relatively high reliability, with an average deviation from schedule per train of only around 1 minute. The fact that the railway is a single-route operation, the system is independent from other transport systems (for example it has no level crossings) and that it uses ATP can explain these figures. The Shinkansen uses an ATP system that enables speeds up to 270 kilometres per hour. It has

\textsuperscript{122} Ebrahim, 1989
\textsuperscript{123} Spraggins, 1994
two back-up systems and agreement between at least two of these three systems is required if a signal is to be regarded as correct\textsuperscript{124}.

ATP systems have also been used in ordinary commuter systems. In the Tokyo metropolitan area, a system called ATS-P (Automatic Train Stop with on-board Pattern) has been in service since 1989. The system covered over 700 kilometres of the network by December 1995.

M. Miyachi and H. Irinatsu have developed an alternative system called ATS-P\(\textsuperscript{N}\), that is simpler than the ATS-P base system, but also cheaper. The goal was to construct a system that would give “equal safety to ATS-P, low cost, no remodelling ATS-P on-board devices, and accommodation for the operation at 160 km/h or less…”\textsuperscript{125}. According to the authors, these goals have all been achieved and the costs of the system have been reduced by 50\%. It is the cost of equipment and construction that has been reduced, while the cost of testing, for example, is the same as for the standard version. The system has been installed on two conventional lines since 1997\textsuperscript{125}.

This is an example of a simple cost-effectiveness analysis. The safety effects of the two alternative systems were judged equal. The level of safety required was reached by both systems. The new system had costs that were 50\% of the costs for the basic system. It was therefore the cost-effective solution.

### 5.4.2 Cost-Benefit Analysis

#### 5.4.2.1 Dangerous goods transport

A modal comparison of the transport of dangerous goods was made by the Swedish National Rescue Services Board\textsuperscript{126}. The purpose of the study was to ensure that dangerous goods should be transported by “the safest mode of transport as far as justifiable from an economic standpoint”\textsuperscript{127}. The study began with the observations that the risks of dangerous goods transport were already very low, that many issues played a role in the total transport system, and that “the human factor appeared in many instances to be the prime cause of abnormal events”\textsuperscript{128}. The board performed a systems safety analysis and found that rail was safer than road, \textit{i.e.} the risk costs favoured rail, but not enough to overturn the commercial cost advantage of road transport.

The study above can be seen as a pilot study for a broader Swedish research project on the risks of dangerous goods transport. That project was led by the Swedish Road and Transport Research Institute (VTI) and resulted in the following six reports\textsuperscript{129}.

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\textsuperscript{124} Kigaku, 1995\textsuperscript{125} Miyachi and Irinatsu, 1996
\textsuperscript{126} Andersson, 1994\textsuperscript{127} Andersson, 1994, p. 499\textsuperscript{128} Andersson, 1994, p. 499\textsuperscript{129} Lindberg and Morén, 1994, Reports no 387:1-6
The project is rather unique in its effort to work through all the aspects of the carriage of dangerous goods. The risk assessment part of the study was reviewed in the section on risk analysis methods (section 2.3.2.1). The project also resulted in an economic evaluation in which the cost of transporting ammonia and petrol by rail and by road was calculated. The costs of dangerous goods transport are not only dependent upon the characteristics of the material transported and the mode of transport. The route chosen, the standard of the infrastructure, distance to population areas and the geographical conditions are also factors that influence the transport risk. These types of factors were included in the analysis, so that the fact that railways often pass through city centres, whereas lorries can use peripheral highways, was taken into account. Svarvar and Persson calculated the following cost components: "medical treatment, loss of production, the value of risk reduction itself (the so-called human value), loss of time, rescue operations, decontamination, loss of crops, damage to property and environmental pollution".

The authors did not draw any conclusions on the issue of whether road or rail was the most cost-beneficial transport mode. The calculations were too dependent on the assumptions made to give any general conclusions on that matter. However, they found that the costs of accidents per vehicle kilometre for dangerous goods transport are in general very low compared to the accident costs for ordinary traffic. This means that choosing safer routes for dangerous goods transport can reduce the costs, but if applied generally "long detours will soon result in high vehicle costs and costs of common traffic accidents exceeding the expected reduced costs of accidents with hazardous materials".

The possibility of establishing safety areas around railways passing through populated areas or of building new roads around cities was also discussed. The calculations showed that the risk reduction could in no way repay the investment costs even with very moderate cost estimates. Establishing a safety area of 30 metres on either side of a railway route through a city would for example demand 22,200 cars of dangerous goods passing through the city every hour the whole year to be profitable.

130 No 5 in List 6 written by Svarvar and Persson, 1994
131 Svarvar and Persson, 1994, p. XII
132 Svarvar and Persson, 1994, p. XXI
5.4.2.2 Tunnels in Norway

In Norway, the infrastructure authority, NSB Banedivisjonen (NSB-B) has about 250 kilometres of railway tunnels. This amounts to about 6% of the total network length and still no tunnel accidents with fatalities have occurred. NSB-B has classified tunnels based on different characteristics reflecting the various levels of risk. The classes are called 0, C, B and A. Tunnels shorter than 1 km and without stations or points are class 0. Tunnels with other characteristics are classified according to the number of trains passing and their lengths.

If there are other characteristics like the ones mentioned above, the tunnel can be classified as one class higher. The higher classes demand more rigorous safety arrangements. The upgrading of the network to allow operation at 200 km per hour will demand more and longer tunnels, and NSB-B has therefore done economic calculations on the costs and benefits of different tunnel safety arrangements. These calculations are shown in the diagram below.

![Diagram showing net benefit-cost ratios for different tunnel safety measures]

Figure 4) Net benefit-cost ratios for different tunnel safety measures, translation from Lillestøl, 1994, p. 10.

These calculations for a 7 km-long double-track tunnel show that derailment protectors, escape tunnels and automatic train protection systems give good value for money. The calculated Net benefit-cost ratios were >10, 2-8 and 1.5-7 respectively for these measures. The intervals indicate the differences in the assumptions on trains per year passing the tunnel (from 20,000 to 80,000). NSB-B found the method of using cost-benefit calculations for evaluating tunnel safety measures to be very useful.\(^\text{133}\)

\(^{133}\) Lillestøl, Lille et al., 1994
5.4.2.3 Automatic train control systems

5.4.2.3.1 ATP in Great Britain

The costs and effects of ATP have been publicly discussed in Britain since the mid 1980s, when British Rail (BR) declared that the costs of installing network-wide ATP were too large to be justified by the safety benefits.

In November 1988, BR changed its mind and decided to install network-wide ATP over a period of 10 years. That decision was reinforced by the recommendations in a Department of Transport report on the train collision at Clapham Junction, written by Sir Anthony Hidden in 1989. BR was recommended to install ATP on the whole network within 5 years. Hidden also recommended that BR should do economic analyses of ATP "so that a financial value can be put on safety".

The BR report that followed stated that there were more cost-effective ways of saving lives. The Health and Safety Commission, now part of the HSE, also advised the Secretary of State that there were other investments that would be more cost effective, that would save more lives and lead to fewer injured. The Secretary of State accepted that and released the successor to BR’s infrastructure division, Railtrack, from the obligation to install network-wide ATP. Evans states in an article that this decision not to proceed with the installation of ATP "is contrary to the long-established tradition on railways that safety is paramount".

5.4.2.3.2 The effects of ATP

BR estimated in the aforementioned report that 2.92 fatalities per year were preventable by ATP. This figure was based on the accidents over the 26-year period between 1968 and 1993. Serious injuries were treated as equivalent to 0.1 fatalities and slight injuries as 0.005 fatalities. This gave a figure of 4.3 fatality-equivalents per year that could be saved by the installation of ATP on the whole network.

The HSE argued that this figure was rather low. None of the accidents in the sample in the BR study was very severe. That did not mean that a serious accident could not have happened. Therefore the HSE raised the figure to 5.5 fatality-equivalents per year. This figure was also reached in a separate study by Evans and Verlander. They distinguished between the frequency and the consequences. The statistical material is rather meagre for calculating the frequency of ATP-preventable accidents. Historical data gives 24 ATP-preventable accidents which gives 24/26 = 0.92 accidents/year.

The consequences can, on the other hand, be derived from all accidents that have occurred during a slightly extended period, which gives 64 accidents in 30 years, with some 254 fatalities. That gives 254/64 = 3.97 fatalities per accident. This gives 3.97x0.92 = 3.66 ATP-preventable fatalities per year. A 95% confidence interval gives 3.66±2.23, reflecting the great variation in the dataset. After some statistical analyses, Evans and Verlander concluded that "there is no reason to believe that the sample mean of 3.66 fatalities per year given above is an underestimate of the true mean".

134 British Railway Board, 1994
135 Evans, 1996, p. 110
136 Evans and Verlander, 1996
137 Evans and Verlander, 1996, p. 189
Assuming that injuries follow the pattern of fatalities, the estimated number of fatality-equivalents was calculated to be 5.5 per year. With this estimated number of possible fatality-equivalents that were preventable by a network-wide installation of ATP, Evans and Verlander reached a cost per life saved of about £11 million. The HSE has adopted the value of £2 million per life saved, which means that network-wide installation of ATP without doubt exceeds this value.

However, Evans also proposed that the assessment of a project should include a comparison of individual risks with the acceptable levels of risk stated by the HSE. The individuals that could see the biggest reduction in risk are train drivers. Their risk does not currently exceed the threshold stated by the HSE. Regular commuters also have low risks. This criterion does not therefore demand the installation of ATP\textsuperscript{138}.

\subsection*{5.4.2.3.3 The alternatives}

The calculations referred to above were made for the BR version of Automatic Train Protection. The outcome of the discussions between the HSE and Railtrack was that cheaper versions of ATP than the BR-ATP exist and it might be possible to install only parts of the system and not the full version of the BR-ATP\textsuperscript{139}. This could prove to be a cost-beneficial measure. Railtrack is currently investigating these possibilities. There are also other alternatives. Two of them, Driver Reminder Appliances (DRA) and the Train Protection and Warning System (TPWS) have been subject to economic analysis and this is reviewed below.

\subsection*{5.4.2.3.4 Driver Reminder Appliances}

Within the framework of what is referred to as a “Train Protection Strategy”\textsuperscript{140}, Railtrack has evaluated a train protection device called a Driver Reminder Appliance\textsuperscript{141}. This device reminds the driver to check the signal aspect when starting from stations or after a stop on the line. There are two principal forms of the appliance, driver-set and automatic. The driver-set version is manually operated. When stopping the train, the driver sets the appliance, and has to reset it before the train can depart. The automatic version is set by the Automatic Warning System, AWS.

The main steps of the evaluation were:

1. Estimation of net benefits on a system-wide level, when safety effects of other changes had been taken into account;
2. Allocation of benefits to the rolling stock fleet and specific types of traction;
3. Calculation of costs;
4. Comparison of benefits and costs.

Railtrack first published a consultation document with the purpose of getting responses from the train operating companies to the methodology and data used in the evaluation. There were significant uncertainties regarding, for example, the effectiveness of DRA, the geographical distribution of risk and the effect of differences in crashworthiness between types of rolling stock.

\textsuperscript{138} Evans, 1996 ,p. 109
\textsuperscript{139} Health and Safety Executive, 1996, Appendix 12b
\textsuperscript{140} The Train Protection Strategy consists of a number of measures including piloting and evaluation of DRA and TPWS.
\textsuperscript{141} Railtrack, 1996, 1997a, 1997b
Attempts were made to reduce these uncertainties as far as possible and the results were presented in a final report. There were still some uncertainties regarding the future development of TPWS, the installation costs on specific rolling stock and on the method used for estimating the effectiveness. These uncertainties were bound to remain.

The general conclusions of the evaluation were that DRA is a cost-beneficial measure for all traction with a remaining service life of five years or more. Furthermore, the driver-set version gives a higher net benefit than the automatic version in almost all cases, although the latter would give a higher net benefit for a handful of rolling stock types. A partial installation of the automatic version would however entail higher costs and higher risks when drivers used to the automatic version drive a unit with the driver-set version. Railtrack therefore concluded that only the driver-set version should be installed where beneficial.

5.4.2.4 Quality of rolling stock

5.4.2.4.1 Mark 1 carriages in Great Britain

The HSE has carried out a study of the costs and benefits of replacing what is called Mark 1 rolling stock. Mark 1 labels a series of passenger vehicles built between 1951 and 1974 and was the first generation of BR carriages. They have an old construction that does not meet the requirements of today and have slam doors that are manually operated by the passengers. These vehicles do not have safeguards against over-riding, which means that in a collision there is nothing to prevent one carriage from slicing into the passenger space of another, leading to severe consequences. Every year there are several fatalities resulting from people falling from these vehicles. This could be prevented by converting the doors to central locking or by rebodying the carriages.

When the study was conducted, there were about 2,300 Mark 1 vehicles in regular passenger traffic. 1000 of these were to be replaced by the year 2000, leaving 1300 with an unclear future. These 1300 vehicles were the subject of the study by the HSE, which considered three options and compared these with a base case of doing nothing until the year 2007, when the Mark 1 vehicles are replaced by new rolling stock. The options were the following.

1. Immediate new build. All Mark 1 vehicles are phased out in a three-year replacement programme.
2. Immediate rebodying. The stock is rebodied over a four-year period. The vehicles will then continue to be in service beyond 2013.
3. Modifications, then replacement. The Mark 1 vehicles are modified to increase crashworthiness and slam doors are replaced. All vehicles are replaced by 2007 as in the base case.

The consultancy company WS Atkins has developed the modification programme for improved crashworthiness. The modifications are relatively simple and cheap and can be carried out on Mark 1 rolling stock. They increase the absorption of energy and prevent over-riding. The elements of the modification are the replacement of couplings, cut-outs in the frame and mounting of “cup and cone”.

142 Railtrack, 1997a, p. 5-6
143 Health and Safety Executive, 1997
144 Kirk and Murell, 1999
Cup and cone can be installed as an anti-over-riding device. In order to ensure their proper functioning, it is also necessary to allow the couplings to shear out. These are therefore replaced with couplings with a shear plane, held together with bolts. In a collision, the bolts crack and the coupling slides down and disengages. When the cup and cone have engaged the carriages cannot override. The energy absorption is increased by simple cut-outs in the underframe. These modifications are relatively simple and cheap. The difference compared to the other options is that the modifications do not give protection against side impacts, nor reduce the consequences of derailments\textsuperscript{145}.

One interesting thing in the calculations made by the HSE is that two different values of a statistical life have been used. For the lives that could be saved by improved crashworthiness, the HSE uses a value of £2.49 million. This is the figure used in the latest Railtrack Group Safety Plan. For the lives that could be saved by the replacement of the slam doors, a lower value of £0.89 million is used. This was the value used by the Department of Transport, Local Government and the Regions in its standard appraisals of road projects. The reason is that passengers are responsible for their behaviour when they open the doors while the train is moving. The measures to improve crashworthiness aim at reducing the risk of multiple-fatality accidents and are therefore valued disproportionately higher.

The HSE limited its study to the safety effects of the different options. The results showed that option 2 (Immediate rebodying) would be favourable compared to the base case and give a benefit of £131 million. The modification programme would almost break even, with a small loss of £13 million.

However, in a commentary on the report, Evans discussed the validity of the result\textsuperscript{146}. The conclusion that rebodying is the best option depends on the fact that complete replacement is avoided until after 2013. It would give an immediate improvement in the passenger environment, but only partially, as the running gear and traction equipment would be the same.

All of the options have about the same safety effects. This means that the decision must be taken on other grounds, such as social and commercial benefits compared to the costs. Doing this would not lead to the conclusion reached in the HSE paper. The modification programme has very low costs, estimated to be about £38 million, and gives about the same safety effects as the other two options. Therefore, this option should be chosen according to Evans. He also pointed to the fact that there are options not considered in the HSE study. He wrote:

"There are obviously other possibilities beyond those explicitly considered. The lowest-cost option that delivers the safety benefits would be to spend the £38 million on installing the crashworthiness modifications and central locking to the Mark I fleet as soon as possible, continue to use the modified Mark I vehicles until the bodies become unserviceable, and then re-body them. That might not have high passenger appeal, but the case for doing more would rest on social and commercial appraisal, not safety."\textsuperscript{147}

5.4.2.4.2  ‘105’ tank wagons

An American study\textsuperscript{148} has been conducted on the use of general purpose tank wagons for transporting halogenated hydrocarbons\textsuperscript{149}. The costs of cleaning up spillages of these chemicals during the period from 1980 to 1989 exceeded $50 million. Even though the transport of these chemicals only represented 1% of the total volume of dangerous goods, the

\textsuperscript{145} Health and Safety Executive, 1997, p. 5
\textsuperscript{146} Evans, 1997a
\textsuperscript{147} Evans, 1997a, p. 4
\textsuperscript{148} Barkan, Glickman et al., 1991, p. 33-43
\textsuperscript{149} Some of these substances contain chloride and are used to produce PVC.

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costs of cleaning up spillages accounted for more than half of the total clean-up costs for
dangerous goods transport.

The study compared the costs and benefits of replacing the general-purpose tank wagons with
the heavier but safer ‘105’ tank wagons (built according to Department of Transport
specification 105A500W). ‘105s’ have a lower capacity than general-purpose ‘111’ wagons.
Therefore, more wagons are needed in order to transport the same quantity of chemicals. 111s
can be loaded from the top and unloaded from the bottom, but 105s can only be loaded and
unloaded from the top. This means that some terminals would have to be rebuilt to make top
loading and unloading possible. The benefits of the investment would be lower clean-up costs
and lower risks of permanent effects on the environment.

The economic analyses showed that changing from general-purpose tank wagons to 105s
would give a total NPV of $94.7 Million or $64,700 per wagon. The switch to the 105s would
therefore be a cost-beneficial way of reducing accident risk and would reduce society’s costs
for this transport.
5.5 The Radioblock – a traffic control system for regional lines

The main purpose of this study was to evaluate a traffic control system for railways called Radioblock. The study was an attempt to quantify all the effects of installing the system and comprised an analysis of the safety effects of the traffic control systems Automatic Line Block and Automatic Train Control (ATC)\(^\text{150}\). Two traffic scenarios and an imaginary average regional line were used in the analysis.

“Radioblock” is a system that has the same functionality as traditional traffic control systems and it enables the full use of all the functions in the on-board ATC system. It is designed to suite regional lines where low traffic does not justify investment in the traditional infrastructure-bound system. There is an installation of this system on a regional line between Linköping and Västervik, and this is referred to as the pilot line or the pilot installation.

Traditional systems use a track circuit to confirm whether or not the line is occupied. Trackside cables carry the information to the signal interlocking system and to the central traffic control (CTC). The Radioblock system communicates with the train via radio. This gives several advantages, such as low investment, maintenance and operational costs. It also gives the same high level of safety as the traditional interlocking system.

When new technical systems are developed, politicians and policy-makers need tools for evaluation. Social cost-benefit analysis is an established method for weighing the pros and cons of societal projects. The study wishes to illuminate two important problems connected with evaluations of new technical systems. The arguments are also valid for all kinds of societal projects that are to be applied under a variety of conditions.

The first problem can be labelled the applicability problem. When policy decisions are taken information is needed not only on the general effects of the system but also more specifically on the effects when applied to existing conditions. On the other hand, case studies of specific projects may be too detailed to give any information for policy decisions. The second problem is the well-known problem of uncertainty. “What conditions are necessary for the system?”, “How large are the expected effects?” and “What are the effects when the capacity is used up?” are all questions connected with uncertainty. A method for handling these problems is presented and tested on the Radioblock system.

The aim is to perform a social cost benefit analysis on the system. It is obvious that the two major factors are the investment cost and the savings on train dispatchers. No other factors have the same magnitude. Therefore, it would appear that it would be enough to perform a simple business cost benefit analysis to see whether, or rather how quickly, the system will pay back the investment. However, this anticipates the interesting question of the possibilities and capabilities of the system. Once the system is installed, flexibility is gained and irregular movements can be conducted at marginal costs. Safety is higher, both for passengers and for railway staff, and extra signal blocks can be installed at very low cost, giving more and shorter line sections. This enables shorter headways between trains and raises the capacity of the line\(^\text{151}\). Taken together these effects can be substantial, but the question is of their magnitude.

Then again, should these effects really be taken into account? Most of the regional lines have very low traffic. On the pilot line, the most heavily-laden train is the commuter train on weekday mornings and afternoons. These trains carry a total of about 70 people of whom 55

\(^{150}\) See section 2.4

\(^{151}\) For a short description of the logic of the system, see Appendix 1.
travel locally (only in Kalmar county) to Västervik in the morning and back in the afternoon. It doesn’t seem likely that patronage will double over the next century. On the other hand, there are other examples that show that investment in rolling stock and new timetables, with more trains and better adjusted departures have raised patronage to several times above the expected levels.

This happened on the Kustpilen (The Coast Arrow), between Malmö and Karlskrona. Patronage grew 174% between 1990 and 1995, compared to the 5% average growth on Swedish railways for the same period. This can be explained by the combination of new, comfortable trains, more departures, lower prices and shorter travel times152.

Another example is Svealandsbanan, an 80-kilometre new railway line between Södertälje and Eskilstuna, opened in June 1997. There had previously been a line on the route with slow local commuter trains. These trains were replaced with high-frequency buses during the construction phase, 1994-1997. Today, it takes around 1 hour to go from Stockholm to Eskilstuna, a distance of about 110 km. The new line allows speeds up to 200 km/h. Patronage increased from 230,000 trips before 1994, to 440,000 during the building phase. In 2000, there were 1.6 million trips, an increase of 700%.

Assuming we have two different lines and that we want to repeat the success of Kustpilen or Svealandsbanan on both of these lines. On one, line A, we have the old traditional manual train dispatching system with one train dispatcher at least at every meeting station. On the other, line B, we have Radioblock installed. Doubling the traffic will probably give higher costs on both lines. Nevertheless, there will without doubt be a difference to the advantage of line B. This difference is an optional benefit of the system, i.e. it cannot be added to the cost benefit analysis unless the doubling of the traffic and the investment in rolling stock really is planned. Otherwise, the benefit will not be realised and including it would overestimate the benefit of the system.

Another parallel example is that the system increases flexibility. Irregular freight trains or night trains can be handled easier. With the old system, several stations had to be staffed for these movements, resulting in higher costs than could be accepted. Such movements were therefore seldom conducted. It is also easier to adapt to changes in demand, with more flexibility when planning the traffic and this will in turn raise the attractiveness of the railway and raise demand. The problem is how to value this flexibility. If there are no irregular transports, the benefit is not realised. Together these problems constitute what are referred to as problems of uncertainty.

The other type of problem is that the 15 lines that are possible cases for installing Radioblock Banverket, 1996, p. 32 differ in relevant aspects such as length, number of trains per day, number of passengers per day, the need for restoration, etc. The question is then if an analysis of the system as installed on the line in Östergötland will tell us anything about the profitability of installing it on the other 15 lines. A case study of the pilot line will fall short of being evidence for policy decisions on whether to install the system where profitable.

These two problems are handled in the following way. A description of an "average regional line" is given based on 11 of the 15 lines mentioned. The costs and benefits for this average line are calculated by analysing the costs for the pilot installation. In this way, many of the specific conditions valid for the pilot line and other specific regional lines can be neglected. A simplified description of an imaginary line will suffice and it will illustrate the effects of the system without being too detailed.

152 Nelldal, Kottenhoff et al., 1996, p. 117
Further, two different scenarios will be used. The first is a base scenario in which the average traffic today on the 11 selected lines is used when calculating the benefits. The second is a high-traffic scenario where patronage and the number of trains are doubled. An analysis of the system as installed on the imaginary regional line with traffic according to the two scenarios is performed. The base scenario shows the benefits of the probable traffic, of the traffic as it is today, and shows what effects can be expected. The “high-traffic scenario” shows the capacity of the system and the possible benefits when that capacity is exploited.

This is a way of handling the problems of applicability and the problems of uncertainty. The experience of this test study is discussed in the summary. The outline of this part of the thesis is as follows. Section 5.5.1 discusses some experience from the pilot installation. Section 5.5.2 gives an account of 11 of the 15 lines that are possible subjects for the installation of the system, and section 5.5.3 describes the imaginary “average regional line”. Sections 5.5.4 and 5.5.5 show the costs and benefits in the base scenario and the high-traffic scenario respectively. The calculated costs and benefits are summarised in a cost-benefit analysis in section 5.5.6.

The term Automatic Traffic Control Systems (ATCS) will be used here. ATCS denotes the three traffic systems Automatic Line Block, Centralised Traffic Control (CTC) and Automatic Train Control (ATC). Automatic Line Block is the system that ensures that only one train at a time is allowed onto a specific section of track. This system is connected to the CTC and it also gives information to the on-board ATC system.

5.5.1 Experience from the pilot installation

5.5.1.1 General description of the pilot installation

The line is 115 km long and has 4 passing stations. About 14 passenger trains depart on average every weekday and the total traffic volume is about 468,000 train kilometres per year. The line is not electrified. Before the Radioblock system was installed, train dispatchers were needed on 6 stations, including Linköping, as this station was served by local train dispatchers before the system was installed. To serve these stations a total of 11 full-time equivalent staff were needed. After the installation, only 2 full-time equivalent staff are needed to serve the whole line.

5.5.1.2 Controllable points

To keep the costs down on the pilot installation, the National Rail Administration chose to install spring points instead of centrally controllable points. This has limited flexibility and put limits on the possible service patterns, and thus formed the major cause of hesitation about the system amongst traffic planners at the county companies. The permitted train speed is also limited when traversing spring points, increasing journey times. The common view is that the system has to have centrally controllable points to be interesting as the subject of investment.

The conclusion can be drawn from this that the system will not be installed widely in its present form and that an evaluation of the system as installed on the pilot line will be of little interest. The imaginary regional line is therefore equipped with centrally controllable points where necessary. The cost of these has been estimated by the National Rail Administration. The development costs are about SEK20 million. These costs are divided into 15 parts and added as a separate cost to the calculations for the imaginary line, on the basis that this cost will, if the system is installed on the proposed lines, be shared among them.
5.5.1.3 The radio system

Another feature of the pilot installation is that the service radio is used for the radio communication. Before the installation only one out of two available channels on the service radio was used. It was therefore a relatively cheap solution to make use of the second channel. However, it is uncommon regional lines to have extra channel available and it is therefore an open question as to what radio system would be chosen in future installations of the radio block system.

The first period of use showed that some stretches of the line were not served by the radio. This has led to extra radio stations being been set up. The current system needs about one radio station every 10 kilometres. In future installations it is possible that other radio systems will be used, such as a GSM-system.

5.5.1.4 Future development

The idea of the Radioblock system is to communicate the position of the train to the central interlocking signalling system via radio. Transponders are mounted between the rails and different combinations of transponders give information to the train. They also transmit information on train location and the permitted speed is then sent from the signal system via radio. This gives Radioblock similarities to traditional systems. The information is bound to the infrastructure. The difference is that the information on the train’s position is sent to the signal interlocking system via radio instead of trackside cables. It is thus a partial step towards a new technology for traffic control.

The full step would have been to put all the information about the line in a central computer or to carry the information on the train. The train’s position would be defined by global positioning systems or other techniques, and the onboard computer would check in the line data file for what to do at this position, for example reduce speed. The ETCS project works with this kind of technology and it seems the right way to go. The benefits are that infrastructure costs can be reduced even more and flexibility is gained. There are also many ideas on what information can be sent between the central traffic control and the trains.

5.5.2 Regional lines suitable for the installation of Radioblock

The National Rail Administration (NRA) has listed about 15 lines that might be suitable objects for the installation of a Radioblock system. In order to get a picture of these lines information on 11 of them has been collected. The 4 remaining lines are excluded here since they only serve freight trains. They have special characteristics and are not likely to high priority for the installation of Radioblock. Data has also been included on the pilot line before the Radioblock system was installed. The information has been gathered from various sources, mainly from the NRA, SJ and the various train operators on the lines, and refers to the situation 1997. Only the Borås-Varberg and Strömstad-Uddevalla lines are electrified.
### County lines

<table>
<thead>
<tr>
<th>County line</th>
<th>Length (m)</th>
<th>Stations and stops</th>
<th>Meeting stations</th>
<th>TAM-sections</th>
<th>Longest section</th>
<th>Dispatchers (year-man)</th>
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<td>29</td>
<td>10</td>
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<tr>
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<td>16</td>
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<td>6</td>
<td>37</td>
<td>13</td>
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<td>Nässjö - Äseda</td>
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<td>9</td>
<td>1</td>
<td>2</td>
<td>37</td>
<td>3</td>
</tr>
<tr>
<td>Jönköping - Vaggeryd</td>
<td>38920</td>
<td>10</td>
<td>2</td>
<td>3</td>
<td>18.5</td>
<td>11</td>
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<tr>
<td>Nässjö - Vaggeryd - Värnamo - Torup - Halmstad</td>
<td>195500</td>
<td>27</td>
<td>7</td>
<td>8</td>
<td>45</td>
<td>7</td>
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<tr>
<td>Borås - Varberg</td>
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<td>13</td>
<td>5</td>
<td>6</td>
<td>19.5</td>
<td>7</td>
</tr>
<tr>
<td>Strömsund - Uddevalla</td>
<td>91820</td>
<td>8</td>
<td>2</td>
<td>2</td>
<td>71.5</td>
<td>6</td>
</tr>
<tr>
<td>Ystad - Simrishamn</td>
<td>45574</td>
<td>10</td>
<td>1</td>
<td>2</td>
<td>26.5</td>
<td>5</td>
</tr>
<tr>
<td>Berga - Kalmar</td>
<td>77391</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>41.3</td>
<td>3</td>
</tr>
</tbody>
</table>

| Average | 99798 | 13.6 | 3.3 | 4.0 | 37.7 | 7.4 |
| Median | 88048 | 11.5 | 3.5 | 4 | 38.95 | 7 |

### Number of departures

<table>
<thead>
<tr>
<th>County line</th>
<th>Pass. trains Awd</th>
<th>Maxd</th>
<th>Cargo trains Awd</th>
<th>Maxd</th>
<th>Total Awd</th>
<th>Maxd</th>
<th>Trainkm / year</th>
<th>Pass/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linköping - Västervik before</td>
<td>14</td>
<td>14</td>
<td>0</td>
<td>0</td>
<td>14</td>
<td>14</td>
<td>468000</td>
<td>206908</td>
</tr>
<tr>
<td>Repbäcken - Malung</td>
<td>8</td>
<td>8</td>
<td>7</td>
<td>8</td>
<td>15</td>
<td>16</td>
<td>288610</td>
<td>75000</td>
</tr>
<tr>
<td>Käl - Torsby</td>
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<td>12</td>
<td>2</td>
<td>2</td>
<td>14</td>
<td>14</td>
<td>246750</td>
<td>170000</td>
</tr>
<tr>
<td>Gårdsjö - Håkantorp</td>
<td>15</td>
<td>15</td>
<td>2</td>
<td>2</td>
<td>17</td>
<td>17</td>
<td>720000</td>
<td>350000</td>
</tr>
<tr>
<td>Nässjö - Oskarshamn</td>
<td>17</td>
<td>17</td>
<td>2</td>
<td>2</td>
<td>19</td>
<td>19</td>
<td>343537</td>
<td>186000</td>
</tr>
<tr>
<td>Nässjö - Äseda</td>
<td>15</td>
<td>15</td>
<td>4</td>
<td>4</td>
<td>19</td>
<td>19</td>
<td>227550</td>
<td>107000</td>
</tr>
<tr>
<td>Jönköping - Vaggeryd</td>
<td>23</td>
<td>23</td>
<td>2</td>
<td>2</td>
<td>25</td>
<td>25</td>
<td>267444</td>
<td>275000</td>
</tr>
<tr>
<td>Nässjö - Vaggeryd - Värnamo - Torup - Halmstad</td>
<td>14</td>
<td>14</td>
<td>4</td>
<td>4</td>
<td>18</td>
<td>18</td>
<td>825170</td>
<td>282000</td>
</tr>
<tr>
<td>Borås - Varberg</td>
<td>16</td>
<td>16</td>
<td>2</td>
<td>2</td>
<td>18</td>
<td>18</td>
<td>429531</td>
<td>369200</td>
</tr>
<tr>
<td>Strömsund - Uddevalla</td>
<td>9</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>9</td>
<td>9</td>
<td>276744</td>
<td>259700</td>
</tr>
<tr>
<td>Ystad - Simrishamn</td>
<td>12</td>
<td>12</td>
<td>2</td>
<td>2</td>
<td>14</td>
<td>14</td>
<td>172000</td>
<td>88000</td>
</tr>
<tr>
<td>Berga - Kalmar</td>
<td>15</td>
<td>15</td>
<td>2</td>
<td>2</td>
<td>12</td>
<td>12</td>
<td>366878</td>
<td>11800</td>
</tr>
</tbody>
</table>

| Average | 14.2 | 14.2 | 2.4 | 2.5 | 16.2 | 16.3 | 386018 | 198384 |
| Median | 14.5 | 14.5 | 2 | 2 | 16 | 16.5 | 316074 | 196454 |

Awd = Average week day traffic
Maxd= Maximum day traffic

TAM section = the Swedish term for a section controlled by a train dispatcher

#### 5.5.3 General description of the imaginary regional line

The following description of an imaginary line is based on the average values of the various parameters listed. We can imagine that the line is situated somewhere in the middle part of Sweden and runs between Anneborg, a city with about 120,000 citizens, and Verum, a smaller town with about 55,000 inhabitants. The line also passes Bäckevik with 35,000 inhabitants, situated about 35 km from Anneborg. The line is 99.8 kilometres long. The part with most passengers is between Anneborg and Bäckevik and the traffic is concentrated around weekday mornings and afternoons when commuters go to or from work.

In the initial situation, the line has four passing stations, Anneborg excluded, of which two are staffed during normal service hours. Anneborg is served by the central train dispatchers. It is possible for trains to cross at the other passing stations, but these are only used for freight trains and the process has to be carried out manually. The line also has 5 stops in villages. A little over 200,000 passengers use the line every year. The line will be run according to two scenarios.
The regional lines analysed have on average 14.2 passenger train departures every weekday. There are also on average 2.4 freight train departures every average weekday. This is used as a starting point for the traffic on the imaginary line. Separate timetables have been set up for winter, summer and weekend traffic. In a base scenario, the line is run as the average regional line. This gives a fair estimate of the effects of the system if installed on the 15 lines when no other measures are taken.

In a high-traffic scenario, the service is more than doubled. Passenger trains depart every hour every weekday. This will show the effects in a situation where investment is made in infrastructure and rolling stock as an attempt to increase patronage and to strengthen the competitiveness of the railway.

### 5.5.4 Base scenario – costs and effects

The lack of detailed information on the costs for the pilot installation made the task of calculating the costs of a Radioblock system somewhat difficult. It was necessary to avoid being too detailed. At the same time, the cost estimates of the system should not be unrealistic. Therefore, the calculations of the costs for the stations were relatively detailed as they bear a major part of the total investment costs. The pilot line was analysed for the costs of the Radioblock system. Crucial cost components include the average number of transponders per kilometre. The total cost for the imaginary line is calculated based on these figures. The calculations in this section rely upon two sources. The first is a graduate report on the costs of different automatic signal systems[^153] and the second, and more important, is a report from the NRA on the costs of the Radioblock system[^154]. The calculation of the costs for the imaginary line has been verified by the NRA.

#### 5.5.4.1 Costs

##### 5.5.4.1.1 Investment costs

#### 5.5.4.1.1 System costs

The system demands investment in the computerised signal interlocking system used at the centralised traffic control. A radio block hub, a manoeuvre system and an interface between the Radioblock and traditional systems are needed. These costs are independent of the traffic and will be the same in the base scenario and the high-traffic scenario. Often an interface to

[^153]: Hellman, 1997
[^154]: Wästgärds, 1997

<table>
<thead>
<tr>
<th>Km</th>
<th>Station name</th>
<th>Meeting possible</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Anneborg</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>Skogsäng</td>
<td>No</td>
</tr>
<tr>
<td>10</td>
<td>Tallnäs</td>
<td>Yes</td>
</tr>
<tr>
<td>23</td>
<td>Kohagen</td>
<td>No</td>
</tr>
<tr>
<td>34</td>
<td>Bäckevik</td>
<td>Yes</td>
</tr>
<tr>
<td>37</td>
<td>Sjökanten</td>
<td>No</td>
</tr>
<tr>
<td>43</td>
<td>Utanfors</td>
<td>No</td>
</tr>
<tr>
<td>50</td>
<td>Medby</td>
<td>No</td>
</tr>
<tr>
<td>56</td>
<td>Genomlida</td>
<td>No</td>
</tr>
<tr>
<td>63</td>
<td>Nordosterby</td>
<td>Yes</td>
</tr>
<tr>
<td>79</td>
<td>Mörklånga</td>
<td>No</td>
</tr>
<tr>
<td>88</td>
<td>Träskmark</td>
<td>No</td>
</tr>
<tr>
<td>99</td>
<td>Verum</td>
<td>Yes</td>
</tr>
</tbody>
</table>
lines without an automatic signalling system will also be needed. The total cost for these units is SEK3.7 million.

5.5.4.1.1.2 Stations

Two different types of stations have been chosen for the base scenario. The first is a single-track station with one passing loop. The station has to be staffed as the points are operated locally. It is worth noting that it is fully possible to have different station types along a line and to adapt the design of the station to the needs of the traffic. In this study, only two station types per scenario are described in order to simplify the analysis.

The ATCS and the safety rules put several demands on the design of the signalling system at the stations. Three groups of transponders on each side of the station and signal control equipment are required if trains are to be allowed to pass the station with a speed higher than 40 kilometres per hour. Extra transponder groups to give the line speed are needed for the ATC-system for trains that have been shunting in the station, etc. The station is shown schematically in the picture below and is the design for Tallnäs, Kohagen, Medby and Mörklägga. The cost of the signal system at this station type is SEK1.2 million.

Figure 48) Base scenario – single track station

The second type is a bigger station with (at least) three tracks, as at Bäckevik, Nordosterby and Verum. This station type has centrally operated points and is designed to allow trains to arrive simultaneously. The station type is described in the picture below. The cost of its signal system is about SEK 1.8 million.

Figure 49. Base scenario – multiple track station

Level crossings in station areas demand extra equipment for the Radioblock system. The costs for these have been calculated by the NRA and are about SEK200,000 per level crossing. This is due to the regulations on signal distances for level crossings. This distance depends on the train speed and is about 700 metres for a permitted speed of 90 km/h. On the imaginary line, there is one level crossing in the station areas at Bäckevik, Nordosterby and Verum. This gives a total cost of SEK600,000 for equipment and road barriers.

5.5.4.1.1.3 Vehicle equipment

Equipment is needed on the vehicles to connect them vehicles with the signal interlocking system. This equipment consists of a radio unit and an interface to the ATC system. This equipment and the adaptation of the existing system costs about SEK100,000 per vehicle Wästgärds, 1997 p. 1. This cost is calculated for the use of GSM-systems. The cost per vehicle in the pilot installation was lower, but as the possibility of using the service radio in future installations is unclear, the higher figure is used.

155 Wästgärds, 1997 p. 4
The number of vehicles needed is dependent upon the timetable, described in the next section. Four trains are needed for the base scenario, three passenger trains and one freight train. In order to gain flexibility and reduce impacts on the service when maintenance work is carried out on the trains, some extra vehicles must be equipped. Two extra trains will suffice for this purpose, giving a total of 6 trains that will need equipment. The cost will then be SEK600,000.

5.5.4.1.1.4 The line
The costs of signalling equipment on the line between stations are calculated in a somewhat more stereotypical way, based on an analysis of the Linköping-Västervik line. All the transponders and signs have been counted and divided into equipment in station areas and equipment on the line between the stations. Based on the assumption that this line is representative for the rest of the regional lines, the equipment per kilometre of the line is calculated, equipment on station areas excluded. It could have been possible to count the number of speed signs on all of the ten relevant lines and then calculate an average, but this would have taken too much time and the assumption had to be made that the pilot line is representative.

On the Linköping-Västervik line, there are 3.47 transponders and 0.25 signs per kilometre. These figures are taken and calculated from BIS, the NRA line database Banverket, 1995-. By means of a graphical output, the transponders on the line between the stations could be located and counted. The transponders for the extra blocks included in the diagram, although no extra blocks are added on the imaginary line in order to preserve comparability. This might seem a little unrealistic, but it is the only way to make a fair comparison. The possibility of adding extra blocks is optional and to the benefit of the Radioblock system and must be analysed separately.

The number of transponders on the line, extra blocks excluded, is 2.61 per kilometre. The average number of signs is 0.01 per kilometre. Using these figures on the imaginary line, we reach a sum of 238 transponders and only 1 new sign. The big difference between the number of transponders and the number of signs is explained by the fact that transponders are required at every speed sign and these speed signs already exist. The new signs that are needed are classified as “other signs” required specifically by the Radioblock system.

The number of radio stations and radio links is also dependent upon the length of the line. The experience of the pilot line showed that about one radio station every 10 kilometres is needed to give full coverage\textsuperscript{156}. It is worth noting that this is valid for the service radio. It is possible that the GSM could require more or fewer stations to cover a line. In lieu of information on this the figure of one radio station every ten kilometres is used. At every radio station two radio relay stations are required to achieve contact with the signal interlocking system.

5.5.4.1.1.5 Total investment costs
The total investment costs are therefore as follows.

\textsuperscript{156} Banverket, 1996, p. 37
Table 37. Costs for the Radioblock system in the "Base" scenario.

It can be seen that the fixed costs makes up about one third of the total costs and that the costs for the stations are almost half of the investment costs for the whole system.

### Costs of service and maintenance

A comparison of the costs of service and maintenance on the pilot installation in 1996 and 1994 shows that the costs have risen by about SEK391,000. The budget for 1997 was SEK351,000. The figures are taken directly from the NRA’s accounting system, called “PAS”. The figures are exclusively for signal and communication systems. In the calculations below, the average value for 1994 and 1995 represents the costs before the system was implemented even though the service started in mid-1995. Most of the initial costs were born by the project so they did not affect the 1995 figures. The average value for 1996 and 1997 represents the maintenance and service costs after the system was installed. It is only the difference between these average values that is used in the cost benefit analysis.

<table>
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<tr>
<th>Year</th>
<th>Cost</th>
<th>Average</th>
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</thead>
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<td>555945</td>
<td>525215</td>
</tr>
<tr>
<td>1995</td>
<td>494485</td>
<td>525215</td>
</tr>
<tr>
<td>1996</td>
<td>817746</td>
<td>902372</td>
</tr>
<tr>
<td>1997</td>
<td>986997</td>
<td></td>
</tr>
<tr>
<td>Difference</td>
<td></td>
<td>377157</td>
</tr>
</tbody>
</table>

Table 38. Changes in maintenance costs for the pilot line.

However, it is not possible to use the figures from the pilot line for the imaginary line as they differ in important aspects. The number of stations is the most relevant way of differentiating the figures as most of the maintenance has been at the stations, where the equipment is concentrated. Maintenance costs for the imaginary line have been calculated by dividing the costs for the pilot installation with the number of stations on the pilot line and then multiplying by the number of stations on the imaginary line. The value reached is 0.38/8x7=SEK0.33 million annually, giving a present value of SEK5.71 million , calculated using a 4% discount rate over a period of 30 years.
5.5.4.2 Effects

5.5.4.2.1 Costs of train dispatchers

In the winter, 14 single-trip passenger trains use the line every weekday on average. In addition, 2 single-trip freight trains use the line. In the summer, the number of passenger train departures is reduced to eight. The same weekend timetable is used for winter and summer and 6 passenger trains depart every Saturday and Sunday.

The journey times between the stations have been calculated rather roughly by approximating the acceleration and retardation curves of a class Y1 railcar with an average value. The Y1 is the train type most commonly used on regional lines in Sweden. It is a diesel railcar, built in 1979-1981 and used mostly on non-electrified lines. The average value used is 0.7 m/s² for both acceleration and retardation. For the freight trains a lower value of 0.3 m/s² is used.

Table 39. Base scenario - graphical winter timetable. The table is a distance-time diagram, with distance on the y-axis and time on the x-axis.

The diagram above shows the winter timetable. The summer and weekend timetables can be found in the full report of the study157. The traffic volume with these timetables is about 430,000 train kilometres every year. This is somewhat (12%) higher than the average of the regional lines studied. This can be explained by the fact that on many of these lines some departures only serve part of the line. In the timetable for the imaginary line, all trains serve the whole line. This gives a somewhat higher traffic volume, but it will not affect the analysis in any substantial way as the calculations are made for the imaginary line. (In the high-traffic scenario, some departures serve only part of the line.)

Based on these timetables, the Swedish Rail Traffic Administration has produced work schedules for the train dispatchers according to current employment legislation and accepted practice. The schedules cover a period of three weeks and give the train dispatchers two free

157 Johansson, 1998b, Appendix A
days per week, with every third weekend worked. The work schedule is shown in the figure below.

<table>
<thead>
<tr>
<th>Station</th>
<th>Pass no</th>
<th>Winter timetable</th>
<th>Summer timetable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Hours</td>
<td>Hours</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M-F F F F F</td>
<td>M-F F F F</td>
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<td>M-F</td>
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<td>I 1 1 1 1 1</td>
</tr>
<tr>
<td>2</td>
<td>M-F</td>
<td>II 2 2 2 2 2</td>
<td>II 2 2 2 2 2</td>
</tr>
<tr>
<td>3</td>
<td>Sa-Su</td>
<td>III 3 3 3 3 3</td>
<td>III 3 3 3 3 3</td>
</tr>
<tr>
<td>Korndalsby 4</td>
<td>M-F</td>
<td>I 4 4 4 4 4</td>
<td>I 4 4 4 4 4</td>
</tr>
<tr>
<td>4</td>
<td>M-F</td>
<td>II 5 5 5 5 5</td>
<td>II 5 5 5 5 5</td>
</tr>
<tr>
<td>5</td>
<td>M-F</td>
<td>III 6 6 6 6 6</td>
<td>III 6 6 6 6 6</td>
</tr>
<tr>
<td>Mörklägga 6</td>
<td>M-F</td>
<td>I 7 7 7 7 7</td>
<td>I 7 7 7 7 7</td>
</tr>
<tr>
<td>7</td>
<td>M-F</td>
<td>II 8 8 8 8 8</td>
<td>II 8 8 8 8 8</td>
</tr>
<tr>
<td>8</td>
<td>M-F</td>
<td>III 9 9 9 9 9</td>
<td>III 9 9 9 9 9</td>
</tr>
<tr>
<td>Verum 9</td>
<td>M-F</td>
<td>I 10 10 10 10 10</td>
<td>I 10 10 10 10 10</td>
</tr>
</tbody>
</table>

Table 40. Base scenario - work schedule for train dispatchers.

To staff the stations, 7 full-time equivalent posts are needed. This amount is in practice multiplied with a factor of 1.3 to compensate for holidays, sick leave, etc., giving a total of 9.1 full-time equivalent posts to serve the stations. The cost per post is SEK350,000 per year, giving a total cost of SEK3.19 million per year.

However, there are costs for the installation of the radio block system. Normally the control of the line can be handed to an existing traffic control centre. We are therefore interested in the amount of extra labour needed at the control centre to serve the line. If we assume that there is some available capacity at the centre, it is likely that the control of the new line will not demand more than a marginal extra contribution of labour. The Swedish Rail Traffic Administration has estimated this to be a half-time post in the base scenario. The average cost for dispatchers at central traffic controls is about SEK400,000 per year, giving a cost of SEK0.2 million per year. The difference is then 3.2-0.2=SEK3.0million per year.

5.5.4.2.2 Safety effects

The safety effects of the system were studied separately. The analysis is found in section 2.4.

5.5.4.2.3 Time savings

Initially it was assumed that the Radioblock system would enable shorter travel times. It emerged however that the travel times on the pilot line after the system was installed were about the same as before the installation. The changes in travel time between 1993 and 1996 for some of the departures are not dependent on the radio block system as they could have been possible even with the former, manual system.

The system minimises restoration times after disruptions. This gives time savings in the form of less delay for passengers, but the effect has not been calculated in this study as it would have required simulations that it has not been possible to do (see p. 173). Time savings are therefore represented by a “+” in the cost-benefit analysis.
5.5.4.2.4 Timetable adjustments

The implementation of the Radioblock system on the line between Linköping and Västervik did not bring any major changes in the timetable. The number of departures is just about the same as before. What has changed is that the system has allowed a better-adjusted timetable. The line shares a section with another regional line between Linköping and Hultsfred. There could only be one train at a time on the shared section between Linköping and Bjärka-Säby before the system was installed. This meant that the minimum time interval between trains on this section was about 20 minutes.

Extra block sections on this part have enabled shorter intervals between the trains, allowing headways as low as five minutes. This has allowed better adjustment of the timetable and, with some assumptions, we can calculate the benefit.

The change is primarily for commuters who can travel 12 minutes later from Linköping, 16:52 instead of 16:40 Monday to Friday, when going home in the afternoon. Passenger counts from one week in autumn 1996 showed that on average 56 people left Linköping on the 16:52 train every day, giving about 282 passengers per week. The time “saved” for these 282 persons would amount to 282x12/60=56.4 hours a week. This effect is only realised with the winter timetable, which is used for about 40 weeks per year, giving a total amount of 56.4x40=x 2256 hours per year.

It is important to note that this effect is not a travel time saving. It is not possible to use the official Swedish values of travel time. These amount to SEK 35 per hour for regional journeys to work. The assumption will instead be that the commuters use the 12 minutes to work and that the value to be calculated is the value of working time.

The average value of one hour of work is about SEK 200 for an employee. This value is sometimes used in other contexts. The total value of the adjustments in the timetable would then be 2256 hours x SEK200/hour = SEK 451,200 per year.

This method of calculation can be discussed. The value used for an hour of work as well as the way the number of “saved” hours are calculated can be questioned. However, the purpose of the exercise is to find the maximum value of the timetable adjustments. Even if other ways of calculating the value are used, the amount will be small in comparison to the savings on train dispatchers. It will only have minor influence on the results of the CBA.

5.5.4.2.5 Flexibility

The Radioblock system allows for extra trains at low marginal cost, flexibility in timetable planning reduced restoration times after delays and a reduced risk of spreading delays to other trains on the line. The problem is how to value these benefits, as they are mainly options and not real benefits until they are realised.

In order to evaluate this flexibility the idea was to construct a third scenario in which the imaginary line is optimally equipped with the Radioblock system. This would then include dividing the line into extra block sections in order to raise the capacity and minimise restoration times after disruptions.

The traffic described in the timetables and disturbances would then be simulated and the effects calculated with a Train Traffic Simulator developed by the NRA and ÅF-Industriteknik. Unfortunately, it was not possible to perform these simulations as the NRA has limited capacity and personnel for this. The flexibility will therefore be represented with a “+” in the cost benefit analysis.
5.5.5 **High-traffic scenario – costs and effects**

5.5.5.1 Costs

5.5.5.1.1 System costs

The fixed costs are the same as in the base scenario. A centralised traffic control is needed independently of the traffic volume and the costs will therefore be the same. In addition, the amount of radio stations needed are the same as they only depend on the length of the line. What will change though are the costs for the stations.

5.5.5.1.2 Stations

In order to enable the traffic in the high scenario several of the stations have to be rebuilt and enlarged. These infrastructure investments are needed independent of whether we have train dispatchers or Radioblock. The costs are the same in both cases and are therefore not calculated. The difference is that more transponders and signs are needed at the stations. The cost of the signalling system is higher than in the base scenario. The manually operated points at single-track stations used in the base scenario have been replaced with centrally controlled points. We call this station type 1.

![Figure 50] High-traffic scenario - station type 1

Station type 1 is found at Tallnäs and Kohagen. The cost for the signalling system at this station type is SEK1.5 million. The stations at Medby and Mörklägga have also been enlarged and match the size and functions of the station in, for example, Bäckevik. We call this station type 3. It is shown in the figure below and is similar to the same station type in the base scenario.

![Figure 51] High-traffic scenario - station type 3

This station type is found in Bäckevik, Medby, Nordosterby, Mörklägga and Verum. The cost of the signal system is SEK1.8 million.

As in the base scenario, the investment at passing stations also necessitates equipment for the level crossings associated with them. In the high-traffic scenario, 5 stations need to be equipped. These stations are Bäckevik, Nordosterby, Verum, Medby and Kohagen. The total cost for these level crossings is SEK1 million.

5.5.5.1.3 Vehicle equipment

The number of vehicles required for the timetable in the high-traffic scenario is 6. As stated earlier, extra vehicles are needed to minimise the effects of rolling stock failures or regular maintenance. 3 extra vehicles therefore need to be equipped, giving a total cost of SEK0.9 million.
5.5.5.1.4 The line

As explained above, no extra blocks are installed between the stations. This is in order to preserve comparability between manual train dispatching and the Radioblock system. This might seem even more unrealistic than in the base scenario, but it is necessary to keep it this way. The possibility of installing extra block sections is optional and is an extra benefit of the system, which can be analysed separately. This means that the cost of the signal system on the line between the stations is the same as in the base scenario.

5.5.5.1.5 Total investment costs

We can now sum up the costs in the high-traffic scenario. The calculations have been checked by the NRA.

<table>
<thead>
<tr>
<th>High scenario</th>
<th>Number</th>
<th>Cost</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manœuvre system</td>
<td>1</td>
<td>1,000,000</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Radio block central</td>
<td>1</td>
<td>2,000,000</td>
<td>2,000,000</td>
</tr>
<tr>
<td>Radio stations</td>
<td>10</td>
<td>50,000</td>
<td>500,000</td>
</tr>
<tr>
<td>Radio links</td>
<td>18</td>
<td>50,000</td>
<td>900,000</td>
</tr>
<tr>
<td>Interface to radio block central</td>
<td>1</td>
<td>300,000</td>
<td>300,000</td>
</tr>
<tr>
<td>Interface to other signal boxes</td>
<td>1</td>
<td>400,000</td>
<td>400,000</td>
</tr>
<tr>
<td>Stations</td>
<td>7</td>
<td></td>
<td>12,021,808</td>
</tr>
<tr>
<td>Equipment at level crossings on stations</td>
<td>5</td>
<td>200,000</td>
<td>1,000,000</td>
</tr>
<tr>
<td>On the line</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Balises</td>
<td>238</td>
<td>8,245</td>
<td>1,963,896</td>
</tr>
<tr>
<td>Signs</td>
<td>1</td>
<td>4,833</td>
<td>4,156</td>
</tr>
<tr>
<td>Planning</td>
<td>1</td>
<td>4,017,972</td>
<td>4,017,972</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>24,107,831</strong></td>
</tr>
</tbody>
</table>

Table 41. Costs for the Radioblock system in the "High-traffic" scenario.

The difference between the base scenario and the high-traffic scenario is only SEK3 million. This is due to the assumptions and restrictions made and will of course affect the result in a substantial way. It is important to point out that the calculations are made for an imaginary line and that when the system is installed in reality more block sections will be a natural way of enhancing the capacity. It will of course increase the difference in investment costs between the lines where low traffic does not require the extra blocks and lines with high traffic which surely will demand them.

5.5.5.1.6 Costs of service and maintenance

The costs of service and maintenance will naturally be higher than in the base scenario. As it is difficult to make any estimates of the costs, it is assumed that the costs will rise by 25% compared to the base scenario. The costs will then be about 0.38x1.25 = SEK0.48 million annually in this scenario, giving a present value of about SEK71 million. This is most likely an overestimate of the costs. In discussions with the NRA, a judgement has been made that the costs will not exceed this amount.
5.5.5.2 Effects

5.5.5.2.1 Costs for train dispatchers

In the high-traffic scenario the traffic is more than doubled compared to the base scenario. Passenger trains depart every hour, starting at 6 a.m. and continuing until 11 p.m., which is 32 departures, every average weekday. This is shown in the diagram below. To that is added 6 freight train departures. In the summer, there are 22 passenger and 4 freight departures. The weekend timetable has 14 passenger trains departing. No freight trains run at weekends.

![High-traffic scenario – graphical winter timetable](image)

This timetable demands investment in the infrastructure. Several passing stations have to be enlarged and other investments made in order to enable traffic according to the timetable. These investments are the same whether Radioblock is installed or not and so the costs are not calculated. Separate timetables are produced for winter, summer and weekend traffic. The traffic volume is also calculated and found to be 1.1 million train kilometres.

As with the base scenario, a work schedule has been set up for the train dispatchers. This can be found in the full report\(^\text{158}\). To serve the stations 12 posts are needed. Multiplied by the factor of 1.3 for holidays, sick leave etc., we reach a total of 15.6 full-time equivalent posts. The total cost for these is SEK 5.46 million per year. To serve the line after the system is installed, a total of 1.5 full-time equivalent posts are needed. The cost for these is SEK0.6 million annually, the difference amounting to 5.46 - 0.6 = SEK4.9 million per year.

5.5.5.2.2 Time savings and flexibility

Using the same arguments as presented in the section on the effects in the base scenario, the time savings and flexibility are represented with a + in the cost benefit analysis.

\(^\text{158}\) Johansson, 1998b, Appendix B
5.5.5.2.3 **Timetable adjustments**

As with the calculations of the costs for service and maintenance, the assumption is made that the benefits of a better adjusted timetable will increase, in this case by 50% compared to the base scenario. This means that the value will amount to $450,000 \times 1.5 = \text{SEK}\,675,000$ per year in the high-traffic scenario.

5.5.5.2.4 **Safety effects**

As the number of accidents is dependent upon the traffic volume and as this is higher in the high-traffic scenario than in the base scenario, the safety effect will be bigger. If the line is divided into more sections, maintenance would be simplified. It would then be possible to occupy smaller parts of the line and the traffic would be disturbed less.

As stated earlier, it is not possible to make any definite statements on the magnitude of the safety effect. It is clear that the effect will be small as the traffic volume is rather low on the regional lines. As an example, we can use the figures reached in section 2.4. The difference in the probability of an accident occurring between lines with and lines without automatic traffic control systems is 0.23 accidents per million train kilometres. The traffic volume on the imaginary line is 1.1 million train-km/year. This means that the system will prevent approximately 1 accident in 4 years.

Let us assume a relatively high value, SEK\,1 million per accident, as an average cost of material damage. The benefit will then be about SEK \,0.25 million per year. Of course, the uncertainty in this is very large, but it gives a hint of the magnitude of the effect. We will represent the safety effect with a “+” in the cost benefit analysis.

5.5.6 **Cost Benefit Analysis**

It is now time to sum up all the values obtained and carry out an evaluation of the system. The official Swedish economic standard that is to be used is an interest rate of 4% and the NRA recommends a period of 30 years for calculating the benefits and costs of signal equipment. Two tax factors are also to be used.

Tax factor I is to be added to investment costs that are not given in consumer prices. All costs in this report are given in net prices (producer prices) and the benefits are naturally given in consumer prices that include value added tax (VAT). In order to get the costs comparable to the benefits that include VAT, the Swedish Institute for Communications Analysis (SIKA) has decided that a factor of 1.23 should be used, and it is on all investment costs in this report.

Tax factor II is to be added to the costs that are financed from public funds. The argument is in short that there is a loss of efficiency when society uses taxes to finance projects because this affects market prices on the and leads to inefficient decisions and distribution of resources. This factor is 1.3 and will be added to all investment costs in infrastructure. It can be assumed that the equipment costs for the rolling stock will be covered by the operators. This means that this cost should only be multiplied with tax factor I as it is not financed by taxes.

There are reasons to use a shorter period in this analysis. The uncertainty of the traffic on many of the regional lines is higher than on the main lines. Moreover, development in the radio field is explosive and it is highly likely that the economic life of the radio equipment is shorter than the technical life. This implies sunk costs when the system is replaced. This means that there is some uncertainty in the calculations below.
However, using the shorter period would lower the benefit-cost ratio by only about 0.1. In order to enable comparisons with other projects of the NRA, it was decided to use the recommended period of 30 years for discounting benefits of signal equipment.

It is also the case that the benefits from the savings on train dispatchers are only realised if the manpower released can be used elsewhere. If the train dispatchers are given an early retirement pension, for example 5 years earlier than if the system was not installed, the salary should not be counted as a saving because no other people will replace them and produce what otherwise would have been produced. The extra production the released people can give should be calculated in the cost-benefit analysis. In other words, it is only the change in producer (and consumer) surplus that should be calculated.

<table>
<thead>
<tr>
<th>COSTS</th>
<th>Base</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrastructure</td>
<td>21.6</td>
<td>24.1</td>
</tr>
<tr>
<td>Service and maintenance</td>
<td>5.71</td>
<td>7.13</td>
</tr>
<tr>
<td>Development cost, controllable points</td>
<td>1.33</td>
<td>1.33</td>
</tr>
<tr>
<td>Costs with tax factors I &amp; II</td>
<td>45.71</td>
<td>52.08</td>
</tr>
<tr>
<td>Rolling stock, incl tax factor I</td>
<td>0.74</td>
<td>1.11</td>
</tr>
<tr>
<td><strong>Total costs (MSEK)</strong></td>
<td><strong>46.45</strong></td>
<td><strong>53.19</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BENEFITS</th>
<th>Base</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Savings - traindispatchers</td>
<td>3.0</td>
<td>4.9</td>
</tr>
<tr>
<td>Time table adjustments</td>
<td>0.45</td>
<td>0.68</td>
</tr>
<tr>
<td><strong>Total benefits per year</strong></td>
<td><strong>3.45</strong></td>
<td><strong>5.58</strong></td>
</tr>
<tr>
<td>Present value (MSEK)</td>
<td>59.67</td>
<td>96.40</td>
</tr>
</tbody>
</table>

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Time savings</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Flexibility</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Safety effects</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td><strong>Total effects</strong></td>
<td><strong>59.67</strong></td>
<td><strong>96.40</strong></td>
</tr>
</tbody>
</table>

| Benefits / Costs | 1.31 | 1.85 |
| NPV              | 0.31 | 0.85 |

Table 42. Cost-benefit analysis of the Radioblock system.

Using the calculated values, we reach a benefit cost ratio of about 1.31 for the base scenario and 1.85 for the high-traffic scenario. The corresponding net present value is 0.31 and 0.85.

### 5.5.7 Summary

The purpose of this study was to evaluate a new traffic control system called Radioblock. The system is a low-cost alternative to traditional traffic control systems (Automatic Line Block and ATC) and it has the same functionality as the traditional systems. This evaluation is also a test of a method for handling problems of applicability and uncertainty. The analysis is partly based on information and experience from a pilot installation on a 115km-long regional line in Sweden.
It was unclear whether the pilot line could be seen as representative for the rest of the regional lines that are possible subjects for installing the system. This led to the decision to collect information on relevant parameters for those lines. Based on this information, an imaginary, “average” regional line was created and described. We have thus handled the problem of applicability and it is hoped that the evaluation is relevant to more cases than just the pilot installation.

The description of the line also included calculations of the costs. Since the equipment at the stations forms a major part of the costs, it was decided to try to make a more elaborate estimate of this part. The NRA did not use a very detailed system for reporting the project costs. This made the task somewhat difficult, as it was not possible to see the exact costs for every part of the project. However, there was some information and a brief report on the costs from the NRA. The costs for the line between the stations were calculated in a more stereotypical way. A single measure of the number of transponders per kilometre was calculated and applied to the imaginary line.

In order to estimate the savings on train dispatchers and the number of Radioblock-equipped vehicles needed it was necessary to produce timetables for the traffic on the line. Separate timetables were set up for the winter, summer and weekend traffic. Based on these, work schedules were produced and it was then possible to calculate the number of train dispatchers needed to serve the line.

The other benefits that would be possible due to the system are time savings, flexibility and safety effects. It is worth remembering that it is only the difference between the traffic on a line with manual train clearance and a line operated with Radioblock that was analysed. It is often possible to have the same traffic with manual train dispatching, as with traffic control systems, and the differences in travel times for example would therefore be small. These effects are often dependent upon other investment in the infrastructure. Calculations of the value of a better-adjusted timetable were performed and this effect can be substantial. Various calculations were performed, but all values were below SEK 1 million per year.

As regards the safety effects, an extensive analysis of the differences between lines with manual train dispatching and those with traffic control systems was undertaken. The Swedish Railway Inspectorate’s accident database, JAS, was used and the analysis showed that the number of accidents on lines without traffic control systems is significantly higher than on lines with such systems. The database only has information from 1989 onwards, so that the dataset is too small to allow any statements on the magnitude of the difference. The effect has been represented in the cost-benefit analysis by a “+” sign.

The Radioblock system raises capacity and flexibility, as it is possible to split block sections into smaller parts by adding extra block posts. The trains can then be sent out on the line at shorter intervals. It is then possible to adjust the timetables to fit demand better. Other effects are that disruptions to traffic can be recovered from faster and that the marginal cost of running an extra train is very low compared to the situation with manual train dispatching. These effects can only be estimated in simulations. As this was not possible in this study the effects are represented in the cost-benefit analysis by a “+” sign. This was also done for the safety effects and the time savings.

The CBA shows that the system is profitable. The calculated benefit-cost ratio in the base scenario is 1.3 and 1.9 in the high-traffic scenario. The “+” signs in the CBA imply that the benefit-cost ratio should be higher than the one calculated. On the other hand, the economic life of the Radioblock system might be significantly shorter than the technical life. This implies that the cost-benefit ratio is lower than the one calculated. A period of 20 years
instead of the 30 years used would lower the benefit-cost ratio by about 0.1 in both scenarios. This discussion gives some moderation to the calculated values.

The study was also a test of a method for handling what has been referred to as problems of applicability and uncertainty. The method of describing an imaginary installation set out in this section has the benefits of clearing away unnecessary details and attracting attention to the relevant aspects of the system. It necessitates some extra work compared to a case study as more information is needed. The result is however valid for more cases than just one specific installation of the system.

The uncertainty is dealt with by using two different traffic scenarios. A complete analysis would have included simulations to investigate all of the benefits of the system. The possibility and effects of installing extra block posts has not been analysed in this paper. A possible way of enhancing the study would have been to describe a third scenario where the imaginary line was optimally equipped with block posts. The number of block stretches would then be higher than the number of stretches controlled by dispatchers and the block stretches would be shorter. Simulations of disruptions in the traffic could be analysed with respect to restoration times, etc. The difference between using dispatchers and using Radioblock would then probably be higher. The basic idea of handling the problems of uncertainty is however illustrated with the two scenarios.
6. Summary and discussion

The railway traffic of today is one of the safest transport modes and passengers are seldom involved in fatal accidents. The decision of the early 1980s to make a major investment in the Automatic Line Block and Automatic Train Control (ATC) traffic control systems can be cited as part of the explanation for the low accident record of the past 10-15 years. Even so, new safety rules are added and there is investment in safety equipment, and there is a constant effort to “keep the record clean”. This is good from a railway safety viewpoint.

However, as with all other societal projects, there is a limit to the amount that can or should be invested in safety. Not all safety projects can be realised, so difficult choices and prioritisations have to be made. These decisions can be taken in a variety of ways, from informal judgements to the explicit weighing of costs and benefits.

The main point of this thesis is that safety rules and safety equipment also often bring about effects other than the risk reductions they are designed to produce. The obvious example is the restrictive traffic rules that are applied when signal failures occur. They can require the service to be stopped or trains to proceed at reduced speed. This naturally leads to delays for passengers and the effects can be substantial. The balance between safety benefits and other costs produced by the safety rules has seldom been discussed. The aim of this thesis is to describe and develop methods for analysing railway safety based on the explicit weighing of safety against other costs and benefits.

A procedure for safety analysis is described in this thesis. The term “safety analysis” has been chosen to distinguish the process from risk analysis. The term “risk analysis” is often used to denote specific methods. Safety analysis is the entire process from the identification of problems to the evaluation of decisions and implementation, and includes analyses of different alternatives. The procedure comprises several steps, and these are described, with methodology, previous research and the contribution of the author. The procedure proposed is a combination of traditional socio-economic cost-benefit analysis and limits in the form of criteria for the absolute level and the distribution of risks. The risk criteria set the level above which risks from an activity are not permitted. Risks below this level should be weighed against other costs and benefits. The approach is quite simple in theory, but the information and conditions needed for the safety analysis are considerable.

The thesis comprises descriptions of risk criteria, methods and applications for their use, and why it is necessary to use risk criteria when analysing safety. Included here are reviews of statistical and risk analysis methods, an analysis of historical data on railway accidents in Sweden and the development of a risk analysis model for passenger train derailments. Further, a study of people’s valuations of safety in different contexts has been conducted, and, finally, the economic analysis of safety is discussed. An economic analysis of a train traffic control system is thereby described.

The railway is a technical system and there are various methods for analysing risks in technical systems. The problem when it comes to using traditional statistical methods for estimating accident probabilities, and so on, is the lack of data. The low accident record of the railway makes life a little more complicated for the statistical analyst (with the exception of level crossing accident statistics). Accident rates have changed over time and there is insufficient data for the last year to estimate the current accident rate, for example. Historical data is needed and it is necessary to model trends in the accident rates. There are also other methods that can and have been used for analysing railway risks. Fault tree and event tree methods, for example, have been used by the Swedish National Rail Administration for
analysing the risks associated with railway tunnels. This and other examples are described in the thesis.

The main problem is to find data for estimating accident risks. Even if risk analysis methods, like the ones exemplified, are used, it is often necessary to have some information on the incident rates or reliability of different parts of the system. This problem will remain and cannot be solved in a simple way. Developing a system for detailed incident reporting could be one possible way of increasing the information available on system disruptions and may lead to a better knowledge of the risks in the railway system.

The uncompromising principle of cost-benefit analysis is to maximise the return on a given investment. It has no relationship with the distribution of the effects. This is not acceptable as it could lead to situations in which the total risks of an activity are reduced and, at the same time, a few people are exposed to a considerable (and unacceptable) increase in risk. There are therefore reasons for using criteria for individual risk that ensure that no person or specific group of people is exposed to unacceptable risks. The argument for using criteria for collective risk is not that clear, however.

The purpose of criteria for collective risk is to reduce the risks in local areas, such as residential districts, or for society as a whole. They aim to reduce the risks from transport, industrial (chemical) plants or other activities, to which towns, housing areas, schools or other large population groups are exposed, for a longer or shorter time. The argument in favour of using collective criteria becomes somewhat clearer when we look at the example of a new chemical plant being erected close to a housing area or a city centre. It seems natural to set absolute limits for the risks that can be accepted from the new activity. Then, in the name of consistency, criteria must also be applied to existing activities. Using criteria for individual and collective risk leads to decisions that are not optimal from the perspective of maximising economic net benefit. This is important to remember, especially when applying criteria for collective risk.

One common way of presenting criteria for collective risk has been in the form of Frequency–Number lines (FN lines). It has been shown elsewhere that using FN criterion lines for judging risks can lead to inconsistent decisions. This is discussed in the thesis and an alternative model for calculating the disutility of collective risks is proposed. It offers the opportunity of giving higher weightings to multiple-fatality accidents than to “smaller”, single-fatality accidents. The calculated level of the disutility is then compared with a threshold value for an unacceptable level of disutility.

The time has come to discuss the potential offered and those aspects that need further investigation. It is not only conceivable but also probable that we currently have safety rules that have major socio-economic effects, with the aim of reducing risks that are already so low that they can be classified as negligible. These safety rules can be described as inefficient or “unnecessary”. The hope is that by using the procedure for evaluating safety described in this thesis, it will be possible to unmask these safety rules and describe the situation correctly. The safety analysis procedure thus provides both a way of describing the safety rules and a standard against which to assess them.

It is possible that the process will end in a situation in which we judge a safety rule as inefficient or unnecessary and state that the risks are already low, below the limits for unacceptable risks. The risk reduction that is achieved here does not compensate for the large economic cost of the rule, even if we use a value of saving a life that is, let us say, ten times the value of avoiding a road-accident fatality.
If “common sense” still tells us to keep the safety rule, we must start to ask questions. What are the reasons for keeping the rule when we cannot justify it with the criteria for risk or by weighing it against other effects, even if we put a high value on safety? Are the risk criteria that have been chosen totally wrong, or should another level for unacceptable risks be chosen? Alternatively, is it the case that we put a higher value on safety than the estimated value? Is it perhaps the instinct for self-preservation that postulates that no accidents can be allowed to happen, regardless of the cost? Is the safety level justified by business economics? Is safety such an important factor for railway operators that no accidents can be allowed to happen, regardless of the cost?

Whatever the reasons, it is important that the work of reviewing and analysing railway safety risks begins. We will need estimates of the weight to be given to multiple-fatality accidents and the threshold value with which the calculated expected disutility should be compared. This must be done before any criteria for collective risk can be applied.
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Appendix 1. The logic of railway traffic with line block or radio block signalling

The purpose of line block, or radio block, signalling is to ensure that only one train at a time occupies a certain section of a line. The sections, or blocks, are connected to a signal control system. When train A enters section 1 information is sent from the tracks, or from the train, to the signal control system to say that the train is occupying the section. In the case of radio block, this information is sent by radio. The control system sets signal II to red. This means that as long as train A occupies section 1, train B cannot enter section 2. This intermediate section is needed to provide a safety margin between the trains. As train B has entered section 3, signal III is set to red, as well as signal IV, which is situated off the diagram, to the left.

The implication of this is that the minimum length of the blocks is dictated by the necessary safety margin between trains, and, conversely, that the minimum distance between trains is dictated by the length of the blocks. If these blocks are split into several shorter sections, the capacity of the line is increased. The trains can be sent out on the line at shorter intervals and traffic disruptions can be rectified faster.

The little triangles on the line in the diagram signify the transponders mounted between the tracks. In traditional lineblock signalling, the transponder relays information to the ATC system on the status of the signal, i.e. whether or not the train can enter the section. With radio-block signalling, the transponder relays information on the train’s position and permission to enter the section is given to the train from the signal control system by radio.
Appendix 2. Description of BOR and the quality of the data

1. Introduction
This section contains information on the different tables constituting BOR and their purposes. The classifications used and the strengths and weaknesses of the data are also described in section 3.

2. Tables in BOR
There are 11 different tables in BOR.

1. “BOR” – main table
2. Accident type
3. Location type
4. Track section
5. Cause
6. Train type
7. Vehicle type
8. Signal systems on all track sections
9. Places on the network, with names and abbreviations
10. Official accident statistics for the period 1940-1960
11. Traffic volume in train kilometres for all track sections.

Table nos. 2-7 are sub-tables of the main table “BOR” and they are there to ensure the consistency of the information in the main table, in which the accident record are stored. The sub-tables contain information on, for example, type of accident, cause, etc. A reference number is stored in the main table, which is replaced by the corresponding text in the sub-table. When a new accident is registered, the primary accident type can be chosen from a drop-down menu. An example of this is given with the description of the accident types below.

Table nos. 8 to 11 contain information required by risk analyses, including data on signalling systems, traffic volumes, etc. These are also described below.

2.1. “BOR” – the main table
Initially, the choice of fields in the database was taken from their use in the data sources. Typically, all data sources used accident date, location, type of accident, etc. However, other fields, like type of sleeper, might only be found in one of the databases. Therefore, in order to be able to use all the information, all data fields were permitted and added to BOR. This list had to be reviewed. None of the databases had specific fields for fire or whether passengers were on board when the accident occurred, and so they had to be added. A complete list of all fields in BOR can be found in section 6 in this appendix.
2.2. Accident types
The table of accident types contains the following information.

<table>
<thead>
<tr>
<th>ID</th>
<th>Accident type</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>Collision</td>
</tr>
<tr>
<td>23</td>
<td>Derailment</td>
</tr>
<tr>
<td>24</td>
<td>Fire</td>
</tr>
<tr>
<td>25</td>
<td>Human accident</td>
</tr>
<tr>
<td>26</td>
<td>Working accident</td>
</tr>
<tr>
<td>27</td>
<td>Level crossing accident</td>
</tr>
<tr>
<td>28</td>
<td>Shedding of goods being carried</td>
</tr>
<tr>
<td>29</td>
<td>Other</td>
</tr>
<tr>
<td>30</td>
<td>Collision with non-moving objects</td>
</tr>
</tbody>
</table>

The accident type is given in two fields in the database: “Primary Accident” and “Secondary Accident”. It is then possible to classify a collision with a road vehicle at a level crossing correctly as a level crossing accident and to state that the train derailed because of the collision.

For those who have no experience of relational databases, the relationship between the accident type table and the main table “BOR” is more easily explained with an example. The main table stores an ID number, rather than the accident type as text. However, when the table is displayed, the ID is automatically replaced with the corresponding accident type, taken from the accident type table, shown above. Furthermore, when a new accident is registered, the analyst chooses the accident type from a drop-down menu instead of writing it in as text. This avoids typographical errors and a consistent classification can be achieved.

2.3. Location type
Accident location is classified according to five different classes given in the following table.

<table>
<thead>
<tr>
<th>Location type ID</th>
<th>Location type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Line</td>
</tr>
<tr>
<td>2</td>
<td>Station</td>
</tr>
<tr>
<td>3</td>
<td>Railway yard</td>
</tr>
<tr>
<td>4</td>
<td>Train halt</td>
</tr>
<tr>
<td>5</td>
<td>Tunnel</td>
</tr>
</tbody>
</table>

The data sources did not use the location type "Railway yard", but it was added as a category because of the needs of the developing risk analysis model. It is essential to separate stations from railway yards when modelling train accidents. A collision or derailment in a station can affect the platform space, giving potentially severe consequences, such as passengers waiting on the platform being injured or killed. The probability of this occurring is very small, but still exists. It is therefore valuable to be able to make the distinction when analysing accidents.
2.4. Track sections

The National Rail Administration (NRA) and the main operator, Swedish State Railways (SJ), have a track labelling system. This uses numbers to label every part of the railway system, totalling 217 different sections in 1997. However, the system has changed several times, which has led to big problems whenever accident information is correlated with traffic volume data. A study of the Radioblock system was conducted in 1998. Within this project, a special study was carried out on the safety effects of signalling systems and, including a revision of the NRA’s and SJ’s labelling system.

SJ changed the labelling system between 1994 and 1995, and there was data for 217 track sections in 1997, but for only 162 sections in 1991. Only 89 of the track sections were labelled in exactly the same way for the whole period, 1991 – 1997. The reason for this was that several track sections were divided into two or more new sections with new numbers between 1994 and 1995. Furthermore, some track sections had simply been renumbered and some new tracks had been built.

This caused more problems and work than was first expected. In order not to lose any grade of detail it was decided to use the actual labelling system of the NRA. Since this work was carried out in 1998, SJ has adapted its labelling system to conform to the one used by the NRA. Updated data files from SJ on traffic volume can therefore be used with the database with minor adaptations.

Some accidents occurred on track sections that have since been taken out of service: closed, moved or changed in other ways. This is a problem and has not been solved. Where it was not possible to assign a track number, that field has been left empty, with the location of the accident is only described in the “Line” or “Location” fields.

The Line and Location fields have also been updated from the NRA list of track sections when a track number could be assigned. This automatic update is made in MS Access and has simplified the process.

2.5. Cause

In order to classify the causes of derailments in BOR, a list of 86 causes on three levels has been used. This classification system is inspired by a risk analysis model developed by Railtrack in Britain. Typically, the analyses in many studies are heavily dependent upon the classifications used in the statistical databases available. In this project, the database was adapted to the needs of the analysis, which is preferable. On the other hand, this necessitated the reclassification of the causes of all accidents.

In the three-level classification, the first level is called “Category”, the second “Group” and the third “Type”. By using this three-level system, it is possible to choose the level of detail in future analyses. It is just as easy to pick all rolling stock faults, for instance, as it is to find all derailments caused by “axle failure due to over-heated bearing”. This is illustrated in the table below. The full list can be found in section 7 in this appendix.
Table 43. Extract from table of causes, full list in section 7 in this appendix.

It is obvious that with 86 different causes specified, the list will contain descriptions of many causes that have not yet led to a passenger train derailment in Sweden. This is not to say that they are too unlikely to be meaningful to use. It is better to have a list that is more or less complete even though some of the codes have still not been used, than to have a large number of accidents in the database that cannot be classified with other codes than “other causes”. This holds as long as it is possible to aggregate the accidents into a more general level, as is the case with the classification above.

The category, group and type fields are automatically updated from the list when the cause number is changed. This simplifies the assignment of cause, as it is only necessary to give a number, which can also be chosen from a drop-down list where the classification system is given. It is then easy to verify that the correct cause number is assigned.

The number of derailments with unclear causes was initially 58 out of a total of 122 studied, around half. After some cumbersome work, the number of accidents with unclear causes was brought down to only 6; around 5% of the material. The reason that no specific cause could be assigned to these was that the cause was not to be found in the accident investigations. Either it was simply not found, or there were several things that could have caused the accident, but contradictory evidence made the case unclear, etc. This is still a leap forward, as BOR now enables reliable analysis of the causes of derailments.

It should be remembered that this work started with the objective of analysing passenger train derailments. Therefore, the classification system was developed initially for the causes of
derailments. When extra funding became available to add information on collisions, the classification system of causes was developed further.

At this stage, the scheme was modified so that it would fit both derailments and collisions. Clearly a signal passed at danger might lead to either a derailment or a collision, or to both at the same time. The same holds for incorrect train movements on points and crossings. The ability to study causes at an aggregate level is still maintained.

As stated in the previous section, there were 129 collisions involving passenger trains. In 97 of these, there were passengers on board. 11 of these accidents had unclear causes, although this figure might be brought down, to around 5, when work on the database is finished.

2.6. Train type

12 different train types are listed in the train type table.

<table>
<thead>
<tr>
<th>No.</th>
<th>Train type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Passenger train</td>
</tr>
<tr>
<td>2</td>
<td>Freight train</td>
</tr>
<tr>
<td>3</td>
<td>Train movement</td>
</tr>
<tr>
<td>4</td>
<td>Traction unit</td>
</tr>
<tr>
<td>5</td>
<td>Train carriage</td>
</tr>
<tr>
<td>6</td>
<td>Works vehicle, trackbound</td>
</tr>
<tr>
<td>7</td>
<td>Other vehicles, trackbound</td>
</tr>
<tr>
<td>8</td>
<td>Road vehicles</td>
</tr>
<tr>
<td>9</td>
<td>Works vehicles, not trackbound</td>
</tr>
<tr>
<td>10</td>
<td>Other vehicles, not trackbound</td>
</tr>
<tr>
<td>11</td>
<td>Other objects</td>
</tr>
<tr>
<td>12</td>
<td>Buffer stop</td>
</tr>
</tbody>
</table>

This list is intended to be exhaustive and is used for both train 1 and train 2. It is apparent that there are not only trains in the list, but also other vehicles and objects. A more general title for the table would have been “object type” but this title does not indicate the content of the table and the title “train type” was therefore chosen.

2.7. Vehicle type

When available, information on vehicle type has been registered. There are numerous vehicle types and it would be almost impossible to formulate an exhaustive list. Furthermore, new vehicles are designed constantly. Below is the version of the list in use at the beginning of 2002. New vehicle types will be added.

<table>
<thead>
<tr>
<th>No.</th>
<th>Vehicle type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Carriage (hauled)</td>
</tr>
<tr>
<td>1</td>
<td>X2000</td>
</tr>
<tr>
<td>2</td>
<td>X2</td>
</tr>
<tr>
<td>3</td>
<td>X10</td>
</tr>
<tr>
<td>4</td>
<td>X9</td>
</tr>
<tr>
<td>5</td>
<td>X1</td>
</tr>
<tr>
<td>6</td>
<td>Y1</td>
</tr>
<tr>
<td>7</td>
<td>Y2</td>
</tr>
<tr>
<td>8</td>
<td>Y6</td>
</tr>
<tr>
<td>9</td>
<td>Hauled passenger train</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>10</td>
<td>Multiple unit</td>
</tr>
<tr>
<td>11</td>
<td>Wagon-load (mixed) freight train</td>
</tr>
<tr>
<td>12</td>
<td>Train-load freight</td>
</tr>
<tr>
<td>13</td>
<td>Inter-modal freight train</td>
</tr>
<tr>
<td>14</td>
<td>Carriage (ordinary, with seats)</td>
</tr>
<tr>
<td>15</td>
<td>Couchette/ Sleeping car</td>
</tr>
<tr>
<td>16</td>
<td>Restaurant car</td>
</tr>
<tr>
<td>17</td>
<td>Preserved train</td>
</tr>
<tr>
<td>18</td>
<td>Tamping machine</td>
</tr>
<tr>
<td>19</td>
<td>Gang car</td>
</tr>
<tr>
<td>20</td>
<td>Powered crane</td>
</tr>
<tr>
<td>21</td>
<td>Lorry</td>
</tr>
<tr>
<td>22</td>
<td>Excavator, Tractor</td>
</tr>
<tr>
<td>23</td>
<td>Lorry</td>
</tr>
<tr>
<td>24</td>
<td>Stone</td>
</tr>
<tr>
<td>25</td>
<td>Rc class locomotive</td>
</tr>
<tr>
<td>26</td>
<td>T44 class locomotive</td>
</tr>
</tbody>
</table>

### 2.8. Signalling systems on all track sections

In the Radio block study, track sections with automatic signalling systems were compared to those without. A problem that had to be addressed was that the signalling systems are different on different track sections and that there was investment in signal technology during the period sampled. The situation today is different from the situation in 1991. Selecting all the accidents on a specific track section that has ATCS today will not give a correct result if the signalling system was been installed during the sample period. Accidents that occurred before the system was installed would be labelled wrongly as accidents on tracks with ATCS. Therefore, a list of the dates when ATCS were installed and taken into use had to be set up. Information on signalling systems before the 1991 was found in a book of infrastructure data from the Swedish Railway Club\(^{159}\). Information on changes to these systems since 1991 has been published in the Swedish journal *TÅG*\(^{160}\). The list has been checked by Bengt Hultin, Anders Lundström and Christer Södergren at the Swedish Railway Inspectorate. Having set up the list with data on the dates on which signalling systems entered service on given track sections, it was possible to get all the accidents right and avoid classifying an accident as an ATCS accident when that signalling system was not present until after the accident happened. A table has been included in BOR with this information in order to simplify future analysis. It contains information on the start and end dates of work to upgrade track sections to double track, line block signalling and to ATC (in total 6 columns) for all track sections. The system of labelling track sections corresponds to the current labelling system of the National Rail Administration. It is therefore possible to correlate the data with the accidents that have occurred and more easily find all accidents on double or single track, on track sections with line block signalling, etc.

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\(^{159}\) Aghult, Lind et al., 1992

\(^{160}\) Olson, 1998
2.9. Places on the network, with names and abbreviations
The National Railway Inspectorate publishes lists of named places on the Swedish rail network. Each name also has a unique abbreviation. The purpose of this is to simplify day-to-day work. The list contained 1721 different names on 17th October 2000. This list has been included in BOR to simplify the location of accidents.

2.10. Official accident statistics for the period 1940-1960
The official accident statistics were produced by the operator SJ up until 1988, and the National Rail Administration became responsible for this in 1989. This information is included in a table in BOR. It contains such information as the total number of passengers and railway staff killed and injured, the number of derailments, collisions, etc. The information is rather aggregated and cannot be used for in-depth statistical analysis. The work with BOR has also revealed flaws in the official statistics. Some passenger deaths are not included in the aggregations. This is rather remarkable. BOR contains information on all passenger deaths from 1960 to 2000.

2.11. Traffic volume in train kilometres for all track sections
Data on traffic volume for all track sections was collected from the Swedish State Railways database TRACK and runs from 1991 onwards. An aggregated list for the years 1985-1990 was also been set up but is not included in BOR.

3. Other classifications
The previous section described the tables in the BOR database. Some classifications in BOR have no support in a sub-table. These classifications are described here.

3.1. Accident or incident
In this project, there has been a focus on accidents. A number of incidents are included as the data source “HÄR” contained information on incidents. The data on incidents has not been controlled. However, the information has not been erased from the database.

When the accidents in BOR where reviewed, it turned out that some of them where wrongly classified as accidents when they were in fact incidents. These faults originated in the data sources and have been corrected in BOR. It is of course possible that there are several faults in the data sources that have not yet been discovered. Whenever a fault is discovered, a note has been written in the “other information”-field.

There is therefore a further possibility that some of the occurrences might turn out to have been wrongly classified as incidents when they where in fact accidents. This is the reason for keeping the information on incidents.

BOR contains information on passenger train derailments and collisions. A derailment accident occurs when at least one wheel leaves the track. If a train comes into contact with another train or other object when it is not supposed to, then this is a collision accident. These are the definitions that have been used when the accidents have been reviewed.
3.2.  Speed
A train’s speed is normally registered by its on-board ATC equipment. Before 1980, other equipment was used, although not always automatic. In some of these cases, the speed was estimated by the driver and noted in the accident report. Frequently no figure is given.

A search was made in order to find the speed of all derailments 1985-1999 and for all accidents with passenger fatalities 1960-2000. It has not been possible to find information for all accidents. Several fields in BOR are used for reporting speed: line speed, the train’s maximum speed and its actual speed. Sometimes conflicting figures are reported in the different data sources. When it has not been possible to confirm the figures given, the lowest speed has been reported in a separate field.

3.3.  Fatalities and injuries
There is seldom any dispute on the definition of fatalities following an accident. The figures given for the number of fatalities in railway accidents are accurate to a very high degree. In contrast, there are several possible ways of defining “seriously injured” and “slightly injured”. A serious injury will, according to one definition, require medical treatment for at least 30 days or lead to an irreparable disability. It follows from this that in order to be able to classify injured people as seriously or slightly injured, the consequences have to be followed up, something that is seldom done.

We actually have a problem as soon as we start reporting injuries because we can always question what counts as an injury. Is a scratch on the arm an injury, or should even a bruise count? This might seem to be academic nonsense, but it matters when we try to use the data in the databases for estimating the consequences of accidents. The figures for injuries have to be used with caution as there is uncertainty regarding the actual consequences. This also holds for the figures reported in BOR. An attempt was made to obtain the most reliable figures possible. However, the data sources are often vague on the severity of injuries and normally only report the total number.

3.4.  Passengers on board
A tick-box is used to indicate if there were passengers on board a train. There are two fields, one for each train involved in an accident. This information has been triple-checked and is reliable. A common problem is avoided in this way, as the analyst often has no choice but to use the train type classifications used in the available database.

However, there might be passengers on board trains that have been classified as works trains. Accidents involving works trains with passengers on-board will therefore be overlooked in the analysis, leading to an underestimate of the risks. Furthermore, passenger trains have been involved in accidents without having any passengers on board, leading to an overestimate of the risks. This is avoided in BOR by the use of the “passengers on board” fields.

3.5.  Circumstances of the accident
Several fields allow a better description of the circumstances of the accidents. This simplifies the analysis of the data.

3.6.  Shunting
A tick-box is used to indicate if an accident happened during shunting.
3.7. Spread
Spread refers to the movement of train carriages or traction beyond the track. It is measured as the maximum distance of a vehicle from the track centre, which is the middle line between the rails. This information is sometimes given, but its reliability is low and the figures in BOR should only be seen as rough estimates. A closer study on this would need photographs from all accident scenes in order to get a more reliable picture.

3.8. Fire
A tick-box is used to indicate if a fire resulted from the accident. There is an accident type called Fire, so that this tick-box serves to repeat information. However, it is sometimes easier to analyse the data using this field.

3.9. Dangerous goods
Whether dangerous goods were being carried on the train / any of the trains.

3.10. Release of dangerous goods
Whether dangerous goods were released.

3.11. Description
When possible, full text descriptions have been included in BOR. This is one of the big advantages of BOR compared to other databases in Sweden. It is much easier to compare different accidents and to quickly find the relevant information. In many cases, several information sources have been used. This is indicated in the descriptions.

3.12. Cause description
Similarly, full text descriptions of the causes have been included where possible. Multiple sources might also have been used here and this is indicated.

3.13. Sources
The information sources used for each accident have been noted. There are several fields for this. For example, sometimes newspaper articles were the only source available. The name of the journal and the date has then been noted. The article is stored in the binder system.
4. The user interface

The BOR user interface is shown above. The left-hand column contains information on the type of accident, date, time and location. The second column contains a description of the accident and information on fatalities and injuries. The third column contains a description of the causes as well as a classification of the causes according to the system developed within the project. In the lower right-hand corner are four different windows containing information on, for example, the track standard at the scene of the accident, rolling stock, and what information sources have been used for this specific accident.

This interface can easily be translated into other languages, except for the textual descriptions. The database will be presented primarily in Swedish, but an English interface will be developed when time allows.
5. Summary
A great deal of effort was been put into obtaining reliable data that could used in the risk analysis model. The information for each accident was revised several times, a time-consuming job. There was a long search for accident reports in order to find the causes for all accidents. Such information as whether the train’s carriages overturned, or whether the accident occurred over points or during shunting, was double-checked. There were also a number of accidents were it was unclear whether any passengers were on board. All this information has been checked. The benefit of this work is that the specific information on each accident is relatively reliable.
6. List of fields in the database

<table>
<thead>
<tr>
<th>Field</th>
<th>Field type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>Counter</td>
<td>Counter</td>
</tr>
<tr>
<td>Reg. no.</td>
<td>Number in the registry</td>
<td>Corresponds to the accident report in the binder system</td>
</tr>
<tr>
<td>BIS</td>
<td>Yes/No</td>
<td>Yes if accident is reported in BIS</td>
</tr>
<tr>
<td>HAR</td>
<td>Yes/No</td>
<td>Yes if accident is reported in HAR</td>
</tr>
<tr>
<td>JAS</td>
<td>Yes/No</td>
<td>Yes if accident is reported in JAS</td>
</tr>
<tr>
<td>SJ</td>
<td>Yes/No</td>
<td>Yes if accident is reported at SJ, as an incident or paper report</td>
</tr>
<tr>
<td>SJ/Sp</td>
<td>Yes/No</td>
<td>Yes if accident is reported in the data-files from Sparre</td>
</tr>
<tr>
<td>Database</td>
<td>Yes/No</td>
<td>Yes if reported in a database, no if only in paper report</td>
</tr>
<tr>
<td>Database name</td>
<td>Text</td>
<td>Corresponds to the field above. Empty if two or more data sources have been merged.</td>
</tr>
<tr>
<td>Database specific no.</td>
<td>Number</td>
<td>The accident entries in the sources used for BOR were given specific numbers, reported here in order to find the information source easily.</td>
</tr>
<tr>
<td>Year</td>
<td>Number</td>
<td>Added in order to simplify the analysis.</td>
</tr>
<tr>
<td>Accident date</td>
<td>Date</td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>Time</td>
<td></td>
</tr>
<tr>
<td>Accident / Incident</td>
<td>Text</td>
<td>See text.</td>
</tr>
<tr>
<td>Primary accident</td>
<td>Text</td>
<td>See text.</td>
</tr>
<tr>
<td>Secondary accident</td>
<td>Text</td>
<td>See text.</td>
</tr>
<tr>
<td>Track no.</td>
<td>Number</td>
<td>According to the current list from the NRA; see text for further comments.</td>
</tr>
<tr>
<td>Line</td>
<td>Text</td>
<td>According to the current list from the NRA, see text for further comments.</td>
</tr>
<tr>
<td>Place</td>
<td>Text</td>
<td>When given.</td>
</tr>
<tr>
<td>Line place from</td>
<td>Text</td>
<td>This together with the following field specifies the part of the line where the accident occurred. The code follows the official list of places on the network set up by the Railway Inspectorate.</td>
</tr>
<tr>
<td>Line place to</td>
<td>Text</td>
<td>See above.</td>
</tr>
<tr>
<td>---------------</td>
<td>------</td>
<td>------------</td>
</tr>
<tr>
<td>Up or down track, or single track</td>
<td>Text</td>
<td>Specifies the track when there is a double track.</td>
</tr>
<tr>
<td>Kilometre</td>
<td>Number</td>
<td>Corresponds to the line place, gives the exact location of the accident together with the metre-figure given in the next field.</td>
</tr>
<tr>
<td>Metre</td>
<td>Number</td>
<td></td>
</tr>
<tr>
<td>Extent, track metres</td>
<td>Number</td>
<td>The extent of the accident, from for example derailment point to the point where the train halts.</td>
</tr>
<tr>
<td>Type of location</td>
<td>Text</td>
<td>Station, line or railway yard. See text for further comments.</td>
</tr>
<tr>
<td>Level crossing</td>
<td>Yes / No</td>
<td>Yes if the accident occurred at a level crossing. Does not necessarily imply that there was a collision with a road vehicle.</td>
</tr>
<tr>
<td>Points</td>
<td>Yes / No</td>
<td>Yes if accident occurred at points.</td>
</tr>
<tr>
<td>Shunting</td>
<td>Yes / No</td>
<td>Yes if accident occurred during shunting.</td>
</tr>
<tr>
<td>Spread</td>
<td>Number</td>
<td>The distance of the carriages from the track centre.</td>
</tr>
<tr>
<td>Overturning carriages</td>
<td>Yes / No</td>
<td></td>
</tr>
<tr>
<td>Fire</td>
<td>Yes / No</td>
<td></td>
</tr>
<tr>
<td>Passengers on board</td>
<td>Yes / No</td>
<td></td>
</tr>
<tr>
<td>Dangerous goods</td>
<td>Yes / No</td>
<td></td>
</tr>
<tr>
<td>Class / type of dangerous goods</td>
<td>Text</td>
<td>Description of the dangerous goods.</td>
</tr>
<tr>
<td>Release of dangerous goods</td>
<td>Yes / No</td>
<td>Yes if dangerous goods have been released in the accident.</td>
</tr>
<tr>
<td>Passenger fatalities</td>
<td>Number</td>
<td></td>
</tr>
<tr>
<td>Passengers seriously injured</td>
<td>Number</td>
<td></td>
</tr>
<tr>
<td>Passenger slight injuries</td>
<td>Number</td>
<td></td>
</tr>
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<td>Railway staff slight injuries</td>
<td>Number</td>
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<tr>
<td>Road user and other fatalities</td>
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<tr>
<td>Description</td>
<td>Text</td>
<td>Full text description of the accident, sometimes taken from different sources.</td>
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<tr>
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<tr>
<td>Other information</td>
<td>Text</td>
<td>Further information, regarding the treatment of the accident, classifications made, lack of data or source of data, etc.</td>
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<td>Cause according to classification system developed within the project.</td>
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<td>Number</td>
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<tr>
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</tr>
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<td>Type</td>
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<tr>
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<tr>
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<td>Vehicle type train 1</td>
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<tr>
<td>Operator train 1</td>
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## 7. Classification system for causes

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<th>Category</th>
<th>Group</th>
<th>Type</th>
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<tbody>
<tr>
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<td>Track faults</td>
<td>Track support failure</td>
<td>Drainage culvert/pipework collapse</td>
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<td>Track faults</td>
<td>Track support failure</td>
<td>Subsidence/landslide under track</td>
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<td>Track faults</td>
<td>Buckled rail</td>
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<td>Track faults</td>
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<td>140</td>
<td>Track faults</td>
<td>Broken fishplate</td>
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<td>Track faults</td>
<td>Gauge spread</td>
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<td>Track faults</td>
<td>Track damage from other</td>
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<td>undetected derailment</td>
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<td>Track faults</td>
<td>Other track faults</td>
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<td>211</td>
<td>Rolling stock faults</td>
<td>Axle failure</td>
<td>Axle failure due to over-heated bearing</td>
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<tr>
<td>212</td>
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<td>Axle failure</td>
<td>Axle failure due to other causes</td>
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<td>Seized axle box bearing</td>
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<td>Rolling stock faults</td>
<td>Suspension system/bogie failures</td>
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<td>241</td>
<td>Rolling stock faults</td>
<td>Wheel failure</td>
<td>Wheel flats or wheel/tyre wear beyond limits</td>
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<td>Other wheel failure</td>
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<td>272</td>
<td>Rolling stock faults</td>
<td>Brake failure</td>
<td>Severe braking/Snatch</td>
</tr>
<tr>
<td>281</td>
<td>Rolling stock faults</td>
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<td>Traction control failure =&gt; SPAD</td>
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<tr>
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<td>311</td>
<td>Running into obstructions</td>
<td>Running into objects on the tracks</td>
<td>Running into large animals</td>
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<tr>
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<td>Running into obstructions</td>
<td>Running into objects on the tracks</td>
<td>Running into objects from building site</td>
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<td>313</td>
<td>Running into obstructions</td>
<td>Running into objects on the tracks</td>
<td>Running into items blown onto the line</td>
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<td>Running into objects on the tracks</td>
<td>Running into trees</td>
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<td>Running into objects on the tracks</td>
<td>Running into items placed onto the track by vandals</td>
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<td>Running into objects on the tracks</td>
<td>Running into engineers’ materials left fouling the track</td>
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<td>Running into obstructions</td>
<td>Running into objects on the tracks</td>
<td>Running into other / unknown objects</td>
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<td>320</td>
<td>Running into obstructions</td>
<td>Running into track locks or brake shoes</td>
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<tr>
<td>331</td>
<td>Running into obstructions</td>
<td>Running into debris from structural failures</td>
<td>Running into debris from over-bridges</td>
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<td>Running into obstructions</td>
<td>Running into debris from structural failures</td>
<td>Running into debris from line-side structures/buildings</td>
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<td>Running into landslip</td>
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<td>Running into debris from OHLE structures</td>
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<td>Running into obstructions</td>
<td>Running into debris from structural failures</td>
<td>Running into debris from retaining walls</td>
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<td>Running into debris from retaining walls</td>
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<td>Running into vehicles</td>
<td>Running into maintenance vehicles</td>
<td>Maintenance carried out at the wrong place</td>
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<td>Running into maintenance vehicles</td>
<td>Maintenance allowed with train already on the section</td>
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<td>Running into maintenance vehicles</td>
<td>Maintenance not allowed</td>
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<td>Running into vehicles</td>
<td>Running into maintenance vehicles</td>
<td>Caused by miscommunication of ambiguous and incomplete information</td>
</tr>
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<td>415</td>
<td>Running into vehicles</td>
<td>Running into maintenance vehicles</td>
<td>Train movement allowed with maintenance already allowed, signalman error.</td>
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<td>Vehicle fallen from over-bridge</td>
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<td>Incorrect train movements on Switches and Crossings (S&amp;C)</td>
<td>Driver/train crew error at S&amp;C</td>
<td>Movement of points under train, due to train crew errors</td>
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<td>512</td>
<td>Incorrect train movements on S&amp;C</td>
<td>Driver/train crew error at S&amp;C</td>
<td>Running through points in wrong position</td>
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<td>Incorrect train movements on S&amp;C</td>
<td>Driver/train crew error at S&amp;C</td>
<td>Other driver/train crew error at S&amp;C</td>
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<td>520</td>
<td>Incorrect train movements on S&amp;C</td>
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<td>531</td>
<td>Incorrect train movements on S&amp;C</td>
<td>Points not in correct position, detected</td>
<td>Objects between rail and point, detected, incorrect control by driver.</td>
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<td>Incorrect train movements on S&amp;C</td>
<td>Points not in correct position, detected</td>
<td>Points not in correct position, detected, incorrect control by driver.</td>
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<td>Faults on S&amp;C</td>
<td>Defective S&amp;C</td>
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<td>Incorrect scotch and clip of points</td>
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<td>650</td>
<td>Faults on S&amp;C</td>
<td>Signalman/crossing keeper error</td>
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<td>Driver disregards signal =&gt; SPAD</td>
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<td>Driver miscommunication =&gt; SPAD</td>
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<td>Driver miscommunication =&gt; SPAD</td>
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<td>Other staff hand-signalman communications HE =&gt; SPAD</td>
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Appendix 3. Statistical probability distributions

1. The normal distribution

1.1. Application
The normal distribution can model the characteristics of population parameters such as weight, height, etc. It is also the distribution of the size of quantities that are the sum of other quantities. The normal distribution is the limit of the binomial distribution. It serves as an approximation of samples drawn from virtually all populations, regardless of shape.

1.2. Density function
The probability distribution is given by

\[ f(x) = \left( \frac{1}{2\pi\sigma} \right) e^{-\left(\frac{x-\mu}{\sigma}\right)^2} \]  

(32)

where \( \mu \) is the mean and \( \sigma \) is the standard deviation, \( \pi \) is the constant 3.14159, and e is the base of natural logarithms and is equal to 2.71828. \( x \) can take on any value from -infinity to +infinity.

1.3. Graphs
To the right is given three graphs for the normal distribution with different means and standard deviations.
2. The Binomial distribution

2.1. Application
The binomial distribution counts the number of successes in a given number of trials. The random variable is discrete and can only take on two, mutually exclusive, outcomes. It is for example used to describe the number of defective items in a sample of a given size n. A common example is also the number of times a head shows up when tossing a coin. The coin is tossed 5 times and the number of heads is counted. The experiment is repeated 10 times. The number of heads in each trial then follows a binomial distribution.

2.2. Density function
The probability distribution is given by

\[ f(x) = \binom{n}{x} p^x q^{n-x} = \frac{n!}{x!(n-x)!} p^x q^{n-x} \quad (33) \]

where p is the probability of success in a single trial, q = 1-p, n is the number of trials and x is the number of successes.

2.3. Graphs
To the right is given graphs where the number of trials is constant, n=15, and the probability of success is 0.1; 0.5 and 0.9. Notice the resemblance with the normal distribution when the probability of success is 0.5.
3. Poisson distribution

3.1. Application
The Poisson distribution is normally used to count the number of occurrences of an event in a given unit of time. Examples are the number of accidents, the number of persons arriving in a queue etc. Instead of time another measurement unit could be used. The mean of the distribution is also the variance.

The requirements for a Poisson distribution are

1. The probability that an event will occur in a short interval of time (or space) is proportional to the size of the interval.
2. In a very small interval, the probability that two events will occur is close to zero.
3. The probability that any number of events will occur in a given interval is independent of where the interval begins.
4. The probability of any number of events occurring over a given interval is independent of the number of events that occurred prior to the interval.


3.2. Density function
\[ f(x) = \frac{\mu^x e^{-\mu}}{x!} \quad (34) \]
for \( x = 0, 1, 2, 3, \ldots \)

where \( \mu \) is the mean of the distribution (and the variance) and \( e \) is the base of the natural logarithm.

3.3. Graphs
To the right is given graphs for three different means. Please note that the scale on the x-axis is not the same on the graphs.

With a low mean the distribution is skewed. As the mean increases, the shape of the Poisson distribution approaches the shape of the normal distribution.
4. The standard lognormal distribution

4.1. Application

The lognormal distribution is commonly used in reliability applications. The lognormal distribution describes for example variables that measure quantities that are a product of a large number of other quantities. A variable X is lognormally distributed when the natural logarithm of X is normally distributed, i.e. if \( Y = \ln(X) \) is normally distributed.

4.2. Density function

The probability distribution is given by

\[
f(x) = \frac{1}{x \sqrt{2\pi \sigma^2}} e^{\left( \frac{-(\ln x - \mu)^2}{2\sigma^2} \right)}
\]

where \( x > 0 \).

4.3. Graphs

To the right is given three graphs for the standard lognormal distribution. In all examples, the mean is 5. The standard deviation is 1, 5 and 15.

When the distributions variance is small relative to the mean, the shape approaches the normal distribution. However, when the variance increases, the skewness appears and the typical shape is given in the middle diagram.

The last diagram is given to illustrate the effect of increasing variance. When variance increases, the tail gets longer and mode of the distribution (the peak of the curve) moves from the mean towards origin.
5. **Negative binomial distribution**

5.1. **Application**

The negative binomial distribution counts the number of trials needed to get $s$ successes when the probability of success is $p$. It could be used to describe the number of wells to drill to find oil $s$ times, or the number of failures required before reaching a fixed number of successes.

The requirements for the binomial distribution are:

1. The experiment consists of a sequence of independent trials.
2. Each trial has two possible outcomes, $S$ or $F$.
3. The probability of success, $p = P(S)$, is constant from one trial to another.
4. The experiment continues until a total of $s$ successes are observed, where $s$ is fixed in advance.

5.2. **Density function**

Let the random variable $X$ follow a negative binomial distribution. This can be denoted $X \sim \text{NB}(s, p)$. The probabilities is given by

$$P(X = x) = \binom{x + s - 1}{s - 1} p^x (1 - p)^{s-x}$$

for all $0 \leq p \leq 1$ and $s = 0, 1, 2, 3, \ldots$.

The expected value of the distribution $E(X)$ is given by

$$E(X) = \frac{s(1 - p)}{p}$$

(37)

The variance of the distribution $V(X)$ is given by

$$V(X) = \frac{s(1 - p)}{p^2}$$

(38)

5.3. **Graphs**

Below is given graphs of the distribution. In the first three graphs, the probability of success is 0.5 and the number of required successes 1 ; 5 and 15. In the fourth graph the number of successes required is 15 and the probability of success is 0.8.
The binomial distribution can also be used to model accidents.
6. Triangular distribution

6.1. Application
The triangular distribution is used when actual data is absent. It is a simple way of describing a random variable. The distribution is for example used in risk assessments.

6.2. Density
\[ f(x) = \frac{2(x-a)}{(b-a)(c-a)} \quad \text{if} \quad a \leq x \leq b \quad (39) \]
\[ f(x) = \frac{2(c-x)}{(c-a)(c-b)} \quad \text{if} \quad b < x \leq c \quad (40) \]

where \( a \) = minimum value, \( b \) = most likely value, \( c \) = maximum value.

6.3. Graphs
To the right is given two example graphs. The distribution can be skewed in both directions.
Appendix 4. Fault trees in the model of passenger train derailments.

Frequency of passenger train derailments

108.8/Gkm

Frequency of PT derailment on open track

39.7/Gkm

Frequency of PT derailment at stations

67.9/Gkm

Frequency of PT derailment in tunnels

1.2/Gkm
**Frequency of PT derailments on open track**

A: 39.7 Gtkm

**Frequency of PT derailments due to track faults**

- D: 48.26 Gtkm
  - Probability that track fault will lead to PTD on open track: 0.37

**Frequency of PTD due to track faults**

- E: 17.45 Gtkm
  - Probability that rolling stock faults will lead to PTD on open track: 0.36

**Frequency of PTD on open track due to rolling stock faults**

- F: 42.06 Gtkm
  - Probability that erratic behaviour will lead to PTD on open track: 0.37

**Frequency of PT derailments due to track faults**

- C: 17.86 Gtkm

**Frequency of PTD on open track due to rolling stock faults**

- B: 6.28 Gtkm

**Frequency of PT derailments due to track faults**

- A: 39.7 Gtkm

**Frequency of PTD due to track faults**

- C: 17.86 Gtkm

**Frequency of PTD due to track faults**

- D: 48.26 Gtkm
  - Probability that track fault will lead to PTD on open track: 0.37
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**Frequency of PT derailments at stations**

- Frequency due to track faults: 30.4/Gtkm
  - Frequency of PTD due to track faults: 48.26/Gtkm
    - Probability that track faults will lead to PTD at stations: 0.63
  - Frequency of PTD due to rolling stock faults: 17.45/Gtkm
    - Probability that rolling stock faults will lead to PTD at stations: 0.63
  - Frequency of PTD due to erratic behaviour: 42.06/Gtkm
    - Probability that erratic behaviour will lead to PTD at stations: 0.63

- Frequency due to rolling stock faults: 10.99/Gtkm
- Frequency due to erratic behaviour: 26.5/Gtkm
- Overall frequency: 67.9/Gtkm
Frequency of PT derailment in tunnels: 1.2/Gkm

Frequency of PTD in tunnels due to rolling stock faults: 0.17/Gkm

Frequency of PTD due to rolling stock faults: 17.45/Gkm

Prob. that roll. stock faults will lead to PTD in tunnel: 0.01

Frequency of PT derailment due to tunnel track faults: 1.03/Gkm
Frequency of PTD due to track faults

48.26/Gtkm

Frequency of PTD due to faults on rails and track support structures

12.31/Gtkm

Frequency of PTD due to faults on S&C

12.31/Gtkm

Frequency of PTD due to environmental conditions on track

0./Gtkm

Frequency of PTD due to running into obstructions

17.46/Gtkm

Frequency of PTD due to various other causes

6.18/Gtkm
Frequency of PTD due to rolling stock faults: 17.45/Gtkm

- **Frequency of PTD due to axle failures:**
  - Seized axle box bearing: 6.15/Gtkm
  - Axle failure due to heated bearing: 2.05/Gtkm
  - Wheel flats: 4.1/Gtkm
  - Wheel wear beyond limits: 1.03/Gtkm

- **Frequency of PTD due to wheel failures:**
  - Wheel failure: 1.03/Gtkm

- **Frequency of PTD due to brake failures:**
  - Severe braking / snatch: 0./Gtkm

- **Frequency of PTD due to traction control failures:**
  - Severe braking / snatch: 0./Gtkm

- **Frequency of PTD due to other rolling stock faults:**
  - Other traction control failure: 7.19/Gtkm
Frequency of PTD due to erratic behaviour 42.06/Gtkm

- Frequency of PTD due to incorrect train movements on S&C
  - Frequency of PTD due to train driver human error
    - 29.74/Gtkm
  - Frequency of PTD due to other railway staff human error => SPAD
    - 0./Gtkm
  - Frequency of PTD due to running into vehicles
    - 1.03/Gtkm

- Overspeeding
  - 2.05/Gtkm
Frequency of PTD due to tunnel track faults

- Frequency of PTD due to tunnel track faults: 1.03/Gtkm
  - Broken fishplate: 0./Gtkm
  - Gauge spread in tunnel: 0./Gtkm
  - Broken rail in tunnel: 0./Gtkm
  - Other track faults in tunnel: 0./Gtkm

Frequency of PTD due to running into obstructions

- Frequency of PTD due to running into obstructions: 1.03/Gtkm
  - Running into debris from tunnel structure: 1.03/Gtkm
  - Other obstructions in tunnels: 0./Gtkm
Frequency of PTD due to faults on rails and track support structures

12.31/Gtkm

Track support failure

1.03/Gtkm

- Drainage culvert / pipework collapse leading to PTD
  - 0./Gtkm

- Subsidence/landslide under track leading to PTD
  - 1.03/Gtkm

- Rail faults leading to PTD
  - 7.18/Gtkm

  - Buckled rail due to heat expansion
    - 4.1/Gtkm

  - Broken rail leading to PTD
    - 3.08/Gtkm

  - Broken fishplate leading to PTD
    - 0./Gtkm

  - Gauge spread leading to PTD
    - 0./Gtkm

Other track faults

4.1/Gtkm

- PTD due to track damage from other undetected derailment
  - 0./Gtkm

- Other track faults leading to PTD
  - 4.1/Gtkm
Frequency of PTD due to faults on S&C

- Defective S&C: 7.17/Gtkm
- Track maintenance staff errors: 0./Gtkm
- Movements of points under train (equipment faults): 0./Gtkm
- Incorrect scotch and dip of points: 1.03/Gtkm
- Signalman / crossing keeper error leading to PTD: 1.03/Gtkm

Frequency of PTD due to point not in correct position, not detected: 3.08/Gtkm

Object between rail and point, not detected: 0./Gtkm

Point not in correct position due to other causes, not detected: 3.08/Gtkm
Frequency of PTD due to running into obstructions

- 17.46/Gtkm

Frequency of PTD due to running into other obstructions

- Running into track locks or brake shoes: 3.08/Gtkm
- Running into flooding: 0./Gtkm
- Running into snow/ice: 5.13/Gtkm
- Running into debris from structural failures
  - Running into debris from overbridges: 1.03/Gtkm
  - Running into debris from lineside structures: 0./Gtkm
  - Running into landslip: 1.03/Gtkm
  - Running into debris from signalling gantries: 0./Gtkm
  - Running into debris from retaining walls: 0./Gtkm
- Frequency of PTD due to running into objects on the tracks
  - Running into large animals: 2.05/Gtkm
  - Running into objects from building sites: 0./Gtkm
  - Running into items blown onto the line: 0./Gtkm
  - Running into trees: 0./Gtkm
  - Running into items placed on the track by vandals: 2.05/Gtkm
  - Running into engineers materials left foul: 1.03/Gtkm
  - Running into objects fallen from trains: 1.03/Gtkm
  - Running into other/unknown objects on the tracks: 1.03/Gtkm
Frequency of PTD due to various other causes

- Bridge bashing: 1.03/Gtkm
- Structural damage due to earthquake: 0./Gtkm
- High winds: 0./Gtkm
- Miscellaneous unknown causes on open track: 2.06/Gtkm
- Miscellaneous unknown causes at stations: 2.06/Gtkm
- Incorrect loading, shifting of the cargo: 0./Gtkm
- Wrongside signalling failure leading to SPAD and PTD: 0./Gtkm
- Other signal faults: 1.03/Gtkm
- Frequency of PTD due to faults on signals or signalling equipment: 1.03/Gtkm
Frequency of PTD due to incorrect train movements on S&C: 29.74/Gtkm

- Frequency of PTD due to driver/train crew error at S&C: 7.19/Gtkm
- Shunter errors: 5.12/Gtkm
- Point not in correct position, detected: 17.43/Gtkm

- Movement of points under train due to train crew errors: 7.19/Gtkm
- Running through point in wrong position: 0./Gtkm
- Other driver/train crew error at S&C: 0./Gtkm
- Objects between rail and point, detected, incorrect control by driver: 0./Gtkm
- Point not in correct position, detected, incorrect control by driver: 17.43/Gtkm
Frequency of PTD due to train driver human error

- Driver disregards signal => SPAD: 3.08/Gtkm
- Driver misreads signal => SPAD:
  - Miscommunication => SPAD: 0./Gtkm
  - Driver misreads signal as a result of misreading previous signal: 1.03/Gtkm
  - Driver misreads signal by reading wrong signal: 0./Gtkm
  - Driver misreads signal by reading correct signal but misreads signal aspect: 0./Gtkm
- Driver misjudgement => SPAD:
  - Driver misjudges environmental conditions => SPAD: 0./Gtkm
  - Driver misjudges train behaviour => SPAD: 0./Gtkm
- Other SPADs that are drivers responsibility: 5.13/Gtkm
Frequency of PTD due to other railway staff human error => SPAD

Signalman human error => SPAD

Other staff communication error

Hand-signalman communication error => SPAD

Signalman human error in operating equipment

Other staff human error

0./Gkm
Frequency of PTD due to running into vehicles

1.03/Gtkm

Frequency of PTD due to running into maintenance vehicles

0./Gtkm

Maintenance carried out at wrong place

0./Gtkm

Maintenance allowed with train already on line

0./Gtkm

Maintenance not allowed

0./Gtkm

Caused by mis-communication

0./Gtkm

Train movement allowed with maintenance already allowed, signalman error

0./Gtkm

Frequency of PTD due to running into vehicles on intersections - vehicle SPAD

1.03/Gtkm

Running into vehicles on intersections - vehicle SPAD

0./Gtkm

Vehicle fallen from overbridge

0./Gtkm

Vehicle through boundary fence

0./Gtkm

Other causes

0./Gtkm

Frequency of PTD due to running into vehicles on other places

0./Gtkm
Appendix 5. Event trees in the model of passenger train derailments.

The event trees used in the model are presented here. As the model has been built in MS Excel, it is difficult to give an attractive presentation of the material. The author hopes that this will be excused. It would have been possible to recreate the event trees with special software, giving a more easily read description. However, no such software was available and all modelling have been done in Excel.

Three different event trees have been used to model the various possible consequences in different locations. The first is the event tree for derailments on open track, the second for derailments at stations and finally the event tree for derailments in tunnels. The total number of scenarios in the three event trees is 92.
## Open Track

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<th>Single track?</th>
<th>Clearance remained?</th>
<th>Collision with other train?</th>
<th>Train on fire?</th>
<th>Path probability</th>
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<th>Fatalities per accident</th>
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Number of fatalities: 0.42

Number of scenarios: 24
Appendix 6. Frequencies used in the model of passenger train derailments.

This appendix contains the frequencies used in the risk analysis model developed in the project. The frequencies have been calculated from the number of accidents that have occurred on Swedish tracks and the traffic volumes for the period from 1985 until 1999. The frequencies feed into the fault trees at the bottom level as the basic initiating events. The traffic volumes on the relevant track sections for this period were 975 million trainkilometres. The frequencies are calculated by dividing the number of occurrences by the traffic volume. The number of occurrences is given in the columns “S&C” (points and crossings) and “Open Track”. Possible causes that have not yet led to a derailment have been given a very low figure. This is due to the need to avoid having zero probabilities when running Monte Carlo simulations. The total sum of the assigned probabilities has no significant influence on the final results of the calculations in the model.

<table>
<thead>
<tr>
<th>Cause no.</th>
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<td>Track faults</td>
<td>Track support failure</td>
<td>Drainage culvert/pipework collapse</td>
<td>0.01</td>
</tr>
<tr>
<td>112</td>
<td>Track faults</td>
<td>Track support failure</td>
<td>Subsidence/landslide under track</td>
<td>1</td>
</tr>
<tr>
<td>120</td>
<td>Track faults</td>
<td>Buckled rail</td>
<td>Buckled rail due to heat expansion</td>
<td>4</td>
</tr>
<tr>
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<td>Track faults</td>
<td>Broken rail</td>
<td></td>
<td>3</td>
</tr>
<tr>
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<td>0.01</td>
</tr>
<tr>
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<td>Gauge spread</td>
<td></td>
<td>0.01</td>
</tr>
<tr>
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<td>Track damage from other undetected derailment</td>
<td></td>
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</tr>
<tr>
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<td>Other track faults</td>
<td></td>
<td>4</td>
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<tr>
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<td>Axle failure due to heated bearing</td>
<td>2</td>
</tr>
<tr>
<td>212</td>
<td>Rolling stock faults</td>
<td>Axle failure</td>
<td>Axle failure due to other causes</td>
<td>4</td>
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<tr>
<td>220</td>
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<td>Seized axle box bearing</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>230</td>
<td>Rolling stock faults</td>
<td>Suspension system/bogie failures</td>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td>241</td>
<td>Rolling stock faults</td>
<td>Wheel failure</td>
<td>Wheel flats or Wheel/tyre wear beyond limits</td>
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</tr>
<tr>
<td>242</td>
<td>Rolling stock faults</td>
<td>Wheel failure</td>
<td>Other wheel failure</td>
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</tr>
<tr>
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<td>0.01</td>
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<tr>
<td>271</td>
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</tr>
<tr>
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<td>Severe braking/Snatch</td>
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<td>Cause no.</td>
<td>Category</td>
<td>Group</td>
<td>Type</td>
<td>Frequency</td>
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<td>------------------------------------------------</td>
<td>-----------</td>
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<tr>
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<tr>
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<td>Other Traction control failure</td>
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<td>Other rolling stock faults</td>
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<td>7</td>
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<td>Running into objects on the tracks</td>
<td>Running into large animals</td>
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<tr>
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</tr>
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<td>Running into trees</td>
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<tr>
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<td>Running into objects on the tracks</td>
<td>Running into items placed onto the track by vandals</td>
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<td>Running into objects on the tracks</td>
<td>Running into Engineers materials left foul</td>
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<td>Running into objects on the tracks</td>
<td>Running into objects fallen from trains</td>
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<td>Running into obstructions</td>
<td>Running into objects on the tracks</td>
<td>Running into other / unknown objects</td>
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<tr>
<td>320</td>
<td>Running into obstructions</td>
<td>Running into track locks or brake shoes</td>
<td></td>
<td>3</td>
</tr>
<tr>
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<td>Running into obstructions</td>
<td>Running into debris from structural failures</td>
<td>Running into debris from overbridges</td>
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</tr>
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<td>332</td>
<td>Running into obstructions</td>
<td>Running into debris from structural failures</td>
<td>Running into debris from lineside structures/buildings</td>
<td>0.01</td>
</tr>
<tr>
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<td>Running into debris from structural failures</td>
<td>Running into landslip</td>
<td>1</td>
</tr>
<tr>
<td>334</td>
<td>Running into obstructions</td>
<td>Running into debris from structural failures</td>
<td>Running into debris in tunnels</td>
<td>1</td>
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<tr>
<td>335</td>
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<td>Running into debris from structural failures</td>
<td>Running into debris from signalling gantries</td>
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</tr>
<tr>
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<td>Running into obstructions</td>
<td>Running into debris from structural failures</td>
<td>Running into debris from retaining walls</td>
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<td>340</td>
<td>Running into obstructions</td>
<td>Running into flooding</td>
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<td>0.01</td>
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<tr>
<td>350</td>
<td>Running into obstructions</td>
<td>Running into snow/ice</td>
<td></td>
<td>5</td>
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<td>411</td>
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<td>Running into maintenance vehicles</td>
<td>Maintenance carried out at the wrong place</td>
<td>0.01</td>
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<tr>
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<td>Running into maintenance vehicles</td>
<td>Maintenance allowed with train already on the section</td>
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<tr>
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<td>Running into maintenance vehicles</td>
<td>Maintenance not allowed</td>
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<td>Running into maintenance vehicles</td>
<td>Caused by miscommunication of ambiguous and incomplete information</td>
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</tr>
<tr>
<td>415</td>
<td>Running into vehicles</td>
<td>Running into maintenance vehicles</td>
<td>Train movement allowed with maintenance already allowed, signalman error.</td>
<td>0.01</td>
</tr>
<tr>
<td>420</td>
<td>Running into vehicles</td>
<td>Running into vehicles on intersection</td>
<td>Vehicle SPAD</td>
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<tr>
<td>431</td>
<td>Running into vehicles</td>
<td>Running into vehicles on other places</td>
<td>Vehicle fallen from overbridge</td>
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<tr>
<td>432</td>
<td>Running into vehicles</td>
<td>Running into vehicles on other places</td>
<td>Vehicle through boundary fence</td>
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<td>433</td>
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<td>Running into vehicles on other places</td>
<td>Other cause</td>
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<td>Group</td>
<td>Type</td>
<td>Frequency</td>
</tr>
<tr>
<td>-----------</td>
<td>----------</td>
<td>-------</td>
<td>------</td>
<td>-----------</td>
</tr>
<tr>
<td>511</td>
<td>Incorrect train movements on S&amp;C</td>
<td>Driver/train crew error at S&amp;C</td>
<td>Movement of Points under train, due to traincrew errors</td>
<td>7</td>
</tr>
<tr>
<td>512</td>
<td>Incorrect train movements on S&amp;C</td>
<td>Driver/train crew error at S&amp;C</td>
<td>Running through points in wrong position</td>
<td>0.01</td>
</tr>
<tr>
<td>513</td>
<td>Incorrect train movements on S&amp;C</td>
<td>Driver/train crew error at S&amp;C</td>
<td>Other driver/train crew error at S&amp;C</td>
<td>0.01</td>
</tr>
<tr>
<td>520</td>
<td>Incorrect train movements on S&amp;C</td>
<td>Shunter errors</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>531</td>
<td>Incorrect train movements on S&amp;C</td>
<td>Point not in correct position, detected</td>
<td>Objects between rail and point, detected, incorrect control by driver.</td>
<td>0.01</td>
</tr>
<tr>
<td>532</td>
<td>Incorrect train movements on S&amp;C</td>
<td>Point not in correct position, detected</td>
<td>Point not in correct position, detected, incorrect control by driver.</td>
<td>17</td>
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<tr>
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<td>Defective S&amp;C</td>
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<td>7</td>
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<td>620</td>
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<td>Track maintenance staff errors</td>
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<td>0.01</td>
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<td>630</td>
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<td>Movement of points under train (equipment faults)</td>
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<td>640</td>
<td>Faults on S&amp;C</td>
<td>Incorrect scotch and clip of points</td>
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<tr>
<td>650</td>
<td>Faults on S&amp;C</td>
<td>Signallman/crossing keeper error</td>
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<td>661</td>
<td>Faults on S&amp;C</td>
<td>Point not in correct position, not detected</td>
<td>Objects between rail and point, not detected,</td>
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<td>Point not in correct position, not detected</td>
<td>Point not in correct position due to other / unknown causes</td>
<td>3</td>
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<tr>
<td>710</td>
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<td>Driver disregards signal =&gt; SPAD</td>
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<td>721</td>
<td>Train driver HE =&gt; SPAD</td>
<td>Driver miscommunication =&gt; SPAD</td>
<td>SPAD caused by miscommunication of ambiguous and incomplete information</td>
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</tr>
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<td>722</td>
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<td>Driver miscommunication =&gt; SPAD</td>
<td>Driver Miscommunication SPAD caused by correct info given but misunderstood</td>
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</tr>
<tr>
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<td>Driver miscommunication =&gt; SPAD</td>
<td>SPAD caused by misconm by information not given.</td>
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<tr>
<td>724</td>
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<td>Driver miscommunication =&gt; SPAD</td>
<td>SPAD caused by misconm of wrong information</td>
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</tr>
<tr>
<td>731</td>
<td>Train driver HE =&gt; SPAD</td>
<td>Driver misreads signals =&gt; SPAD</td>
<td>Driver misreads correct signal by misreading signal aspect</td>
<td>1</td>
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<tr>
<td>732</td>
<td>Train driver HE =&gt; SPAD</td>
<td>Driver misreads signals =&gt; SPAD</td>
<td>Driver misreads signal as a result of misreading previous signal</td>
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<tr>
<td>733</td>
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<td>Driver misreads signals =&gt; SPAD</td>
<td>Driver misreads signal by viewing wrong signal</td>
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<td>741</td>
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<td>Driver misjudges signal =&gt; SPAD</td>
<td>Driver misjudges environmental conditions =&gt; SPAD</td>
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<td>Driver misjudges signal =&gt; SPAD</td>
<td>Driver misjudges train behaviour =&gt; SPAD</td>
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<td>Uncategorised SPAD which are drivers responsibility</td>
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<td>Cathegory</td>
<td>Group</td>
<td>Type</td>
<td>Frequency</td>
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<td>----------------------------------------------------------------------</td>
<td>-----------</td>
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<td>Vegetation on track =&gt; SPAD</td>
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<td>Other environmental conditions =&gt; SPAD</td>
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<td>911</td>
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<td>Signalman HE =&gt; SPAD</td>
<td>Signalman HE in operating signalling equipment =&gt; SPAD</td>
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<td>Signalman HE =&gt; SPAD</td>
<td>Signalman communication HE =&gt; SPAD</td>
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<td>Other staffs HE =&gt; SPAD</td>
<td>Other Staff Handsignalman communications HE =&gt; SPAD</td>
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<td>Other staffs HE =&gt; SPAD</td>
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<td>1000</td>
<td>Overspeeding</td>
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<td>2</td>
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<td>1110</td>
<td>Various other causes</td>
<td>Bridge bashing</td>
<td></td>
<td>1</td>
</tr>
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<td>1120</td>
<td>Various other causes</td>
<td>Structural damage due to earthquake</td>
<td></td>
<td>0.01</td>
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<td>1130</td>
<td>Various other causes</td>
<td>High winds</td>
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<td>Miscellaneous unknown causes on plain line</td>
<td></td>
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<td>1150</td>
<td>Various other causes</td>
<td>Miscellaneous unknown causes on stations</td>
<td></td>
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</tr>
<tr>
<td>1161</td>
<td>Various other causes</td>
<td>Faults on signals or signalling equipment</td>
<td>Wrongside signalling failure =&gt; “SPAD”</td>
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<tr>
<td>1162</td>
<td>Various other causes</td>
<td>Faults on signals or signalling equipment</td>
<td>Other cases</td>
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<tr>
<td>1170</td>
<td>Various other causes</td>
<td>Incorrect loading, shifting of the cargo</td>
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<td>0.01</td>
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</tbody>
</table>
Appendix 7. Distribution of answers to equivalence questions in the risk valuation study

Figure 54. Distribution of equivalence question Railway v. Road Safety.

Figure 55. Distribution of equivalence question, Metro v. Road Safety.
Figure 56. Distribution of equivalence question, Fire v. Road safety

Figure 57. Distribution of equivalence question, Prevention of Large v. Small Railway Accidents
Figure 58. Distribution of equivalence question, Prevention of Large v. Small Metro Accidents.

Figure 59. Distribution of equivalence question, Prevention of Large v. Small Fire Accidents.
Appendix 8. Questionnaire used in the risk valuation study.

The full questionnaire used in the main study is reproduced on the following pages. Two different question orders were tested, but this version is the one that was used for the major part of the groups. The change of order was an attempt to enhance comprehension of the issues. This version was the most intuitive and the one that the respondents seemed to find easiest to answer.
Accident risks in different contexts

Introductory questions

1. Are you
   - Man
   - Women

2. How old are you?
   _____ years?

3. How many members do you have in your household?
   _____ 0-3 years
   _____ 4-10 years
   _____ 11-17 years
   _____ 18 years and older

4. Do you have access to a car in your household?
   - Yes
   - No

5. How long distance do you go by car during one year?
   - <1000 mil
   - 1000 – 1500 mil
   - 1500-2000 mil
   - 2000-2500 mil
   - >2500 mil
   (1 mil = 10 km)
6. How long distance do you go with public transports during a normal week:
Bus, Underground, Commuter train, Train
a) during winter (October till March) ?
   • I never use public transports at winter
   • Less than 100 km
   • 100 – 250 km
   • 250 – 400 km
   • More than 400 km

b) during summer (April till September) ?
   • I never use public transports at summer
   • Less than 100 km
   • 100 – 250 km
   • 250 – 400 km
   • More than 400 km

7. What transport modes do you use?
   Several alternatives can be marked!
   • Bus
   • Underground
   • Commuter train
   • Train

8. How long do you go by bike a normal week?
   a) during winter (October till March)?
      • I never go by bike during winter.
      • Less than 25 km
      • 25-50 km
      • 50-100 km
      • More than 100 km
b) during summer (April till September)?
- I never go by bike during summer.
- Less than 25 km
- 25-50 km
- 50-100 km
- More than 100 km

9. How long do you go by motorcycle a normal week?
   a) during winter (October till March)?
- I never go by motorcycle during winter
- Less than 100 km
- 100-250 km
- 250-400 km
- More than 400 km

b) during summer (April till September)?
- I never go by motorcycle during summer
- Less than 100 km
- 100-250 km
- 250-400 km
- More than 400 km

10. a) Have you ever been hurt in a traffic accident? “To be hurt” means so seriously that you have to seek medical help.
- Yes
- No

   b) Have you been hurt in a traffic accident last year?
- Yes
- No

   c) Have someone in your household been hurt in a traffic accident last year?
- Yes
- No
11. You have been told that 20 persons in your city have died in accidents. Five died in a car accident, five in a railway accident, five in a fire accident and five persons died in an underground accident.

Which one of these do you feel to be worse than the others. Rank the accidents through putting “1” in the box next to the accident that you feel is the most serious/worst, a “2” for the second most serious etc.

☐ Railway accident ☐ Car accident
☐ Fire ☐ Underground accident

Write down in short why
12. Suppose that you through investing in safety measures could have prevented some of these accidents. You do not know if the money is enough to prevent all four accidents. The cost of preventing a fatality is the same no matter if the money is spent on safety measures for the road traffic, railway, underground or for increased fire safety.

How would you spend the money. Put a “1” for the accident that you would prefer to prevent first, a “2” for the next etc.

☐ Railway accident   ☐ Car accident
☐ Fire             ☐ Underground accident

Write down in short why

____________________________________________________________________________________
____________________________________________________________________________________
____________________________________________________________________________________
13. On the next side there is a cross-ruled paper where the risks to die in a traffic accident or a fire is showed. The paper contains 100,000 boxes and the number of boxes that are marked shows the risk to die during a ten year period.

The marked boxes shows the risks for different persons. The risks are calculated for a normal travelling. This means that

- The road risks are calculated for a person travelling approximately 15000 kilometres a year by car
- The railway risks are calculated for a person that commutes 75 kilometres one way to his work every weekday
- The underground risks are calculated for a person that commutes 20 kilometres to work every weekday.
- The fire risks is a calculated average risk for all Swedes.

Turn two pages. There you will find a enlargement of the cross-ruled paper shown on next page. You are now asked to mark the number of boxes that indicates how big risks you estimate that you have. Mark the number of boxes that corresponds to your risk.
How big are your risks?
You are now asked to state what you consider should be prioritised when the government invests in traffic safety.

14. Suppose that the government will make extra investments in traffic safety. The investments will prevent accidents during 20 years. How would you prefer the money to be spent?

<table>
<thead>
<tr>
<th>Prioritise railway safety</th>
<th>Hard to choose</th>
<th>Prioritise road</th>
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</thead>
<tbody>
<tr>
<td>Prevent 100 fatalities in small-scale railway accidents</td>
<td>□</td>
<td>Prevent 15 fatalities in road accidents</td>
</tr>
<tr>
<td>Prevent 70 fatalities in small-scale railway accidents</td>
<td>□</td>
<td>Prevent 15 fatalities in road accidents</td>
</tr>
<tr>
<td>Prevent 50 fatalities in small-scale railway accidents</td>
<td>□</td>
<td>Prevent 15 fatalities in road accidents</td>
</tr>
<tr>
<td>Prevent 40 fatalities in small-scale railway accidents</td>
<td>□</td>
<td>Prevent 15 fatalities in road accidents</td>
</tr>
<tr>
<td>Prevent 30 fatalities in small-scale railway accidents</td>
<td>□</td>
<td>Prevent 15 fatalities in road accidents</td>
</tr>
<tr>
<td>Prevent 25 fatalities in small-scale railway accidents</td>
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Hard to choose
15. Suppose that the government will make extra investments in traffic safety. The investments will prevent accidents during 20 years. How would you prefer the money to be spent?

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16. Suppose that the government will make extra investments in safety. The investments will prevent accidents during 20 years. How would you prefer the money to be spent?

Prioritise fire safety

prioritise fire safety

Prioritise road

Prioritise road

Hard to choose
17. Suppose that the government plans to invest in a new safety system for the **railway**. The system will prevent accidents during 20 years. Different systems give different effects. Which type of accidents would you prefer to prevent?

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18. Suppose that the government plans to invest in a new safety system for the **underground**. The system will prevent accidents during 20 years. Different systems give different effects. Which type of accidents would you prefer to prevent?

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19. Suppose that the government plans to invest in a new safety system for the underground. The system will prevent accidents during 20 years. Different systems give different effects. Which type of accidents would you prefer to prevent?

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20. A person has 120 kilometres to his work and commutes every working day by train. This person will during one year travel 40,000 kilometres by train. In addition he uses his car on leisure time and will then drive about 5,000 kilometres a year.

On the following page shows the actual risk that this person during a ten year period will be victimised in a railway accident respectively in a road accident. The total risk of a fatal traffic accident is showed by the marked boxes together.

Imagine that you are this person and that you are planning to buy a safety equipment that will reduce your risk of fatal traffic accidents. The equipment is personal and cannot be used by others. (for example family members). The equipment will work for ten years and then it must be replaced in order to have continued protection.

Your fatality risks will be reduced and this reduction is correspond to three of the marked boxes. You can chose between an equipment that will protect you when going by train (three of the marked "train boxes" will be unmarked) and an equipment that protects you when driving (three of the marked "car boxes" will be unmarked).

What will you chose?

☐ Train, continue to question no 21

☐ Road, skip question no 21 and continue to question 22.
21. Below is an enlargement of the previous square net. The risk of a fatal traffic accident is now represented by the boxes that have been framed. You could choose between reducing your risk of fatal train accidents and reducing your risk of fatal road accidents.

You have chosen to reduce the risk of a fatal railway accident. The risk will be reduced with as much as is showed by the marked boxes in the left alternative.

How much must the risk of a fatal road accident be reduced for you to view that as valuable as the left alternative?

Please note that when you chose to reduce the risks of your road transports, you will at the same time chose not to reduce the risks of your train transports.

Answer the question by marking the number of boxes that makes the risk reduction for your road transports as valuable as the risk reduction of the train transports (the left alternative)

You can now continue to question 23
22. Below is an enlargement of the previous square net. The risk of a fatal traffic accident is now represented by the boxes that have been framed. You could choose between reducing your risk of fatal train accidents and reducing your risk of fatal road accidents.

You have chosen to reduce the risk of a fatal **road** accident. The risk will be reduced with as much as is showed by the marked boxes in the left alternative.

How much must the risk of a fatal train accident be reduced for you to view that as valuable as the left alternative?

Please note that when you chose to reduce the risks of your train transports, you will at the same time chose not to reduce the risks of your road transports.

Answer the question by marking the number of boxes that makes the risk reduction for your train transports as valuable as the risk reduction for the road transports (the left alternative)
23. A person has 75 kilometres to his work and commutes every working day by train. This person will during one year travel 30,000 kilometres by train. In addition he uses his car on leisure time and will then drive about 15,000 kilometres a year.

On the following page shows the actual risk that this person during a ten year period will be victimised in a railway accident respectively in a road accident. The total risk of a fatal traffic accident is showed by the marked boxes together.

Imagine that you are this person and that you are planning to buy a safety equipment that will reduce your risk of fatal traffic accidents. The equipment is personal and cannot be used by others. (for example family members). The equipment will work for ten years and then it must be replaced in order to have continued protection.

Your fatality risks will be reduced and this reduction is correspond to three of the marked boxes. You can chose between an equipment that will protect you when going by train (three of the marked "train boxes" will be unmarked) and an equipment that protects you when driving (three of the marked "road boxes" will be unmarked).

What will you chose?

- [ ] Train, continue to question no 24
- [ ] Car, skip question no 24 and continue to question 25
24. Below is an enlargement of the previous square net. The risk of a fatal traffic accident is now represented by the boxes that have been framed. You could choose between reducing your risk of fatal train accidents and reducing your risk of fatal road accidents.

You have chosen to reduce the risk of a fatal railway accident. The risk will be reduced with as much as is showed by the marked boxes in the left alternative.

How much must the risk of a fatal road accident be reduced for you to view that as valuable as the left alternative?

Please note that when you chose to reduce the risks of your road transports, you will at the same time chose not to reduce the risks of your train transports.

Answer the question by marking the number of boxes that makes the risk reduction for your road transports as valuable as the risk reduction of the train transports (the left alternative).

You can now continue to question 26
25. Below is an enlargement of the previous square net. The risk of a fatal traffic accident is now represented by the boxes that have been framed. You could choose between reducing your risk of fatal train accidents and reducing your risk of fatal road accidents.

You have chosen to reduce the risk of a fatal road accident. The risk will be reduced with as much as is showed by the marked boxes in the left alternative.

How much must the risk of a fatal train accident be reduced for you to view that as valuable as the left alternative? Please note that when you chose to reduce the risks of your train transports, you will at the same time chose not to reduce the risks of your road transports. Answer the question by marking the number of boxes that makes the risk reduction for your train transports as valuable as the risk reduction for the road transports (the left alternative).
26. A person has 20 kilometres to his work and commutes every working day by underground. This person will during one year travel 10,000 kilometres by underground. In addition he uses his car on leisure time and will then drive about 15,000 kilometres a year.

On the following page shows the actual risk that this person during a ten year period will be victimised in a underground accident respectively in a road accident. The total risk of a fatal traffic accident is showed by the marked boxes together.

Imagine that you are this person and that you are planning to buy a safety equipment that will reduce your risk of fatal traffic accidents. The equipment is personal and cannot be used by others. (for example family members). The equipment will work for ten years and then it must be replaced in order to have continued protection.

Your fatality risks will be reduced and this reduction is correspond to three of the marked boxes. You can chose between an equipment that will protect you when going by underground (three of the marked "underground boxes” will be unmarked) and an equipment that protects you when driving (three of the marked "road boxes” will be unmarked).

What will you chose?

☐ Underground, continue to question no 27

☐ Road, skip question no 27 and continue to question 28
27. Below is an enlargement of the previous square net. The risk of a fatal traffic accident is now represented by the boxes that has been framed. You could chose between reducing your risk of fatal underground accidents and reducing your risk of fatal road accidents.

You have chosen to reduce the risk of a fatal **underground** accident. The risk will be reduced with as much as is showed by the marked boxes in the left alternative.

How much must the risk of a fatal road accident be reduced for you to view that as valuable as the left alternative?

Please note that when you chose to reduce the risks of your road transports, you will at the same time chose **not** to reduce the risks of your underground transports.

Answer the question by marking the number of boxes that makes the risk reduction for your road transports as valuable as the risk reduction of the underground transports (the left alternative).

You can now continue to question 29
28. Below is an enlargement of the previous square net. The risk of a fatal traffic accident is now represented by the boxes that has been framed. You could chose between reducing your risk of fatal train accidents and reducing your risk of fatal road accidents.

You have chosen to reduce the risk of a fatal **road** accident. The risk will be reduced with as much as is showed by the marked boxes in the left alternative.

How much must the risk of a fatal train accident be reduced for you to view that as valuable as the left alternative?

Please note that when you chose to reduce the risks of your train transports, you will at the same time chose **not** to reduce the risks of your road transports.

Answer the question by marking the number of boxes that makes the risk reduction for your train transports as valuable as the risk reduction for the road transports (the left alternative)
29. Every year there are around 100 fatalities in fire accidents. An average Swede travels about 15,000 kilometres a year by car. The square boxed net on the following page shows the actual risk that an average Swede during a ten year period will be victimised in a fire accident respectively in a road accident. The total risk of a fatal road accident and a fire accident is showed by the marked boxes together.

Imagine that you are this person and that you are planning to buy a safety equipment that will reduce your risk of fatal road or fire accidents. The equipment is personal and cannot be used by others. (for example family members). The equipment will work for ten years and then it must be replaced in order for you to have continued protection.

Your fatality risks will be reduced and this reduction is correspond to three of the marked boxes. You can chose between an equipment that will protect you when going by car (three of the marked "road boxes" will be unmarked) and an equipment that protects you against fires (three of the marked "fire boxes" will be unmarked).

What will you chose?

- Fire, continue to question no 30
- Road, skip question no 30 and continue to question 31
30. Below is an enlargement of the previous square net. The risk of a fatal traffic accident is now represented by the boxes that has been framed. You could chose between reducing your risk of fatal fire accidents and reducing your risk of fatal road accidents.

You have chosen to reduce the risk of a fatal fire accident. The risk will be reduced with as much as is showed by the marked boxes in the left alternative.

How much must the risk of a fatal road accident be reduced for you to view that as valuable as the left alternative?

Please note that when you chose to reduce the risks of your road transports, you will at the same time chose not to reduce the risks of a fatal fire accident.

Answer the question by marking the number of boxes that makes the risk reduction for your road transports as valuable as the risk reduction of fire accidents (the left alternative).

You can now continue to question 32
31. Below is an enlargement of the previous square net. The risk of a fatal traffic accident is now represented by the boxes that has been framed. You could chose between reducing your risk of fatal fire accidents and reducing your risk of fatal road accidents.

You have chosen to reduce the risk of a fatal road accident. The risk will be reduced with as much as is showed by the marked boxes in the left alternative.

How much must the risk of a fatal fire accident be reduced for you to view that as valuable as the left alternative?

Please note that when you chose to reduce the risks of a fire accident, you will at the same time chose not to reduce the risks of your road transports.

Answer the question by marking the number of boxes that makes the risk reduction for a fatal fire accident as valuable as the risk reduction for the road transports (the left alternative).
Concluding questions

32. What education do you have?
   - Elementary school or comparable
   - Upper secondary school or comparable
   - University or comparable
   - Other: ____________________________________________

33. What is your household’s combined income before tax per year?
   - 0-80.000 SEK
   - 80.000-160.000 SEK
   - 160.000-240.000 SEK
   - 240.000-320.000 SEK
   - 320.000-400.000 SEK
   - 400.000-600.000 SEK
   - 600.000 SEK or more

34. How did you apprehend the questionnaire?
   - Easy to answer
   - Neither easy nor difficult
   - Difficult to answer

THANK YOU FOR YOUR HELP!
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