A COMPUTATIONAL MODEL FOR OPTIMAL DIMENSIONAL SPEED ON NEW HIGH-SPEED LINES

Master Thesis
26 May 2011
Version 4.1(final)

Written by: Kayvan Yousefi Mojir
kayvanym@kth.se
EMIS-DSV

Supervisors:
Oskar Fröidh: KTH, ABE, Railway group
Fredrik Kilander: KTH, DSV

This thesis corresponds to 20 weeks (30hp) of fulltime work.
Abstract

Written By: Kayvan Yousefi Mojir
Master of Engineering and management of information systems
KTH – DSV

High Speed Lines (HSL) in rail passenger services are regarded as one of the most significant projects in many countries comparing to other projects in the transportation area. According to the EU (European Council Directive 96/48/EC, 2004), high-speed lines are either new-built lines for speeds of 250km/h or greater, or in some cases upgraded traditional lines. At the beginning of 2008, there were 10,000 km of new HSL lines in operation, and by taking into account the upgraded conventional lines, in total, there were 20,000 km line in the world. The network is growing fast because of the demand for short travelling time and comfort is increasing rapidly.

Since HSL projects require a lot of capital, it is getting more important for governments and companies to estimate and to calculate the total costs and benefits of building, maintaining, and operating of HSL so that they can decide better and more reliable in choosing between projects.

There are many parameters which affect the total costs and benefits of an HSL. The most important parameter is dimensional speed which has a great influence on other parameters. For example, tunnels need larger cross section for higher speed which increases construction costs. More important, higher speed also influences the number of passengers attracted from other modes of transport. Due to a large number of speed-dependant parameters, it is not a simple task to estimate an optimal dimensional speed by calculating the costs and benefits of an HSL manually. It is also difficult to do analysis for different speeds, as speed changes many other relevant parameters. As a matter of fact, there is a need for a computational model to calculate the cost-benefit for different speeds. Based on the computational model, it is possible to define different scenarios and compare them to each other to see what the potentially optimal speed would be for a new HSL project. Besides the optimal speed, it is also possible to analyze and find effects of two other important parameters, fare and frequency, by cost-benefit analysis (CBA). The probability model used in the calculation is based on an elasticity model, and input parameters are subject to flexibility to calibrate the model appropriately. Optimal high-speed line (OHL) tool is developed to make the model accessible for the users.

Keywords: HSL (High Speed Line), dimensional speed, computational model, speed-dependant parameter, elasticity model, CBA (Cost Benefit Analysis), OHL
This page is intentionally left blank.
Acknowledgments

First of all, I like to appreciate Oskar Fröidh and his colleagues, at ABE railway group, for the precious help during my thesis work. I gained totally good knowledge about railway transport system by the help of Oskar and the resources he introduced to me. There were also situations in which Oskar suggested valuable solution to the problems and he made a lot of progress in my thesis.

Oskar also gave many constructive comments and feedbacks on the result of my thesis which I used them to verify and evaluate my work.

My other supervisor, Fredrik Kilander at DSV, also helped me a lot in the structure and methodology of my thesis work and thesis report. We had several meetings to talk about the progress of the thesis. He kindly attended my pre-seminars at ABE and gave me valuable feedbacks about my work.

I like to thank Anders Lindahl for coordinating many things between the DSV and ABE. He helped me to do the official procedure and also explained to me the rules and routines.

Finally, I like to thank Darvish Fattahi at Trafikverket who helped me in gathering data for my thesis. He also explained useful information to me and it was really helpful to me.
This page is intentionally left blank.
# Table of Contents

1. **INTRODUCTION** .................................................................................................................. 13
   1.1. BACKGROUND ........................................................................................................... 14
   1.2. GENERAL PURPOSE OF THIS THESIS ....................................................................... 15
   1.3. SPECIFIC GOALS ....................................................................................................... 15
   1.4. METHODOLOGY ....................................................................................................... 16
   1.5. LIMITATION ........................................................................................................... 20
   1.6 OPTIONS AVAILABLE ............................................................................................... 20
   1.7 SCIENTIFIC FOUNDATION ...................................................................................... 20
2. **HIGH SPEED LINE (HSL)** ................................................................................................. 23
   2.1. HSL DEFINITION ..................................................................................................... 23
   2.2 HSL DEVELOPMENT OPTIONS .................................................................................. 23
   2.3. HSL SERVICE BENEFITS ......................................................................................... 25
   2.4. OPTIMAL SPEED .................................................................................................... 25
   2.5. REVIEW OF HSL COST STRUCTURE ....................................................................... 26
   2.6. INFRASTRUCTURE .................................................................................................. 27
   2.6.1 SPEED DEPENDENT COMPONENTS/SYSTEMS ...................................................... 27
   2.6.2 SPEED INDEPENDENT COMPONENTS .................................................................. 31
   2.7 ROLLING STOCK (TRAINS) ........................................................................................ 33
   2.8 DEMAND ................................................................................................................ 36
   2.9 SERVICE (TIMETABLE) ............................................................................................. 37
   2.10 REVENUE AND TRAVELLING TIME GAIN ............................................................... 37
3. **PREDICTIVE MODELING** ................................................................................................... 39
   3.1 WHY PREDICTIVE MODELS ...................................................................................... 39
   3.2 DIFFERENT MODELS ............................................................................................... 40
   3.3 MODEL SELECTION ................................................................................................... 41
   3.3.1 LOGISTIC REGRESSION (LOGIT MODEL) ............................................................. 41
   3.3.2 ELASTICITY OF DEMAND MODEL ....................................................................... 42
   3.3.3 LOGIT MODEL OR ELASTICITY OF DEMAND MODEL ........................................ 44
4. **MODEL CONSTRUCTIONS** ................................................................................................ 45
   4.1 DIFFERENT COMPONENTS FOR CBA ....................................................................... 45
   4.2 DEMAND CALCULATION .......................................................................................... 45
   4.3 INFRASTRUCTURE COSTS CALCULATION ................................................................ 50
   4.4 OPERATING COSTS CALCULATION .......................................................................... 51
   4.5 BENEFITS CALCULATION ......................................................................................... 52
   4.6.1 REVENUE ......................................................................................................... 53
   4.6.2 TRAVELING TIME GAIN ...................................................................................... 53
   4.6.3 TOTAL BENEFITS ............................................................................................... 53
   4.8 CBA ANALYSIS (NPV) ............................................................................................. 53
5. **OHSL TOOL** .................................................................................................................... 55
   5.1 RATIONALE BEHIND THE EXISTENCE OF THE OHSL ........................................... 55
   5.2 WEB-BASED TOOL ................................................................................................... 56
   5.2.1 TOOL ARCHITECTURE .......................................................................................... 56
   5.3 MANIPULATION OF PARAMETERS - DATABASE ...................................................... 58
   5.4 CATEGORIZATION OF PARAMETERS ......................................................................... 60
   5.4.1 NEW SCENARIO AND BASE SCENARIO .............................................................. 60
   5.4.2 COMMON SETTING ............................................................................................. 61
List of figures

FIGURE 1.1 : PHASE OF THE THESIS WORK ................................................................. 16
FIGURE 1.2 : RESEARCH PROCESS DIAGRAM ............................................................ 18
FIGURE 2.1 : HIGH-SPEED NETWORK IN EUROPE ....................................................... 24
FIGURE 2.2 : IMPORTANT CONCEPTS IN HSL TO STUDY IN THIS THESIS ................. 26
FIGURE 2.3 : OPERATING COST MODEL ................................................................. 33
FIGURE 3.1 : MODELS BASED ON LARGE INPUT DATA SET ...................................... 40
FIGURE 3.2 : MODELS BASED ON PROBABILITY FUNCTION .................................. 40
FIGURE 3.3 : SIMPLE LOGISTIC FUNCTION ............................................................... 41
FIGURE 4.1 : DEPENDENCY OF DEMAND ON IMPORTANT PARAMETERS ................ 46
FIGURE 4.2 : INFRASTRUCTURE COSTS IMPORTANT COMPONENTS ....................... 50
FIGURE 4.3 : OPERATING COSTS IMPORTANT COMPONENTS .................................... 51
FIGURE 4.4 : IMPORTANT COMPONENTS IN BENEFITS CALCULATION .................. 52
FIGURE 5.1 : ARCHITECTURE OF THE OHSL TOOL ............................................... 57
FIGURE 5.2 : DIFFERENT TECHNOLOGIES USED IN DEVELOPING OF THE OHSL .... 58
FIGURE 5.3 : DATA STRUCTURE OF THE OHSL IN DATABASE MANAGEMENT SYSTEM 59
FIGURE 5.4 : A SCREEN SHOT OF OHSL PAGE WHERE USER ENTERS THE INPUT PARAMETERS ................................. 60
FIGURE 5.5 : A SCREEN SHOT OF OHSL PAGE WHERE NEW SCENARIO AND BASE SCENARIO ARE USED TO COMPARE TWO SCENARIOS ............................................................... 62
FIGURE 5.6 : PLAIN TEXT FORMAT GIVES ENOUGH DETAILED INFORMATION ABOUT THE RESULT AND STEPS OF THE CALCULATION ................................................................. 63
FIGURE 5.7 : TABLE FORMAT GIVES ENOUGH DETAILED INFORMATION ABOUT THE COMPONENTS WHICH ARE USED IN CALCULATION ................................................................. 63
FIGURE 5.8 : SAMPLE GRAPH OUTPUT WHICH SUMMARIZES DATA .............................. 64
FIGURE 6.1 : MARGINAL CALCULATION ................................................................. 68
FIGURE 6.2 : OUTPUT VALUES FOR DIFFERENT SPEEDS ............................................ 71
FIGURE 6.3 : OUTPUT VALUES FOR DIFFERENT FREQUENCY OF SERVICES .................. 72
FIGURE 6.4 : OUTPUT VALUES FOR DIFFERENT FARES ............................................. 73
FIGURE 6.5 : NPV AND COST-BENEFIT FOR DIFFERENT SPEEDS ............................... 75

This page is intentionally left blank.
List of tables

TABLE 2.1 : IMPORTANT COMPONENTS/SYSTEMS IN INFRASTRUCTURE .................................................. 27
TABLE 2.2 : DIFFERENT TRACK TYPES AND THEIR DEFAULT PRICE .................................................. 28
TABLE 2.3 : DEFAULT SETTING FOR USING TRACKS IN DIFFERENT SPEEDS ..................................... 28
TABLE 2.4 : TRACK DISTANCE ON DOUBLE TRACK LINE FOR DIFFERENT SPEEDS ............................... 29
TABLE 2.5 : CONSTRUCTION COSTS – TUNNELS FOR SPEED 250KM/H ............................................. 29
TABLE 2.6 : CONSTRUCTION COSTS – BRIDGES/VIADECTS FOR SPEED 250KM/H ......................... 30
TABLE 2.7 : CONSTRUCTION COSTS – EMBANKMENT FOR SPEED 250KM/H ..................................... 30
TABLE 2.8 : CONSTRUCTION COSTS – CUTTINGS FOR SPEED 250KM/H ........................................... 30
TABLE 2.9 : CONSTRUCTION COSTS – Catenary for SPEED 250KM/H ..................................................... 31
TABLE 2.10 : CONSTRUCTION COSTS – SIGNALING SYSTEM FOR ALL RANGES OF SPEED ................... 31
TABLE 2.11 : CONSTRUCTION COSTS – POWER SUPPLY FOR DIFFERENT FREQUENCY OF TRAINS .......... 32
TABLE 2.12 : CONSTRUCTION COSTS – STATION FOR DIFFERENT FREQUENCY OF TRAINS ............... 32
TABLE 2.13 : FOUR DIFFERENT TRAIN SETS FOR DIFFERENT SPEEDS ............................................ 34
TABLE 2.14 : MAINTENANCE COSTS FOR SAMPLE TRAIN SETS ......................................................... 35
TABLE 2.15 : FINAL SERVICE COSTS FOR SAMPLE TRAIN SETS ......................................................... 36
TABLE 2.16 : MONETARY VALUE FOR TRAVELLING TIME GAIN ......................................................... 38
TABLE 4.1 : SUMMARY OF IMPORTANT CONSTANT IN HSL CBA ...................................................... 47
TABLE 4.2 : DISTANCE MATRIX ............................................................................................................. 47
TABLE 4.3 : TOTAL NUMBER OF JOURNEYS BETWEEN DESTINATIONS ............................................. 48
TABLE 4.4 : MARKET SHARE FOR TRAIN JOURNEY BETWEEN DESTINATIONS ............................. 49
TABLE 6.1 : COST-BENEFIT VALUES FOR DIFFERENT YEARS ............................................................ 74
This page is intentionally left blank.
1. Introduction

High Speed Line (HSL)\(^1\) in rail passenger services are regarded as one of the most significant projects in many countries compared to other projects in the transportation area. According to the EU (European Council Directive 96/48/EC, April 2004), high-speed lines are either new-built lines for speeds of 250 km/h or greater, or in some cases upgraded traditional lines. At the beginning of 2008, there were 10,000 km new high-speed lines in operation, and by taking into account the upgraded conventional lines, in total 20,000 km lines in the world. The network is growing fast because the demand for short travelling time and comfort is increasing rapidly (Campos & De Rus, Some stylized facts about high-speed rail: a review of HSR experience around the world, 2009).

Since HSL projects require a lot of capital, it is getting more important for governments and companies to estimate and to calculate the total costs and benefits of building, maintaining, and operating of HSL. (European commission(2001a), 2010)

There are many parameters and dependent variables which affect the total costs and benefits of an HSL project. For example, topography, operating speed, line length, demand, etc. which are discussed in detail in this thesis. One of the most important parameters in calculation is “dimensional speed” which affects many other variables and cost factors in an HSL project because higher speed demands more expensive infrastructure and equipment. It also provides shorter travelling time which can have enormous impact on attracting passengers to the train mode. Finding an optimal speed can increase the benefits and decrease the additional costs, and thus improve the economy in the project.

Due to the complexity of the rail system, modeling the problem is essential for estimation and prediction. It is tried in chapter 4 to create a computational model based upon variables and constants. This computational model formulates the cost-benefit calculation of high-speed line operation based on chapter 2 and also makes it possible to use a computer to study different variables and their behaviors. A predictive model is chosen in chapter 3 and is applied to the computational model to facilitate the cost-benefit analysis in the future. There are many predictive models such as machine learning techniques, and models which is based on regression analysis. Regression analysis is chosen as the base predictive model for this thesis and it is discussed in detail in chapter 3.

In chapter 5, development of the optimal high-speed line (OHS) tool is explained. This tool makes the computational model accessible to the users and experts. It also allows the evaluation of the model by the analysis of the result. This tool is a web based tool based on Microsoft .Net technology and a SQL Server database. This tool provides an interactive interface for the user to work with the model. User obtains the result quite instantly in several seconds and it is significant when it comes to validation and evaluation of model because user

---

\(^1\) Abbreviation HSL will be used as a noun, with no distinction between singular and plural forms.
is able to run the model many times, to manipulate the parameters, and to obtain the result to observe how the model works based on the input parameters.

In Chapter 6, the result of this thesis is discussed and evaluated. Finally, in chapter 7 it is tried to validate the result obtained by the computational model and the OHSL tool.

1.1. Background

In recent years, there has been a strong desire in running high-speed train services in Sweden (Statens Offentliga Utredningar(SOU 2009:74), 2009) and Europline/Götaland lines are recommended to be built in Sweden. It is because of the demand that exists in this area where passengers want more convenience for their journey. Convenience for passengers means shorter travelling time, higher frequency of trains running, lower ticket price and better comfort when they use train services.

Arguments about the costs and benefits of an HSL project are usually too general and imprecise (Gramlich, 1994) because they do not take into account the specific characteristic of HSL projects and they consider it as a usual infrastructure development project. Development of an HSL project may create socio-economic values which are important to calculate too. Time savings of passengers and long term welfare gains are examples of socio-economic values that an HSL generates. There is a discussion (De Rus & Nombela, Is Investment in High Speed Rail Socially Profitable?, 2007) about these values. However, the model in the discussion does not implement the prediction algorithm to calculate the cost-benefit of an HSL project in the long term.

The cost of an HSL line was about 17 million euro per kilometer in average in 2006 in European countries like France, Spain, Germany and Italy (Campos, Javier, & De Rus, The cost of building and operating a new high speed rail line, 2008). Therefore, it is quite expensive and it makes countries take a closer look at the economic view of construction, maintenance, and operation of high-speed lines, in order to make the right decisions of strategic importance.

Benefits of an HSL are context specific and strongly depend on the location of the project (Martin, 1997). Population densities, the crossing of urban areas, geographical and topographical conditions are factors that might affect an HSL project. For example, high density urban area means higher construction costs. Mountainous locations also increase the construction costs because they demand more tunnels and bridges. The benefits also heavily depend on the line length and population density which affects the total number of passengers (demand) using the new HSL service.

The cost of an HSL project can be divided into two main categories: infrastructure and rolling stock (Campos, Javier, & De Rus, The cost of building and operating a new high speed rail
line, 2008). Cost of infrastructure means the investment in building and maintaining tracks, stations, signaling systems, energy consumption, equipment, etc. Rolling stock costs mean investment in the purchase, maintenance and operation of train sets. It is discussed more in detail in chapter 2.

To determine the parameters and variables which affect costs, the following components will be discussed in detail to specify the model that would represent the cost-benefit analysis in the railway operation.

1. Train (rolling stock) characteristics
2. Line (infrastructure) characteristics
3. Service (timetable) characteristics
4. Market/Revenues

In each of the above components, there are parameters and variables through which the values heavily depend on each other. For example, higher demand requires more trains which cause a higher maintenance costs. The goal is to specify all these parameters, constants and variables and put them in a model to represent the costs and benefits analysis model of railway operation. Then it is possible to produce another model from the first model and use it in a search algorithm to find the best values for the variables to make the speed optimal in railway operation regarding profitability.

1.2. General purpose of this thesis

The ultimate purpose of this thesis is to find optimal design speed for a high-speed line by using a computational model in order to optimize the railroad companies costs and benefits in order to stay competitive in the market. Optimal speed also leads to an increase in social benefits as it is a response to passengers demand for increased convenience in a high-speed train service.

Speed has a direct influence on travelling time and as a result, on demand, moreover, there are two others important parameters which are the matter of interest in this thesis. In this thesis, fare and frequency of service are also studied to find their effects on demand together with travelling time. Therefore, the research question of this thesis work is to find the optimal speed in high-speed train services with respect to profitability.

1.3. Specific goals

The exact goal of this thesis is categorized into two parts (figure 1.1):
The first is to create a computational cost-benefit analysis model for high-speed lines in order to find optimal speeds and to study other important parameters. This model intends to articulate different parameters involved in the cost-benefit analysis of an HSL and tries to find the relationship between them. By formalizing the different parameters, it would be possible to use a computer to calculate faster and study the parameters effect on the model more conveniently than traditional methods such as paper based method or using general tools to do analysis like Microsoft Excel.

The second is to make the model created in part 1 accessible to users and experts. This is done by creating a web-based tool which enables experts to access the model, work with it and test it. This tool is called the OHSL tool and is accessible via www.ohsl.se. OHSL is very important for the validation and evaluation of the model, which is created in first phase.

![Figure 1.1 - phase of the thesis work](image)

1.4. Methodology

In this part, it is attempted to present a clear method for achieving the defined goals in this thesis. Of course, there is not only a single method for achieving the goal. Method selection is justified and is motivated. Limitations, strengths and weaknesses of the selected method are discussed in the context of the thesis. Research process of this thesis work is shown in figure 1.2.

Since the subject of the thesis is multidisciplinary, qualifications of cost-benefit analysis in the transport domain and also computer science are needed. At the beginning, a thorough literature review was done to get enough knowledge and qualification about the problem domain. It means the review of cost-benefit analysis theory in the domain of transports and also creating the computational model in the domain of computer science. The literature review also gave the impression of the exact existing gaps, components, and variables in the problem domain and also basic knowledge and terminology in this area.

In next step, analysis of the different components in HSL begun and their effects on cost-benefit of a new HSL project and different important speed-dependent parameters were indentified. It was important to gain a complete knowledge about the structure and components of an HSL project before starting the implementation of the model because the following phases relied highly on these elicited parameters. This phase was done by analysis of different literature in this area. There were and also interviews conducted with experts knowledgeable about this domain.
There are three important cost-benefit sections in this thesis: construction costs, operating costs, benefits (including revenue and socio-economic benefits). There are many parameters in these components. Since there was no established model in Sweden, these parameters are formulated and articulated by empirical observation in Sweden\(^2\). It guarantees that the formulation was according to the condition of Sweden and will work for other projects in Sweden or similar countries. In this phase, focus was on speed dependent variables and also socio-economic values were considered significantly.

After study of the three important components in HSL cost-benefit analysis, a prediction algorithm was selected and based on this algorithm and formulated parameters, the computational model was created. The prediction algorithm, which is discussed in detail in chapter 3, is important to make a precise model. Choosing the algorithm in this phase was mostly based on the review of the other similar works in this area, an extensive literature review, considering the condition of the projects in Sweden, and the amount of existing data in Sweden.

Based on the works carried out in the previous parts, a computational model was proposed, which was mostly based upon the observation of manual calculation. There was manually done example of different components in HSL about cost-benefit (Fröidh, Future rail traffic on the Eastern Link, 2010). These examples was reviewed, formulated and finally transformed to a mathematical model which could be run by computer. This computational model was used to study the effect of speed along with fare and service frequency on the costs and benefits of HSL projects. Observation was done on a established project called Gröna tåget (Fröidh, Resande och trafik med Gröna tåget, 2010) and most manual calculation is extracted from this project in Sweden.

There are different ways to use the implemented computational model. It could be on paper or with automated general tools like Microsoft Excel. A web-based tool (OHSL) was developed to make the model accessible to users. In fact, by using this tool, a user can interact with the model and input data and get a result from the model. The OHSL tool has three separate phases which are: database design, interface design, and coding the computational model. The database should save the parameters and default data that are needed for the model so the user does not have to enter the input parameters every time. The user interface is very important because it is the only way that the user interacts with the model. It should be user-friendly, easy to understand and good response time.

In the next step, by help of experts and National Transport Authority(Trafikverket) in Sweden, data about an existing case was gathered. This data was gathered in meeting with servants in trafikverket.

\(^2\) Empirical observation is according to the manual calculation method used today in Sweden (Fröidh, Future rail traffic on the Eastern Link, 2010)
Figure 1.2 – Research process diagram
The model had to be adjusted before running. Model adjustment is the procedure in which constants and factors used in the model are set to the right value. For example, discount rate is a factor that should be set. Period of analysis, monetary constants, etc. are the examples of data that should be adjusted before the model is run. This phase was done with help from expert users of the model.

The methodology used in this research is a quantitative method and evaluation and validation of the result is mostly done using numerical values in tables and graphs which obtained from the model. For the validation of the model, in this work, firstly, important output criteria of the model were identified. These criteria were frequency of services, fare level, speed, and demand, thereafter; the rationality of the output was discussed with experts. Sensitivity analysis was done to indentify the impact on the indentified criteria on the model. Result of the sensitivity analysis was also discussed with expert to verify the accuracy. Source of the data also discussed in the validation part. Secondly, since OHSL is a web-based tool it is accessible from any place in any time and it facilitates the procedure of validation because expert can access it easily. Experts played important roles in the validation of the result by comparing the result with the result obtained manually by experts to see if the model was acceptable or not.

For the validation of the model, there were also another way worked more precisely in this case but it was not done in this work. It was the comparison of an existing HSL project and the output result of computational model on the same project. It means that data of an existing project is put in the computational model and then the result of the computational model is compared with real existing data. This method is precise and can identify the deficiencies of the model; however, it is not simple to use this method. There is no established HSL project in Sweden to use the data of it. HSL projects in other countries are context-specific and it needs a complete context analysis before using their data. Context analysis is not in the scope of this thesis work and it can be done as a separate work to verify the proposed model in this thesis work. Therefore, due to complexity this method is proposed as a future work and was not done in this thesis.

For the evaluation part, a default scenario on a line between Stockholm-Malmö was discussed. Different outputs of the model were shown in the form of tables and graphs. Relation to the input parameters and the components of the model was also described in the evaluation part.

It was attempted to make the model enough flexible that it could be used in different cases. Since this model interacts with the user and user can see the response immediately, it was very helpful to even adjust the model more precisely during the validation process.

The advantage of this methodology was the valid source of data and the validation of the result by domain experts. However, validation was limited to personal opinion and experience of experts. Quality and accuracy of model adjustment which differ noticeably from one environment to other environment might affect the evaluation too. There were also some
limitations in the data collection. Empirical data was gathered from Swedish railroad industry and it was not possible to involve other countries data due to complexity.

1.5. Limitation

Since there are many parameters which have influence on the cost of HSL, it was attempted to focus on the main costs. Other minor costs which mostly are externalities costs (SIKA, 2003) are ignored in this work. These costs do not have great effect in main cost of HSL. We only focus on speed dependent variables that affect the cost-benefit. It is supposed that the entire HSL is a single or double track. A line consisting of both single and double track is not in the scope of this thesis. It is also supposed that all trains run from the first station to last station and that there is no mixed running of trains. The result is only valid for new built high-speed lines. Upgraded lines would require a more complicated model.

Data in this area is limited, and since there are a few countries which have HSL. In countries with HSL geographic conditions and topography of an area is different from Sweden. Therefore it is not practical to use other countries’ data without analysis of the location and as a result, in some cases, a rough estimation is used.

1.6 Options available

Instead of making a forecast model for the cost-benefit analysis of an HSL, it is possible to refer to projects in other countries and find the real costs. From that, a conclusion of the real costs and benefits can be drawn empirically. However, except for (Campos, Javier, & De Rus, The cost of building and operating a new high speed rail line, 2008) most empirical studies are about selected cases which highly depend on the situation of the place the project is establishing and is not practical to apply to other contexts. Deep analysis of the environment and case situation is needed in order to extend it to other cases.

There are also various methods in the area of the prediction model which we will discuss the advantage and disadvantage of them in chapter 3. Since an accurate and large data set about HSL projects is not accessible it was decided to use the probability methods for forecasting.

1.7 Scientific Foundation

HSL (High Speed Line) construction is increasing rapidly in many countries in Europe and Asia. Due to the high costs, there are discussions on what the best way is to construct a HSL and how it can produce more benefits (Campos, Javier, & De Rus, The cost of building and

Currently, researchers in Spain work hard on this issue (Campos, Javier, & De Rus, The cost of building and operating a new high speed rail line, 2008). There are also efforts in European commission to do economic analysis of high-speed lines (Barron, Campos, & al., 2009). Other countries are also interested in the optimal solution when they want to start an HSL project (Akgungora & Demirel, 2010). There are many parameters which affect the costs and the way of construction, however in this thesis we review the speed dependent parameters in construction of an HSL.

To formulate the cost-benefit analysis (CBA) of an HSL project we should consider many variables with different domains. Most of these variables’ values depend on each other and when one variable changes, an elasticity model is used, which is based on probability, to study other variable variations. However, there are different methods in computer science and mathematics to find the effects of variables on one another (chapter 3). Due to the limitation discussed in chapter 3, regression analysis is chosen for the prediction method in the CBA computational model.

There is also a manual method as well to run the model. In this work, a web-based application was developed to facilitate and to automate the procedure of running the model. Different technologies are used in developing this tool. ASP.NET is used as base technology for web programming. ASP.NET is a sophisticated technology which gives enough flexibility for the developer to implement the computational model in this thesis. SQLServer is used as the database which is quite powerful and suitable for this problem. Ajax and JavaScript is also used to make this tool as user-friendly as possible for the user.
2. High Speed Line (HSL)

In this chapter, basic concepts and definitions of HSL are mentioned at first and after that detailed information about parameters of different components in HSL system are presented. Therefore, this chapter is mostly in the domain of economic analysis of rail transport mode.

2.1. HSL Definition

There is no precise and authoritative definition of HSL and there are different standards about what constitutes HSL. In the following, two different definitions by the UIC (International Union of Railways) and the Federal Railroad Administration of USA (Department of Transportation, Federal Railroad Administration, September 1997) are mentioned which each one defines HSL from different aspects.

The European Union defines HSL as:
- Newly built or dedicated lines and equipment which run trains with a speed of 250 km/h or greater. (Class I)
- Upgraded lines which run trains with the speed of 250 Km/h. (Class II, III)
- Upgraded or newly built lines on which train speed is limited by some circumstances like topography or urban development.

FRA has a market-driven definition of HSL which put more importance on travelling time than on top speed:
“HSL is a service that is time-competitive with other modes of transport like air and auto for travel markets in the range of 100 to 500 km distance.”

The definition by the FRA depicts that total travelling time by different transport modes is a matter of importance and passengers do not judge only by top speed.

To make it clear in this thesis, only new built dedicated high-speed lines are considered in the calculation and analysis. These new lines should be capable of running a train at a speed of 250 km/h or more. Since there is a growing trend towards building new high-speed lines and also because existing lines have many limitations to operate as high-speed lines, we do not enter the analysis of existing and upgraded lines.

2.2 HSL Development Options

To develop a high-speed rail service there are two main options (High Speed Line Study: Milestone 8 - Cost Model Report, 2002):
- Upgrading existing lines, equipment, signaling system and other infrastructure in order to run trains faster than before. Using this option, there are many limitations which
Figure 2.1 – High-Speed network in Europe (UIC-High-Speed 2009)
cause a speed limit. Existing curves, at-grade road crossings, track distance, etc. are such limitations for improvements.

- To build a new line and use totally new equipment and infrastructure to run faster trains than the existing service. Construction costs are very important here as well as benefits to decide which option is most suitable.

Figure 2.1 shows existing and planned high-speed lines in Europe according (UIC 2009). For example, Sweden has mostly conventional lines and also it has plans for new high-speed line. Countries like France, Spain and Italy have already high-speed lines in operation.

According to the limitation of this thesis which is discussed in chapter 1.5, the focus in this thesis in only on new dedicated lines. The analysis of upgraded lines is out of scope of this thesis.

### 2.3. HSL Service Benefits

There are usually some potential benefits cited in different sources in support of developing HSL. According to (Peterman 2009) HSL can reduce the congestion in other modes of transportation such as highways and airports, improve transportation safety, reduce pollution, passengers can choose between more options for transportation, and increase reliability by creating redundancy in the national transport system. Time savings, additional traffic and capacity, reduced externalities from other modes of transport like accidents, noise, pollution, congestion, and wider economic benefits are other items which (De Rus & Nach, In what circumstance is investment in HSR worthwhile?, December 2007) refer in support of an HSL. (Is this believable?)

### 2.4. Optimal Speed

In construction of an HSL, dimensional speed is an important factor which affects costs. As speed increases, costs rise. High-speed needs grade-separated corridors, with wide curves both horizontally and vertically to prevent passenger discomfort. It is also necessary to provide enough power for the increased speed compared to a conventional line in the route. Higher consumption of energy also depends on the speed directly. Noise protection barriers to prevent noise in urban areas is another expensive issue. On the other side, higher speed makes railway companies able to be competitive with other modes of transport and attracts more passengers. Therefore, there is a trade-off between speed, costs and generated traffic (demand). In the following section, an attempt is made to extract the optimal speed from the result for HSL operated on a new line, and chose a standard level, i.e. dimensional speed.
2.5. Review of HSL Cost Structure

It is not easy to calculate the cost of an HSL project because there is a wide range of variation in such projects and it is completely site-specific and project specific. Generalization of cost structure is not possible due to the number of variables and the local situation; however, it is possible to forecast costs in a simpler form and with some assumptions. To review the cost, the following components and concepts and their effect on costs and benefits of HSL are reviewed (figure 2.2).

1. Infrastructure
2. Line characteristic
3. Rolling stock
4. Demand
5. Service (timetable)
6. Revenue and travelling time gain

This type of categorization allows calculating and estimating the costs and benefits of building a new HSL according to our wish to find the optimal speed.

Speed dependent variables which cause a rise in the cost, are the matter of importance here. Other costs are considered as speed independent costs. In the following, each component will be discussed in detail and important parameters which affect costs heavily are considered in the calculations.

In the following section in this chapter, speed dependent parameters and their effect on the costs are discussed. For each component, cost calculation and estimation is shown and finally in chapter 4 we create a cost-benefit analysis model (CBA).

All costs are given in Swedish Crowns (SEK). As of April 2011, the exchange rate is 1 EUR = 9 SEK (1 USD = 6.5).
2.6. Infrastructure

Infrastructure costs include the cost of construction and maintenance of tracks, terminals, stations, tunnels, bridges, etc. Some of these items are speed dependent and some of them depend on the topography of the area or even frequency of services (table 2.1). Building a new HSL requires the elimination of some restriction for higher speed such as level crossing and sharp curves. Due to the specific design of the HSL infrastructure, it is usually more expensive than conventional lines. The following table (2.1) summarizes different important items in the calculation of infrastructure costs:

<table>
<thead>
<tr>
<th><strong>Infrastructure Costs</strong></th>
<th><strong>Important parameters</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Track</td>
<td>Length, speed</td>
</tr>
<tr>
<td>Tunnel</td>
<td>Length, cross section, speed</td>
</tr>
<tr>
<td>Viaducts and bridges</td>
<td>Length, clearances and track center distance/double track</td>
</tr>
<tr>
<td>Embankment</td>
<td>Length, clearances and track center distance/double track</td>
</tr>
<tr>
<td>Cuttings</td>
<td>Length, clearances and center distance/double track</td>
</tr>
<tr>
<td>Catenary</td>
<td>Track Length, Speed</td>
</tr>
<tr>
<td>Stations (sidings and platforms and protection for passengers)</td>
<td>Number of stopping trains</td>
</tr>
<tr>
<td>Signaling system</td>
<td>Track Length</td>
</tr>
<tr>
<td>Power Supply</td>
<td>Line Length, frequency of service</td>
</tr>
</tbody>
</table>

*Table 2.1 - important components/systems in infrastructure*

2.6.1 Speed dependent components/systems

The construction costs of these components varies for different speeds. In the following section each item is described in detail.
2.6.1.1 Track:

Tracks may have different configurations for different speeds. There are two main types of track: Conventional ballasted track, and ballastless track (table 2.2).

Ballastless track is more expensive and also installed in two configurations either for tunnel/bridges or on soil (cutting and embankment). Ballastless track on soil needs more soil stabilization which increases the cost on construction.

<table>
<thead>
<tr>
<th>Track Type</th>
<th>Default price MSEK/track-km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional ballasted track</td>
<td>5</td>
</tr>
<tr>
<td>Ballastless track on bridges and soils</td>
<td>1.1-1.5 times more than ballasted track</td>
</tr>
<tr>
<td>Ballastless on soil</td>
<td>1.3-3 times more than ballasted track</td>
</tr>
</tbody>
</table>

Table 2.2 - Different track types and their default price (2010-trafikverket and expert’s estimation)

**Different configurations:**

For different speeds, there are different track types. It highly depends on the dimensional speed which the line is constructed for. Suggestions for default settings used in this thesis is as shown in table 2.3. This suggestion is from experts’ opinion:

<table>
<thead>
<tr>
<th>Dimensional speed</th>
<th>Ballasted track 5,0 MSEK/track-km</th>
<th>Ballastless track 7,0 MSEK/track-km</th>
<th>Ballastless track 10 MSEK/track-km</th>
</tr>
</thead>
<tbody>
<tr>
<td>200-250 km/h</td>
<td>100% of all track</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>251-325 km/h</td>
<td>100% of cuttings and embankments</td>
<td>100% of tunnels and bridges</td>
<td>0%</td>
</tr>
<tr>
<td>326-400 km/h</td>
<td>50% of cuttings and embankments</td>
<td>100% of tunnels and bridges</td>
<td>50% of cuttings and embankments</td>
</tr>
<tr>
<td>401-500 km/h</td>
<td>0%</td>
<td>100% of tunnels and bridges</td>
<td>100% of cuttings and embankments</td>
</tr>
</tbody>
</table>

Table 2.3 - Default setting for using tracks in different speeds

Table 2.3 shows that, for example, for speed of 400 km/h usually 50% of total cuttings and embankments are ballasted track while 50% remaining are ballastless track on soil which is more costly than ballasted track. 100% of tunnel and bridges are ballastless track for 400km/h.
**Track distance:**

Another important factor is track distance which is varying according to the speed (table 2.4). To cope with pressure waves when trains are meeting at high speed, a larger distance between tracks should be considered which also increases the cost of construction.

The following table shows an estimation of the track distance for different speed ranges.

<table>
<thead>
<tr>
<th>Dimensional speed</th>
<th>Track distance (c-c) at double track</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 km/h</td>
<td>4.50 m</td>
</tr>
<tr>
<td>300 km/h</td>
<td>4.70 m</td>
</tr>
<tr>
<td>400 km/h</td>
<td>4.90 m</td>
</tr>
<tr>
<td>500 km/h</td>
<td>5.10 m</td>
</tr>
</tbody>
</table>

*Table 2.4 - Track distance on double track line for different speeds
(Source: experts estimation based on empirical values worldwide)*

**2.6.1.2 Tunnels:**

Tunnels are considered in two different types: concrete tunnels and rock tunnels with different construction costs. For higher speed, a larger cross section needs to be built which causes an increase in construction costs. (table 2.5).

<table>
<thead>
<tr>
<th>Single/Double</th>
<th>Concrete Tunnels(MSEK/km)</th>
<th>Rock Tunnels(MSEK/km)</th>
<th>Cost Increase per 50km/h dimensional speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single track bore</td>
<td>360</td>
<td>120</td>
<td>2.5%</td>
</tr>
<tr>
<td>Double track bore</td>
<td>510</td>
<td>170</td>
<td>3.3%</td>
</tr>
</tbody>
</table>

*Table 2.5 - Construction costs –Tunnels for speed 250km/h*(Trafikverket 2010 and expert’s estimation)
2.6.1.2 Bridges/Viaducts:

This component is speed dependent too. For higher speed, it demands a wider structure (larger track distance) and more stability (damping vibrations) which causes an increase in construction costs (table 2.6).

<table>
<thead>
<tr>
<th>Single/Double track</th>
<th>Bridge/Viaduct (MSEK/km)</th>
<th>Cost increase per 50km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>200</td>
<td>2%</td>
</tr>
<tr>
<td>Double</td>
<td>320</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

*Table 2.6 - Construction costs –Bridges/Viaducts for speed 250km/h (Trafikverket 2010 and expert’s estimation)*

2.6.1.3 Embankments:

For higher speed, embankments need to be built in a larger cross section which causes an increase in construction costs (table 2.7).

<table>
<thead>
<tr>
<th>Single/Double track</th>
<th>Embankments (MSEK/km)</th>
<th>Cost increase per 50km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>12</td>
<td>0.5%</td>
</tr>
<tr>
<td>Double</td>
<td>15</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

*Table 2.7 - Construction costs –Embankment for speed 250km/h (Trafikverket 2010 and expert’s estimation)*

2.6.1.4 Cuttings:

For higher speed, cuttings need to be built in larger cross section which causes an increase in construction costs (table 2.8).

<table>
<thead>
<tr>
<th>Single/Double track</th>
<th>Cuttings (MSEK/km)</th>
<th>Cost increase per 50 km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>15</td>
<td>0.5%</td>
</tr>
<tr>
<td>Double</td>
<td>20</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

*Table 2.8 - Construction costs –Cuttings for speed 250km/h (Trafikverket 2010 and expert’s estimation)*
2.6.1.5 Catenary:

When speed increases, the catenary demands more mechanical tensions and more stable masts which cause an increase in construction costs (table 2.9).

<table>
<thead>
<tr>
<th>Catenary (SEK/track-km)</th>
<th>Cost increase per 50km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4</td>
<td>3%</td>
</tr>
</tbody>
</table>

*Table 2.9 - Construction costs –Catenary for speed 250km/h (Trafikverket 2010)*

2.6.2 Speed independent components

Other components construction costs do not depend on speed whereas other parameter like the frequency of services may have great influence on it. In the following section 3 of them are studied: signaling system, power supply, stations

2.6.2.1 Signaling system:

The signaling system includes Interlocking and ERTMS/ETCS Level 2 or (preferably when developed) Level 3 in the whole speed range (table 2.10).

<table>
<thead>
<tr>
<th>Signaling system (SEK/track-km)</th>
<th>Speed(km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>All ranges</td>
</tr>
</tbody>
</table>

*Table 2.10 - Construction costs –Signaling system for all ranges of speed (Source: experts estimation based on empirical values worldwide)*

2.6.2.2 Power supply:

Power supply is highly dependent on the number of trains which run every day. In fact, substations should be placed on shorter distance but here it is assumed that there are more powerful substations which can compensate/serve the long distance too. Higher speed also needs more power but it can be dampened due to better train aerodynamics and increased regenerative breaking for higher train design speed.
An estimation of power supply construction costs is in table 2.11. It is used in this thesis as the default.

<table>
<thead>
<tr>
<th>Number of trains</th>
<th>Construction costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-15 per day</td>
<td>3 MSEK/line-km</td>
</tr>
<tr>
<td>16-30 per day</td>
<td>4 MSEK/line-km</td>
</tr>
<tr>
<td>31-50 per day</td>
<td>5 MSEK/line-km</td>
</tr>
<tr>
<td>51-100 per day</td>
<td>6 MSEK/line-km</td>
</tr>
</tbody>
</table>

*Table 2.11 - Construction costs –Power supply for different frequency of trains (Source: experts estimation)*

2.6.2.3 Stations:

Station construction costs do not depend on the speed but is strongly depends on the number of stopping trains. The primary cost of a station includes two main tracks for passing trains and two platform tracks. Additional platform tracks depend on the number of stopping trains and also terminals should be bigger for more passengers. No costs for construction of connecting mode (car, bike, bus etc) terminals are included since it usually is covered by regional and local funding in Sweden.

The following table (2.12) shows a default value for cost of station construction:

<table>
<thead>
<tr>
<th>Number of stopping trains</th>
<th>No. of platform tracks</th>
<th>Construction costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-15 per day</td>
<td>2 (+2 main)</td>
<td>150 MSEK</td>
</tr>
<tr>
<td>16-30 per day</td>
<td>4 (+2 main)</td>
<td>300 MSEK</td>
</tr>
<tr>
<td>31-50 per day</td>
<td>6 (+2 main)</td>
<td>600 MSEK</td>
</tr>
<tr>
<td>51-100 per day</td>
<td>8 (+2 main)</td>
<td>1000 MSEK</td>
</tr>
</tbody>
</table>

*Table 2.12 - Construction costs –station for different frequency of trains (Source: experts estimation)*

Another important issue is the overtaking of a slower train when the running time difference increases between trains (very fast train, fast train). By higher frequency of services, the number of overtaking station increases but in this model we assume that overtaking here occurs solely on stations with passenger exchange.
2.7 Rolling Stock (Trains)

The next component in HSL is the cost of the rolling stock which plays an important role in the CBA model too. For various speed, train sets have different specification and therefore cost differently. In addition, unlike the cost of the HSL infrastructure where most of the parameters are independent of traffic and demand, the type of maintenance and operation have great influence on the calculation.

In the most basic form, it is possible to divide the rolling stock into three parts:
- Acquisition
- Operation
- Maintenance

However, this categorization is too general for mathematical calculation and we use the rolling stock cost model which Oskar Fröidh suggests in “Resande och trafik med Gröna tåget, (2010)” as our base model for calculation (figure 2.3):

Figure 2.3 - operating cost model (Fröidh, Resande och trafik med Gröna tåget, 2010)
(Simplified model from original model)
According to this model, both train set specification data and traffic data (demand) have influence on the calculation.

There are sets of parameters in the train set specification and altering them causes a corresponding change in the cost too. The most important ones are:

- The number of car bodies per train unit
  - The number of steering trailers/powered cars
  - The number of intermediate trailers/coaches
- The number of seats
- Weight in working order (tons)
- Installed power (kw)
- Train length
- Aerodynamic factor
- Regenerative braking (Yes/No)

It is also possible to define new train sets and add them to table 2.13. Different configurations in table 2.13 cause the cost to change at different speeds but they are not dependent on traffic data. For example, numbers of seats, operating speed have effects on cost of train sets independently of the traffic data. To make the CBA model simpler we defined some sample train sets (table 2.13). Later in this chapter, appropriate calculations will be done for these types of train sets.

<table>
<thead>
<tr>
<th>Train set configuration and speed</th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
<th>Type 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type name</td>
<td>GTW-6</td>
<td>GTW-6</td>
<td>GTW-6</td>
<td>GTW-6</td>
</tr>
<tr>
<td>Class</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top Speed km/h</td>
<td>200</td>
<td>300</td>
<td>400</td>
<td>500</td>
</tr>
<tr>
<td>Configuration</td>
<td>WEMU</td>
<td>WEMU</td>
<td>WEMU</td>
<td>WEMU</td>
</tr>
<tr>
<td>Power units/loco’s</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Steering trailers/powered cars</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Intermediate trailers/coaches</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Car bodies per train unit</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Number of seats</td>
<td>480</td>
<td>460</td>
<td>440</td>
<td>420</td>
</tr>
<tr>
<td>Operating speed km/h</td>
<td>200</td>
<td>300</td>
<td>400</td>
<td>500</td>
</tr>
<tr>
<td>Weight in working order tons</td>
<td>360</td>
<td>360</td>
<td>360</td>
<td>360</td>
</tr>
<tr>
<td>Installed power kW</td>
<td>4800</td>
<td>7200</td>
<td>9600</td>
<td>12000</td>
</tr>
<tr>
<td>Train length m</td>
<td>160</td>
<td>160</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>Aerodynamic factor</td>
<td>1,20</td>
<td>1,00</td>
<td>0,70</td>
<td>0,50</td>
</tr>
<tr>
<td>Regenerative braking Yes/No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

*Table 2.13 - Four different train sets for different speeds, source: (Fröidh, Resande och trafik med Gröna tåget, 2010)*

It is possible to define a new train set and add it to the table 2.13 for a new calculation. We only consider the final result (table 2.15) which is used in the CBA model. Detailed
calculations can be found in (Fröidh, Resande och trafik med Gröna tåget, 2010). It should be noted that train specification in this case is based on a wide-body (approx. 3.5 m wide), single deck high speed train based on Gröna Tåget concept which seems to be an economic solution for Scandinavian. However, for very high speeds, 350 km/h and more, little is known on how an economic train concept could be configured. All data should therefore more be seen as indications on possible train concepts.

**Energy costs:**

Energy consumption depends on the train set specification, like aerodynamic factors and train set formation. It also differs in various speeds too. Other factors like acceleration energy consumption, air condition inside the train and other facilities cause a change in costs but since these parameters do not affect a large part of the energy consumption, they can be ignored in the calculation.

**Maintenance costs:**

According to the model, maintenance costs divide into four categories:

- Light maintenance (weekly maintenance)
- Heavy maintenance (out of service)
- Insurance (damages)
- Upgrading (modernizing)

<table>
<thead>
<tr>
<th>Rolling stock - Maintenance costs (SEK/train-km)</th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
<th>Type 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type name</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light maintenance (weekly)</td>
<td>18.00</td>
<td>26.00</td>
<td>31.50</td>
<td>38.40</td>
</tr>
<tr>
<td>Heavy maintenance (out of service)</td>
<td>4.20</td>
<td>4.50</td>
<td>4.80</td>
<td>5.40</td>
</tr>
<tr>
<td>Insurance (damages)</td>
<td>2.25</td>
<td>3.24</td>
<td>3.78</td>
<td>4.32</td>
</tr>
<tr>
<td>Upgrading, modernizing</td>
<td>0.75</td>
<td>0.90</td>
<td>1.05</td>
<td>1.20</td>
</tr>
<tr>
<td>Total, maintenance costs</td>
<td>28.70</td>
<td>38.04</td>
<td>44.15</td>
<td>51.95</td>
</tr>
</tbody>
</table>

*Table 2.14 - maintenance costs for sample train sets, source: (Fröidh, Resande och trafik med Gröna tåget, 2010)*

These costs partly depend on speed because for a higher speed, more complicated equipment and less tolerance are accepted.

Table 2.14 shows calculated data for the example train sets in table 2.13.
Other costs

Costs such as train staff costs, terminal costs (cleaning, water supply, etc.), track access charge, overhead costs (planning, administration, sales and marketing) are in this category.

These costs do not depend on the speed. Since the focus of this paper and our calculation is based upon speed factor, these costs are considered as a constant factor in our calculation.

Total costs:

Doing a complete analysis and calculation of the rolling stock costs is complicated enough and it is out of the scope of this project. To access the total costs, the Gröna Tåget cost model is used and data from this model are used as default data in this thesis (table 2.15).

<p>| Rolling Stock Costs (SEK/passenger-km)(load factor 60%) |</p>
<table>
<thead>
<tr>
<th>Stop</th>
<th>Non-Stop</th>
<th>Train set type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>0.47</td>
<td>Type 1</td>
</tr>
<tr>
<td>0.57</td>
<td>0.52</td>
<td>Type 2</td>
</tr>
<tr>
<td>0.63</td>
<td>0.56</td>
<td>Type 3</td>
</tr>
<tr>
<td>0.72</td>
<td>0.62</td>
<td>Type 4</td>
</tr>
</tbody>
</table>

*Table 2.15 - Operating costs for sample train sets, source: (Fröidh, Future rail traffic on the Eastern Link, 2010)*

2.8 Demand

Demand is defined in this thesis as the numbers of passengers that choose to use the train service mode. To calculate the exact number of passengers, important parameters should be studied. Demand usually changes with any variation in these three important factors:

- Travelling time
- Frequency of departures
- Fare

Shorter travelling time attracts more people from air transport mode and also cheaper tickets than today causes more people decide to use train service mode.

In this thesis, it is focused on these three factors and their effects on the HSL operating costs and revenue.
The total number of passengers in all transport modes is assumed constant and it varies for different years according to following factors:

- Estimated increase of domestic journeys per year (1st Period)%
- Estimated increase of domestic journeys per year (2nd Period)%

First factor indicates the increase in the first period. For example, it is assumed that the increase in number of passengers until 2030 is 1.3% while after that it reduces to 0.5% per year.

Market share for train service mode is also assumed as a constant and it does not change for different years but variations in parameters makes a variation in market share, which leads to demand changes as a result.

### 2.9 Service (Timetable)

Operating costs are dependent on train frequency, the number of passengers and rolling stock costs. In section 2.7 rolling stock costs are described and in table 2.15 are concluded. A loading factor of 60% is the basis of the calculation for the cost in table 2.15. Number of passengers and train frequency change the number of the empty seats in the trains which may cause an increase in operating costs.

A higher frequency of services attracts more passengers to the service but if the number of passengers is not enough to fill the load factor of a train then passengers should pay for the empty seats. It automatically increases the fare which has a negative influence on the demand.

### 2.10 Revenue and travelling time gain

Benefits in HSL mostly include the revenue and travelling time gain. Revenue is directly dependent on the number of passengers (demand) and also the average fare. Higher speed and higher frequency attract more passengers so they increase the revenue value. It is assumed that the average fare does not depend on speed.

Travelling time gain is another important factor when the benefits are calculated. It means that higher speed shortens the travelling time and that is valuable. In this thesis, trips are categorized in business trips and leisure trips (table 2.16). In chapter 4, it is shown how travelling time gain is calculated.
<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Business Time Monetary Value (SEK/h)</td>
<td>275</td>
</tr>
<tr>
<td>Leisure Time Monetary Value (SEK/h)</td>
<td>100</td>
</tr>
<tr>
<td>Business Trip Portion (%)</td>
<td>30%</td>
</tr>
</tbody>
</table>

*Table 2.16 - monetary value for travelling time gain* (Fröidh, Resande och trafik med Gröna tåget, 2010)
3 Predictive Modeling

One of the oldest dreams of human beings through history has been the dream of prophecy. It means that we can guess what would happen in the future and we can adjust our plan regarding that knowledge to profit from future events. (Popper, 1963).

Predictive modeling can be defined as a modeling process in which it is attempted to create a model that predicts the future, based on past data. In most cases, the model receives some existing real input data and predicts something of the future with adequate approximation. (Geisser, 1993)

The model itself may be created in different ways using different techniques and algorithm but the outcome is to guess what happens in the future and based on that statement it is possible to plan for upcoming events.

In this chapter, two categories of predictive model are discussed. One needs a large data set and the other does not need a large dataset for prediction. It is discussed why the second category is chosen for this work and also discussed why the elasticity of demand model is preferred to a logit model (a technique which is used in market analysis and it is based on logistic function). Although both of them are based on a probability and does not need large data set.

3.1 Why Predictive models

There are many cases that people, including managers, politicians, engineers, etc., need to be aware of how a situation may changes in the future. For instance, when a new project is planned it is important to know something about the outcome of the project before starting it. In some cases, it may not be beneficial to start the project at all because the analysis shows that it is not a good investment.

Predictive models try to find an association between the past data and new data. It means that with observation of data and applying a method on existing data set, it is possible to get a result for the future. In this work, the main goal was to predict the costs and benefits of new HSL projects in the future based on existing data from current projects. Finally based on cost-benefit analysis, the ultimate goal was to find the optimal speed.

In this work, it was attempted to model the cost-benefit of a new HSL project. The model accepts existing data about implemented projects which might be non-HSL project too. A probability method was applied to this data and the output of the model is the costs and benefits of the new HSL project. This model also works on important parameters like dimensional ‘speed’ to find the optimal value considering cost-benefit optimum.
3.2 Different models

There are different models based on statistical and probabilistic methods. Performance of these models mostly depends on the accuracy of input data, method used and also settings of the model. Accurate data, good algorithm and also correct adjustment of parameters lead to a better output.

Predictive models may fit into two categories according their input data. The first category needs a large set of input data and their functionality really depends on the quality of the input data. They work on training data set (input data set), classify the training data set and try to fit any other input data in a class (figure 3.1). Most classifiers work like that and need large set of high quality training data set and precise adjustment of algorithm setting to work efficiently and effectively. Machine learning methods like k-nearest neighbor, support vector machine are of this type.

Second category does not need training data set and it acts based on probability. These kinds of models receive input data and use some kinds of probability method and guess an output (figure 3.2). A main drawback for these models is that the quality of output depends on the probability factors and functions. No need to training data set makes these models useful in the situation in which there is not existing data or it is very difficult to access high quality data. Methods such as logit model (logistic function) and elasticity model are of this type.
3.3 Model Selection

HSL projects are still considered as new technology. In many countries they have not started yet or they are ongoing projects which they do not have yielded the useful data yet (Campos & De Rus, Some stylized facts about high-speed rail: a review of HSR experience around the world, 2009) Of course, there are a few projects in different countries but the problem is that the data of these projects is site-specific and they are not applicable to other areas. It means that the data usually depends on demographic situation of country, topographic situation, climate and many other factors. Therefore, it is not really possible to access a reliable, high quality relevant dataset for HSL project or at least it is very difficult and time consuming to gather such a dataset. The first category of predictive models which need large training dataset are not useful here and cannot be used because of lack of dataset. However, second category can be used in this situation because they do not demand training dataset and act based on probability. In this thesis work, we focus on logit model and elasticity model and choose elasticity model for the predominant model for this project.

3.3.1 Logistic Regression (Logit model)

Logit analysis is a technique which is used in market analysis (Cramer, August 2003). Acceptance of a product or service can be assessed by converting passenger travel intention to real probabilities. It uses passenger preferences to determine the probability of using a particular transport mode in travel market analysis. Travelling time, fare and service frequency are three main passengers’ preferences to choose a transport service.

For logit analysis, we used the standard logistic function (figure 3.3) which is:

\[
P(x) = \frac{1}{1 + \exp(-x)}
\]  

(figure 3.3)
In order to determine the market share a utility function was used to map the important parameter values into the measurable value for general logistic function. (Oscar Fröidh, 2009)

The utility function could be defined and used like following example:

\[ U_{\text{train}} = \text{traveling time weighting} \times \text{traveling time (minute)} + \text{price sensitivity} \times \text{fare (SEK)} + \text{service frequency weighting} \times \text{service frequency (minutes)} \]

\[ U_{\text{car}} = \text{traveling time weighting} \times \text{traveling time (minute)} + \text{price sensitivity} \times \text{price} + \text{travel mode constant} \]

For example for the following calculation, utility functions give following value:

\[ U_{\text{car}} = 0.02 \times 80 + -0.02 \times 150 + 1.5 = -2.70 \]
\[ U_{\text{train}} = 0.02 \times 80 + -0.02 \times 100 + -0.10 \times 60 = -4.20 \]

\[ U_{\text{car}} - U_{\text{train}} = 1.5 \]

According to logit model’s logistic function (figure 3.3), for the \( x=1.5 \) the value of \( y \) is about 0.82. It means that 82% of traveler will choose the car and only 18% will choose train service (according to the mentioned utility functions).

Price sensitivity constant: determines how the price is valued in different alternatives.

Travelling time constant: weighting determines how journey travelling time is valued by different alternatives.

Travel mode constant: a constant utility for a specified travelling alternative.

### 3.3.2 Elasticity of demand model

In economics, elasticity is the ratio of change in a variable to change in another variable. In elasticity model it is studied that how a small change in one variable influences on change in another variable. Elastic variable is the variable which small change in it causes a lot change in another variable. Inelastic variables do not respond with change in other variables.

Elasticity of demands means ratio of change in the quantity demanded to percentage change in a variable like price (figure 3.4). It is a useful method in probability to see how elastic a variable is in response to change in other variables. (Andrew, 2007)
Elasticity of demand = \[ \frac{\text{Percentage change in the quantity demanded}}{\text{Percentage change in a parameter}} \]

In fact, elasticity of demand tries to study the sensitivity and responsiveness of quantity demanded to change in different parameters like price.

There are three different supply parameters which highly affect the demand of travel (Fröidh, Future rail traffic on the Eastern Link, 2010).

- Travelling Time
- Fare
- Service Frequency

Any change on these variables causes more or less people decide to use the HSL service. Number of train journeys is highly dependent on these three variables and in this thesis, it was attempted to study the changes in these three parameters.

For example, travelling time elasticity factor can be defined as (empirical values; Fröidh 2010):
- 31 to 120 minutes: -0.9
- 121 to 240 minutes: -1.5
- 241 to 360 minutes: -0.9
- >360 minutes: -0.6

If the travelling time decreases from 250 to 115 minutes, how much do the number of train journeys increase?

Base scenario: 250 minutes travelling time (tB)
New scenario: 115 minutes travelling time
Gain: 135 minutes in total (54%)
Gain is segmented on:
10 minutes (t3) in the interval 3 (241-420); \(e_3=-0.9\)
120 minutes (t2) in the interval 2 (121-240); \(e_2=-1.5\)
5 minutes (t1) in interval 1 (31-120); \(e_1=-0.9\)

\[
\text{Elasticity of demand} = \frac{\text{Percentage change in the quantity demand}}{\text{Percentage change in travelling time}}
\]

Increase in number of journeys increases = \((-t1/tB*e1) + (-t2/tB*e2) + (-t3/tB*e3)\)

In the example \((-5/250*-0.9) + (-120/250*-1.5) + (-10/250*-0.9)=0.774\)

\[
\text{Percentage change in the quantity demanded} = +77.4\%
\]

Since elasticity is unit less and it does not depend on the type of variable, it simplifies the data analysis and makes it easier to calculate marginal values. In this thesis, the interest is in the change of demand when something changes. Therefore, the elasticity model is a good tool for marginal calculation which is a matter of interest in this thesis.

### 3.3.3 Logit model or elasticity of demand model

Logit model is useful in the situation when it is needed to compare different modes of transport together. For example if the interest is in studying other modes of transport like car and air mode and compare them to each other when a parameter like price changes, it is worth to use the logit model. Logit model needs data about other modes of transport too. Utility functions definition in logit model needs extra care because the result is strongly dependent on utility functions. Data about different modes of transport should be available to be able to define utility functions properly. Logistic function in the sample (figure 3.3) is also the simplest function. In reality, accurate calculation demands more complicated function.

In this thesis, the focus was only on HSL demand change and to make it simple we did not go through other modes of transport; however, it is an interesting matter for future work.

Elasticity of demand is the preferred model in this thesis. The focus is only on the HSL and access to the data of other transport mode is difficult at this time. Using logit model needs data of other modes of transport. Elasticity also supports well the marginal calculation which is matter of interest in this thesis.
4 Model Constructions

In this chapter, the discussion in chapter 2 and chapter 3 is formulated and a computational model is built to calculate the cost-benefit of an HSL project. This model is based on mathematical relations and the final result of this model would be the cost-benefit of an HSL project.

In chapter 2, different components and concepts which have great influence on cost-benefit of HSL were discussed. There are many factors which cause cost and there are many other that produce benefits for an HSL project. Formulation of these parameters was done using a mathematical model. To calculate the change in costs and benefits, prediction model from chapter 3 was used. Elasticity of demand is the main prediction method, which was used in current chapter.

4.1 Different components for CBA

To simplify the model construction process and in order to make it easy to understand and easy to follow, CBA model was divided into three important components:

- Infrastructure costs
- Operating costs
- Benefits

All of these components together determine the benefit-cost of an HSL project. After detailed description of each of these components, the Net Present Value (NVP) was calculated based on these components.

For each of these components a mathematical formulation was suggested. Formula was based on discussion in chapter 2 and main parameters used in this formula have already been discussed there.

Before starting the formulation of different components, demand in HSL projects needed to be computed because it is a general concept which is used almost in all three components of CBA. Fluctuation in demand was calculated and studied based on important parameters and constants.

4.3 Demand calculation

There are three different parameters which have great influence on demand:

- Travelling time
- Frequency of service
Fare

In chapter 2, it was discussed how these parameters change the demand. As figure 4.1 shows, speed has influence on travelling time. Higher speed means shorter travelling time which may attract more passengers from other types of transport which are nearly competent.

With higher frequency, more trains run every day and waiting time reduces for passengers. It may again attract more people from other types of transport especially air transport mode which has great waiting time before checking in and sometimes after the trip.

Lower fare also attracts passengers from other transport modes which have higher fare compared with train services.

![Diagram](null)

**Figure 4.1 - Dependency of demand on important parameters**

To find how demand changes when speed, frequency and fare change, it was discussed in chapter 3 that a prediction model need to be used. Elasticity of demand was used as prediction method in this work. Table 4.1 shows different elasticity factors and their default values which were used in the calculations.

It was supposed that total number of passengers has a constant increase in two periods. For example, it was supposed that from 2010 to 2030 “estimated increase of domestic journeys per year” would be 1.3% and after 2030 it would be 0.5%. In this way, increase in the number of passengers, which might be lower in future than today, was considered.
## Constant – Summary

<table>
<thead>
<tr>
<th>Constant Name</th>
<th>Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elasticity- Travelling Time(31-120 minutes)</td>
<td>-0.9</td>
</tr>
<tr>
<td>Elasticity- Travelling Time(121-240 minutes)</td>
<td>-1.5</td>
</tr>
<tr>
<td>Elasticity- Travelling Time(241-360 minutes)</td>
<td>-0.9</td>
</tr>
<tr>
<td>Elasticity- Travelling Time(&gt;360 minutes)</td>
<td>-0.6</td>
</tr>
<tr>
<td>Elasticity- Frequency (1-10%)</td>
<td>-0.3</td>
</tr>
<tr>
<td>Elasticity- Frequency (11-30%)</td>
<td>-0.4</td>
</tr>
<tr>
<td>Elasticity- Frequency (31-100%)</td>
<td>-0.5</td>
</tr>
<tr>
<td>Elasticity- Fare = 1 SEK</td>
<td>-0.8</td>
</tr>
<tr>
<td>Elasticity- Fare = 2 SEK</td>
<td>-1.5</td>
</tr>
<tr>
<td>Estimated increase of domestic journeys per year(1st Period)%</td>
<td>1.3</td>
</tr>
<tr>
<td>Estimated increase of domestic journeys per year(2nd Period)%</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Table 4.1 - Summary of important constant in HSL CBA**

### Distance matrix (D)

This matrix contains table 4.3 the distance between destinations in km in which \( d_{i,j} \) means the distance between \( D_i \) and \( D_j \) in kilometer.

<table>
<thead>
<tr>
<th>Distance(km)</th>
<th>( D_1 )</th>
<th>( D_2 )</th>
<th>( D_3 )</th>
<th>( D_4 )</th>
<th>( D_5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D_1 )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( D_2 )</td>
<td>( d_{1,2} )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( D_3 )</td>
<td>( d_{1,3} )</td>
<td>( d_{2,3} )</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( D_4 )</td>
<td>( d_{1,4} )</td>
<td>( d_{2,4} )</td>
<td>( d_{3,4} )</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( D_5 )</td>
<td>( d_{1,5} )</td>
<td>( d_{2,5} )</td>
<td>( d_{3,5} )</td>
<td>( d_{4,5} )</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 4.2 - Distance matrix**

### Total number of journeys in a year \( t \) (\( J(t) \))

To show the total journeys per year, a half-full matrix of number of journeys was used in the base year (for example 2010) in table 4.3.

To calculate total journeys in other year, two constants was used:
- Estimated increase of domestic journeys per year (2010-2030): 1.3%
- Estimated increase of domestic journeys per year (>2030): 0.5%
<table>
<thead>
<tr>
<th>Number of journeys</th>
<th>D_1</th>
<th>D_2</th>
<th>D_3</th>
<th>D_4</th>
<th>D_5</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>D_2</td>
<td>j_{1,2}</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>D_3</td>
<td>j_{1,3}</td>
<td>j_{2,3}</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>D_4</td>
<td>j_{1,4}</td>
<td>j_{2,4}</td>
<td>j_{3,4}</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>D_5</td>
<td>j_{1,5}</td>
<td>j_{2,5}</td>
<td>j_{3,5}</td>
<td>j_{4,5}</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4.3 – Total number of journeys between destinations

D_i: Destination i  
J_{i,j}: Number of journeys between destination i and j in base year

**-Top Speed (S_t) and Commercial Speed (S_c)**

Top speed is the dimensional speed that an HSL line infrastructure is built to serve. In reality, commercial speed is always lower than top speed. The commercial speed is a function of line topography, speed restrictions, train acceleration and deceleration, number of stops and dwell time at stations.

For the sake of simplicity, in this thesis work, it was supposed that the commercial speed is a linear function of top speed in the HSL project.

S_c = S_t * c  
S_c: Commercial Speed  
S_t: Top Speed  
c: constant

**-Travelling time matrix (T)**

Travelling time between destinations was calculated as scalar division of distances between destinations by the commercial speed.

T = D / S_c  
S_c: Commercial Speed  
D: distance matrix

**-Market Share base (M_b) and market share change (M_c)**

It was supposed that market share has constant value between destinations and it does not change in the following years (table 4.4). It was defined as a matrix M_b in which m_{i,j} means the market share for the train journeys between two destinations D_i and D_j.
To calculate the change in market share when speed, frequency and fare change, elasticity of demand was used and it was calculated as following:

\[ M_c(S_t, f, p) = M_b * E(T) + M_b * E(f) + M_b * E(p) \]

- **M_b**: market share base
- **M_c**: change in market share
- **E(T)**: elasticity of demand probability function for travelling time (travelling time elasticity of demand)
- **E(f)**: elasticity of demand probability function for frequency (Frequency elasticity of demand)
- **E(p)**: elasticity of demand probability function for ticket price (Price elasticity of demand)

\[ M(S_t, f, p) = M_c + M_b \]

- **M**: market share for speed \((S_t)\), service frequency \((f)\) and fare \((p)\)

### Total number of Journeys by train matrix \((JT(t))\)

Total number of journeys by train in year \(t\) was calculated from market share in year \(t\) and total number journeys in year \(t\).

\[ JT(t) = J(t) * M(S_t, f, p) \]

- **J(t)**: total number of journeys in all transport modes in year \(t\)
- **M**: market share for speed \((S_t)\), service frequency \((f)\) and fare \((p)\)

### Total Passenger-km by train matrix \((PT(t))\)

Total passenger-km matrix was calculated from total number of journeys by train between different destinations and the distance between different destinations.

\[ PT(t) = JT(t) * D \]

- **PT(t)**: “Total passenger-km by train” matrix between destinations in year \(t\)
- **JT(t)**: total journeys by train in year \(t\)
- **D**: Distance Matrix
4.4 Infrastructure costs calculation

In chapter 2, different components involved in infrastructure costs were discussed and it was shown that infrastructure costs for HSL depends on both desired top speed and service frequency in the future. High-speed train’s width, height and axle load are constants in this case.

“Speed dependent components” costs vary when the top speed is changed (figure 4.2). To calculate the change in cost when speed changes there is a coefficient which depicts how cost changes in relation to change in speed. This coefficient called “cost increase per 50 km/h” and it is the change in cost when speed is changed by a 50km/h increment.

Speed independent costs were also explained in chapter 2. “power supply” and “station” cost will change if there are more trains running per day.(see chapter 2)
Line characteristic demonstrates how different components distribute in an HSL project. It contains the total line length, line type which is single or double tracks, and what percentage different components have in an HSL.

According to above explanation, formulation of infrastructure costs would be:

\[
\text{Infrastructure costs} = \\
\text{Track costs} + \text{Tunnel costs} + \text{Viaduct and Bridge costs} + \text{Embankments costs} + \text{Cuttings(s)} + \text{Catenary costs} + \text{Power supply(s)} + \text{Signaling system costs} + \text{Power supply cost}
\]

### 4.5 Operating costs calculation

Operating costs include the cost of running trains which was discussed in detail in chapter 2. It was finalized as a passenger per km cost according to the Gröna Tåget cost model (Fröidh, Resande och trafik med Gröna tåget, 2010). It means that for different train types and a given load factor (in this thesis work it is 60%) the cost per passenger per kilometer was taken from that model. This computed unit cost and demand were used to calculate the whole operating costs in the HSL.

\[\text{Operating costs} = \frac{\text{Unit cost} \times \text{Demand}}{\text{Load factor}}\]

**Figure 4.3 – Operating costs important components**

Operating costs also depend directly on frequency. Given cost per passenger per kilometer is for a specific load factor. If there are more trains (higher frequency) and an excess supply, then the trains may not be filled to 60% and there are many seats left empty. In this case,
existing passengers should compensate this cost that means higher ticket price for passengers. Higher ticket price itself has a negative effect on demand and it causes a decrease in the total number of passengers. In this thesis work, this negative effect was ignored because it was supposed that the average fare is constant in the project and the trains are flexible to the number of seats (passengers).

To calculate total discounted operating costs in one year $t$:

Total operating costs ($t$) = $PT(t) \times (O(S_t) + c)$

Where:
$PT(t)$ : is Total number of passenger-km between destinations in year $t$ which is calculated from section 4.3
$O(S_t)$ : is the operating costs per passenger-km for a given top speed (from top speed the train type is selected. Different train types support different speeds)
$c$ : is operating costs compensation for lower load factor than the default value (lower than 60%)

### 4.6 Benefits calculation

As explained in chapter 2.3, Benefits in HSL was categorized as:
- Revenues
- Travelling time gain

![Figure 4.4 – Important components in benefits calculation](image-url)
4.6.1 Revenue

It was supposed that average fare is a constant and other parameters do not have any effect on it. To calculate revenue in year $t$:

Total revenue in year $t = PT(t) \times f$

Where:
$PT(t)$ is Total number of passenger-km between destinations in year $t$ which is calculated from section 4.3
$f$ is the average fare per passenger-km

4.6.2 Traveling time gain

As discussed in chapter 2.10, two types of trips were assumed in this work: business trips and leisure trips. Travelling time gain was directly calculated from marginal traveling time in new service and monetary value for different trips:

Total Travelling time gain in year $t = (T_m(t) \times b \times bc) + (T_m(t) \times l \times lc)$

Where:
$T_m(t)$ is total travelling time reduction in all trips (hour)
$b$ : the portion of passengers which choose business trip
$bc$ : monetary time value (SEK/h), business trips
$l$ : the portion of passengers which choose leisure trip
$lc$ : monetary time value (SEK/h), leisure trips
$t$ : year

4.6.3 Total benefits

Total benefits in year $t$ simply means:
Total benefits ($t$) = Total revenue ($t$) + total Travelling time gain($t$)
$t$ : year

4.8 CBA analysis (NPV)

Since the analysis of an HSL project is in long term, present values are calculated. Present values are the current value of sum of money (cash flows) in the future. NPV reflects the sum of the all PVs and it is a tool in financial analysis to assess the rationality of an investment. To conclude the effect of parameters and especially the effect of speed in cost-benefit, NPV was used to show which case is better than others.
NPV = \sum_{t=1}^{n} \frac{A}{(1+r)^t}

Where:
A: is cash flow in each year
r: is discount rate (4%)
t: is calculation period from 1 to n years

Cash flow is defined as:

A = Benefits - Total costs = Benefits – (Infrastructure costs + Operating costs)
5 OHSL Tool

In this chapter, the different aspects of development of a tool are discussed. This chapter is mostly in computer science domain and the discussion subjects are inside design and development of a software tool, called OHSL.

OHSL stands for “Optimal High Speed Line” and it is a software tool which implements the computational model discussed in this work. OHSL, which is a web-based tool, enables the user to work with computational model. User inputs the needed parameters and gets the result from the tool. Without the OHSL, it is not comprehensive and simple to access the computational model. Using paper or any manual way to use the computational model is tough, time-consuming, confusing, and not flexible because of large number of parameters in the model. Using the OHSL, user easily works with computational model and obtains the result without any necessary involvement in the complexity of the model.

5.1 Rationale behind the existence of the OHSL

The computational model discussed in this work contains various formulas and equations. There are many constants that build the structure of the model. There are also large numbers of input parameters that model needs to do the calculation. Putting all of them together makes the model enough complicated to work with. Using paper or excel to do the calculation needs huge amount of time and also involvement in the model complexity to run the model correctly. Of course, it is possible to use some other tools like Microsoft Excel to facilitate the calculations; however, the numerous parameters and formulas make even working with Excel complex.

Another important factor in running the model is the model responsiveness. How the model acts when user changes some parameters and want to see the results. OHSL tries to build a black box for the user. This black box is the computational model and it has some inputs, and some outputs. User can easily change the input and see the output while he does not need to do the calculation again manually. Calculation even was optimized not to be repeated every time the model is run and only those parts that need to be recalculated, are calculated again each time. In fact, it helps the user to focus more on the parameters rather than the model complexity. Focusing on parameters leads user to input data more accurately and to adjust the constants precisely to get a correct result.

Using programming language to implement the model and to run the model, produced faster response time because it was possible to optimize the code for the current problem. User sees the model that responds in several seconds and makes the model enjoyable for the user to work with. Since OHSL has been developed to run the specific computational model discussed in this work, it tries to use machine resource optimally to run the model as fast as possible.
OHSL is accessible via web anywhere and anytime. Since data is in a centered place it does not need to transfer data from one machine to another machine and it always guarantees that data is not corrupted during the access by different users from different places.

5.2 Web-based tool

There are different types of applications:

- Web-based applications
- Machine specific-based applications (e.g. Windows-based application, Unix based application)

Machine specific application examples are Windows based applications which are specific to windows platform and it is not possible to run them on other platform like Linux, Mac OS, and etc. There is also another problem about deployment of Windows applications. Windows applications need to be distributed to every machine that needs to run it. It is not accessible from anywhere and installation sometime may be an obstacle to use the tool. To overcome these problems, in this work, it was decided that web-based application is used as the fundamental rules of development. It is:

- Platform independent: users can access it from different platforms by using only web-browsers.
- Easy deployment: users do not need to install anything or do any specific setting on their machine. They can run the model by using a URL like (www.ohsl.se) without any need to do anything else.
- Easy update: version of the software is updated easily on a web server and automatically is delivered to the users. It does not need to be updated on every client.

Of course, there are drawbacks too. Web applications are working when there are internet connections available and also the performance of data delivery might diminish as the performance of the internet connection decreases.

5.2.1 Tool architecture

OHSL obeys the principle of software architecture and has three primary layers which are usual in developing software (Fowler, 2003).

- Presentation Layer
- BL (Business logic)
- Data layer
These layers are shown in figure 5.1. Presentation layer consists of the user interface that is accessible for the user to interact with the application. User interface in the OHSL was based on web forms and was launched using a regular web browser. Business logic layer is the layer where the computational model was implemented. Data layer is the layer where the database system of the OHSL was located. This database was used to store the parameters and also constants entered by the user. In this way user has access to this data next time and user does not need to enter data again. OHSL uses this database to access the parameters in a structured way.

![Figure 5.1 - Architecture of the OHSL Tool](image)

Business logic layer is the heart of the OHSL where the whole model is implemented and calculations are done. This layer takes the parameters value from users and database and delivers the result to users.

There are also different Technologies which were used in developing of the OHSL. Complete explanations of these technologies are out of the scope of this thesis work. There are good information and tutorial on World Wide Web Consortium(W3C).

Important technologies in the OHSL are:
• ASP.NET: is utilized to develop web-based applications on .NET framework.
• n-tier design (MVC): is a 3-tier software architecture which makes the communication between layers more structured and efficient and it was first introduced by (Reenskaug & Trygve, 2011)
• MSSQL database: is a database management system by Microsoft which is used as data storage of the OHSL.

Fix 5.2 - Different technologies used in developing of the OHSL

5.3 Manipulation of Parameters - Database

One of the main barriers in implementing the computational model was the large number of parameters that the model needed to run. Manipulating these parameters needed to be simplified in order to implement it inside the tool.

There are two types of input parameters:
- Pivot tables
- Scalar values

Pivot tables represent the parameters that are in the form of OD-pairs (origin-destination). For example distance between cities, base market share, and total numbers of journeys between ODs are examples of these types of parameters. In the OHSL, data table called “PivotTable” was used to store and retrieve pivot tables. It is possible to save several pivot tables in this database table.

Scalar parameters have a single value, such as fare, frequency of services, total line, and many others. These parameters help the user to make the computational model as dynamic as
possible. It means that for different parameters model works differently and produces various results. There is more explanation about interactive computational model in chapter 5.4.

Due to the large number of parameters, it was very important to design a database structure that could get the parameters from user and store them and retrieve them optimally. A simple data structure shown in figure 5.3 was used to handle parameters. This simple structure reduced the complexity of database and increased the performance of database since it did not have many complex elements to store and retrieve. Using parameters to do the calculation was done in BL (chapter 5.2.1) components of the OHSL. The structure of tables is shown to give an intuition of how simple the data table of the OHSL is, despite the complexity of model and parameters.

Despite the large number of parameters, it was attempted to make the parameters accessible to the user in a very simple way. Figure 5.3 shows a screen shot of the OHSL where user should put the values for the parameters. As it is shows in figure 5.4, user sees categorized parameters which simply are understandable and easy to follow. It is straightforward to find a parameter and to change the value of that. There are different categories in left hand side which navigate the user to the place of right parameter. This categorization also helps the user to remember the place of each parameter and after a while user can work with model in a more convenient way. There are also several tab pages on top of the screen which depict different parts of the application. Since OHSL has different parts, it is logical to break it down to several important smaller parts which indicate different logical components of the OHSL. For example, parts named “Result” and “Analysis” show the output of the calculations of the model. ”Settings” and “Construction Data” are used to set the basic parameters of the model.
"Base Scenario" and “New Scenario” are the place where users define different scenarios to be run by the OHSL.

![Image of OHSL page](image)

**Figure 5.4 - A screen shot of the OHSL page where user enters the input parameters**

### 5.4 Categorization of parameters

Categorization of the parameters and functions in the OHSL has made it easy to work with this tool. Important categories of the OHSL are discussed in more detail in the following chapter. It shows how different groups of parameters and functions help to improve the quality of the user navigation and user perception of the OHSL.

#### 5.4.1 New scenario and base scenario

The computational model in this work is able to compute and to show the output for a defined scenario. However, because there are many other details in construction of HSL, the desire is often to compare two scenarios with one another, i.e. a base scenario and a new scenario. These strategies make other benefits too which are discussed in more details in chapter 6.

Both base scenario and new scenario contain similar parameters and options, and user usually fills the parameters for the base scenario from an existing HSL project. The new scenario is the set of parameters for the line that user wish to analyze.
New scenario and base scenario are accessible from tab pages at the top of the screen (figure 5.4). They have different parts to group the parameters. Groups of parameters are listed in below with a short description about each one:

- Supply constants: main supply parameters in base/new scenario like frequency of services, top speed, etc
- Line characteristics: distribution of different components like tunnels, bridge, and etc. on a high-speed line
- Train data: type of train is used in the base/new scenario for analysis
- Speed independent costs: other costs that are not dependent on speed

5.4.2 Common setting

There are many settings that are common for both base and new scenario (Appendix A). There are also constants that are connected to structure of analysis. For example, discount rate is one constant which is used in all calculations when NPV analysis is being done. Analysis period, tax factors, monetary values for time are examples of these constants. User will access these constants from “Setting” tab pages. It has several parts which are located at left hand side (figure 5.4):

- CBA constants: contains general constants for cost-benefit analysis. e.g. discount rate
- Demand constants: contains general constants connected to calculation of demand
- Calculation range: constants in this part indicate how the OHSL should do the calculation. This part is mainly use in sensitivity analysis
- Distance(km): distance of OD-pairs
- Total journeys(passenger per year): total number of passengers in base year(2010) between OD-pairs
- Train market share(%): journeys by train market share between OD-pairs
5.5 Different outputs of the OHSL

OHSL is able to show output in different formats for different situations:

- Plain Simple Text
- Table format
- Graph

Depending on the type of the data, one of the above formats is selected to show the output data to the users. The ultimate goals of these formats are to produce comprehensible output in a way that is easily understandable by the user.

Plain Text Format:

This type of presentation is usually relevant in situation where a part of analysis is done. For example, when only operating costs is calculated in a single year, the result is shown in plain text with enough details. This type of presentation is mainly useful when user wants to look at a single part of model specifically and observes the detail data about that part. In the time of validation and testing the model, this type of presentation was mostly used to validate the data which was shown in graphs. Since graphs contain summarized data and do not show the detail, plain texts can present detail well (figure 5.6).
Figure 5.6 - Plain text format gives enough detailed information about the result and steps of the calculation

-Table format

This type of presentation even gives information that is more detailed than the plain text format. Sometimes it is needed to show the different components that have influence on the calculation. Table format is used to give enough detailed information to the user if the user likes to investigate into more detail (figure 5.7).

Figure 5.7 - Table format gives enough detailed information about the components which are used in calculation

There are also other results presented in table format. Examples are OD-pairs of market share change, Total journeys by train. Looking at these results user can observe how the model
works in detail and does the calculations. Users who like to use these types of data should be familiar with structure and different components of the model (chapter 2,4).

**-Graphs**

Using graphs in the OHSL is very helpful to summarize lots of data in a simple way that user can perceive the meaning instantly.

For example, in order to show the cost-benefit analyses, there are many parameters constitute the analysis such as construction costs, operating costs, revenue, socio economic value. By using a graph, it is possible to show all of these values to the user in a single graph.

![Sample graph output which summarizes data](image)

*Figure 5.8 - Sample graph output which summarizes data*
5.4 Interactive model

One of the primary reasons behind the existence of the OHSL was to make the computational model in this work interactive. It was discussed in the beginning of this chapter that although it is possible to run this model manually or in Excel, it is very time consuming and not responsive to changes.

After implementation of the OHSL, user has the ability to define his own scenario and put it as an input to the model. It means that the OHSL accepts different scenarios and it is not dependent on the type of input data. For example, it can be used to calculate the speed for any high-speed line in Sweden. Of course, it might not be applicable to project from other countries because it depends on the context of the project too. It is not limited to specific line or cities. Any scenario can be defined and is put into the model. It is believed that this feature makes the model as interactive as possible to be used for different scenarios. It may help to increase the number of users as well as feedbacks which has a great influence on validation and evaluation process too. More users and different feedbacks reveal the model deficiency, fault and correctness. In long time, this process makes the model reliable.

Another important factor in the OHSL is instant response to the user change in parameters. It makes the model more interesting when the user observes the result instantly in several second and sees what happens when he or she plays with different parameters. It may help user get good intuition of how model works in different situations.

Since OHSL is accessible via the web and also it is possible to put different parameters into the model, it is possible that various experts work with model according to their preferences.
6 Data Analysis and Evaluation

In this chapter, different types of data analysis are discussed. Running the computational model, different data outputs were generated and here it is attempted to explain and explore how this data can be used to obtain desired analysis and result, i.e. the concept of data, their relation and how they are interpreted relating to input parameters.

Although it was possible to generate different output values by using the computational model in this work, the focus was only on limited number of these outputs and their interpretation. Before discussing the different important outputs of the model, there is a rule in running the model. This rule indicates that most parts of the calculation are marginal calculation. It means that the obtained result is mainly the marginal cost-benefit comparing with another problem or scenario. Following section discusses this rule in more detail.

Accuracy of data and correctness of the calculation is not center of focus in this chapter and it is discussed in next chapter. It is attempted to discuss how it is possible to interpret the outputs and how it is possible to infer from different outputs.

6.1 Base scenario, new scenario

As the subject of this thesis work depicts, the focus of the computational model is mainly on the speed dependent variables. It means that only speed dependent variables and their influence on a high-speed line project are considered (detail discussion in chapter 2.4). However, there are many other influencers that change the costs and benefits of a high-speed line project. Such parameters are costs of staff, energy, administration, externalities (such as influence on pollution, noise, etc). Including these parameters in computational model made it more complicated while it did not match with the ultimate goal of this work.

To be able to diminish the model complexity and also neutralize the impact of speed-independent variables, there is always a comparison between a new scenario and an existing scenario. It makes it possible to do marginal calculation based on new and base scenario. By marginal calculation, it is possible to remove the influence of the parameters that are not in matter of interest. In addition, marginal calculation indicates how a new scenario can make improvement to an existing scenario and how it is done. Users of the model can utilize this feature and adjust parameters in different ways. It generates different results so users can observe how different sets of parameters can improve an existing line.
An example: Suppose there is regular train service (line) between destination A and B. Since this line is in operation and data exist about that, it is possible to define a base scenario based on the existing data. New scenario is a desired new train service which assumed to improve the base scenario. User inputs different parameters and observes how base scenario improves in terms of marginal calculation. For example, how many percentages the benefits increase or decrease, how revenue changes in new scenario, and how it is possible to change the socio-economic value in new scenario. Therefore, concentration is only on the parameters that users are interested in when using the model. Of course, it was possible to build another model which manipulates more complete set of parameters (speed-dependent and speed-independent); however, it was not in the scope of this thesis work.

6.2 Different types of analysis

Users who use the computational model usually are interested in two types of analysis:

- Single year analysis
- Periodic analysis

It really depends on the user’s expectation from model that he or she chooses one of the types of analysis. In single year analysis, the matter of interest is on a single year in the future to observe the situation of a new high-speed line project. In single year analysis, all the output values of the model are associated with a specific year in the future. Therefore, user can observe all output parameters in the future. User usually uses single year analysis when there is a need to analyze a single year in more detail. Suppose user has looked at graphs of revenues in different years and wants to explore the detail in a single year. Single year analysis of revenue gives more information about number of passengers on that year, train market share on that year and also different values that affect the revenue.
While in single year analysis, only a single year is studied, it may not be very helpful to look at long term effect of new HSL project. These types of projects are calculated for long time more than 40 years in CBA. It will be very valuable if user can look at the values of the whole period. Periodic analysis covers that issue and presents accumulated output values to the user for different years in a long period. Decision makers decide based on the long term effects of a project. For example, accumulated values for revenue in 40 years are more important for users rather than value for revenue for a single year. Periodic analysis is used to study the variation of different important parameters in the model to observe the fluctuation in the output values. In the sensitivity analysis (chapter 6.4), it is discussed in more detail about the usage of periodic analysis in this matter.

### 6.3 Important output

There are limited number of output parameters in this model that user needs to study the new project in the future. Although there are many other parameters constitute the output values but here, the focus was on a few numbers of them. Since decision makers and planners usually use this model, it is not a good idea to provide them with a lot of different outputs. They are interested in summary of data to study the whole project in terms of a few output values. It is also possible to use the model to look deeper in other output values. Important output values which are analyzed in this chapter are as following. All of these concepts were discussed in more detail in chapter 2 and 4.

- Construction costs
- Operating costs
- Revenues
- Benefits
- Cost-benefit
- NPV

**Construction costs:**

There are different components in calculation of construction costs of an HSL project (shown in chapter 2). This value represents the summation of all those components together and gives the user the marginal construction costs of a new HSL project, i.e. how much it is more expensive to build a new HSL instead of the existing line.
**Operating costs (Train services)**

As discussed previously, running trains and providing service is costly and depends on other supply factors. This value represents the cost of an HSL service regarding all minor costs discussed in chapter 2 and 4.

**Revenues**

Revenue at here means the amount of money is earned by selling tickets and strongly depends on the number of passengers and average fare for the service. It does not contain other values that are created by services. Socio-economic values are such values.

**Benefits**

Benefits in this work mean the total benefits that a project produces. It includes both profit from fare and socio-economic values called travelling time gain. Travelling time gain means the time which is being saved when passengers are using a service with a higher speed.

**Cost-Benefit**

Cost-benefit values are discounted values of summation of all costs and benefits. Discounted values are calculated based on the discount rate which is 4% in this work.

**6.4 sensitivity analysis**

It was discussed in 6.3 that there are a few output values that are matter of interest for the users of a computational model. There are also limited numbers of important parameters that users need to observe their effect on the output values. These input parameters are supply factors which are important in analysis of an HSL project.

- Speed
- Frequency of services
- Fare

These supply factors have great influence on the output values in section 6.3. The way that they affect the output values was discussed in chapter 2 and 4. For example, a higher speed means a more expensive infrastructure costs, moreover, running trains are more costly, but in other side, more passengers are attracted to the service which produces more benefits.

Variations in Frequency of services and also fare level have similar impact on output values. Study of fluctuation of output values when input supply factors changes leads to a better understanding of how an HSL project should be built, based on supply factors.
In the following sections, sensitivity analysis is done on a new double track line with the length of 600 km between Stockholm-Malmö. There are many other constants and parameters that the result is dependent on them too. The complete set of input data of this scenario is available on the appendix A to E. The goal of following section is to show how it is possible to interpret data and to do study by means of sensitivity analysis.

6.4.1 Speed

Sensitivity analysis of speed over the period of HSL project construction (figure 6.2) shows that there are almost steady increases in all output values. The increase in some output values is sharper than others. All curves except benefits have almost same steepness because higher speed input value affects all output values. Benefits curve shows a sharper increase for higher speed due to generated socio-economic values and also increasing number of passengers. Benefits include the travelling time gain values. Omitting the travelling time gain values, remains only revenue which shows that there are slight changes in revenue when speed changes.

![Figure 6.2 - Output values for different speeds](image)

Figure 6.2 also depicts that there is also more slightly change in operating costs when speed increases. It seems that the increase in speed mostly changes the construction costs and benefits and the influence on other output values are not as high as these two values.
6.4.2 Frequency of services

Higher frequency means more trains running between OD-pairs and leads to shorter waiting time for the passengers. More passengers are attracted by the service and it means more benefits; however, running more trains means higher operating costs too. In figure 6.3 there is sensitivity analysis of frequency of services between 5 to 30 trains per day and it shows that when frequency goes up the benefits and revenues go up sharply too. For lower level of frequency variation (for example between 5-15), the effect is stronger when the frequency increases; however, it seems that this effect is dampened when frequency level increases.

Figure 6.3 - Output values for different frequency of services

Although there is a sharp rise in both benefits and revenues when frequency increases, there is slight increase in operating costs. It means that the increase in operating costs are not as much as benefits and perhaps it is a good idea to run more trains according to figure 6.3.3

6.4.3 Fare

Cheaper train service attracts more passengers to the service. Looking at figure 6.4, an increase in fare level has an interesting influence on benefits and operating costs. It is

---

3 It is supposed that trains are flexible and there are not so many seats left empty in the trains.
apparent that fare level does not have any influence on construction costs and it is only connected to demand. Starting from 0.4 SEK/passenger*km shows that revenue and benefits both increase very sharply but after 1.4 SEK/passenger*km it continues going down even more sharply. It is mostly because of the reduction in number of passengers because of the higher price for fare.

Graph also shows that operating costs have a steady decrease as the price for fare rises. In the computational model of this work, the operating costs are highly dependent on number of passengers so when fare increases number of passengers decreases. It leads to a lower cost in operating costs.

![Figure 6.4 - Output values for different fares](image)

6.5 CBA and NPV

To analyze all costs and benefits values of an HSL project, NPV analysis is done. Present values are calculated for different years and NPV is calculated for the whole project. Higher NPV means valuable investment on a project.
<table>
<thead>
<tr>
<th>Year</th>
<th>Construction Costs</th>
<th>Operating Costs</th>
<th>Revenues</th>
<th>Benefits</th>
<th>Cost-Benefit</th>
<th>Discount Factor</th>
<th>Present Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>-6 870</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-6 870</td>
<td>1</td>
<td>-6 870</td>
</tr>
<tr>
<td>2011</td>
<td>-6 870</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-6 870</td>
<td>0.9615</td>
<td>-6 605</td>
</tr>
<tr>
<td>2012</td>
<td>-6 870</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-6 870</td>
<td>0.9246</td>
<td>-6 351</td>
</tr>
<tr>
<td>2013</td>
<td>-6 870</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-6 870</td>
<td>0.889</td>
<td>-6 107</td>
</tr>
<tr>
<td>2014</td>
<td>-6 870</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-6 870</td>
<td>0.8548</td>
<td>-5 872</td>
</tr>
<tr>
<td>2015</td>
<td>0</td>
<td>-93</td>
<td>804</td>
<td>1 170</td>
<td>1 077</td>
<td>0.8219</td>
<td>886</td>
</tr>
<tr>
<td>2016</td>
<td>0</td>
<td>-94</td>
<td>814</td>
<td>1 185</td>
<td>1 091</td>
<td>0.7903</td>
<td>863</td>
</tr>
<tr>
<td>2017</td>
<td>0</td>
<td>-95</td>
<td>825</td>
<td>1 201</td>
<td>1 106</td>
<td>0.7599</td>
<td>840</td>
</tr>
<tr>
<td>2018</td>
<td>0</td>
<td>-96</td>
<td>835</td>
<td>1 216</td>
<td>1 120</td>
<td>0.7307</td>
<td>818</td>
</tr>
<tr>
<td>2019</td>
<td>0</td>
<td>-97</td>
<td>846</td>
<td>1 232</td>
<td>1 135</td>
<td>0.7026</td>
<td>797</td>
</tr>
<tr>
<td>2020</td>
<td>0</td>
<td>-99</td>
<td>857</td>
<td>1 248</td>
<td>1 149</td>
<td>0.6756</td>
<td>776</td>
</tr>
<tr>
<td>2021</td>
<td>0</td>
<td>-100</td>
<td>868</td>
<td>1 264</td>
<td>1 164</td>
<td>0.6496</td>
<td>756</td>
</tr>
<tr>
<td>2022</td>
<td>0</td>
<td>-101</td>
<td>880</td>
<td>1 281</td>
<td>1 179</td>
<td>0.6246</td>
<td>737</td>
</tr>
<tr>
<td>2023</td>
<td>0</td>
<td>-103</td>
<td>891</td>
<td>1 297</td>
<td>1 195</td>
<td>0.6006</td>
<td>718</td>
</tr>
<tr>
<td>2024</td>
<td>0</td>
<td>-104</td>
<td>903</td>
<td>1 314</td>
<td>1 210</td>
<td>0.5775</td>
<td>699</td>
</tr>
<tr>
<td>2025</td>
<td>0</td>
<td>-105</td>
<td>914</td>
<td>1 331</td>
<td>1 226</td>
<td>0.5553</td>
<td>681</td>
</tr>
<tr>
<td>2026</td>
<td>0</td>
<td>-107</td>
<td>926</td>
<td>1 349</td>
<td>1 242</td>
<td>0.5339</td>
<td>663</td>
</tr>
<tr>
<td>2027</td>
<td>0</td>
<td>-108</td>
<td>938</td>
<td>1 366</td>
<td>1 258</td>
<td>0.5134</td>
<td>646</td>
</tr>
<tr>
<td>2028</td>
<td>0</td>
<td>-109</td>
<td>951</td>
<td>1 384</td>
<td>1 274</td>
<td>0.4936</td>
<td>629</td>
</tr>
<tr>
<td>2029</td>
<td>0</td>
<td>-111</td>
<td>963</td>
<td>1 402</td>
<td>1 291</td>
<td>0.4746</td>
<td>613</td>
</tr>
<tr>
<td>2030</td>
<td>0</td>
<td>-112</td>
<td>975</td>
<td>1 420</td>
<td>1 308</td>
<td>0.4564</td>
<td>597</td>
</tr>
<tr>
<td>2031</td>
<td>0</td>
<td>-113</td>
<td>979</td>
<td>1 426</td>
<td>1 313</td>
<td>0.4388</td>
<td>576</td>
</tr>
<tr>
<td>2032</td>
<td>0</td>
<td>-113</td>
<td>983</td>
<td>1 431</td>
<td>1 318</td>
<td>0.422</td>
<td>556</td>
</tr>
<tr>
<td>2033</td>
<td>0</td>
<td>-114</td>
<td>987</td>
<td>1 437</td>
<td>1 323</td>
<td>0.4057</td>
<td>537</td>
</tr>
<tr>
<td>2034</td>
<td>0</td>
<td>-114</td>
<td>991</td>
<td>1 442</td>
<td>1 328</td>
<td>0.3901</td>
<td>518</td>
</tr>
<tr>
<td>2035</td>
<td>0</td>
<td>-115</td>
<td>994</td>
<td>1 448</td>
<td>1 333</td>
<td>0.3751</td>
<td>500</td>
</tr>
<tr>
<td>2036</td>
<td>0</td>
<td>-115</td>
<td>998</td>
<td>1 453</td>
<td>1 338</td>
<td>0.3607</td>
<td>483</td>
</tr>
<tr>
<td>2037</td>
<td>0</td>
<td>-115</td>
<td>1 002</td>
<td>1 459</td>
<td>1 344</td>
<td>0.3468</td>
<td>466</td>
</tr>
<tr>
<td>2038</td>
<td>0</td>
<td>-116</td>
<td>1 006</td>
<td>1 465</td>
<td>1 349</td>
<td>0.3335</td>
<td>450</td>
</tr>
<tr>
<td>2039</td>
<td>0</td>
<td>-116</td>
<td>1 010</td>
<td>1 470</td>
<td>1 354</td>
<td>0.3207</td>
<td>434</td>
</tr>
<tr>
<td>2040</td>
<td>0</td>
<td>-117</td>
<td>1 014</td>
<td>1 476</td>
<td>1 359</td>
<td>0.3083</td>
<td>419</td>
</tr>
</tbody>
</table>

**Table 6.1 - cost-benefit values for different years**

Table 6.1 shows the different output values (construction costs, benefits, and etc.) and cash flow values. It also shows the discount factor for different years and present value for different years. First 5 rows show the period of construction which there is no profit from the project. After 5 years, train service start serving passengers and it produces the benefits as shown. For example in 2038 the benefit-cost, which is not discounted, is 1349 MSEK while the present value at 2038 is 450. It means that 450 MSEK today is equivalent to 1349 MSEK.
in 2038 and this approach of study the cost-benefit is important to be considered when the project is studied in long term.

6.7 Best speed by NPV

Following graph shows NPV calculation for different speeds. In fact, this graph is a summary of all the output values and it is the final graph which may be considered by the user to make the decision. As it is shown in figure 6.5, speed of 400 km/h has better NPV value than other speeds. After speed of 400 km/h in the graph, there is a steep decline in the cost-benefit curve, which is mostly because of the considerable increase in construction cost for higher speed than 400km/h. It means that higher than 400 km/h is not a good investment based on the analysis was done by this computational model and OHSL.

![figure 6.5 - NPV and cost-benefit for different speed](frequency and fare are constant)
7 Validation

In this chapter, important components of the computational model are highlighted and their effects on the accuracy of the model discussed. Methodology used to validate model is based on general validation methods explained in (Lundqvist & Mattsson, 2001). There is also a discussion about the validity of input data and source of data in this chapter. Accuracy of input data has great influence on the final result of the computational model. Discussion about the result is done to give an intuition of how model works based on input data. Alternative way of validation of the model is also discussed in the context of this thesis work. Finally, some future works are suggested that can be complementary to this thesis and future works.

7.1 Important components and source of input data

In order to validate the obtained result from the model, the model is broken down into smaller sections which have great influence on the whole calculation of the computational model and the accuracy of the final output. According to the method used in “Economic analysis of high speed rail in Europe” (Barron, Campos, & al., 2009) following component are discussed.

- Infrastructure costs
- Supply and demand
- Maintenance costs (Rolling stock costs)

De Rus also discusses the originality and reliability of data in the similar project in Spain (De Rus & Inglada, Cost-benefit analysis of the high-speed train in Spain, 1997) to do the validation on each component and their effect on the final result.

7.1.1 Infrastructure Costs

Infrastructure costs consist of different components like tracks, tunnels, bridges, etc. In this work, data about infrastructure costs in Sweden were partly gathered from Trafikverket based on the current infrastructure costs in year 2010. Infrastructure costs are for the line with top speed of 250 km/h or lower in Sweden and it highly depends on the geographical condition and topographic situation of Sweden. It might not be applicable to other countries before an extensive analysis of the location and environment. Data for higher speed than 250 km/h, from UIC Infrastructure Commission – Civil engineering support group – was acquired. Since this data was not for Sweden, author’s estimation and also supervisor’s estimation to this thesis work (Oskar Fröidh) are used based on comparing different speeds on other countries and how cost changes for different speeds. It might affect the accuracy of the input data and as a result the final output; However, gathered data is based on real data and the calculation is based on percentage of the variation of the cost when speed changes. Marginal calculation also helps to balance many unknown and omitted data. To get a more accurate result in this
section it is needed to do a very extensive planning and analysis of the location where the data belongs to and then adapt the data to the situations in Sweden.

There are other characteristics of the HSL which are important here. One of them is total line length which has direct influence on the infrastructure costs and the demand for long distances. Distribution of different components on a line is matter of importance too because it demands higher cost if for example there are more tunnels on a line. These input variables are set by empirical study and planned high-speed line sections in Sweden, i.e. the Eastern Link Södertälje-Linköping, and Borås-Göteborg. In this work, initial data gained from expert users in this domain.

Maintenance of the infrastructure is here estimated to be constant for different speed standards (range 250-500 km/h). This simplification is motivated by high construction costs for higher dimensional speed, with the aim to keep maintenance costs low. For example, the share of ballastless track is increasing by increasing dimensional speed, and ballastless track have lower maintenance costs than the ballasted track.

### 7.1.2 Supply and Demand

Supply and demand are next components that play major roles in cost-benefit analysis of an HSL (Barron, Campos, & al., 2009). Accuracy of this component strongly depends on initial input data and prediction of future data based on different supply factors. Demand has a direct impact on the operating costs and benefits of the HSL because the benefits in this computational model calculated mostly from number of passengers and operating costs also connected to the number of passengers who are going to be served by HSL (chapter 4).

Demand data is based on the real data for the line Stockholm-Malmö in Sweden journeys between A-regions in 2005. This line consists of 11 stations and distances between stations are fed to computational model. Further analysis is relied on this existing data; however, it is possible to feed the model on any other desired line. Total number of journeys and market share are also based on the current data in Sweden in 2005 and other supply factors like operating speed (commercial speed) and frequency of services are also based on realistic conditions. To study the fluctuation in demand when supply factors change, elasticity of demand factors are used in this work. These factors are obtained from another study on the Gröna tåget project (Fröidh, Resande och trafik med Gröna tåget, 2010). The project is also discussed in context of Sweden and high-speed line in Sweden and the reliability is discussed on that project.

### 7.1.3 Maintenance costs of HSL (Rolling stock costs)

To avoid complexity in this thesis work the model for calculating the operating costs was extracted partly from Gröna tåget (Fröidh, Resande och trafik med Gröna tåget, 2010) and applied to this work. Operating cost model in Gröna Tåget research program has different parts; however, only those parts that were needed for this thesis work were used. This model works based on different train types with various capacities. Output of this operating cost
model is the cost value by \((\text{passenger} \times \text{km})\) which is directly used in the computational model in this work.

### 7.2 Dynamic model – Calibration

One of the main features of the computational model in this thesis work is to being dynamic. It means that there are parts of the model that expert users can build when interact with the model. There are many constants and initial input data that users need to enter to get the output. This can be changed each time a result is gained in order to improve the result. It makes the model more responsive to users and the model is able to generate more accurate output based on users’ initial values. Therefore, the validity and accuracy of data could depend on the experience of the users too. It is a positive feature if the user wants a flexible model to change it to the situation of the project he is working on. It may also be a negative point because many users may not like to adjust different settings to get a reliable result and they need a pre-defined model with fixed parameters. In this thesis work, it is supposed that flexibility is a positive point because the nature of the HSL project is complicated and very different from one situation to another situation. Therefore, it needs to be adjusted for different projects separately to generate the reliable and accurate result.

Another benefit that flexibility of model produces is to reveal the model problems. Users interact with the model and observe what happens when they manipulate different input parameters. This instant response from model along with user interactivity with the model leads to better understanding of model; therefore, users are able to give better feedback about the model performance and functionality.

### 7.3 Validation by expert

First of all, this thesis work was divided into several parts and then each part was discussed and reviewed with experts during numerous meetings. It had a great effect on quality of the model. This way revealed many problems from the first step and caused the model to be built more accurately. Most parts of the work of this thesis are based on continuous feedback on the work from experts. Expert people also tested final model with different input data and there were many valuable feedbacks that made the model even more accurate. The only drawbacks of this method might be the limited number of experts. The environment and the situation that experts are working might affect the model.

In the following, several important changes are discussed which experts suggested to apply to final model.
Length of the line:

Total length of the line was limited from 200-2000 km. For shorter length of 200 km, car competition is more sever and the model is getting more complicated and difficult to build. Above 2000 km, air transport mode seems to be the alternative mode and high-speed line is hardly an alternative in competition even for higher speed as 500 km/h

Range of the speed

According to the definition of (International Union of Railways) the high-speed trains considered in this work are the trains with the speed of 250 km/h or more. Lower speed is not the matter of interest in this computational model because they are not interesting for future.

Upper limit for Market share

In order to make the model more accurately responsive to the change, the elasticity model for market share should be limited in comparison to other modes of transport. By increasing the travelling time, competition from airlines considerably increases and train market should be limited by travelling time. Elasticity model does not consider other modes of transport and, therefore; following formula is used from (Lundberg, 2011) to limit the market share for train mode:

\[ y = \exp(1.5076 - 0.2921x) \]

where \( x \) is travelling time and \( y \) is the market share by train.

It still simplifies the model since it does not consider the effect of car transport mode which the competition increases in shorter travelling time and distance.

Fare elasticity factor

To make the fare elasticity of demand closer to reality, the fare elasticity model was improved by implementing a linear function based on two default fare levels: 1 SEK/passenger*km with the elasticity factor of -0.8, and 2 SEK/passenger*km with the elasticity of -1.5; For other fare levels, interpolation and extrapolation were done based on a linear function. Since the fare level was broken down in two main levels then the effect of fare level is studied in more detail and led to more accurate result in the model.

According to evidence in worldwide, there are different top speed services that are referred to. RENFE Spanish railways expects top speed of 350 km for Madrid-Barcelona to play a more important role compared with other competitors in the future. TGV in France has also recorded top speed about 500 km however, the operating speed is about 300 km/h. In china, CRH380A train hit a maximum speed of 416.6. Analysis in OHSL and the result from the computational model in this thesis works also shows that top speed about 400 km/h could lead to optimal cost-benefit.
7.5 Alternative way of validation

There were also alternative ways of validation of the output result. The first method was to choose an existing high-speed line project. Getting the data of such a project, it would be possible to feed the model on this data and see the result of the model. Since the project would be real and working, comparing between the gained data from model and real data from the project would reveal a deficiency of the model. This method works well if there is an existing project and data is available. At the time of writing of this report, there was no existing operating high-speed line project in Sweden. Using data from other countries needed an extensive analysis of the location and environment of the project which was out of the scope of this work but could be a future work.

Another way is to feed the model using automatic extensive arbitrary data entry. In this way the model generates different outputs and it is possible to analyze the output values and their relation to the input data. This may help to improve the model.
8 Concluding remarks and future work

In this chapter, the work done in this thesis is summarized and described. Relevant future work is also suggested.

8.1 Concluding Remark

In this thesis work, it was attempted to calculate the cost-benefit of an HSL project in Sweden with the respect to profitability. Only new dedicated lines were considered and there were some simplifications in order to make the model understandable and easy to follow. Simplification was mostly done on the parts that do not have a great influence on the final result. Three main parameters (supply factor) were considered in the calculation; travelling time, frequency, and fare. The focus of this work was mostly on the optimal speed of the line because speed has a direct impact on the travelling time, construction cost and operation cost. A higher speed means that more expensive infrastructure and components must be built. It also means a shorter travelling time that attracts more passengers from other modes of transport (demand), and it generates higher revenue and benefit including socio-economic values. Demand also changes the operation cost in the model. Therefore, finding an optimal speed was the ultimate goal of this thesis work. An elasticity model was chosen as a prediction algorithm to calculate future values. Other algorithms like the logit model needs more accurate data of other modes of transport but the focus of this work was on the train mode.

A scenario was chosen to examine the model. A line from Stockholm to Malmö with a double track and with a length of 600 km was the chosen scenario. Some data was available from existing projects and lines, and the data which could not be gained elsewhere was estimated by experts. The model suggested a top speed of 400 km/h as the optimal speed for this scenario. When compared with other countries like Spain and China, it showed that the model worked close to the top speed in those countries.

There were two valuable experiences won in developing the model. Working with experts in the domain of transportation helped a lot to develop the model in the right direction. It also allowed the model to be built based on the opinion of the experts in the field. However, in some cases it might be too restricted to the environmental situation of a few experts. The development of the OHSL tool beside the model development helped the model construction process. Users could work with the model easily and test it. Using the OHSL tool provided a flexible access to the model while the encapsulation of the model’s complexity caused that users to focus on the setting adjustment and final result of the model.
8.2 Future Work

One of the efforts of the author was to prevent this thesis work to become very complicated. Therefore, there were some simplifications during the construction of the model which might be interesting for future work. In the following, there are some suggestions about future work on the computational model.

In this work, the commercial (operating) speed was calculated as a linear function of top (maximum) speed of a high-speed line. In reality, the commercial speed depends on other factors like line topography, speed restrictions, train acceleration and deceleration, the number of stops, and dwell time at stations. It makes the model more correct if the commercial speed is calculated more accurately because the commercial speed directly affects the travelling time and demand.

There is no thorough analysis of other modes of transport when there is a competition between an HSL and those modes. Of course, there are some considerations in the computational model, but it is not complete due to simplification in the model. It is worth to complete the model by adding the feature of analyzing of other modes of transport.

The computational model in this work is only valid for the lines that run trains from the first station (A) to the last station (B). Mixed model services and non-stop services are not covered. To improve the model to work with more complicated situations, these items are important and should be implemented in the model.
References


Barron, I., Campos, J., & al., e. (2009). Economic analysis of high speed rail in Eroupe. FBBVA.


Department of Transportation, Federal Railroad Administration. (September 1997). High-Speed Ground Transportation for America.


## Appendix A – OHSL default setting

### CBA Constants

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discount rate %</td>
<td>4%</td>
</tr>
<tr>
<td>Analysis Period (Year)</td>
<td>60</td>
</tr>
<tr>
<td>Analysis Base Year (Year)</td>
<td>2010</td>
</tr>
<tr>
<td>Construction Period (Year)</td>
<td>5</td>
</tr>
<tr>
<td>Tax Factor 1</td>
<td>1.21</td>
</tr>
<tr>
<td>Tax Factor 2</td>
<td>1</td>
</tr>
<tr>
<td>Analysis For Single Year (Year)</td>
<td>2030</td>
</tr>
</tbody>
</table>

### Demand Constants

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elasticity- Travelling Time (31-120 minutes)</td>
<td>-0.9</td>
</tr>
<tr>
<td>Elasticity- Travelling Time (121-240 minutes)</td>
<td>-1.5</td>
</tr>
<tr>
<td>Elasticity- Travelling Time (241-360 minutes)</td>
<td>-0.9</td>
</tr>
<tr>
<td>Elasticity- Travelling Time (&gt;361 minutes)</td>
<td>-0.6</td>
</tr>
<tr>
<td>Elasticity- Frequency (1-10%)</td>
<td>-0.3</td>
</tr>
<tr>
<td>Elasticity- Frequency (11-30%)</td>
<td>-0.4</td>
</tr>
<tr>
<td>Elasticity- Frequency (31-100%)</td>
<td>-0.5</td>
</tr>
<tr>
<td>Elasticity- Fare = 1 SEK</td>
<td>-0.8</td>
</tr>
<tr>
<td>Elasticity- Fare = 2 SEK</td>
<td>-1.5</td>
</tr>
<tr>
<td>Estimated increase of domestic journeys per year (1st Period)</td>
<td>1.3%</td>
</tr>
<tr>
<td>Estimated increase of domestic journeys per year (2nd Period)</td>
<td>0.5%</td>
</tr>
<tr>
<td>Start Year of Second Period</td>
<td>2030</td>
</tr>
<tr>
<td>Service day (in Operation per 24h) (minutes)</td>
<td>960</td>
</tr>
<tr>
<td>Monetary Time Value (SEK/h), Business journeys</td>
<td>275</td>
</tr>
<tr>
<td>Monetary Time Value (SEK/h), Leisure journeys</td>
<td>100</td>
</tr>
<tr>
<td>Business Trip Share (%)</td>
<td>33</td>
</tr>
</tbody>
</table>
Calculation Range

<table>
<thead>
<tr>
<th>Calculation Range</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (departures in one direction per day) from</td>
<td>0</td>
</tr>
<tr>
<td>Frequency (departures in one direction per day) to</td>
<td>30</td>
</tr>
<tr>
<td>Frequency increment</td>
<td>5</td>
</tr>
<tr>
<td>Fare (average revenues) from</td>
<td>0.4</td>
</tr>
<tr>
<td>Fare (average revenues) to</td>
<td>3</td>
</tr>
<tr>
<td>Fare increment</td>
<td>0.2</td>
</tr>
<tr>
<td>Dimensional speed from</td>
<td>250</td>
</tr>
<tr>
<td>Dimensional speed to</td>
<td>500</td>
</tr>
<tr>
<td>Dimensional speed increment</td>
<td>25</td>
</tr>
<tr>
<td>A-regions</td>
<td>Cst/Söd</td>
</tr>
<tr>
<td>------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>Stockholm/Södertälje</td>
<td></td>
</tr>
<tr>
<td>Nyköping</td>
<td></td>
</tr>
<tr>
<td>Norrköping</td>
<td></td>
</tr>
<tr>
<td>Linköping</td>
<td></td>
</tr>
<tr>
<td>Mjölby/Motala</td>
<td></td>
</tr>
<tr>
<td>Jönköping</td>
<td></td>
</tr>
<tr>
<td>Nässjö/Eksjö/Vetianda</td>
<td></td>
</tr>
<tr>
<td>Växjö</td>
<td></td>
</tr>
<tr>
<td>Kristianstad</td>
<td></td>
</tr>
<tr>
<td>Hässleholm</td>
<td></td>
</tr>
<tr>
<td>Helsingborg/Landskron</td>
<td></td>
</tr>
<tr>
<td>Malmö/Lund/Trelleborg</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Region</th>
<th>Cst/Säd</th>
<th>Nk</th>
<th>Lp</th>
<th>My/Mot</th>
<th>Jö</th>
<th>NE/Kva</th>
<th>Vö</th>
<th>Cr</th>
<th>Hb/Lk</th>
<th>MLu/Tg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stockholm/Södertälje</td>
<td>11%</td>
<td>24%</td>
<td>36%</td>
<td>7%</td>
<td>6%</td>
<td>8%</td>
<td>3%</td>
<td>8%</td>
<td>3%</td>
<td>0%</td>
</tr>
<tr>
<td>Nyköping</td>
<td>22%</td>
<td>13%</td>
<td>20%</td>
<td>17%</td>
<td>8%</td>
<td>8%</td>
<td>0%</td>
<td>8%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Norrköping</td>
<td>34%</td>
<td>14%</td>
<td>19%</td>
<td>24%</td>
<td>3%</td>
<td>11%</td>
<td>3%</td>
<td>11%</td>
<td>3%</td>
<td>0%</td>
</tr>
<tr>
<td>Linköping</td>
<td>29%</td>
<td>14%</td>
<td>14%</td>
<td>17%</td>
<td>20%</td>
<td>3%</td>
<td>3%</td>
<td>8%</td>
<td>3%</td>
<td>0%</td>
</tr>
<tr>
<td>Mjölby/Motala</td>
<td>30%</td>
<td>13%</td>
<td>14%</td>
<td>17%</td>
<td>8%</td>
<td>8%</td>
<td>0%</td>
<td>8%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Jonköping</td>
<td>47%</td>
<td>33%</td>
<td>34%</td>
<td>25%</td>
<td>20%</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
<td>0%</td>
</tr>
<tr>
<td>Näsjö/Eksgård/Vetlanda</td>
<td>35%</td>
<td>20%</td>
<td>20%</td>
<td>24%</td>
<td>20%</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
<td>0%</td>
</tr>
<tr>
<td>Växjö</td>
<td>39%</td>
<td>20%</td>
<td>20%</td>
<td>24%</td>
<td>20%</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
<td>0%</td>
</tr>
<tr>
<td>Kristianstad</td>
<td>35%</td>
<td>20%</td>
<td>20%</td>
<td>24%</td>
<td>20%</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
<td>0%</td>
</tr>
<tr>
<td>Hässelholm</td>
<td>35%</td>
<td>20%</td>
<td>20%</td>
<td>24%</td>
<td>20%</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
<td>0%</td>
</tr>
<tr>
<td>Helsingborg/Landskrona</td>
<td>35%</td>
<td>20%</td>
<td>20%</td>
<td>24%</td>
<td>20%</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
<td>0%</td>
</tr>
<tr>
<td>Malmö/Lund/Trelleborg</td>
<td>35%</td>
<td>20%</td>
<td>20%</td>
<td>24%</td>
<td>20%</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
<td>0%</td>
</tr>
</tbody>
</table>
Appendix B – OHSL base scenario settings

Supply constants

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>HST dimensional speed (km/h)</td>
<td>200</td>
</tr>
<tr>
<td>HST commercial speed factor (km/h)</td>
<td>0.7</td>
</tr>
<tr>
<td>Frequency (departures in one direction per day)</td>
<td>12</td>
</tr>
<tr>
<td>Fare (average revenues) (SEK/Km)</td>
<td>1</td>
</tr>
</tbody>
</table>

Line Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of the line</td>
<td>Double Track</td>
</tr>
<tr>
<td>Total Length of Line (200-2000 km)</td>
<td>600</td>
</tr>
<tr>
<td>Number of Stations</td>
<td>12</td>
</tr>
<tr>
<td>Concrete Tunnels (%)</td>
<td>2</td>
</tr>
<tr>
<td>Rock Tunnels (%)</td>
<td>5</td>
</tr>
<tr>
<td>Bridge (%)</td>
<td>3</td>
</tr>
<tr>
<td>Cutting (%)</td>
<td>45</td>
</tr>
<tr>
<td>Embankments (%)</td>
<td>45</td>
</tr>
</tbody>
</table>

Train Data – Operating Costs (SEK/train-km)

<table>
<thead>
<tr>
<th>Train Type</th>
<th>Cost (SEK/train-km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train Type 1</td>
<td>0.47</td>
</tr>
<tr>
<td>Train Type 2</td>
<td>0.52</td>
</tr>
<tr>
<td>Train Type 3</td>
<td>0.56</td>
</tr>
<tr>
<td>Train Type 4</td>
<td>0.62</td>
</tr>
</tbody>
</table>
## Distance(km) : Stockholm - Malmö Line

<table>
<thead>
<tr>
<th>Area regions</th>
<th>Cst86d</th>
<th>Nk</th>
<th>Nr</th>
<th>Lp</th>
<th>My/Mot</th>
<th>Jö</th>
<th>NEK/Va</th>
<th>Vö</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stockholm/Söderfjärde</td>
<td>103</td>
<td>162</td>
<td>209</td>
<td>241</td>
<td>372</td>
<td>329</td>
<td>433</td>
<td>544</td>
</tr>
<tr>
<td>Nököping</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nököping</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linköping</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mjöby/Motala</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jönköping</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nässjö/Eksjö/Etlanda</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Växjö</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kristianstad</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hässleholm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helsingborg/Landskrona</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Malmö/Lund/Trelleborg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix C – OHSL new scenario settings

Supply constants

<table>
<thead>
<tr>
<th>Supply constant</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HST dimensional speed (km/h)</td>
<td>400</td>
</tr>
<tr>
<td>HST commercial speed factor (km/h)</td>
<td>0.7</td>
</tr>
<tr>
<td>Frequency (departures in one direction per day)</td>
<td>30</td>
</tr>
<tr>
<td>Fare (average revenues) (SEK/Km)</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Line Characteristics

<table>
<thead>
<tr>
<th>Type of the line</th>
<th>Double Track</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Length of Line (200-2000 km)</td>
<td>600</td>
</tr>
<tr>
<td>Number of Stations</td>
<td>12</td>
</tr>
<tr>
<td>Concrete Tunnels (%)</td>
<td>5</td>
</tr>
<tr>
<td>Rock Tunnels (%)</td>
<td>10</td>
</tr>
<tr>
<td>Bridge (%)</td>
<td>5</td>
</tr>
<tr>
<td>Cutting (%)</td>
<td>40</td>
</tr>
<tr>
<td>Embankments (%)</td>
<td>40</td>
</tr>
</tbody>
</table>

Train Data – Operating Costs (SEK/train-km)

<table>
<thead>
<tr>
<th>Train Type</th>
<th>Operating Cost (SEK/train-km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train Type 1</td>
<td>0.47</td>
</tr>
<tr>
<td>Train Type 2</td>
<td>0.52</td>
</tr>
<tr>
<td>Train Type 3</td>
<td>0.56</td>
</tr>
<tr>
<td>Train Type 4</td>
<td>0.62</td>
</tr>
</tbody>
</table>
### Appendix D – Construction Costs

<table>
<thead>
<tr>
<th></th>
<th>Base Scenario (MSEK)</th>
<th>New Scenario (MSEK)</th>
<th>Marginal (MSEK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel</td>
<td>11 590</td>
<td>32 007</td>
<td>20 417</td>
</tr>
<tr>
<td>Bridge</td>
<td>5 904</td>
<td>11 411</td>
<td>5 507</td>
</tr>
<tr>
<td>Cutting</td>
<td>5 432</td>
<td>5 005</td>
<td>-427</td>
</tr>
<tr>
<td>Embankment</td>
<td>4 074</td>
<td>3 754</td>
<td>-320</td>
</tr>
<tr>
<td>Catenary</td>
<td>2 966</td>
<td>3 542</td>
<td>576</td>
</tr>
<tr>
<td>Signaling System</td>
<td>3 600</td>
<td>3 600</td>
<td>0</td>
</tr>
<tr>
<td>Power Supply</td>
<td>1 800</td>
<td>2 400</td>
<td>600</td>
</tr>
<tr>
<td>Stations</td>
<td>1 800</td>
<td>3 600</td>
<td>1 800</td>
</tr>
<tr>
<td>Track</td>
<td>6 000</td>
<td>11 280</td>
<td>5 280</td>
</tr>
<tr>
<td>Speed independent costs</td>
<td>1 200</td>
<td>1 500</td>
<td>300</td>
</tr>
</tbody>
</table>

Total Marginal Construction Cost (excl. tax): **33 432 MSEK**

Total Marginal Construction Cost (incl. tax): **40 453 MSEK**
Appendix E – Analysis Graphs

Cost-Benefit for different speeds – New scenario
Cost-Benefit for different frequency of services – New scenario
Cost-Benefit for different fares – New scenario
NPV for different speeds – New scenario