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Combined Effects of Track Gradient Related Parameters on Energy Consumption and Capacity

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Abstract:

The predicted growth in passenger and freight traffic toward 2050 is considerable. To meet this growth, it is important to utilize new and existing railway infrastructure in a sustainable way. Track gradient could potentially have a large impact on operational parameters, which could again affect the sustainability of a railway line. It is therefore of scientific interest to study how these relate. The main goal of this study is to identify parameters that have the largest influence on the combined effect of energy consumption and capacity on a railway section.

Relevant parameters related to track gradient have been identified. Thus, an infrastructure model has been built in a microscopic model and run with scenarios combining different parameter levels. Outputs from the model were used to calculate the energy consumption and capacity. These responses were utilized to identify the critical parameters for the combined effect of capacity and energy consumption using a full factorial design.

The largest significant single effect for the combined outputs is the train mix. The single effect gradient direction and the interaction effect between train mix and gradient direction have also significant effect on the combined outputs of energy consumption and capacity.

Results from the study also imply that an increasing ascending track gradient does not have a significant effect on the track's capacity until heavy freight trains have trouble maintaining a reasonable speed. However, track gradient will considerably increase the energy consumption of the train operation for a train running uphill, and the effect will be much higher if combined with higher train speed and heavier train weights, the study implies.

Keywords

1. Combined effects
2. Railway capacity
3. Energy consumption
4. Track gradient
5. Parametric study

(sign.)

Preface

This document is the concluding work of the master's thesis at the Department of Civil and Environmental Engineering at NTNU, worth 30 credits.

The thesis has been supervised by Prof. Elias Kassa and Dr. Anne Christine Torp Handstanger. Thank you both for insightful feedback and helpful discussions.

I am very grateful for Christopher Wink's comprehensive e-mails that gave me a considerately better understanding of the LUKS software, as well as Albert Lau's help with optimization struggles.

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Trondheim, June 2018

Bendik Fürst Mustad

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Keywords:

Combined effects, Railway capacity, Energy consumption, Track gradient, Parametric study

An extended abstract, submitted and accepted for the RAILWAYS2018 conference, is attached in appendix E.

Sammendrag

Det er forventet en betydelig vekst i passasjer- og godstog mot 2050. For å møte denne veksten er det viktig at ny og eksisterende jernbaneinfrastruktur benyttes på en bærekraftig måte. Stigning kan potensielt ha en stor innflytelse på driftsmessige parametere, som igjen kan påvirke bærekraftigheten av linja. Det er derfor av vitenskapelig interesse å undersøke sammenhengen mellom disse. Hovedmålet med oppgaven er å identifisere parametere som har størst innvirkning på den kombinerte effekten av energiforbruk og jernbanekapasiteten på en strekning.

Relevante parametere er identifisert, før en infrastrukturmodell er bygget i en mikroskopisk modell. Deretter har det blitt kjørt scenarier som kombinerer de ulike parameternivåene. Utverdier fra modellen er brukt til å regne ut energiforbruket og kapasiteten på strekningen. Disse responsverdiene er deretter brukt for å identifisere kritiske parametere for den kombinerte effekten av kapasitet og energiforbruk ved hjelp av *full factorial design*-metoden.

Den største signifikante hovedeffekten for de kombinerte utverdiene er togmiksen. Om toget kjører i stigning eller fall og kombinasjonen mellom togmiks og stigningsretning har også betydelig innvirkning på den kombinerte effekten av energiforbruk og kapasitet.

Resultatene fra forskningen impliserer at en økende stigning virker å ha relativt liten innvirkning på jernbanekapasiteten inntil tyngre godstog sliter med å opprettholde en rimelig hastighet. Derimot virker overskridelse av normalkravene knyttet til stigning å ha en betydelig effekt på energiforbruket for togene, spesielt om dette kombineres med høyere toghastigheter og tyngre godstog.

Stikkord:

Kombinerte effekter, Jernbanekapasitet, Energiforbruk, Stigning, Parameterstudie

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Chapter 1

Introduction

The introduction is structured in a way that first presents some background relevant for the thesis. Then the main goal of the thesis is stated, before limitations are presented.

1.1 Background

Predicted growth in passenger traffic toward 2050 is 28-36 % in the four major cities in Norway (Jernbaneverket, 2015a). In the same time span, the European Union's target is to shift as much as 50 % of road freight travelling over 300 km to more green modes like railway (The European Commission, 2011). Also, extensive investments in improvements for the Norwegian railway have been committed to by the Norwegian Government (Det Kongelige Samferdselsdepartement, 2017).

Because of the predicted growth, it is important that new and existing railway infrastructure is utilized in a sustainable way. When designing an infrastructure section, investment costs are a major contribution in regard to chosen alternatives. However, some infrastructural decisions could have a large impact on the operations of a line, from both a train operator's and an infrastructure owner's point of view.

For train operators, the energy consumption has a direct correlation to operational expenses. For infrastructure owners, the track capacity is important regarding punctuality and increase productivity of their railway sections. This is exemplified in NSB's goal of reducing their energy consumption (NSB, 2011) and Bane NOR's stated development opportunities lying in increasing capacity (Bane NOR, 2018).

Track gradient is one of the parameters that seem to have a substantial effect on both energy consumption and capacity. Although steep gradients can be avoided, a trade-off for this is often a longer horizontal alignment which could lead to higher investment costs. It is therefore of scientific interest to study the effects a track gradient has on operational outcomes.

When it comes to the energy consumption and railway capacity, there has, to the best of the authors' knowledge, not been conducted research to assess the *combined* effect of the two. These combined effects could be important for both operators and infrastructure owners for scenarios with larger axle loads, a large mix of train speeds and longer freight trains. Therefore, it is necessary to investigate how the track gradient and related parameters affect the capacity and energy consumption, combined.

1.2 Goal and research questions

The main goal of the master's thesis is to identify parameters that have the largest influence on the combined effect of energy consumption and capacity on a railway section.
Research questions and goals for the thesis are stated below.

1. What are the track gradient related parameters that effect the energy consumption and capacity for a double-tracked railway stretch?

2. Develop a method to study both the energy consumption and train capacity in relation to the track gradient.

3. What are the critical parameters with the largest effect on energy consumption and capacity, combined?

The range of the parameters should be in such a way that the study can give a realistic view of the modelled situations, while also results from the parametric studies should be manageable.

At the end of the master thesis, it will be possible to determine which of the studied parameters that will have the largest effect on the combined effects of capacity and energy consumption. The responses will be from an infrastructure model built in the LUKS software.

The study is to focus on parameters related to the railway infrastructure, the rolling stock and interactions between these. Investigations related to cost are not included.

1.3 Limitations

This thesis has several limitations.

In capacity regards, the thesis will focus solely on a tangent, double-tracked line. Only the theoretical capacity will be considered.

Energy consumption is limited to resistance occurring between tracks and the rolling stock. Regenerative braking and coasting benefits are not included in the parametric study. Neither is energy loss from the catenary or third rail lines, as well as auxiliary systems on-board the train. These are excluded due to limitations in the software to model and incorporate these factors.

Analyses regarding cost and robustness are not included in this study.

Chapter 2

Literature review

To build a theoretical background as well as getting an impression of the state of the art, a literature review has been carried out. The methodology will be presented in chapter 3, while results are presented in this chapter.

The theoretical background will be based on the topics track alignment, train dynamics, energy consumption and capacity. A presentation of the state of the art follows, with focus on energy consumption and capacity.

2.1 Track alignment

A longitudinal railway track alignment consists of three geometrical elements, according to Hay (1982) and Esveld (2001). These are:

1. Tangent tracks in the straight direction
2. Curves, cant, transition curves and transition gradients in the horizontal direction
3. Gradients and vertical curves in the the vertical direction

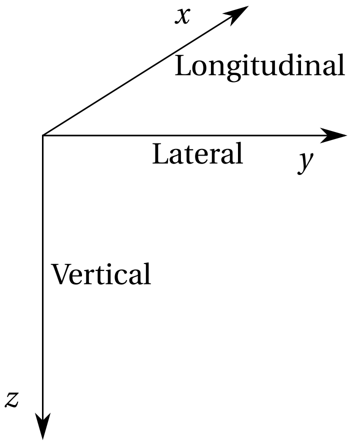

Figure 2.1: Coordinate system utilized for railways

In relation to the coordinate system usually utilized for railways, visualized in Figure 2.1, it can be seen that these elements are related to longitudinal movement (1), lateral movement (2) and vertical movement (3). Different forces will affect the train running behaviour while travelling along the different axes.

Track gradient is the relative elevation along the track in relation to the vertical axis. The unit used in this thesis is the rise per thousand units horizontally [‰]. A positive gradient means that the train is rising or ascending, while a negative gradient means that the train is dropping or descending.[1]

2.2 Train dynamics

2.2.1 Resistance

When a train is moving, it will have to overcome a total resistance force (Hay (1982) uses the term gross resistance). The resistance force is usually categorized into different components depending on how they occur. Andrews (1986) uses bearing resistance, rolling resistance and air resistance. Internal resistance, journal friction, flange resistance, track modulus resistance, wind resistance etc. are all mentioned by Hay (1982). Esveld (2001) however defines these as running resistance, air resistance, curve resistance and gradient resistance.

The definitions used in this report will be most corresponding to the latter example, where the total resistance, W, is the sum of the basic resistance, W_0, air resistance, W_a, curve resistance, W_c, and gradient resistance, W_g. This is presented in equation (2.1).

$$W = W_0 + W_a + W_c + W_g \qquad [\text{kN}] \tag{2.1}$$

For a given weight of a train, G_T, the total specific resistance, w, is presented in equation (2.2).

$$w = \frac{W}{G_T} \qquad [‰] \tag{2.2}$$

Likewise, the other resistance components also have specific resistance values, as seen in equation (2.3).

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[1] Unless otherwise is explicitly stated.

$$w = w_0 + w_a + w_c + w_g \qquad [‰] \tag{2.3}$$

The components of the total resistance will be elaborated in separate subsections. However, the gradient resistance will be discussed most thoroughly.

Basic resistance

The basic resistance is a term used for several smaller components contributing to the total resistance. Mainly, it consists of the rolling resistance caused between the wheel-rail-interaction and the journal resistance. Compared to road vehicles, the basic resistance will be considerably smaller (Esveld, 2001). Some of the basic resistance will also come as a consequence of track irregularities and rail deflection. In this report, resistance in switches, crossings and joints will be considered in this category. Also train acceleration resistance, a resistance occurring when the speed is changing due to rolling inertia (Steimel, 2008), will be considered in this component. The term vehicle resistance from the infrastructure model is equivalent to this.

Air resistance

The air resistance is usually proportional with the speed to the power of two. To which degree the rolling stock is aerodynamic will also highly influence the air resistance of a travelling vehicle. Headwinds should also be considered when this occurs (Esveld, 2001).[2] If a train is travelling through a tunnel, the air resistance can be considerably increased compared to travelling on an open track (Raghunathan et al., 2002).

Curve resistance

When travelling through a horizontal curve, the wheels will be rolling with different circumferences. This will lead to slipping in one or both of the wheels before the vehicle again adjusts. In tight curves the wheel flange might also come in contact with the rail. These aspects will increase the curve resistance (Esveld, 2001).

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[2] Headwinds of 15 km/h are in fact included in the infrastructure model for air resistance calculations on an open track (e-mail from Christopher Wink (Verkehrswissenschaftliches Institut der RWTH Aachen), May 16th 2018).

In Norway, Röckl's formula (equation (2.4)) is usually used to calculate the curve resistance. When the curve radius, $R \geq 1100$ m, the curve resistance is neglected (Jernbanekompetanse, 2013).

$$w_r = \frac{650}{R - 50} \qquad [‰] \tag{2.4}$$

Gradient resistance

Because of topographic differences, it is not possible to avoid a certain use of track gradient when constructing a train track. Heavy traffic might have trouble with too steep climbs (Lindahl, 2001). Because of this it is usual to try to reduce the track gradient for mixed lines where possible. One way of minimizing the elevation of which one has to ascend or descend, is to build bridges or tunnels, but this will increase investment costs. There are also other considerations that have an effect on operations. These include that power supply and energy consumption will increase with large gradients and that braking distances will increase with descending gradients (Lindahl, 2001).

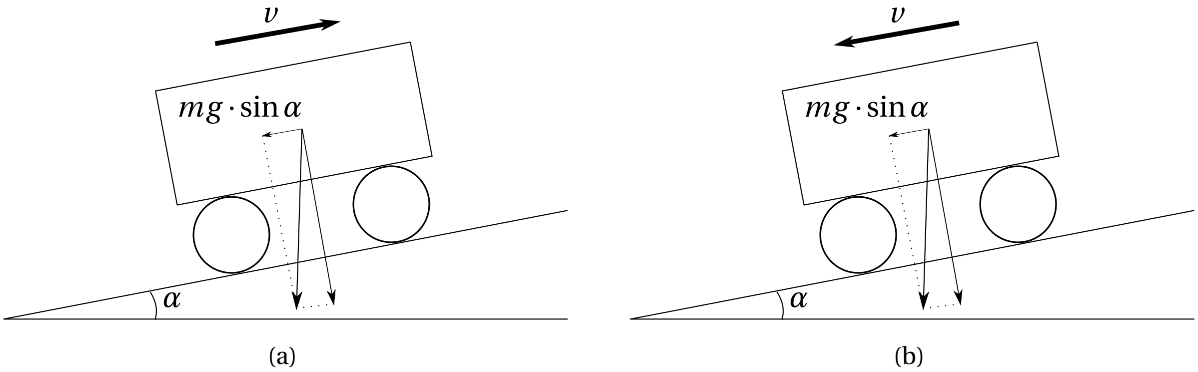

Figure 2.2: Gradient resistance for an (a) ascending and (b) descending train

Figure 2.2 shows how the gravitational force on a train on an inclined plane will decompose to a gradient resistance when in motion. In the figure, g is the gravitational force, m is the total mass of the train's components and α is the angle of the plane. The resistance force along train tracks, called the gradient resistance, W_g, is as formulated in equation (2.5). The gradient resistance acts as a resistance only when the train is climbing uphill, while the gravitational contribution will decrease the resistance along the direction of motion when descending.

$$W_g = mg \cdot \sin\alpha \tag{2.5}$$

Since track gradients usually are not very steep, it can be assumed that $\alpha \ll 1$. Because of this it is possible to make the assumptions formulated in equation (2.6) (Esveld, 2001; Steimel, 2008).

$$\sin\alpha \approx \tan\alpha = s \tag{2.6}$$

where s is the track gradient [‰].

From this, the gradient resistance, W_g, and the specific gradient resistance, w_g, is formulated as in equation (2.7) and (2.8) respectively. m_l is the mass of the locomotive, while m_w is the mass of the wagons, both in tonnes.

$$W_g = \frac{(m_l + m_w) \cdot g \cdot s}{1000} \qquad [\mathrm{N}] \tag{2.7}$$

$$w_g = s \qquad [‰] \tag{2.8}$$

Other terms

The terms *vehicle resistance, resistance tractive unit* and *line resistance* are used in the infrastructural model, rather than those introduced in this subsection. However, both terms generally cover the same aspects, although some of the them may overlap. Figure 2.3 shows what resistances the infrastructure model includes in its calculations.[3] Yellow boxes are terms used in the infrastructure model.

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[3] Clarified by Christopher Wink (Verkehrswissenschaftliches Institut der RWTH Aachen) May 15th 2018.

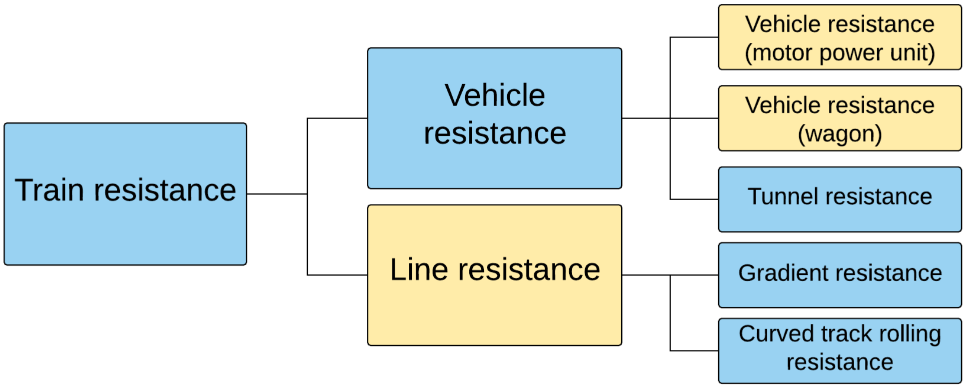

Figure 2.3: Train resistance terms used in infrastructure model

2.2.2 Traction force

The forces pushing a train forward, traction forces, are now considered. For vehicles with both electric and fossil fuels, the rotation of the wheels are run by the locomotive motor, generating a force between the wheels and the rail that end up pushing the train in the desired direction. The force at the interim of the driving wheels against the rail is what is called a traction force. This force is defined as positive when the train is caused to move forward and negative when braking (Steimel, 2008).

For a train to maintain a certain speed, the traction force, F, has to equal the train resistance, as in equation (2.9).

$$F = G_T \cdot w \tag{2.9}$$

where G_T = the gravitational force of the train.

Likewise a train gathers speed when $F > G_T \cdot w$ and loses speed when $F < G_T \cdot w$ (Steimel, 2008).

In the same aspect as for the train resistance, a specific traction force, f, is defined as the occurring traction force per the weight force of the train, G_T, see equation (2.10) (Jernbanekompetanse, 2013).

$$f = \frac{F}{G_T} \qquad \left[\frac{\mathrm{N}}{\mathrm{kN}} = ‰\right] \tag{2.10}$$

Adhesion

Adhesion is by Andrews (1986) defined as a maximum force which can be transmitted by a friction drive between the wheels and rails. Therefore adhesion limits the tractive effort produced by a locomotive that can be converted to a traction force.

The adhesion coefficient is related to the slip of a wheel. Figure 2.4 shows forces and speed of a driving wheel set. Relevant abbreviations and equations are listed from (2.11) to (2.15) (Steimel, 2008).

- Weight force, G_T
- Traction/braking force, F_X
- Wheel radius, r
- Adhesion coefficient, μ
- Train speed, v_t
- Wheel circumferential speed, v_w
- Difference speed, Δv
- Slip (when driving), s_d
- Slip (when braking), s_b

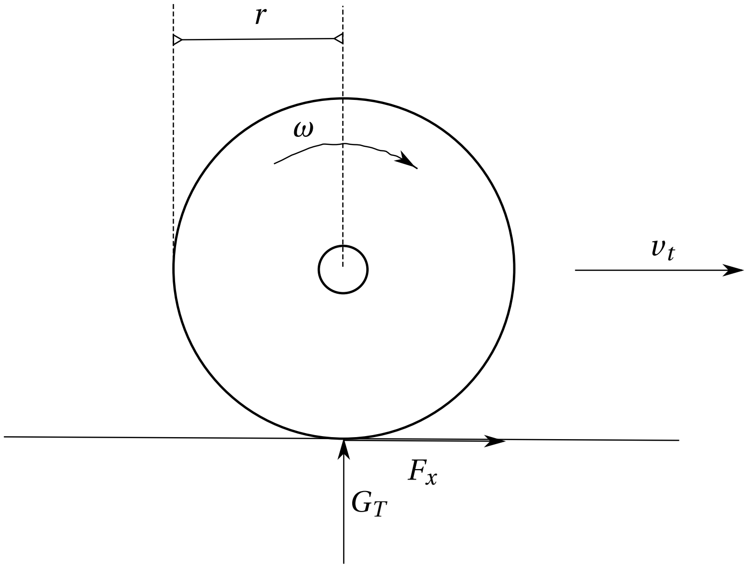

Figure 2.4: Forces and speed affecting a driving wheel set. Based on Steimel (2008)

$$\mu = \frac{F_x}{G_T} \tag{2.11}$$

$$v_w = \omega \cdot r \tag{2.12}$$

$$\Delta v = |v_w - v_t| \tag{2.13}$$

$$s_d = \frac{\Delta v}{v_t} \quad (v_w > v_t) \tag{2.14}$$

$$s_b = \frac{\Delta v}{v_w} \quad (v_w < v_t) \tag{2.15}$$

Thus, slip can occur in two ways. When driving slip occurs when the wheels' circumferential speed is higher than the train speed. When braking, slip occurs when the train speed is higher than the wheels' circumferential speed (Steimel, 2008).

The adhesion coefficient is highly dependent on several factors. One of the highest effects will be the difference speed, in effect the degree of slipping. Also local factors like coating (in decreasing order: dry rail, wet rail, oily rail), material quality, surface roughness and temperature will highly effect the adhesion coefficient. Also an increasing speed will give a lower adhesion coefficient (Steimel, 2008).

The possible traction force that can be transferred from wheel to rail is limited by powered wheelsets' axle load, G_l, and the adhesion coefficient, μ, as seen in equation (2.16) (Jernbanekompetanse, 2013).

$$F \leq \mu \cdot G_l \tag{2.16}$$

Power of locomotive

For a given traction force, F, at a given speed, v [m/s], the train will require a net power, P (equation (2.17)).

$$P = F \cdot v \qquad \Leftrightarrow \qquad F = \frac{P}{v} \tag{2.17}$$

This equation shows that an increasing speed will lead to a decreasing traction force. This will also limit the speed of a train (Jernbanekompetanse, 2013).

Available traction

Traction force, in theory, has four main limiting factors: (I) an upper value for adhesion, (II) decreasing traction force from increasing speed, (III) power supply from locomotive limition and (IV) allowable line speed. Note that this curve is significantly different for an electric and a diesel vehicle and would also vary from vehicle to vehicle.

The available traction force is the difference between the specific tractive force and the specific basic resistance, see Figure 2.5.[4] Available traction force can be used to ascend gradients or for acceleration. For a heavy freight train which can't reach the maximum line running speed because of limiting traction force, the train will reach a maximum possible running speed, called

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[4] It should be pointed out that the share of powered wheelsets in passenger trains is usually considerably higher than for freight trains in Norway, limiting traction force for the latter in a larger degree. See eq. (2.16)

a basic speed, v_g, smaller than the speed limit, $v_{\max}$. If it then meets a gradient, the freight train may lose additional speed, see Figure 2.5 (Jernbanekompetanse, 2013).

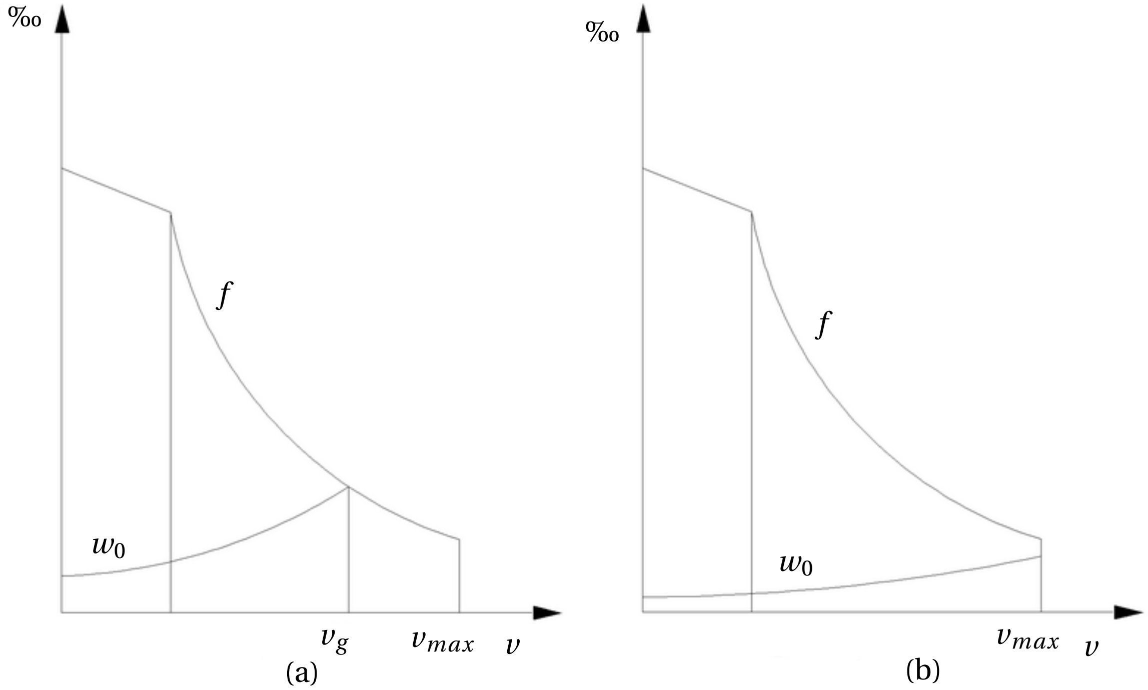

Figure 2.5: Typical example of how a relation between specific traction force and specific basic resistance for (a) freight train and (b) passenger train could be in Norway, from Jernbanekompetanse (2013)

2.3 Energy consumption

The energy consumption of a train is closely related to resistances and tractive forces. By definition, energy consumed, E, is defined as the power, P, used over a given time interval, t, for a constant power. Thus, energy consumption is defined as in equation (2.18).

$$E = P \cdot t \tag{2.18}$$

By definition, power is the rate at which work, W, is done as a function of time (equation (2.19)).

$$P = \frac{dW}{dt} \qquad \text{[W]} \tag{2.19}$$

Work is defined as a force, F, applied over a distance, s (equation (2.20)).

$$W = F \cdot s \qquad \text{[Nm]} \tag{2.20}$$

Combining equation (2.19) and (2.20), we see that:

$$\begin{aligned} P &= \frac{dW}{dt} \\ &= \frac{d}{dt}(F \cdot s) \end{aligned}$$

$$P = F \cdot \frac{ds}{dt} \tag{2.21}$$

Thus, combining equation (2.18) and (2.21), it is understood that:

$$E = F \cdot s \qquad \text{[Nm]} \tag{2.22}$$

For a constant traction force, this means that the energy consumption is equal to the traction force, F, multiplied over the distance covered, s. The total energy consumption, $\sum E$, is found as the sum of these components, as well as factoring in the conversion factor between Nm and kWh, as shown in equation (2.23).

$$\sum E = \sum \left(\frac{F \cdot s}{3\,600\,000} \right) \qquad \text{[kWh]} \tag{2.23}$$

This means that all increases in resistance will require an increased traction force, which leads to a higher energy consumption. Likewise reducing resistances leads to a reduced energy consumption.

On trains, auxiliary systems such as heating/cooling, lighting and information will also factor in on the total energy consumption. These systems are not related to the driving the rolling stock and in turn not the driving behaviour. Heating and ventilation systems, usually responsible for the significant share of this consumption, is highly dependant on the climate in the area (González-Gil et al., 2014).

However, the fact that this contribution is quite constant for a given geographical location and time of year, as well as the fact that the infrastructural model doesn't take this into account[5], energy consumption from auxiliary systems are not considered further in this thesis. Therefore it should hereby be noted that quantified energy consumption figures from this study are not meant as absolute figures, but comparisons.

2.4 Capacity

2.4.1 Definitions

Skartsæterhagen (1993) discusses the effects of capacity in relation to railway. A train's capacity might be the amount of passengers or tonnes that can be transported, while a shifting station's capacity might be considered how many trains that can be served per time. The capacity for a section or network however is usually defined as the number of trains that can be transported per time unit. Railway capacity of a line is defined by Pachl (2002) as "the maximum number of trains which may be operated through a line". For this report, the capacity will be defined as the amount of trains per time unit on a section.

A central concept in railway capacity is block occupation time (blocking time). Blocking time is a time interval where part of a track section is exclusively dedicated for a specific train – hence blocked for other trains. This part is usually a block section related to signalling. The blocking time consists of six parts. These are: time for clearing signal, signal watching time, approach time, time between block signals, clearing time and release time (Pachl, 2002).

Closely related to the blocking time is the minimum headway time, $t_{s,min}$. Minimum headway time is defined as the minimum amount of time between two trains on a given section consisting of several block sections (Pachl, 2002).[6] Visualization of headway times and block sections in operation is usually done in distance-time-diagrams. Figure 2.6 shows an example of this, with some other basic aspects. An increased running time of either the first or second train would lead to a longer minimum headway time as well.

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[5] E-mail from Christopher Wink (Verkehrswissenschaftliches Institut der RWTH Aachen) dated December 12th 2017.

[6] The Norwegian method for deciding block section lengths is introduced in appendix B.

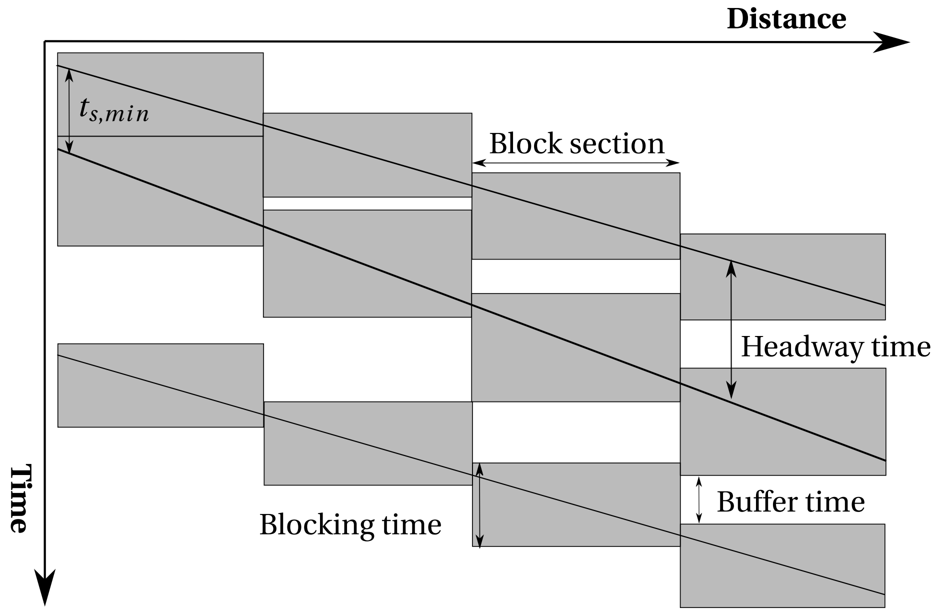


Figure 2.6: Distance-time-diagram with some central concepts in capacity planning, from Landex et al. (2006)

When there is a mix of trains with different running times, the mean minimum headway time, $\overline{t_{s,min}}$ is used. This is a weighted value that estimates a mean minimum headway time when the amount of different trains types are given, as well as the minimum headway times between these. How to calculate this value will now be presented.

On a given section, it is known that there is a total amount of N trains and k different train types. There are n_a type a trains, n_b type b trains etc. (equation (2.24)). The probability that the preceding train (i) and the succeeding train (j) is the occurring case is presented in equation (2.25). The minimum headway in this case is $t_{i,j}$. Thus, the mean minimum headway time for the whole section, $\overline{t_{s,min}}$, is given by equation (2.26).

$$N = n_a + n_b + \ldots + n_k \tag{2.24}$$

$$p_{i,j} = \frac{n_i \cdot n_j}{N^2} \tag{2.25}$$

$$\overline{t_{s,min}} = \sum_{i=1}^{k} \sum_{j=1}^{k} p_{i,j} \cdot t_{i,j} \tag{2.26}$$

2.4.2 Theoretical and practical capacity

It is usually differentiated between the theoretical and the practical capacity of a section. The theoretical capacity, K_{theo}, is defined as the time observation period, T, divided by the mean minimum headway time, $\overline{t_{s,min}}$ (equation (2.27)), while the practical capacity, K_{prac}, also takes into effect the buffer time, t_b, a time difference between an actual headway time and a minimum headway time (equation (2.28)).

$$K_{\text{theo}} = \frac{T}{\overline{\overline{t_{s,min}}}} \tag{2.27}$$

$$K_{\text{prac}} = \frac{T}{\overline{t_{s,min}} + t_b} \tag{2.28}$$

The theoretical capacity would mean that a line is constantly occupied, while the practical capacity will have an unoccupied time period. International Union of Railways (UIC) (2004) defines an occupancy time rate, ρ, as in equation (2.29).

$$\rho = \frac{\text{Occupancy time}}{\text{Observation time period}} \qquad [\%] \tag{2.29}$$

Thus the relationship between the theoretical and practical capacity can be found as seen in equation (2.30).

$$K_{\text{prac}} = \rho \cdot K_{\text{theo}} \tag{2.30}$$

When designing a track, one should take into account the capacity. International Union of Railways (UIC) (2004) proposes occupancy rates as presented in Table 2.1 for a track to be able to keep the original timetable characteristics.

Table 2.1: Proposed occupancy time rates, from International Union of Railways (UIC) (2004)

Type of line	**Peak hour**	**Daily period**
Dedicated suburban passenger traffic	85 %	70 %
Dedicated high-speed line	75 %	60 %
Mixed-traffic line	75 %	60 %

For the proposed occupancy time rates, there is an optimal number of trains, n_{opt}. Waiting times, ET_w, are expected to grow exponentially when the amount of trains, n, exceed the n_{opt}. When the amount of trains approach n_{max} (corresponding to the theoretical capacity), waiting times approach infinity, as can be seen in Figure 2.7, from Verkehrswissenschaftliches Institut (2008).

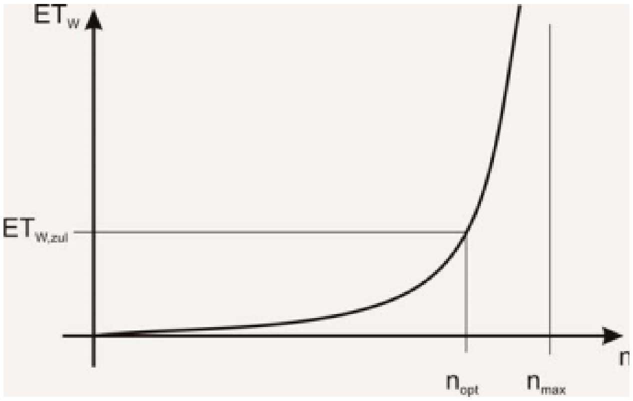


Figure 2.7: Relationship between number of trains and expected waiting times, from Verkehrswissenschaftliches Institut (2008)

However, the term capacity will relate to the theoretical capacity from here on in this document.

2.4.3 Velocity diagrams and running time calculations

Kim et al. (2013) describes five motion regimes related to trains moving from station to station, see Figure 2.8.

- Acceleration
- Cruising
- Coasting
- Braking
- Standing

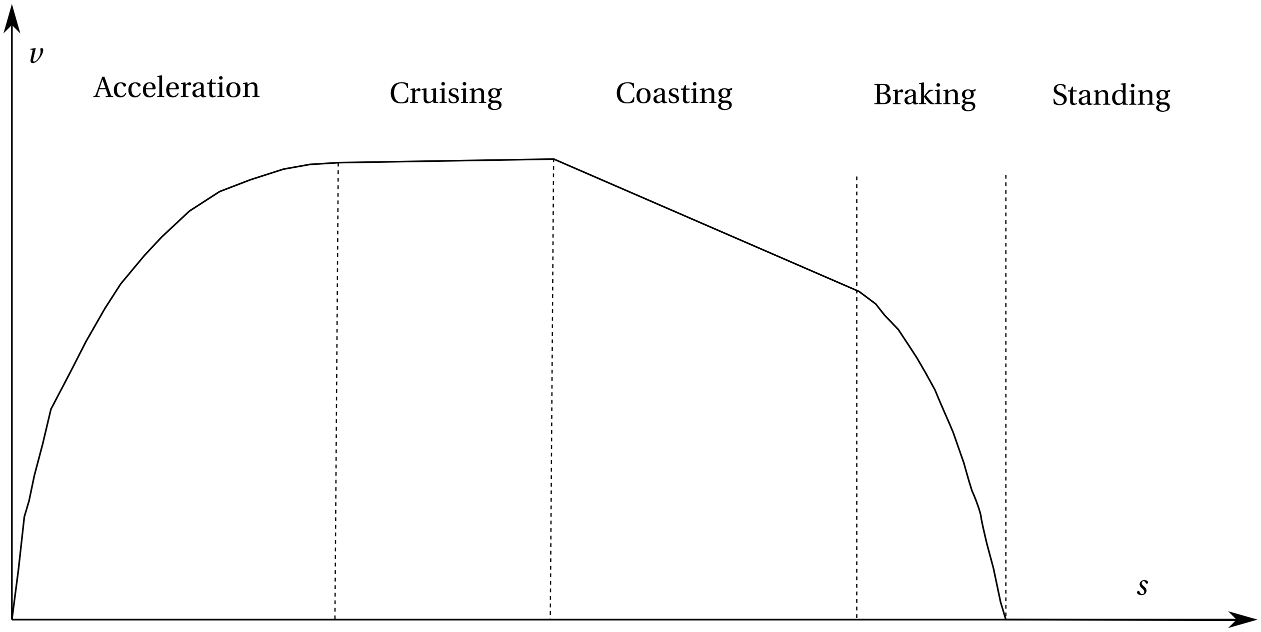


Figure 2.8: Motion regimes, from Kim et al. (2013)

For the different motion regimes introduced in Figure 2.8, different forces apply to the train body. The terms used in the equations in Table 2.2 are tractive forces, F, total resistance, W, acceleration forces, F_a, braking forces, F_b, as well as a the inertial force, R_{in}. The equations in Table 2.2 describe the forces working on a train body when moving in different motion regimes (Pachl, 2002).

Table 2.2: Equations describing motion regimes

Acceleration	Cruising	Coasting	Braking
$F = W + F_a$	$F = W$	$R_{\text{in}} = W$	$R_{\text{in}} = W + F_b$

For a standstill train, no longitudinal forces apply.

A train's acceleration is non-constant, because of a locomotive's tractive characteristics and the possibility of shifting line resistances over a short distance. It is therefore necessary to calculate the train's movement along the distance with an analytic, sequence-based approach. It is possible to use fixed distance intervals, Δs steps, or fixed speed intervals, Δv steps (Pachl, 2002).

The infrastructure model uses fixed speed intervals to incrementally calculate the acceleration force at the new speed, and thereby the acceleration, distance covered etc. In cases where there is a change in infrastructure between speed steps, a new step is applied here. The software takes into account specific vehicle parameters and information about the infrastructure. The output of this is a velocity diagram. An example is given in Figure 2.9. The upper part of the figure shows the velocity as a function of chainage, while the bottom part visualizes the gradient. We can clearly see three of the motion regimes; respectively acceleration, cruising and braking.

With this method, the accuracy of the model increases with smaller Δv steps (Pachl, 2002).

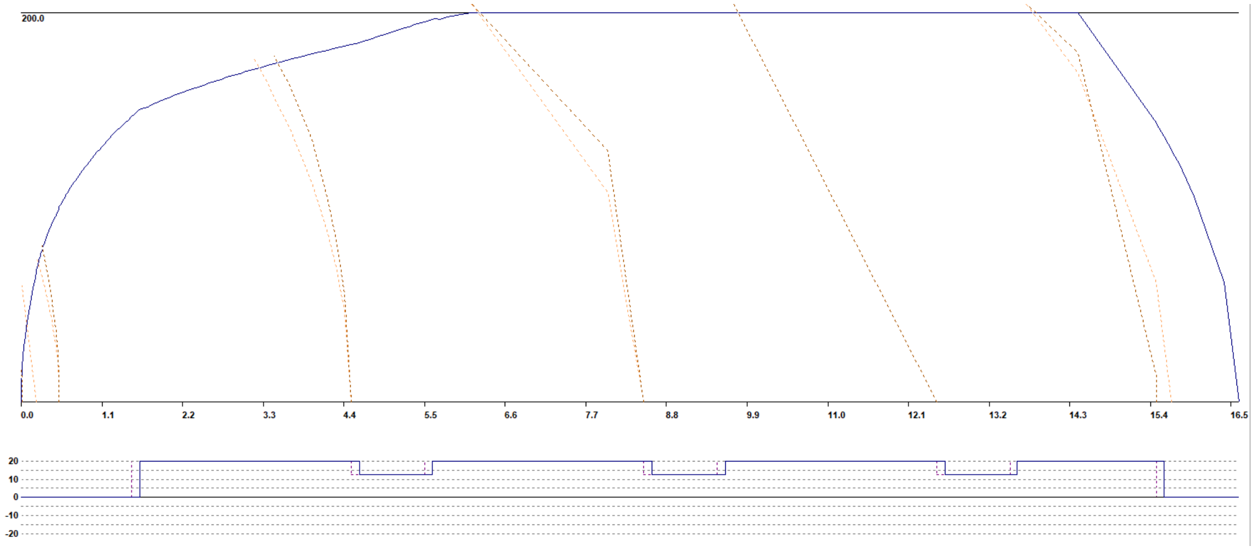


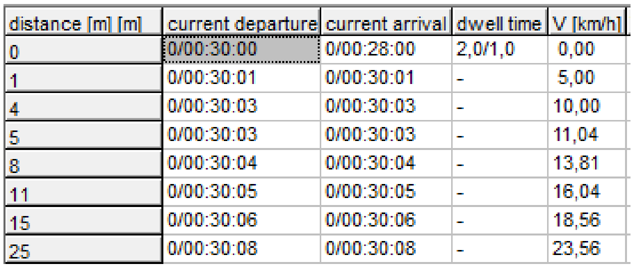
Figure 2.9: Example of velocity diagram

When the speed curve is determined, running times can be calculated by numerical integration, see equation (2.31) (Pachl, 2002).

$$t = \int \frac{1}{v(s)} \mathrm{ds} \tag{2.31}$$

In the infrastructure model, the calculated running times are gathered in a matrix called *running time*. A screenshot of the calculated information is presented in Table 2.3.

Table 2.3: Example of running time calculations in *running time* matrix from infrastructure model during acceleration



distance [m] [m]	current departure	current arrival	dwell time	V [km/h]
0	0/00:30:00	0/00:28:00	2,0/1,0	0,00
1	0/00:30:01	0/00:30:01	-	5,00
4	0/00:30:03	0/00:30:03	-	10,00
5	0/00:30:03	0/00:30:03	-	11,04
8	0/00:30:04	0/00:30:04	-	13,81
11	0/00:30:05	0/00:30:05	-	16,04
15	0/00:30:06	0/00:30:06	-	18,56
25	0/00:30:08	0/00:30:08	-	23,56

2.5 State of the art

Several studies concerning railway capacity and energy consumption have been conducted. This section will present some of these sorted by the key factors of the studies' goals and conclusions.

2.5.1 Energy consumption

In recent years, there has been an increased focus on energy consumption in the transport sector. For mere economic reasons, train operators can reduce costs if energy consumption can be decreased. The topic has also been relevant because of rising energy costs, pollution and CO_2 emissions (González-Gil et al., 2014; Lukaszewicz, 2004).

González-Gil et al. (2014) depicts a holistic, typical traction energy flow in Figure 2.10.[7] Literature regarding some of these terms will be listed in this section.

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[7] The figure represents an urban rail system, not a traditional regional railway, so the numbers are not accurate. However, the energy flows are also representative for traditional railway.

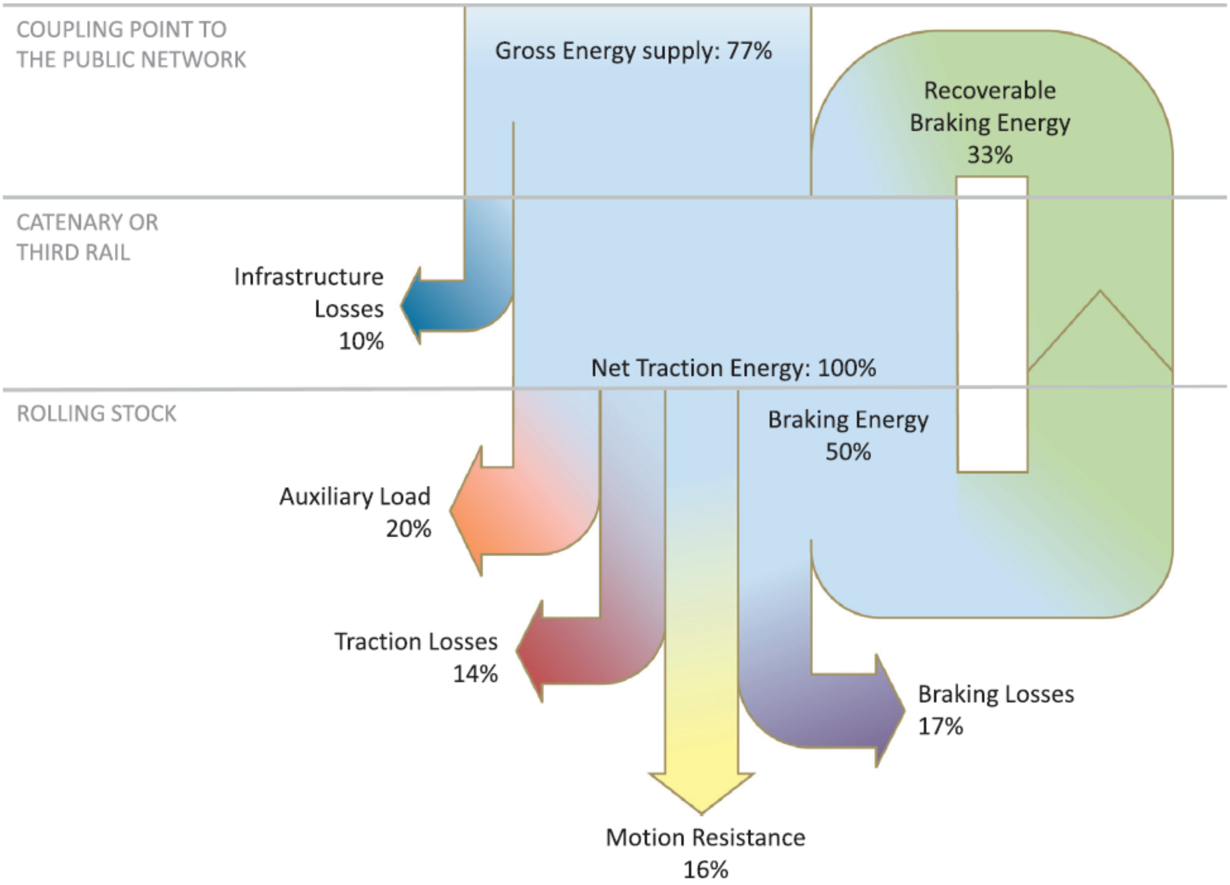

Figure 2.10: Typical traction energy flow, from González-Gil et al. (2014)

Infrastructure losses and auxiliary loads

In 2011 SINTEF conducted a comprehensive research project related to the transport of goods in Norway in a green, eco-friendly fashion. The research results were published by Norvik et al. (2011). In the project report, the project group has mentioned that an energy consumption as a function of train mass and distance (used for road transport) is not sufficient when travelling by rail, and suggests further research on the field. However, some results were found. When using the measured values from the catenary, they also found there was a significant energy loss with the use of electric energy, dependent of the line and the train type. Bane NOR highlights that there is about a 20 % energy loss in the process of converting energy from the public or regional power supply to the standard 15 kV voltage, 16 $^2/_3$ Hz frequency that is delivered to the electric locomotives in Norway. There is a loss both in the converter station and in the catenary line (Ruud & Remme, 2015). This is what is referred to as infrastructure losses in Figure 2.10.

Further, several studies conclude in energy saving measures including optimizing the usage of the auxiliary loads and better usage of the power supplying infrastructure (Gunselmann, 2005; González-Gil et al., 2014), but these will not be further addressed in this thesis, as focus will be towards infrastructure and train running related energy saving.

Operational measures for energy saving

Some factors have been proven important when it comes to reducing the energy consumption in relation to the train body. Operational measures, usually related to driver behaviour or control systems, have turned out to have a considerable effect on the total energy consumption.

González-Gil et al. (2014) states that approximately half of traction energy can be dissipated during braking phases. This shows the potential for energy saving using regenerative braking – a system that converts kinetic energy back to reusable energy. It is also highlighted that operational measures usually have low investment costs and can be minor modifications, but can have considerable impacts on the energy consumption.

For a section, energy consumption can be reduced by 5-7 % and 10-15 % if the driving is better planned (hence reducing unnecessary braking) and makes use of coasting respectively (Lukaszewicz, 2004). A downside of coasting however is that the running time may increase and, if regenerative braking is in use, the full potential of energy saving is not reached. This was concluded by Lukaszewicz & Andersson (2009) in relation to estimations on a high-speed rail.

Liu & Golovitcher (2003) have seen an energy efficient train control as a formulation of Optimal Control Theory and has as a result found a quite detailed calculation algorithm and a computer program for energy efficient train control in effect of the optimal controls.

Howlett et al. (2009) have calculated critical switching points for track with steep gradients by using an energy minimization principal related to control actions.

Albrecht (2010) has used running time control to be able to reduce the power peaks with Genetic Algorithms. But doing this, they also hope to reduce the energy consumption. These results are also mostly relevant to the operation of the train.

Jong & Chang (2005) have found two quite accurate estimation models to estimate the energy consumption for electric trains. Their stated goal is to minimize the energy consumption through driving strategies.

An energy measuring system called Erex is being used in Norway. This system logs the energy consumption and bills the operators according to their actual energy consumption. In this way, there is an economic incentive to reduce the energy consumption, according to Bane NOR. When it comes to the actual reduction of energy consumption in operation, Bane NOR refers to their operators, but they note that NSB has been able to reduce their energy consumption (per tonn kilometer) with 18 % (2004-2015) because of the energy measuring system (Ruud & Remme, 2015).

As seen above, all these references use energy consumption minimization as a mean of reducing operation costs and the output is usually in regard to the driving behaviour or a control system. So operational measures can have a significant impact on the total energy consumption of a given railway stretch.

Infrastructural impact

Kim et al. (2013) have used a deterministic simulation model to analyse different vertical alignments, especially with focus on dipped and undipped vertical alignments – concepts that in a best way utilizes cruising. They conclude that optimized alignments can significantly reduce travel time, energy use, brake wear, operating cost and total cost compared to a baseline alignment. Relevant factors they have concluded as contributing are station spacing, maximum gradients, maximum (de)acceleration rate and power.

Kim & Chien (2011) have found an optimization method that minimizes energy consumption considering several factors, whereas track alignment, speed limit and schedule was among them. The mode used was a simulated annealing algorithm. One of the conclusions was that train weight is major factor when considering energy consumption.

Lindahl (2001) points out that increasing gradients increase the need for power supply and energy consumption, that heavy freight trains may have problems climbing steep gradients and that braking distances increase with larger gradients.

Rolling stock impact

Aerodynamic features of the rolling stock, especially for high-spped trains have proven more important with higher speeds and lighter vehicles (Lindahl, 2001; González-Gil et al., 2014). Less aerodynamic features lead to a larger drag, thus also a higher energy consumption.

As mentioned earlier, the vehicle's mass also has been seen to have a considerable impact on the total energy consumption.

2.5.2 Capacity

According to Landex et al. (2006), factors that can affect a track capacity negatively are increasing amount of trains, increased heterogeneity and lower punctuality. Increased average speed can affect the capacity in both ways.

Krueger (1999) is cited a lot in literature and has developed a Parametric Capacity Model. The goal of the model is to identify limiting section elements of the track and in that way be able to better utilize the existing infrastructure. Delay is expressed as a function of train volume and criteria based coefficients. The main parameters that were identified as crucial for the capacity were speed, signalling and side track capacity. Gradients were not considered in this study.

Mitra et al. (2010) have considered an estimation of railroad capacity using parametric regression methods. The method used is a modification of a train dispatching simulation based on Prokoby & Rubin (1975). Of the parameters studied, grouped as infrastructural, operational and traffic-related, several are identified as important for the capacity, with speed, signalling distance and sidetracks' capacity as important inputs. Gradient is not included as a parameter in this study.

Hu & Huang (2014) have built a model with a log-linear type multivariate regression. The assumption is that a capacity loss is based on the gradient of a climb, the section length and the average speed on the section. Their conclusion is in general that an increased gradient or section length will increase the capacity loss, while an increased average speed will decrease the capacity loss in the range of their study on high-speed trains.

Abril et al. (2008) have also conducted research in regards to parameters that affect the capacity. The identified parameters that affect the capacity are robustness, commercial stops, train speed and heterogeneity.

Eggum et al. (2017) concludes that gradient does not have a *significant* effect on the capacity. However, train mix and section length has a bigger degree of impact. The study also suggests further research on how the full of effect of gradient can be expressed regarding energy consumption.

2.5.3 Summary

These researches have contributed to a better understanding on how the energy consumption and capacity are affected by different parameters, including track gradient.

However, it can be seen that a lot of research provided in regards to energy consumption is in relation to operational measures. This is quite natural, as a lot of the research can be seen as direct energy, thus also economic, savings for train operators with rather low investment rates.

Concerning railway capacity, parameters related to infrastructure are included to a larger degree. This is often because infrastructure owners have a bigger economic interest in maximizing the capacity of a section.

When it comes to the energy consumption and railway capacity, there has, to the best of the authors' knowledge, not been conducted research to assess the *combined* effect of the two. These combined effects might even be highly considerable for both operators and infrastructure owners for scenarios with larger axle loads, large mix of train speeds and longer freight trains. Therefore, it is necessary to investigate how the track gradient and related parameters affect the capacity and energy consumption, combined.

On this theoretical basis, the methodology for this thesis will now be presented.

Chapter 3

Methodology

The chapter considers the methodology used for reaching the stated goal and answer the research questions of the master's thesis. The main steps of the work are presented in Figure 3.1.

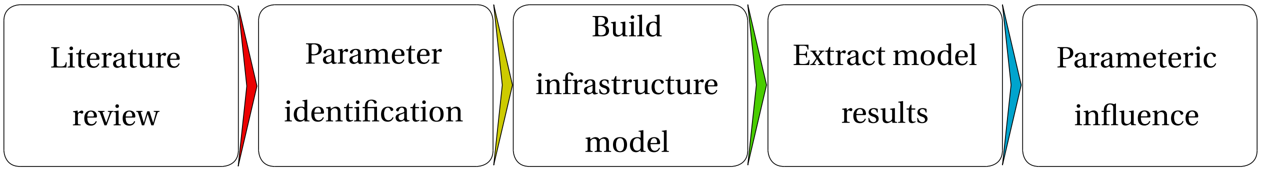

Figure 3.1: The main steps of the methodology

3.1 Literature review

Much of the work done in the literature review is based on the author's project thesis (Mustad et al., 2017).

An academic literature search was conducted using international online databases such as Scopus (`http://www.scopus.com`) and Google Scholar (`https://scholar.google.com`), and national databases like Oria (`http://www.oria.no`). All of these are linked to major electronic resources online. Main keywords for the study are listed in Table 3.1.[8] Snowballing from relevant literature has been found to be an effective way of finding more relevant information.

Personal communication with relevant field experts has been a good contribution. Also, acknowledged textbooks in the academic community have been studied. Bane NOR's Tech-

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[8] The usage of asterisks at end of keywords includes different suffixes in the search

nical regulations (`https://trv.banenor.no/`), *Jernbanekompetanse* (initiated by Jernbaneverket Teknologi, `http://www.jernbanekompetanse.no`) and lecture notes from NTNU have contributed to general understanding where this is needed.

Table 3.1: Main keywords used in literature search

Subject	Keywords
Related work	`parametric study railway; energy consumption capacity rail*; effects energy capacity rail*; "track gradient" "energy consumption" parameters`
Track gradient	`track gradient; track gradient rail*; stigning jernbane`
Energy consumption	`energy consumption rail*; energy saving rail*; tog energi*; jernbane energi*; energiforbruk jernbane sintef; auxiliary systems rail*`
Capacity	`capacity rail*; capacity gradient rail*; theoretical capacity; block sections capacity; minimum headway times rail*`
Resistance	`train resistance; tunnel resistance rail*; traction force rail*; tractive force rail*`
Other topics	`adhesion rail*`

3.2 Parameter identification

Track gradient related parameters influencing the combined effects of the railway capacity and energy consumption are identified through literature and interviews with experts in the field. When choosing the relevant parameters, it was important that they could be built in the model. Because of this criteria, some parameters like driving behavior and degree of coasting are excluded, mainly due to model limitation in incorporating these parameters. It should also be pointed out that the approach for this project is mainly from a track infrastructural, long-term point of view. To limit the scope to a manageable size, some parameters, mostly in relation to operations, were also excluded from the work.

The chosen parameters will be presented and briefly commented, before they are summed up in Table 3.3 and 3.4 on page 32.

Track gradient, *X1*

In Europe, Technical Specifications for Interoperability allows a maximum gradient of 35 ‰ (if average is less than 25 ‰ over 10 km and maximum length of continuous 35 ‰ does not exceed 6 km) for sections with dedicated high speed passenger trains (The European Commision, 2014).

Technical regulations in Norway are based on these values, but most lines in Norway are mixed traffic, and therefore specific regulations for this situation are mostly in use. The normal limit for allowed track gradient on a mixed traffic section in Norway is 12.5 ‰. The equivalent least requirement is 20 ‰. However these are only permitted in lengths up until 3 kilometers after an depth consideration of the relevant railway section (Bane NOR, 2017c). The chosen parameters are the normal limit values (12.5 ‰ constant gradient, Profile 3), least requirement values (alternating 20 ‰ (for 3 km) and 12.5 ‰ (1 km), Profile 2) and exceeding normal values (20 ‰ constant gradient, Profile 1). These gradient profiles are visualized in Figure 3.2.

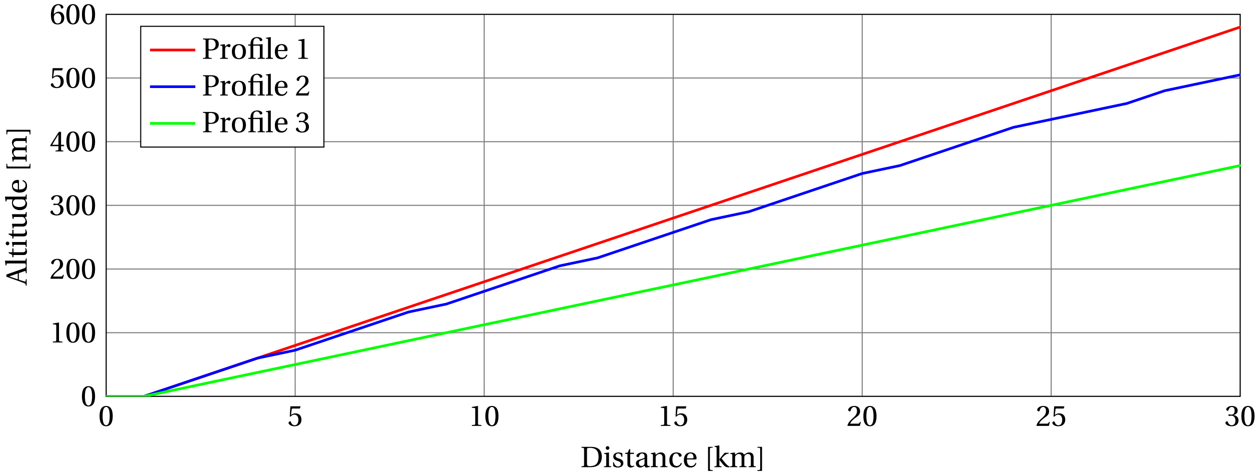

Figure 3.2: Visualization of gradient profiles

Max passenger train speed, *X2*

As of today, the fastest passenger trains in Norway travel at speeds up to 200-210 km/h (Stadler Rail Group, 2017; Bane NOR, 2017b). However, with the development of new InterCity infrastructure, the goal is to increase the top speed of passenger trains on stretches between the major cities to 250 km/h (Jernbaneverket, 2016, 2015b). Therefore, when it comes to the max passenger train speed, a future scenario, 250 km/h, and a present scenario, 200 km/h, will be considered.

Train mix, *X3*

Landex et al. (2006) states that heterogeneity on a railway section has a major negative contribution on the capacity. Therefore, three levels of train mixes will be considered. As a Norwegian rail line has a majority of passenger train traffic, this is the case with the scenarios as well. All scenarios have maximum two different train types (freight train (FT) and passenger train (PT)), but these may have different characteristics depending on the model run. The total train amount for all levels is four and a timetable-independent approach is used. The three scenario mixes are presented in Table 3.2.

Table 3.2: Train mix levels

High level	Medium level	Low level
4PT 0FT	3PT 1FT	2PT 2FT

Gradient direction, *X4*

Braking distances for vehicles will be considerably longer with a descending gradient than when ascending. This is expected to have and impact on the capacity. Also gradient resistance increases with an ascending gradient as seen in Figure 2.2 (page 8), while it ”pushes” a vehicle with a descending gradient. Therefore differentiating between an ascending and descending gradient is a parameter that is considered to have an effect on the capacity and energy consumption.

Freight train speed profile at entry, *X5*

The entry speed profile defines if a train enters the analysis stretch at maximum speed, *flying start*, or if it starts standing, *from stop*. This parameter might determine if freight train acceleration versus entry cruising will have a significant impact on the energy consumption and capacity.

Section length, *X6*

With a longer section length, there will be a longer running time and could be seen as a bottleneck when considering a total capacity (Abril et al., 2008). It is also interesting to see how the energy consumption per running kilometer is affected by this parameter.

Weight of freight train, *X7*

The weight of freight trains have proven to have an important impact on the energy consumption (Kim & Chien, 2011; Ribeiro et al., 2007; Gunselmann, 2005).

In Norway, a ”light” freight train is between 700-800 tonnes, while the maximum weight of 1200 tonnes is allowed for gradients below 18 ‰.[9]

Although gradient profiles 1 and 2 will have higher gradients than allowed as of today, 1200 tonnes is chosen as a ”heavy” train weight, while the ”light” train is 750 tonnes.

It should also be pointed out that the heavy freight trains have 38 carriages (total length of 589 m[10]), while the light trains have 28 carriages (439 m). This is done to make a more realistic picture, but it could affect especially the capacity, as longer trains will occupy block sections longer.

Tunnel, *X8*

The resistance in a tunnel is assumed to increase compared to that on an open track (Raghunathan et al., 2002). Therefore it should impact the total energy consumption and is therefore included.

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[9] E-mail from Alf Helge Løhren (Chief Engineer, Technical Department, Infrastructure, Bane NOR) dated May 14th 2018. According to the concerned, adhesion conditions limit this weight.

[10] Just under the maximum train length in Norway today. This is limited by the diverging track lengths (same e-mail from Løhren).

Summary

The chosen parameters are summed up in Table 3.3. The table also presents high and low levels of each parameter. Table 3.4 presents the quantifiable levels where possible, as well a medium level where this is included.

Table 3.3: Presentation of parameters and corresponding high and low levels

Parameter	**Abbreviation**	**High level, $+I$**	**Low level, $-I$**
Track gradient	*X1*	Exceeding normal values	Normal values
Max passenger train speed	*X2*	Fast	Slow
Train mix	*X3*	Mixed	Uniform
Gradient direction	*X4*	Ascending	Descending
Freight train speed profile at entry	*X5*	From stop	Flying start
Section length	*X6*	Long	Short
Weight of freight train	*X7*	Heavy	Light
Tunnel	*X8*	In tunnel	Open track

Table 3.4: Parameter level values. See Table 3.3 for parameter description

	High level, *+I*	Medium level, *0*	Low level, *-I*
X1	Profile 1	Profile 2	Profile 3
X2	250 km/h		200 km/h
X3	100 % mix	75 % mix	50 % mix
X4	Ascending		Descending
X5	From stop		Flying
X6	30 km		15 km
X7	1200 t		750 t
X8	In tunnel (59 m^2)		Open track

3.3 Infrastructural model and inputs

An infrastructure model is built in a microscopic software. The model uses a deterministic approach, meaning that all output variables solely depend on the relationship between the input variables and has no room for random variation. The model is meant to reflect an excerpt of a dummy stretch in Norway where passenger trains operate a line between several stations, whereas freight trains want to travel through the stretch as fast as possible. Unlike what the case on a given stretch in Norway most likely would be, the model is double-tracked. A double-tracked model is chosen mainly because the capacity for double-tracked lines are less complicated to calculate than for single-tracked lines, where operational complexities have a larger impact.

The model is built in a data software called LUKS. It's name is drawn as an abbreviation of *Leistungsuntersuchung Knoten und Strecken* (German for *Analysis of nodes and lines*) (VIA Consulting & Development GmbH, 2016).

The program has several modules all using different methods. The developer's goal for the program is to be able to use these modules in different phases of planning, dependent of the time horizon and whether a timetable is known (short-term), a timetable structure is given (mid-term) or if only general constrains are available (long-term) (VIA Consulting & Development GmbH, 2016).

In this thesis, the general module and the LUKS-A (Analysis) module will be used.

Desired output variables from LUKS are minimum headway times between different train types and a basis for being able to calculate the energy consumption.

To structure this section, subheads corresponding to names of tabs in the software are used. Italics are used for terms taken directly from the program.

3.3.1 Infrastructure

The infrastructure part of the model is meant to contain a double-tracked line with a station on each end. Each station should have a diverging track in both directions, making the each station have a total of four tracks. *StasjonA (StA)* has a lower altitude than *StasjonB (StB)*. The intermediate line between the stations is called *Line*. See Figure 3.3 for a principal sketch of the situation to be built.

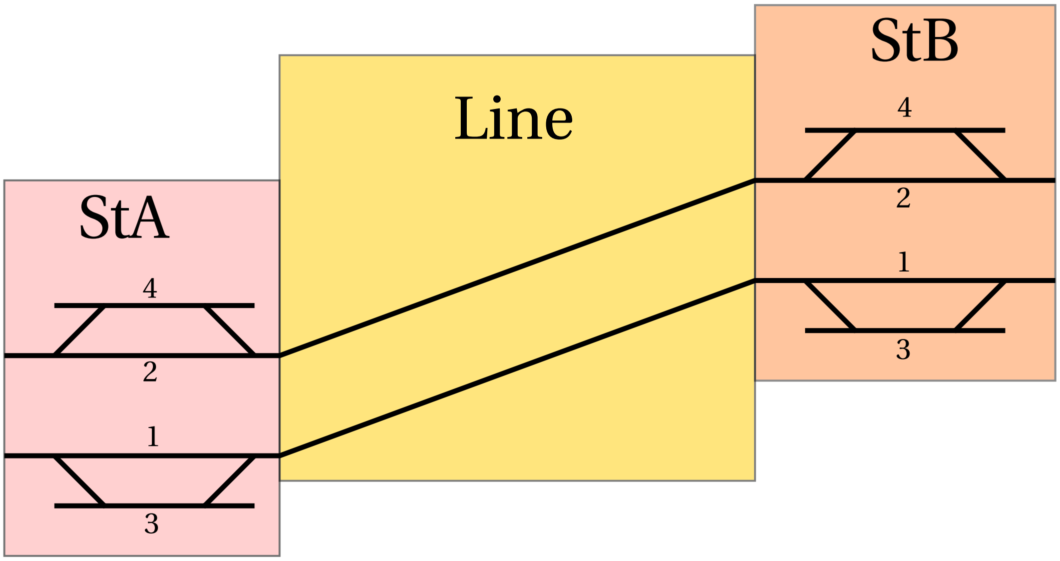

Figure 3.3: Principal sketch of the analysis area. Numbers represent different track names

Stations

Each station is added by using the template *Station 2-track with extra track on both sides V60*. The first station is *insert*ed *separately*, while the second is *connect*ed *to current station* with an intermediate line. One file is created with 15 km intermediate line and one file with 30 km intermediate line.

Further it is important that signalling equipment is sufficient. This includes main signals, signal liberation equipment and route liberation equipment for signals and switches. Switches and crosses, as well as main signals should have a corresponding signal liberation equipment.

Main signals are all placed minimum 10 meters ahead of the stopping positions, so they are visible to the vehicle driver.

ETCS (European Train Control System) level 2 (specifically the variant called *JB <ETCS 2>*, a Norwegian version) is added at the start of each line.

When using ETCS level 2, a train's position and speed is controlled by a radio block centre (RBM) track-side, which through the GSM-R radio network is shown on the driver's on-board computer (Dhahbi et al., 2011). Because of this, distant signals can be removed.

A while it was considered modelling for even longer freight trains (750 meters). In this case, the stopping position for the freight train was overlapping with switches. Therefore all objects at the start and end half of respectively *StasjonA* and *StasjonB* where moved 200 m. Although the final simulations didn't end up using as long trains, the prolonged stations was used further in all simulation runs. Thus, stopping positions are changed to 470 m and 770 meters for passenger and freight trains respectively as well.

Allowed line speeds are defined. The allowed line speed is 250 km/h for track 1 and 2. The infrastructure model does not include specifically details about switches. Therefore it is necessary to define an allowed speed in the diverging track. This speed is defined as 80 km/h. This corresponds to a switch type 1:15 R760 or 1:14 R760 according to Norwegian technical regulations (Bane NOR, 2017d), meaning that the radius has to be at least 760 m for the turnout.

Other than this, the stations are kept as in the template.

Figure 3.4 shows a detailed overview over the result of *StasjonA*. It should be noted that tracks 1 and 3 (see Figure 3.3 for track numbers) carry ascending trains (traveling from left to right), and the infrastructure is built to correspond in this direction. The opposite is the case the infrastructure on tracks 2 and 4, where descending trains travel from right to left. The large *km -0.100* indicates the middle chainage of the station (as it stretches from km -0.925 to km 0.725).

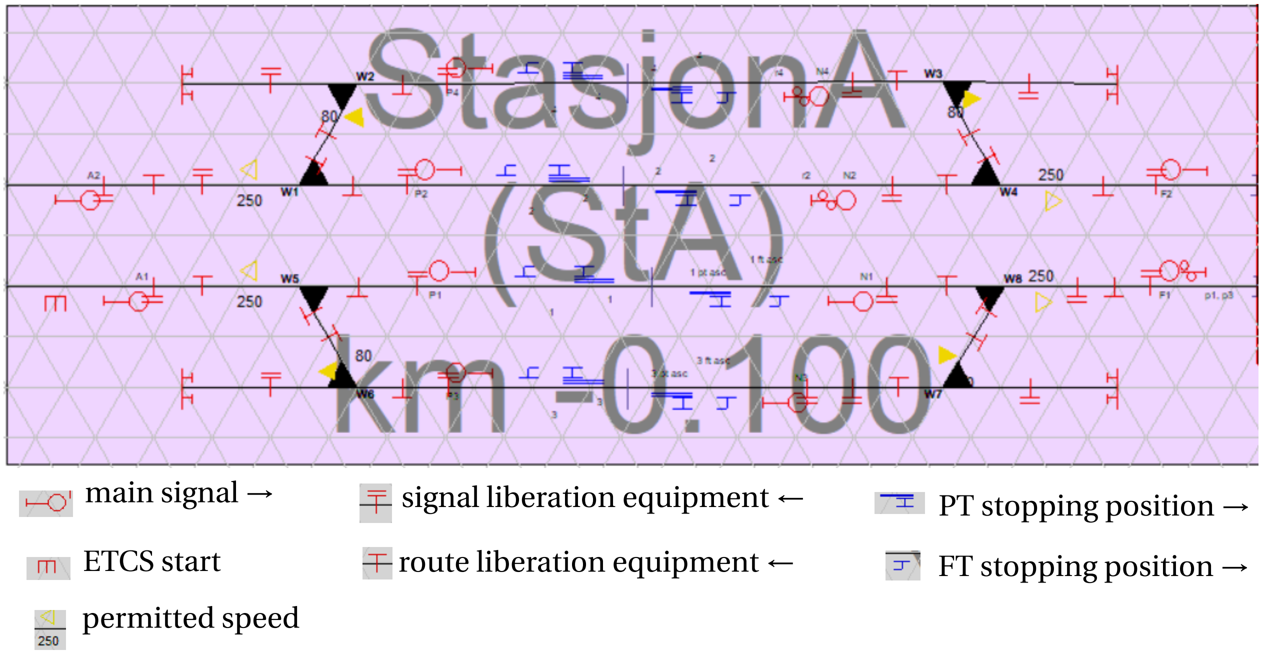

Figure 3.4: Close-up of station with legend. Arrows indicate direction where relevant. Screenshot from LUKS

Line

Signal liberation equipment is placed at same chainage as main signals[11], with a distance equal to block section length. Due to the fact that the ideal state is desired, the block section length differs in track 1 and 2, as well as for the different track gradient profiles. See appendix B for approach and calculation of block section length. However, block section lengths are not changed for different trains for simulation runs. Permitted speeds are added to *Line* as well.

Because the *Line* segment in the software is defined as a station, stopping positions are required. However, these are not used.

From here, different model files are made for different parameter levels. Specifically, separate files are made for all track gradient profiles, tunnel/open track cases and freight train entry speed profiles – and for all the combinations of these.

When including tunnel infrastructure, the cross section of 59 m^2 is used. This cross section is chosen as it is what is being designed for in single-track tunnels on the InterCity project between Drammen and Kobbervikdalen (Bane NOR, 2017a).

Gradient changes are added corresponding to the track gradient profiles shown in Figure 3.2. All ascending gradients start one kilometer after the station boundary from *StasjonA* to imitate how a typical situation would be. This decision will be further discussed in section 5.3. A case with no gradient is included for some comparative reasons.

Figure 3.5 shows a detailed overview of a specific case of the intermediate line, specifically gradient profile 2 through tunnel. See Figure 3.4 for additional symbol description.

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[11] Usual practice in Norway, according to Christine Handstanger, Infraplan AS

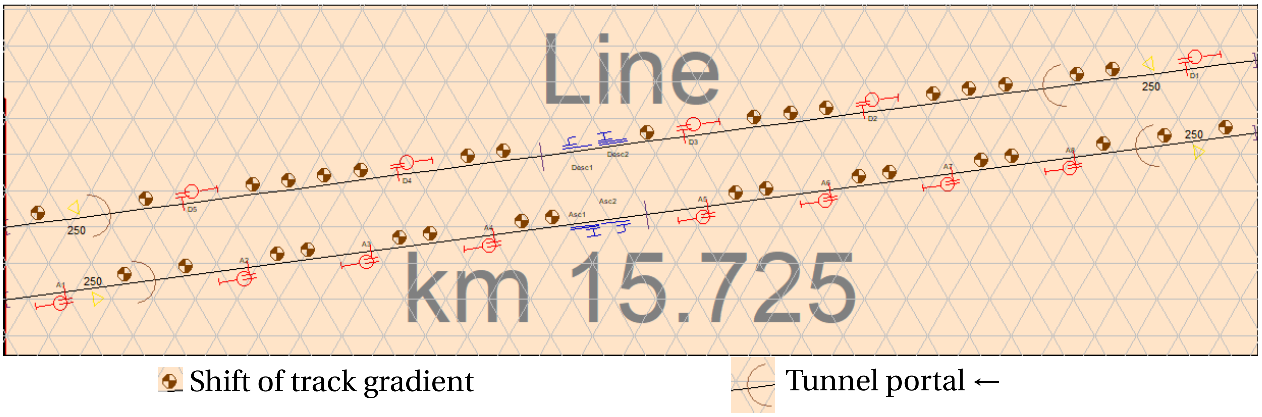


Figure 3.5: Close-up of intermediate line with legend. Arrows indicate direction where relevant. Screenshot from LUKS

An overview of the final infrastructure from LUKS is presented in Figure 3.6.

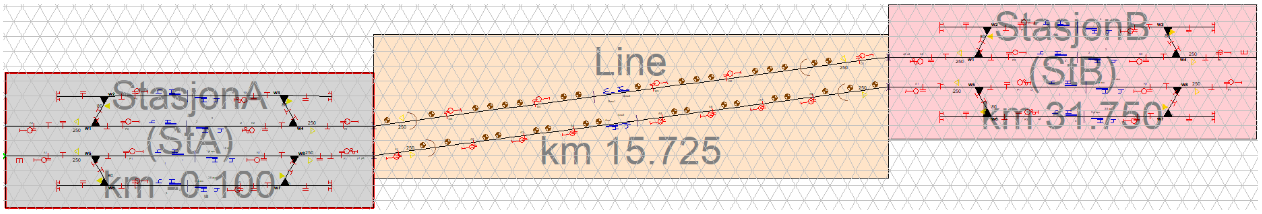


Figure 3.6: Infrastructure overview. Screenshot from LUKS

Alternative construction of track infrastructure

It was also attempted to build track infrastructure for the model in a different data software. The program used, RailCOMPLETE, is a CAD system plug-in with several specific railway infrastructure features. Developers state that the program "enables owners, designers, contractors and testers to organize and edit railway data", and in that way simplifying both production of 2D drawings and 3D visualizations in all stages and for several professional disciplines of a railway project (Railcomplete AS, 2017).

A meeting with the program developers was held followed by a quite comprehensive training in the program. The CAD model was built with the infrastructure needed to run the model simulations. A screenshot of the model showing some details on one of the stations is shown in Figure 3.7.

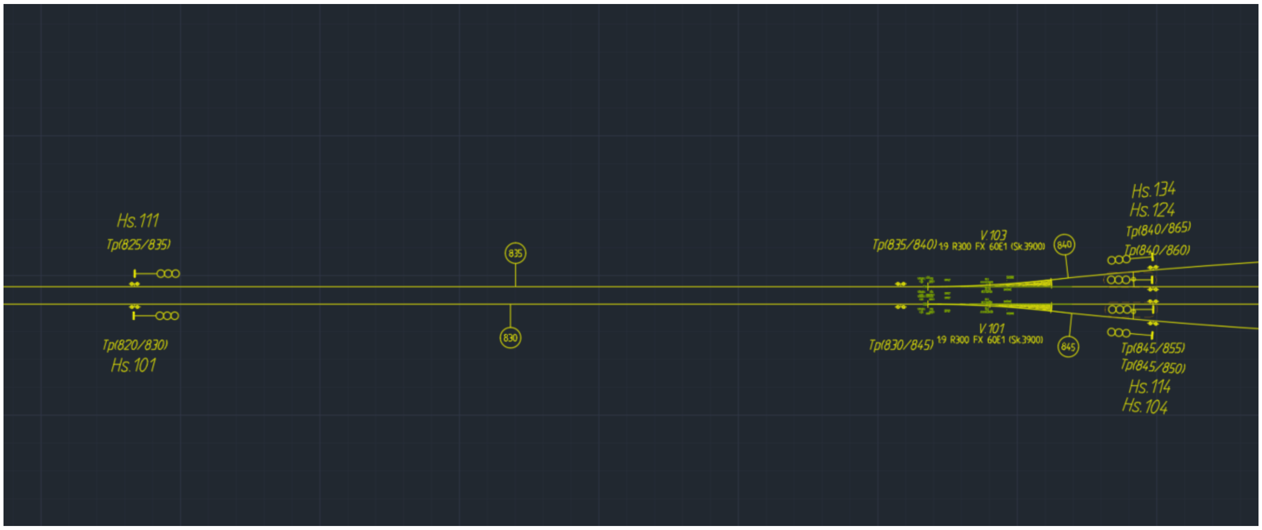


Figure 3.7: Alternative model showing some infrastructural details. Screenshot from RailCOMPLETE

To be able to use the CAD model for analysis of operating factors, such as energy consumption and capacity, there was a need to open the built model in LUKS. To do this, there was a need to convert the CAD model to a railML file, an open-source file format with a goal to enable railway applications to communicate with each other (railML.org, 2018). Both RailCOMPLETE and LUKS are capable of using this format.

However, there was some trouble in this conversion, and LUKS was not able to open the railML file created in RailCOMPLETE. After both the author and the developers of the latter program had conducted troubleshooting, but were not able to find any immediate solutions to the problem, the infrastructure was built in the LUKS program, as described.

3.3.2 Itineraries

In the *Itineraries* tab, train routes are defined for each station. All routes in use for these simulations exit/entry from *StasjonA* and *StasjonB*, as stops are defined at a later stage. Main tracks are defined as track 1 and 2 (respectively left to right and right to left), while diverging tracks are tracks 3 and 4 (see also Figure 3.3 for visual representation). Routes going opposite directions are not used.

Figure 3.8 shows a representation of a defined itinerary, in this case track 4. The green arrow indicated the train's direction of motion.

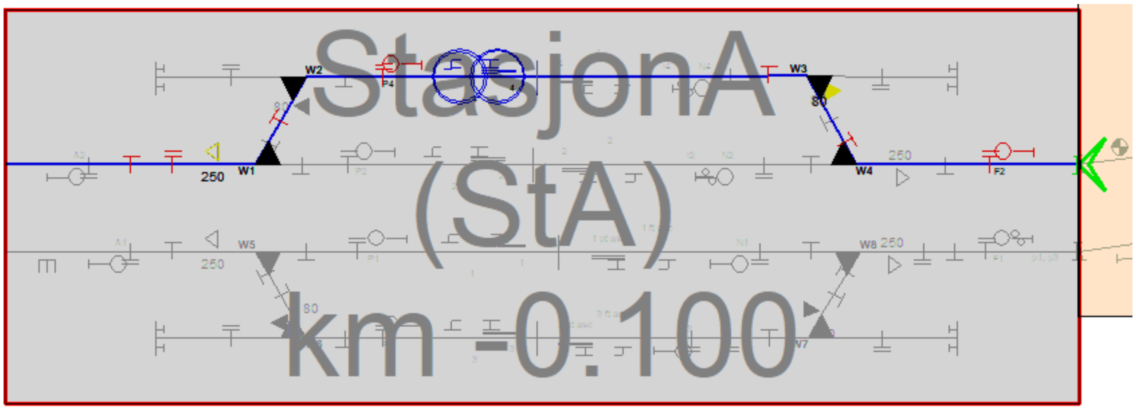


Figure 3.8: Representation of itinerary definition. Screenshot from LUKS

3.3.3 Train runnings

In the *Train runnings* tab, the trains to run on the infrastructure is defined. The LUKS train hierarchy is from top to bottom *train families*, *pattern trains* and *discrete trains*. For the first two levels, there is no need to do any major changes, although for the pattern trains, a reference station has to be defined. *StA* is used for ascending trains and *StB* is used for descending trains.

The discrete train production is created so planners rather easily can generate a correct amount of discrete trains with timetable inputs to visually identify conflicts. However, in this case, one train running is sufficient to find values needed for the energy consumption, while the minimum headway times, needed for the theoretical capacity are found using the LUKS-A module.

There will be four different train types in each direction. Table 3.5 presents these.

Table 3.5: Train types used in infrastructure model

Parameter	Level	Name	Short description
X2	+I	PT_fast	Passenger train, 250 km/h
	-I	PT_slow	Passenger train, 200 km/h
X8	+I	FT_heavy	Freight train, 1200 tonnes
	-I	FT_light	Freight train, 750 tonnes

Under the *Train runnings* tab, there are several new tabs. These will be presented separately.

No changes have been done from standard values unless stated explicitly.

***train data* tab**

Table 3.6 represents inputs under *train data* tab.

Table 3.6: Summary of *train data* inputs in LUKS

	PT_fast	PT_slow	FT_heavy	FT_light
Train type	LDPT	LDPT	LDFT	LDFT
Commeric. type	ICE	IC	Godstog	Godstog

***vehicle dynamics* tab**

Table 3.7 represents inputs under *vehicle dynamics* tab. In cases where values are not specified default values are used.

Table 3.7: Summary of *vehicle dynamics* inputs in LUKS

	PT_fast	PT_slow	FT_heavy	FT_light
main tractive unit	Velaro TOBR110515-1.0	BM74 SJS 100720-1.0 BM74_75	El19 TOBR110515-1.0	El19 TOBR110515-1.0
additional tractive unit	–	BM74 SJS 100720-1.0 BM74_75	–	–
train length [m] (carriages)	200 (1)	212	589 (38)	439 (28)
mass of train set [t]	–	–	1200	750
v max [km/h]	250	200	100	100
braking position	R+Mg	R+Mg	G	G
brake perc. [%]	200	200	80	80
ETCS Level 2	☑	☑	☑	☑

***delay data* tab**

Initial delays at entry are needed to calculate minimum headway times. LUKS' *Approxim. values* are used.

***train course* tab**

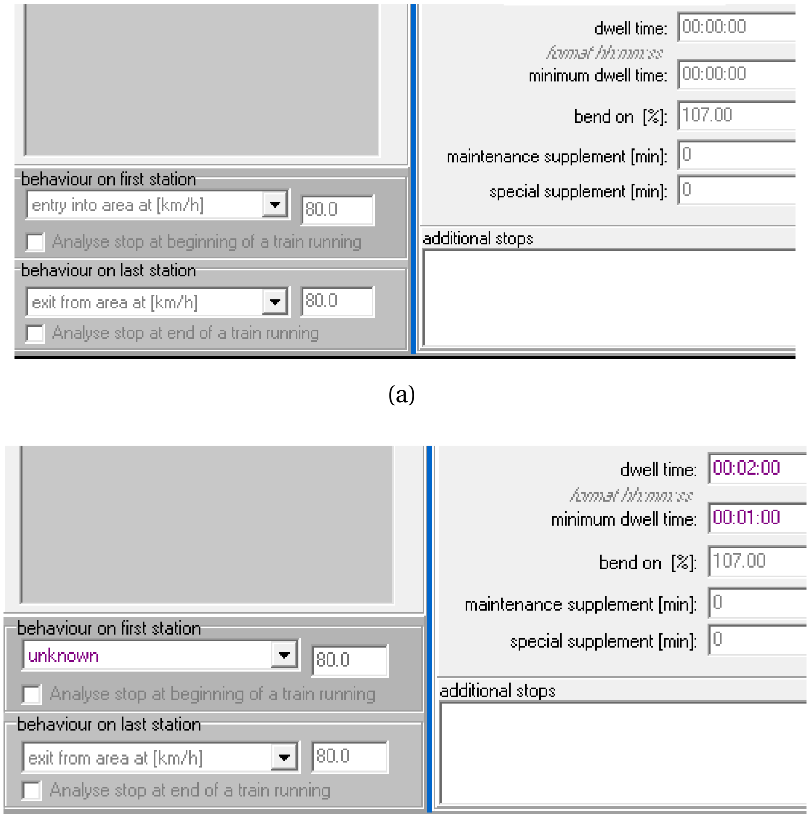
In the *train course* tab, several input parameters are decided. Based on itineraries previously decided, the train course for each train is defined.

Dwell times are set to 2 minutes, while minimum dwell times are set to 1 minute. *Bend on* values (supplement) are changed to 107 % and 109 % for respectively freight and passenger trains (as LUKS has a basis addition of 3 % that is not visible in the user interface). This corresponds to characteristic values for a Norwegian railway line.[12]

Thereafter, the behaviour entering the first station and leaving the last station is defined. For the flying start situation. Figure 3.9 illustrates inputs for flying stop and from stop scenarios. When *behaviour on first station* is *unknown*, the train starts from stop at station. All passenger trains start from stop.

---

[12] Freight train: 10 %. Passenger train: 12 %.
E-mail from Christine Handstanger dated April 22nd 2018



dwell time: 00:00:00
format hh:mm:ss
minimum dwell time: 00:00:00
bend on [%]: 107.00
maintenance supplement [min]: 0
special supplement [min]: 0
additional stops

behaviour on first station
entry into area at [km/h] 80.0
☐ Analyse stop at beginning of a train running
behaviour on last station
exit from area at [km/h] 80.0
☐ Analyse stop at end of a train running

(a)

dwell time: 00:02:00
format hh:mm:ss
minimum dwell time: 00:01:00
bend on [%]: 107.00
maintenance supplement [min]: 0
special supplement [min]: 0
additional stops

behaviour on first station
unknown 80.0
☐ Analyse stop at beginning of a train running
behaviour on last station
exit from area at [km/h] 80.0
☐ Analyse stop at end of a train running

(b)

Figure 3.9: *delay data* inputs for difference between (a) flying start and (b) from stop for FT

running times **tab**

The *running times* calculations are *Saved as csv* for all train types and infrastructure elements, before the data file is further processed (see subsection 3.3.6).

velocity diagram **tab**

Velocity diagrams are studied to validate that an expected speed profile is created. In some relevant cases, the velocity diagrams will be presented in chapter 4.

3.3.4 Node analytics

The *node analytics* tab is a part of the LUKS-A module. When opening the tab, LUKS requests whether a capacity analysis should be conducted, which it should. Thereby, minimum headway times are found in the tab with the same name.

These are found by choosing the proceeding and succeeding train. Minimum headway times are read directly from the program, see example in Figure 3.10. The minimum headway time is shown in red.

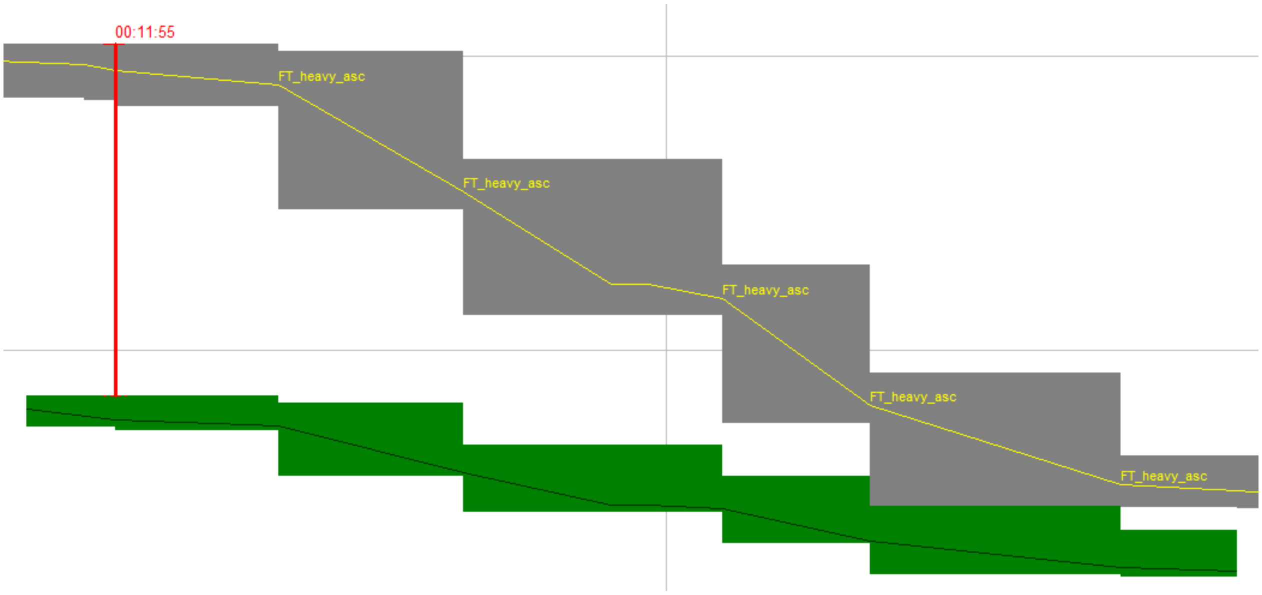


Figure 3.10: Example of how minimum headway time is read for situation with a heavy FT succeeded by a fast PT. Screenshot from LUKS

3.3.5 Other settings

Other relevant settings that can be noted in the infrastructure is that the Δv-step is at the standard value of 5 km/h. Also the tunnel resistance is set to *Schwanhäußer*, which is the most common method used in Germany.[13]

3.3.6 Outputs

Capacity

For each scenario, the outputs from LUKS are train following times, $t_{\text{i-j}}$[s] (i being the proceeding, j the succeeding train), of the following four combinations:

---

[13] E-mail from Christopher Wink, dated May 16th 2018

- FT-FT
- FT-PT
- PT-FT
- PT-PT

The mean minimum headway time is calculated as in equation (2.26) (page 16) for the three different train mix scenarios. Example given in equation (3.1) is for the 75 % train mix with three passenger trains and one freight train.

$$\overline{t_{s,min}} = \frac{1\cdot 1}{4^2}\cdot t_{(\text{FT-FT})} + \frac{1\cdot 3}{4^2}\cdot t_{(\text{FT-PT})} + \frac{3\cdot 1}{4^2}\cdot t_{(\text{PT-FT})} + \frac{3\cdot 3}{4^2}\cdot t_{(\text{PT-PT})} \tag{3.1}$$

Further the theoretical capacity, K, is found using equation (2.27). The observation period, T, is 3600 seconds (1 hour).

Energy consumption

The calculation basis for the energy consumption is the *train runnings* diagram. For the calculations, it is assumed that the resistance is constant for the different distance intervals, as different infrastructure elements creates a new data row in the diagram.

The resistance, W, is the sum of the columns *resist. vehicle*, *resist. tractive unit* and *resist. line* (the latter can be negative, i.e. in descending gradients).[14] Further the tractive effort, F, is presented in its own column. The distance column consists of information on when infrastructure changes occur, as well as the calculations from the Δv-step model. The distance elements in each row, i, is notated s_i.

The section length, L_s, is set to 15 or 30 km depending on the case examined. Hence the total energy consumption per row, E_i, is found in equation (3.2) and the total energy consumption run per section length for a discrete train, E_t, is found in equation (3.3) (based on equation (2.23), page 14).

---

[14] Note that the defined positive direction for resistances is opposite of the direction of the train's motion, unlike the other outputs.

$$E_i = \frac{(s_{i+1} - s_i) \cdot (F - W)}{3\,600\,000} \qquad [\text{kWh}] \tag{3.2}$$

$$E_t = \frac{\sum E_x}{L_s} \qquad \left[\frac{\text{kWh}}{\text{km}}\right] \tag{3.3}$$

The total energy consumption output given a scenario run, E, sums the energy capacity for each train mix, i.e. $E_{FT} \cdot 1 + E_{PT} \cdot 3$ for 75 % mix.

3.4 Parametric influences

3.4.1 Regression analysis

To study the effects calculated by LUKS, a regression analysis is to be used. The methodology (referred to as the method of least squares in the reference) is based on Box (2005). The general model can be written as in equation (3.4), where $\hat{y}$ is the estimated model response, β's are unknown constants to be estimated and x's are known values. ϵ represents the deviation from the observed value.

$$\hat{y} = \beta_0 + \beta_1 \cdot x_1 + \beta_2 \cdot x_2 + \cdots + \beta_k \cdot x_k + \epsilon \tag{3.4}$$

When the infrastructure model has been run and calculations have been completed, there are two output parameters: The theoretical capacity, K and the energy consumption, E.

Since a high capacity and a low energy consumption is considered optimal, there is a need to code the parameters to range from an undesired (0) to a desired score (1). The coded capacity, Y_1, and coded energy consumption, Y_2, are defined in equations (3.5) and (3.6).

$$Y_1 = \left(\frac{K - K_{\min}}{K_{\max}}\right) \cdot \frac{1}{1 - \frac{K_{\min}}{K_{\max}}} \tag{3.5}$$

$$Y_2 = \left(1 - \frac{E}{E_{\max}}\right) \cdot \frac{1}{1 - \frac{E_{\min}}{E_{\max}}} \tag{3.6}$$

To weight the outputs, weighting factors, w_1 and w_2, are introduced. The combined weighted output, Y, is called the observed response. The weighted output elements can be gathering in a vector consisting of n elements, where n is the number of simulation runs. See equations (3.7), (3.8) and (3.9).

$$Y = w_1 \cdot Y_1 + w_2 \cdot Y_2 \qquad w_1, w_2 \in [0,1] \tag{3.7}$$

$$w_1 + w_2 = 1 \tag{3.8}$$

$$\boldsymbol{Y} = \begin{bmatrix} Y_1 & Y_2 & \dots & Y_n \end{bmatrix} \tag{3.9}$$

Corresponding to the observed response variables from the infrastructure model, K and E, there is an X matrix, consisting of information on which scenario run is related to the outputs. For each element, $X\mathrm{p}_{\#}$, p is the parameter, while # is the simulation run.

Due to trouble with notation in the statistical tool, the authors were unfortunately not able to include medium values, 0, in the parametric study. Also one of the parameters was not able to be modelled, see sections 4.1.8 and 5.4 for elaboration. As a consequence of this, the $\mathbf{X}_{\text{onefactor}}$ matrix consists of elements is a two-level design matrix consisting of high ,1, and low, -1, levels with $2^7 = 128$ different scenarios. Hence, the 7x128 matrix is defined in equation (3.10).

$$\boldsymbol{X}_{\text{onefactor}} = \begin{bmatrix} X1_1 & X2_1 & X3_1 & X4_1 & X5_1 & X6_1 & X7_1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ X1_{128} & X2_{128} & X3_{128} & X4_{128} & X5_{128} & X6_{128} & X7_{128} \end{bmatrix} \tag{3.10}$$

It is also desired to include the quadratic and two-factor interactions. This makes a 28x128 matrix defined in equation (3.11).

$$\boldsymbol{X}_{\text{twofactor}} = \begin{bmatrix} X1_1^2 & X1_1 \cdot X2_1 & X2_1^2 & X2_1 \cdot X3_1 & \dots & X7_1^2 \\ X1_2^2 & X1_2 \cdot X2_2 & X2_2^2 & X2_2 \cdot X3_2 & \dots & X7_2^2 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ X1_{128}^2 & X1_{128} \cdot X2_{128} & X2_{128}^2 & X2_{128} \cdot X3_{128} & \dots & X7_{128}^2 \end{bmatrix} \tag{3.11}$$

The two matrices are combined to a total X matrix. A new first column consisting of all 1's are added to weigh in the β_0 value. This sums up to a total size of 36x128. See equation (3.12).

$$\boldsymbol{X} = \begin{bmatrix} 1 & X1_1 & \dots & X7_1 & X1_1^2 & X1_1 \cdot X2_1 & \dots & X7_1^2 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & X1_{128} & \dots & X7_{128} & X1_{128}^2 & X1_{128} \cdot X2_{128} & \dots & X7_{128}^2 \end{bmatrix} \tag{3.12}$$

A beta vector, consisting of 36 β-values is defined as in equation (3.13). The β values are unknown constants to be estimated.

$$\boldsymbol{\beta} = \begin{bmatrix} \beta_0 & \beta_1 & \beta_2 & \dots & \beta_7 & \beta_{11} & \beta_{12} & \beta_{22} & \dots & \beta_{77} \end{bmatrix} \tag{3.13}$$

From this, the predicted response, $\hat{Y}$, is defined in as equations (3.14) and (3.15).

$$\hat{\boldsymbol{Y}} = \boldsymbol{X}\boldsymbol{\beta} \tag{3.14}$$

$$\begin{aligned} \hat{Y} = {} & \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \beta_7 x_7 + \beta_{11} x_1^2 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 \\ & + \beta_{14} x_1 x_4 + \beta_{15} x_1 x_5 + \beta_{16} x_1 x_6 + \beta_{17} x_1 x_7 + \beta_{22} x_2^2 + \beta_{23} x_2 x_3 + \beta_{24} x_2 x_4 + \beta_{25} x_2 x_5 \\ & + \beta_{26} x_2 x_6 + \beta_{27} x_2 x_7 + \beta_{33} x_3^2 + \beta_{34} x_3 x_4 + \beta_{35} x_3 x_5 + \beta_{36} x_3 x_6 + \beta_{37} x_3 x_7 + \beta_{44} x_4^2 \\ & + \beta_{45} x_4 x_5 + \beta_{46} x_4 x_6 + \beta_{47} x_4 x_7 + \beta_{55} x_5^2 + \beta_{56} x_5 x_6 + \beta_{57} x_5 x_7 + \beta_{66} x_6^2 + \beta_{77} x_7^2 \end{aligned} \tag{3.15}$$

For the regression analysis, the β values are to be optimized to the degree where the residual, S, presented in equation (3.16), is minimized (equation (3.17)). In this way, the model is expected to best correspond to the observed situation.

$$S(\boldsymbol{\beta}) = \sum \left((Y - \hat{Y})^2 \right) \tag{3.16}$$

$$\min S(\boldsymbol{\beta}) \tag{3.17}$$

Genetic Algorithms (GA) are used to minimize the equation (3.17). See Listing C.1 and C.2 in appendix C for MATLAB coding of this problem.

The output β values were expected to give a statistical insight in which parameters that had the largest effect on the combined effects, where the largest β values would have the largest impact on the total effects of the parameters.

3.4.2 Full factorial design

Full factorial design (FFD) in two levels was later used to visualize significant effects for both individual and two-factor interaction parameters. The method only includes linear effects between the parameters, unlike the regression analysis. The methodology is based on Box (2005) and Antony (2003).

The response vector (1x128), $\boldsymbol{Y}$, is used as previously. In this method, quadratic effects are not included, although two-factor interactions are. The first column of all 1's corresponding to β_0 is removed as well. As a consequence, the $\boldsymbol{X}$ 28x128 matrix is defined as in equation (3.18).

$$\boldsymbol{X} = \begin{bmatrix} X1_1 & \dots & X7_1 & X1_1 \cdot X2_1 & \dots & X6 \cdot X7_1 \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ X1_{128} & \dots & X7_{128} & X1_{128} \cdot X2_{128} & \dots & X6 \cdot X7_{128} \end{bmatrix} \tag{3.18}$$

Box (2005) defines a main effect as the difference between two averages, $\overline{y}_+$, the average for high level responses, and $\overline{y}_-$, the average for low level responses (equation (3.19)).

$$\text{Main effects} = \overline{y}_+ - \overline{y}_- \tag{3.19}$$

It is important to keep in mind that for each parameter and two-factor interaction parameter, the $\boldsymbol{X}$ matrix contains values equal to either 1 or -1. In fact, each column contains 64 1's and 64 -1's. To find the sum of the high and low level responses for a single parameter, one can then simply multiply the vector for the parameter in row i, X_i, with the response, Y, see equation (3.20)

$$\boldsymbol{X_i} \cdot \boldsymbol{Y} = \sum Y_+ - \sum Y_- \tag{3.20}$$

For the total amount of n runs, the number of each level is $^n/_2$, and the average is found by dividing with this value, see equation (3.21).

$$\frac{\boldsymbol{X_i} \cdot \boldsymbol{Y}}{{}^{n}/_{2}} = \overline{y}_{+} - \overline{y}_{-} \tag{3.21}$$

Combined with equation (3.19), it can be seen that the main effects of each parameter can be gathered in a vector, **Eff**, as presented in equation (3.22).

$$\mathbf{Eff} = \frac{\boldsymbol{X} \cdot \boldsymbol{Y}}{{}^{n}/_{2}} \tag{3.22}$$

To identify significant values, an error function is defined , see equation (3.23).

$$\mathrm{err} = \frac{\sqrt{\sum\left(\left(\mathbf{Eff} - \frac{\sum Y}{n}\right)^{2}\right)}}{{}^{n}/_{2}} \tag{3.23}$$

The effects are plotted as a normal probability plot (NPP). If effects are to be considered significant, they will have a large deviation from the expected line. Also, a box plot with the error is plotted and used to visualize whether an effect is significant or not.

See Listing C.3 in appendix C for MATLAB code used for calculations.

Chapter 4

Results

4.1 Single parameter effects

Prior to considering the combined effects of the capacity and energy consumption, outputs from the infrastructure model can give some insight in how single parameter effects contribute.

This will be done for one parameter at a time. Tables and figures considered relevant will be presented and most cases will be compared to the scenario presented in Table 4.1. Where else is not specified, only the parameter in question will have been changed. See Table 3.3 and 3.4 for detailed parameter values.

For the two parameters directly including the track gradient – *X1*, track gradient profile and *X4*, gradient direction – the outputs for a scenario with no gradient is presented as well.

Table 4.1: Parameters used in basis scenario

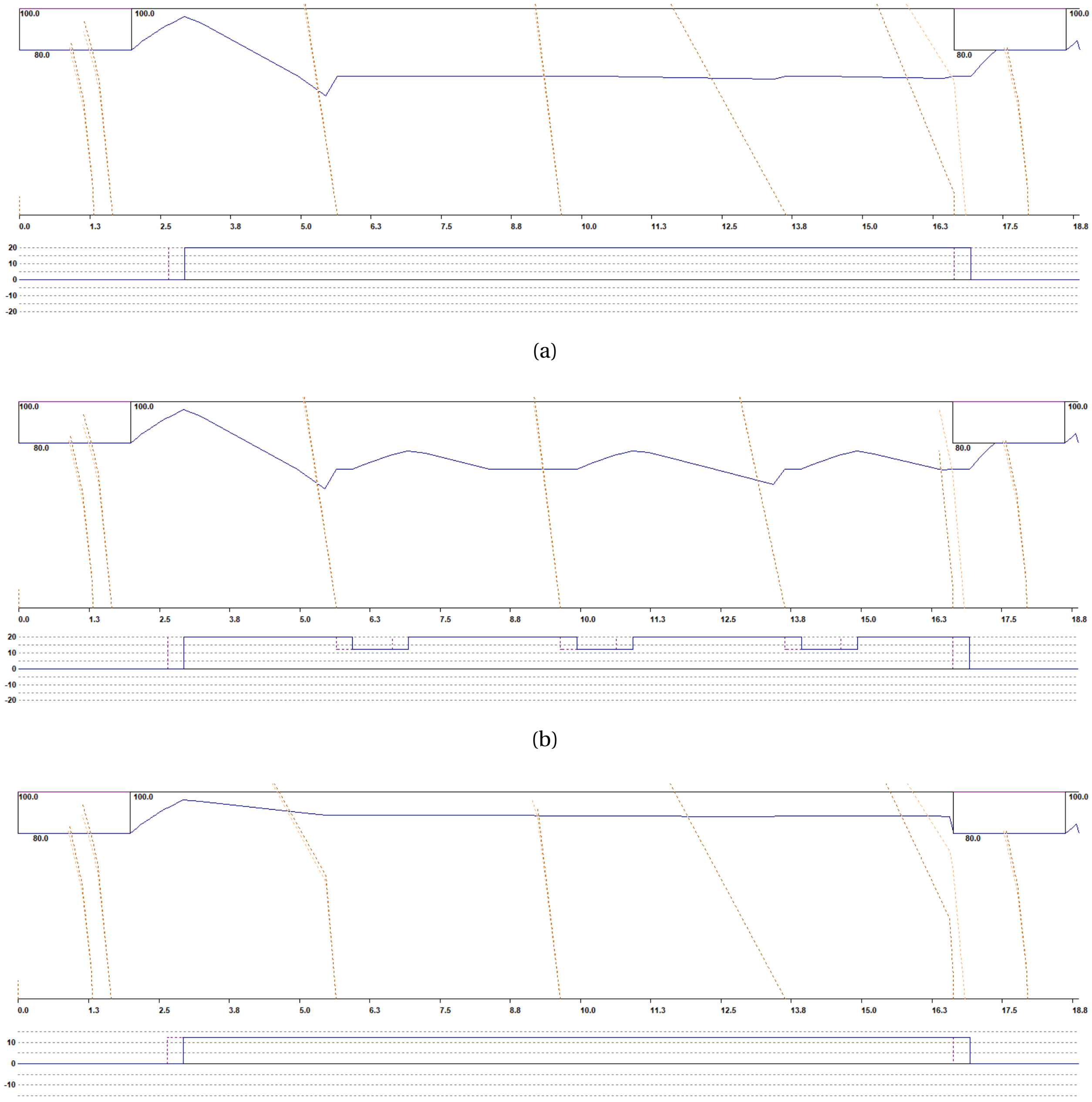
X1	*X2*	*X3*	*X4*	*X5*	*X6*	*X7*	*X8*
0	-I	-I	+I	-I	-I	+I	-I
Pr. 2	Slow	50 % mix	Asc	Flying	15 km	Heavy	OpT

4.1.1 Track gradient profile

Table 4.2 and Figure 4.1 imply the impact of parameter *X1*, track gradient profile.

Table 4.2: Contribution to capacity and energy consumption; track gradient profile

	Profile 1	Profile 2	Profile 3	No gradient
Capacity [trains/hour]	10.8	11.1	13.2	13.6
Energy consumption [kWh/km]	517.1	497.1	426.0	301.6



(a)

(b)

(c)

Figure 4.1: Velocity diagrams for heavy FTs for gradient profile (a) 1 (b) 2 and (c) 3

The freight train has trouble maintaining its speed when travelling in steep gradients, especially when it hits the 20 ‰ gradient. It can be seen that this has a considerable effect on both the capacity and the energy consumption.

4.1.2 Max passenger train speed

Table 4.3 implies the impact of parameter *X2*, max passenger train speed.

Table 4.3: Contribution to capacity and energy consumption; max passenger train speed

	Fast	Slow
Capacity [trains/hour]	11.0	11.1
Energy consumption [kWh/km]	491.3	497.1

It can be seen that this parameter has a minor impact on the capacity and the energy consumption.

4.1.3 Train mix

Table 4.4 implies the impact of parameter *X3*, train mix.

Table 4.4: Contribution to capacity and energy consumption; train mix

	Mixed	75 % train mix	Uniform
Capacity [trains/hour]	11.1	13.9	24.2
Energy consumption [kWh/km]	497.1	399.8	302.5

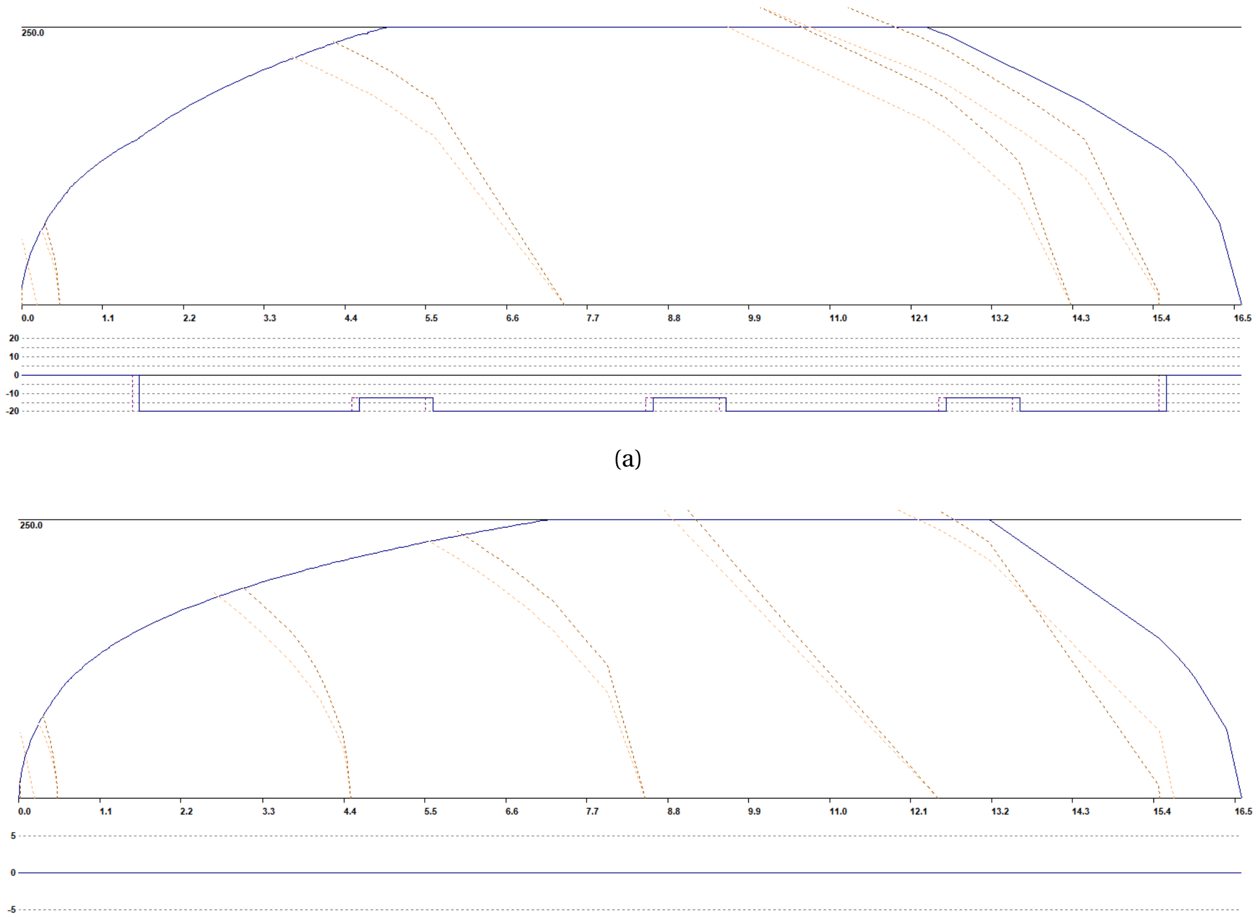
When reducing the number of freight trains in the train mix, it can be seen that this reduces the energy consumption as well. However, it has an even larger effect on the capacity, and the train mix appears to have a major influence.

4.1.4 Gradient direction

Table 4.5 implies the impact of parameter *X4*, gradient direction. Figure 4.2 shows the velocity diagram for a no gradient and descending heavy freight train on a 15 km section.

Table 4.5: Contribution to capacity and energy consumption; gradient direction

	Ascending	Descending	No gradient
Capacity [trains/hour]	11.1	11.0	13.6
Energy consumption [kWh/km]	497.1	142.0	301.6



(a)

(b)

Figure 4.2: Velocity diagrams for heavy FTs for (a) descending profile 2 and (b) no gradient scenario run

The parameter seems to have a minimal effect on the capacity going up- or downhill, while the a the no gradient situation seems to lead to an increased performance. The energy consumption seems extremely dependant of the gradient direction.

4.1.5 Freight train speed profile at entry

Table 4.6 implies the impact of parameter *X5*, freight train speed profile at entry.

Table 4.6: Contribution to capacity and energy consumption; freight train speed profile at entry

	From stop	Flying
Capacity [trains/hour]	10.9	11.1
Energy consumption [kWh/km]	484.9	497.1

This parameter seems to have an inconsiderable impact on both outputs.

4.1.6 Section length

Table 4.7 implies the impact of parameter *X6*, section length.

Table 4.7: Contribution to capacity and energy consumption; section length

	30 km	15 km
Capacity [trains/hour]	7.7	11.1
Energy consumption [kWh/km]	490.7	497.1

The capacity seems to increase with shorter section lengths, and the energy consumption per running kilometer slightly increases.

4.1.7 Weight of freight train

Table 4.8 implies the impact of parameter *X7*, weight of freight train.

Table 4.8: Contribution to capacity and energy consumption; weight of freight train

	Heavy	Light
Capacity [trains/hour]	11.1	14.3
Energy consumption [kWh/km]	497.1	411.1

With light freight trains, the capacity seems to increase. This is in relation to the running time, where the light train will not have as much trouble climbing the gradients as was seen for the heavy freight train in Table 4.1 (b). The minimum headway time between the freight and passenger train decreases, and correspondingly the capacity increases. The light freight trains also seem to have a positive impact on the energy consumption.

4.1.8 Tunnel

At a late stage of the thesis, it was discovered that additional resistance due to the tunnel resistance is not included in the *running time* diagrams from LUKS. Apparently the running time calculations are conducted before the tunnel resistance calculations. As a consequence of this, the energy consumption appears totally unaffected by the tunnel resistance, according to the calculations. However, the velocity diagram calculations are conducted last of the three, and it is therefore possible to see *an* effect of increased tunnel resistance.[15] This effect is illustrated in Figure 4.3.

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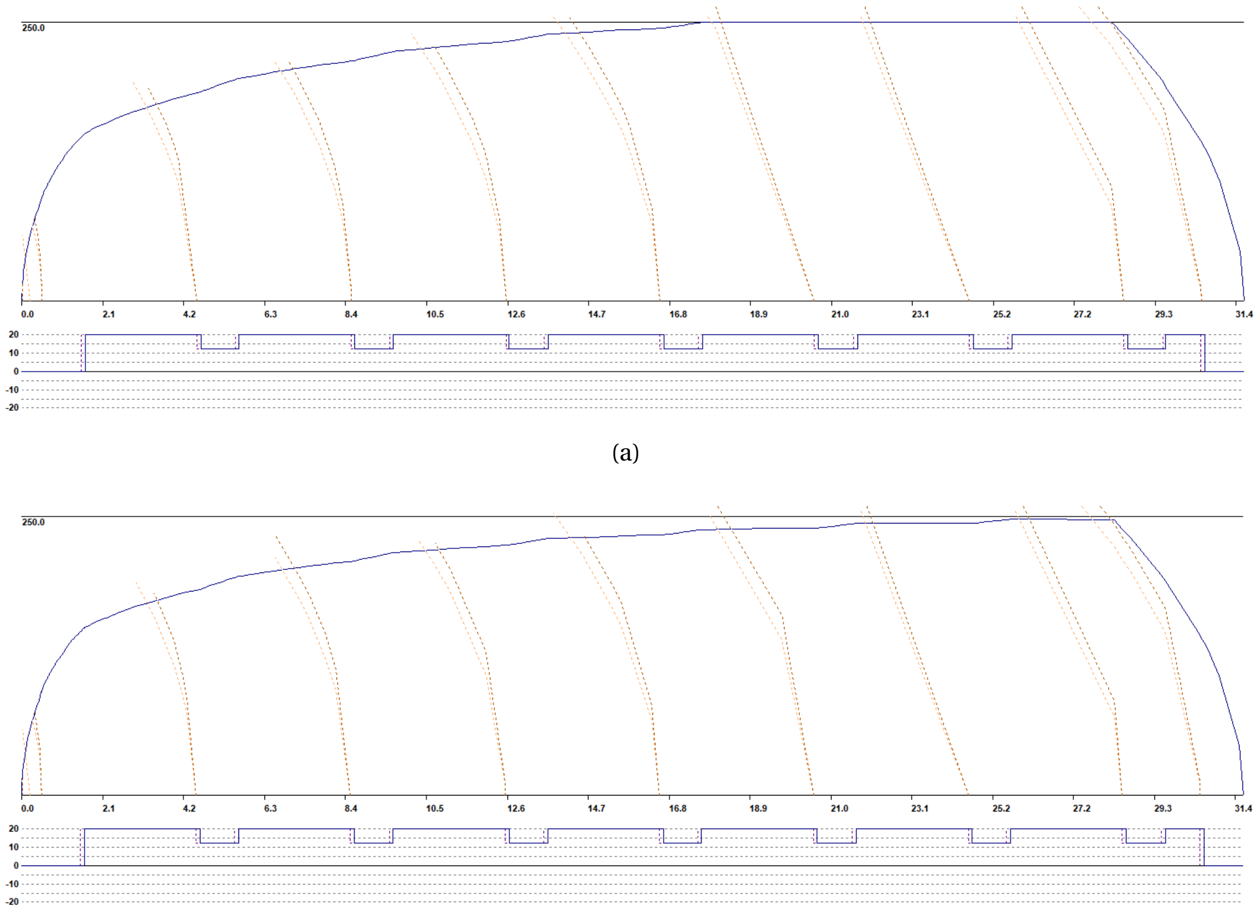
[15] E-mail from Christopher Wink dated May 16th 2018



(a)

(b)

Figure 4.3: Velocity diagrams for a fast PT on a profile 2, 30 km stretch (a) on open track (b) in tunnel

It can clearly be seen that when the fast passenger train is travelling in a tunnel, it does not reach its top speed. This is a consequence of the increased tunnel resistance, and would have an effect on both energy consumption and capacity (due to a longer running time on the section).

Because the energy consumption can not be calculated for the tunnel parameter, *X8*, only parameters from *X1* to *X7* will be included in further calculations.

4.2 Combined parameter effects

4.2.1 Regression analysis

Figure 4.4 shows the results from the first ten runs of the GA. The red dots represent the mean of the first ten values. For these runs, the best residual found was consistently in the 6.48… range.

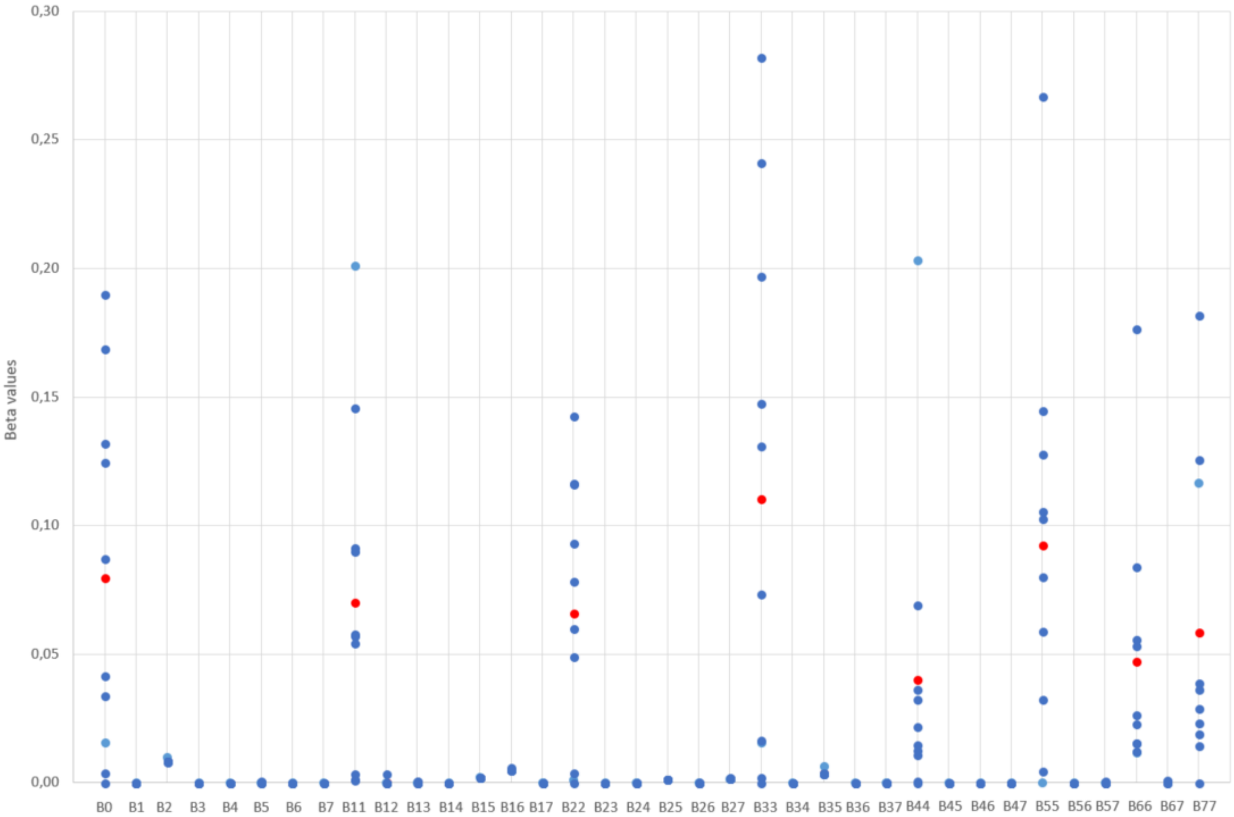


Figure 4.4: Result plot of β-values from GA algorithm with two-factor and quadratic interactions

Although the β values follow some tendencies, it is not sufficient to give a clear understanding of the situation. It should also be pointed out that the β_0 and quadratic values have notably high values. This is to be discussed in section 5.2.

4.2.2 Full factorial design

The calculated combined effects of the parameters and interactions where energy consumption and capacity are weighted equally ($w_1 = w_2 = 0.5$, see equation (3.7) and further discussion in 5.2) are presented in Figure 4.5 and Figure 4.6. The former consists of a Normal Probability

Plot (NPP) for the calculated effects. The solid line joins the first and third quartiles, while the dashed line is an extrapolation of this. For the accumulated normal distribution, points that end up far away from this line are considered having a large effect on the response. The latter figure represents a bar chart containing mostly the same information. The horizontal line represent the absolute error, and effect values that clearly exceed this limit are considered significant. Negative effect values indicate that low, $-I$, values have a positive effect on the total response.

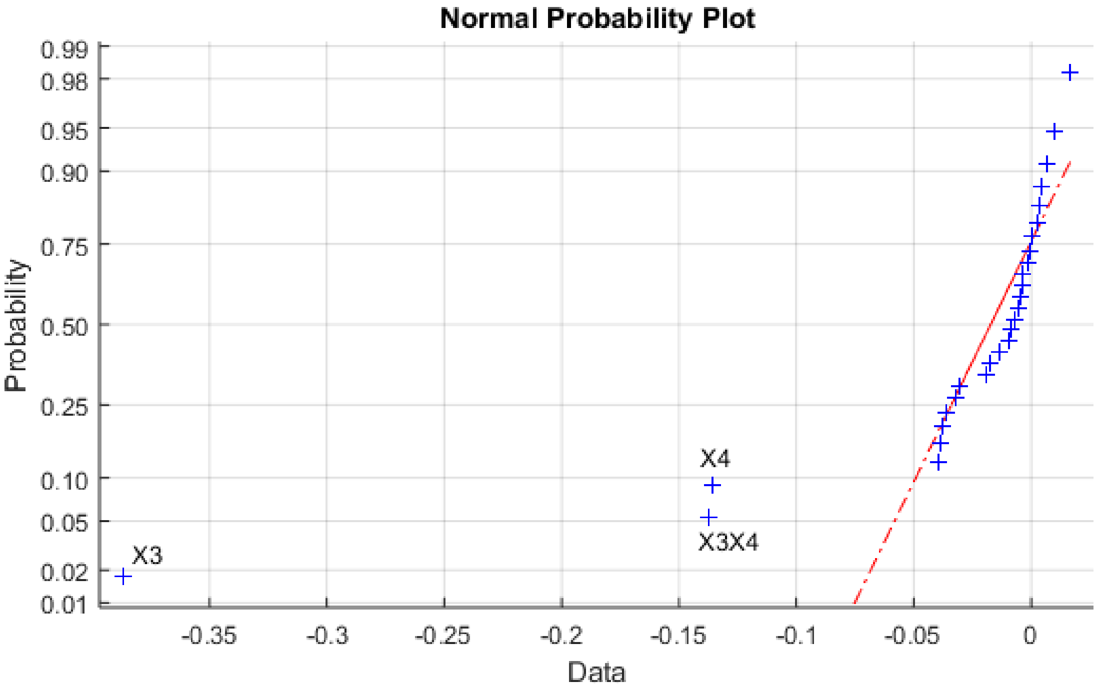


Figure 4.5: Normal Probability Plot of the combined effects of energy consumption and capacity

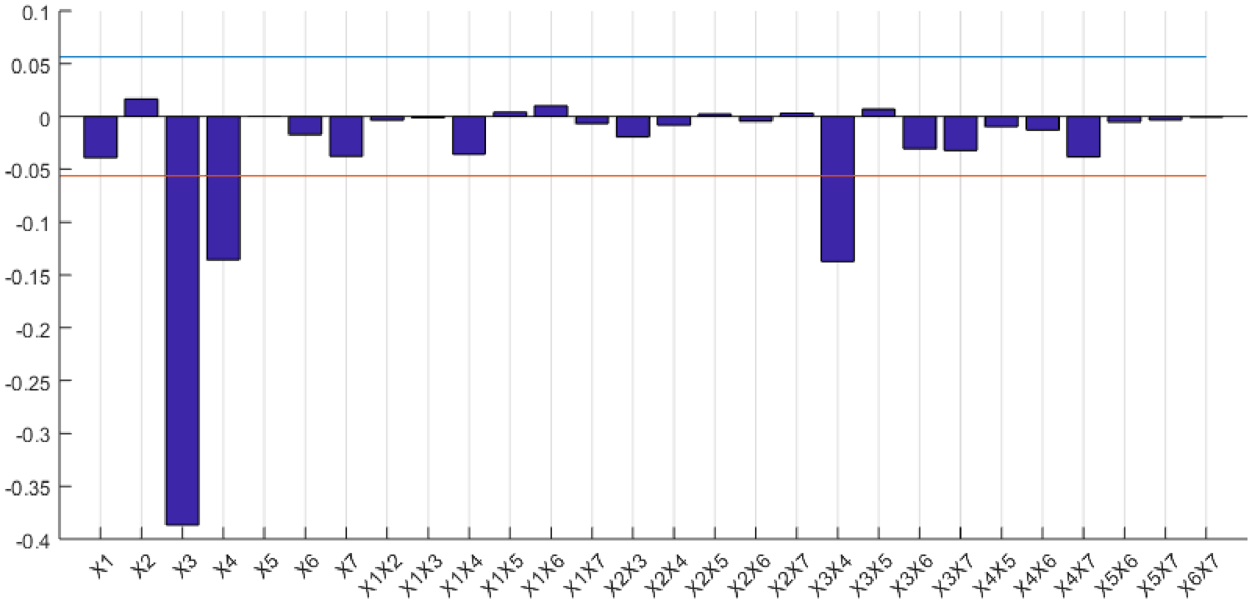


Figure 4.6: Bar plot of combined effects of capacity and energy consumption for each parameter

The largest significant single effect for the combined outputs is the train mix, $X3$. The single effect gradient direction, $X4$, and the interaction effect between train mix and gradient direction, $X3X4$, have also significant effect on the combined output. These are the only parameters with significant effects that can be clearly seen in the normal probability plot.

The track gradient profile, $X1$, is in fact one of the parameters with the largest effects, although it is not considered significant. Other parameters with an equivalent effect is the train weight, $X7$, as well as several two-factor interactions.

Table 4.9 and 4.10 present the parameters for the best and worst case scenario cases respectively.

Table 4.9: Parameters in best case scenario

X1	*X2*	*X3*	*X4*	*X5*	*X6*	*X7*
-I	I	-I	-I	I	I	-I
Pr. 3	Fast	Uniform	Desc	From stop	Long	Light

Table 4.10: Parameters in worst case scenario

X1	*X2*	*X3*	*X4*	*X5*	*X6*	*X7*
I	-I	I	I	-I	I	I
Pro. 1	Slow	Mixed	Asc	Flying	Long	Heavy

4.2.3 Isolated effects on capacity and energy

Similar calculations were also conducted with different weighting factors (w_1 and w_2); both with capacity weighted 100 % (w_1 = 1) and with energy consumption weighted 100 % (w_2=2) to see what parameters are identified as most influential. The figures are placed in appendix D. Results will not be elaborated extensively, but a short summary is presented.

For the capacity, the significant effects are the train mix, $X3$, the gradient direction $X4$, as well as the interaction between the two, $X3X4$. It also seems like the section length, $X6$, has a considerable effect on the capacity of a stretch.

For the energy consumption, the significant single effects are the gradient direction, $X4$, and the train mix, $X3$. The two-factor interaction between the gradient profile and the gradient direction, $X1X4$, as well as that of train mix and gradient direction, $X3X4$, also seem to have a significant value. Section length, $X6$, also looks to have a considerable impact.

Chapter 5

Discussion

5.1 Results

Considering the results from the FFD, it seems to plausibly reflect results found in relevant literature. This indicates that the model built and the study of the parametric influences give a realistic contribution in regard to the stated main goal and research questions.

The fact that the train mix has the largest effect is not surprising. It is known to have a large effect on the capacity. In the way the energy consumption as an output is defined in this thesis, it also quite logically has a considerable effect on the energy consumption. This is because a mixed train mix (2FT, 2PT) basically means two freight trains instead of two passenger trains compared to the uniform mix (4PT), and the larger freight trains obviously has a huge impact on the consumption of energy.

Also it is obvious that the gradient direction has a large impact on energy consumption. Gradient resistance is quite considerable when climbing, while the gravitational contribution also reduces the resistance when descending. The fact that the gradient direction had a significant effect on the capacity isolated however, was a bit more surprising. This probably has is related to the used block section lengths in the ascending and descending directions. This will be discussed in depth later.

One of the effects that were expected to have a an even larger effect on the combined situation was the freight train weight. In section 4.1.7, it can be seen that the situation with a lighter train has a capacity with three more trains/hour as well as the fact that the energy consumption is reduced by 17 % from the heavy situation. Even for the isolated effects on the energy consumption, this effect was not clearly significant. One thing that, in retrospect, logically impacts the freight train's weight again lies in the definition of the energy consumption for this thesis. For all the situation runs with a uniform mix, it shows that even if you change the freight train from a heavy to a light, it has no effect on either the energy consumption or the capacity. This will be the case in half the model runs. This is also the case considering the entry speed profile of the freight trains. If the high level had been chosen as the 75 % train mix, this might have evaluated the freight train weight as more influential on the combined effects. Further consequences of parameter definitions will be discussed in section 5.2.

Considering the single parameter effects of how a scenario with no gradient compares to the track gradient profile and gradient direction (presented in Table 4.2 and 4.5), some implications can be noted. In the ascending case, it can be seen that there is a quite considerable distinction between the capacity for profile 2 and profile 3. However, the no gradient case only has a capacity gain of 0.4 trains/hour compared to the situation with 12.5 ‰ gradient. When considering profile 3 (Figure 4.1 (c)), it can be seen that although the freight train does not reach maximum speed, it is able to maintain a noticeably higher speed than for the two other gradient profiles. This implies that the track gradient profile does not have a significant effect on the railway capacity until heavier freight trains start having trouble maintaining a constant speed.

When it comes to the descending trains, there also seems to be a capacity loss when travelling downhill compared to the no gradient case. Figure 4.2 shows the velocity diagrams for a descending train running on gradient profile 2 and a no gradient scenario. Because of the negative gradient, the descending train reaches its maximum speed approximately two kilometers before the no gradient case. However, the prior case has to start braking just under a kilometer before the latter case. Totally, the running time for the two cases end up at respectively 08:34 and 09:00. Thus, the capacity loss is not because of an increased running time. This implies that the capacity loss is as a consequence of the differentiated block sections lengths. This will be further discussed in section 5.3.

In relation to the track gradient, results show that although the gradient profile does not seem significant for the combined effects, it can be seen that it has quite the effect on the capacity. Also, it was seen that the speed decreases considerably for heavy freight trains travelling uphill (Figure 4.1), and that the energy consumption is increased when going uphill.

5.2 Parametric studies

The results from the regression analysis did not give the desired output. As mentioned, it seems as though the β_0 value and the quadratic effects of the parameters are unreasonably high, compared to those presented in literature and also those later found with the FFD. When considering the coding of the parameters' high and low values, one can see that all quadratic effects, as well as the column in the $\boldsymbol{X}$ matrix corresponding to the β_0 value, will be positive through all the 128 runs. This might ”trick” the algorithm into thinking that the response always should be affected by this value and thus the quadratic values become artificially high. The regression analysis might have given more plausible results if the quadratic effects and their corresponding β values were removed from the data set. Unfortunately, time ran out and the effects were rather studied using the FFD.

Another consideration was the coding of the parameters. First of all the medium level values had to be removed from the data set due to the fact that they were ”creating noise” in the data set by overruling the high and low levels and thus ”confusing” the algorithm. Also, the quadratic effects were doing something similar. This leads to thinking that the coding could be done in a different way to better identify the critical parameters. Quantitative parameters, like passenger train speed and weight of freight train, could have used their actual values as inputs. The tricky part then would have been coding the qualitative parameters, like gradient direction and freight train speed profile at entry. A better coding methodology for the parameters could have improved the parametric studies.

The weighting of the response is something else that could have an impact on the results. Results presented in chapter 4 are from the equal weighting of the energy consumption and capacity. As can be seen in appendix D, the outcome is quite different when the weighting is changed. When considering a railway section, the point of view is quite different for a train owner and operator or the infrastructure owner and operator. For the train operator the goal is to carry the highest amount of goods or passengers between A and B for the lowest possible price. For them the energy consumption is directly translated to cost. From the infrastructure owner's point of view however, the capacity of the section is equally important, so the most amount of train owners can pay for their services. However, the train operator does not want to be delayed as a consequence of a too high occupancy due to low capacity. Likewise, for if the infrastructure owner is not able to deliver i.e. the demanded power for the locomotives, this will decrease their capacity as a result of the slower running times. Because of these relationships, it was desired for the combined effects to be weighted equally in this thesis. In later work, the desired weighting might be considered differently.

5.3 Inputs in the infrastructure model

Block section lengths

As mentioned, different block section lengths are chosen for different scenario runs. Specifically, the two parameters deciding what the block section length are the gradient direction and the gradient profiles, and a total of four block section lengths are used, see appendix B. The design speed used to calculate the block sections were in all cases 250 km/h. However, if the speed would have been reduced to 200 km/h, the block section lengths would be reduced considerably (calculations in section B.2 in appendix B). For the cases with the slow passenger train, this could considerably increase the capacity, and this parameter could have had a larger impact than anticipated. However, block section lengths are chosen from the ”worst case” scenario, so if both 200 and 250 km/h passenger trains operate on a line, the case modelled is correct. One could also discuss whether the choice of using a different block section length ascending and descending is a realistic approach. The fact that it is included in the way it is, is that it was desired to study whether different gradient profiles would have considerable effects on the descending high speed trains. An increased block section length would have been a consequence of larger gradients.

No gradient case

The case with track gradient profile without up- or downhill is used only for comparative purposes in this thesis. Having included a flat case in the track gradient profile, $X1$, or gradient direction parameter, $X4$, could have had a scientific benefit as well. The main reason it was not included was that the statistical model most likely would have disrupted some of the more marginal parameters. In essence, including a no gradient case in the statistical model would have answered *if* track gradient affects the combined effects. However, it was decided more interesting to see *to which extent* a changing track gradient influences the combined effects. The no gradient case could then rather be used to see implications regarding the isolated effects on energy consumption and track gradient, although to a somewhat less certain degree.

Gradient placement

In the infrastructure model, the ascending gradient start is placed one kilometer after the station boundary. As mentioned, this was considered as a realistic approach to a real life situation. However, this could also have had an effect on the results. In the way energy consumption is defined, it is now divided by the distance travelled to find the energy consumption per kilometer. Hence, the gradient for the 15 and 30 km section lengths are occurring in respectively 93.3 % and 96.7 % of the stretch length, which could be considerable on the weighting of the gradient responses.

5.4 Infrastructure model tool

LUKS as a software tool is used mostly for capacity related studies. To the authors' knowledge, the infrastructure data from the microscopic model has not been used to study energy consumption before, at least not in Norway. Thus the study can be considered a pilot test for LUKS' ability to incorporate energy consumption simulations in its software. Several situations during the work has led to a better understanding of LUKS' strengths and weaknesses in this regard.

First of all, it should be stated again that the energy consumption outputs from the infrastructure model are made for comparisons and not absolute. Several factors that according to literature seem to have an important contribution to capacity and energy consumption are not able to be modelled. Examples of this are both driving related (i.e. degree of coasting, regenerative braking), but also related to infrastructure (i.e. energy loss from electric infrastructure). However, one does not have to look at this as exclusively negative. A model will always have some simplifications and will never be able to fully cover the real life situation. For the scope it is specialized in – track infrastructure – the model is able to simulate a plausible outcome given its inputs. Although this excludes some values, it gives a clear indication of how inputs can correlate to the desired outcomes, and for a comparative usage, this could be sufficient.

The downside of commercial software is that for the sake of business models, secrecy and so on, the user is not always able to see how the program is working. Therefore, it is not always clear why results end up as they do. In one case during the project work, this became very clear. This in regard to the use of the tunnel as an infrastructure element. Although input parameters were specified and even the methodology for how to calculate the tunnel resistance was chosen, LUKS did not include this in the *running times* diagram. Luckily this was clarified through second-hand communication with the program developers, but there could be other cases were similar issues have arisen that the authors are not aware of.

Chapter 6

Conclusion and further research

6.1 Conclusion

The thesis has given an insight in critical parameters regarding the combined effects of capacity and energy consumption. Firstly, relevant parameters related to track gradient were identified. Then, an infrastructure model was built and run with scenarios combining different parameter levels. Lastly, the responses from the model were utilized to identify the critical parameters for the combined effect of capacity and energy consumption. Core findings and implications of the study are summarized below.

- The significant parameters affecting combined effects of the energy consumption and capacity are in significance order the train mix, the gradient direction and the two-factor interaction between these two.

- Isolated, the capacity's identified significant parameters are train mix and gradient direction. With preconditions set for this thesis, gradient direction and train mix are identified as the significant factor for the energy consumption as well.

- Results from the study also imply that an increasing ascending track gradient does not seem to have a significant effect on the track's capacity until heavy freight trains have trouble maintaining a reasonable speed. However, track gradient will considerably increase the energy consumption for a train running uphill, and the effect will be much higher if combined with higher train speed and longer train length.

6.2 Further research

It is of interest to include more than the eight included parameters in this study. By including more parameters and defining different levels, a more holistic and general understanding of how the parameters effect the outputs in question.

Results from this study should also be considered with focus on the power supply. Including a loss in the energy transformation, an increasing energy consumption could have even larger effects on the running time and thus the capacity of the system. This could have negative impacts on the power grid.

In a longer perspective, the methodology of including operation related factors' combined effects should be integrated to a larger extent in design processes of railway at an early stage. This should include railway capacity and energy consumption, but also factors like maintenance, reliability and environmental issues.

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Appendix

Appendix A

Assignment description

MASTEROPPGAVE

(TBA4995 Jernbane, masteroppgave)

VÅREN 2018
for
Bendik Fürst Mustad

Combined effects of track gradient related parameters on energy consumption and capacity

BAKGRUNN

Towards 2050, it is predicted an increase of between 28-36 % for passenger transport in the four major cities in Norway. In the same time span, the European Union's target is to shift as much as 50% of road freight travelling over 300 km to more green modes like railway. Also, extensive investments in improvements for the Norwegian railway have been committed by the Norwegian Government.

Because of the predicted growth, it is important that new and existing railway infrastructure is utilized in a sustainable way. When designing an infrastructure section, investment costs are often a major contribution in regard to chosen alternatives. However, some infrastructural decisions could have a substantial impact on the operations of a line, from both a train operator's or an infrastructure owner's point of view. For a train operator, the energy consumption has a direct correlation to economic expenses. For infrastructure owners, the track capacity is important regarding utilization of the line, punctuality and delays on the railway sections.

Track gradient is one of the parameters that seem to have a considerable effect on these measures. Although steep gradients can be avoided, a trade-off for this is often a longer horizontal alignment which could lead to higher investment costs. It is therefore of scientific interest to study the effects a track gradient has on operational outcomes.

When it comes to the energy consumption and railway capacity, there has, to the best of the author's knowledge, not been conducted research to assess the *combined* effect of the two. These combined effects could be highly considerable for both operators and infrastructure owners for scenarios with larger axle loads, large mix of train speeds and longer freight trains. Therefore, it is necessary to investigate how the track gradient and related parameters affect the capacity and energy consumption, combined.

OPPGAVE

The main goal of the master's thesis will be to identify parameters that have the largest influence on the combined effect of energy consumption and capacity on a railway section.

Research questions and goals for the thesis are stated below.

1. What are track gradient related parameters that effect the energy consumption and capacity for a double-tracked railway stretch?
2. Develop a method to study both the energy consumption and train capacity in relation to the track gradient.
3. What are the critical track related parameters with the largest effect on energy consumption and capacity, combined?

The scope of the parameters should be in such a way that the study can give a realistic view of the modelled situations, while also results from the parametric studies should be manageable.

At the end of the master thesis, the student should be able say which of the studied parameters that will have the largest effect on the combined effects of capacity and energy consumption. The responses will be from an infrastructure model built in the LUKS software.

The study is to focus on parameters related to the railway infrastructure, the rolling stock and interactions between these. Investigations related to cost (operational or investment) are not be included.

GENERELT

Oppgaveteksten er ment som en ramme for kandidatens arbeid. Justeringer vil kunne skje underveis, når en ser hvordan arbeidet går. Eventuelle justeringer må skje i samråd med faglærer ved instituttet.

Ved bedømmelsen legges det vekt på grundighet i bearbeidingen og selvstendigheten i vurderinger og konklusjoner, samt at framstillingen er velredigert, klar, entydig og ryddig uten å være unødig voluminøs.

Besvarelsen skal inneholde

- standard rapportforside (automatisk fra DAIM, http://daim.idi.ntnu.no/)
- tittelside med ekstrakt og stikkord (mal finnes på student ved IBM wikiside)
- sammendrag på norsk og engelsk (studenter som skriver sin masteroppgave på et ikke-skandinavisk språk og som ikke behersker et skandinavisk språk, trenger ikke å skrive sammendrag av masteroppgaven på norsk)
- hovedteksten
- oppgaveteksten (denne teksten signert av faglærer) legges ved som Vedlegg A.

Besvarelsen kan evt. utformes som en vitenskapelig artikkel for internasjonal publisering. Besvarelsen inneholder da de samme punktene som beskrevet over, men der hovedteksten omfatter en vitenskapelig artikkel og en prosessrapport.

Instituttets råd og retningslinjer for rapportskriving ved prosjektarbeid og masteroppgave befinner seg på student ved IBM wikiside

Hva skal innleveres?
Rutiner knyttet til innlevering av masteroppgaven er nærmere beskrevet på http://daim.idi.ntnu.no/. Trykking av masteroppgaven bestilles via DAIM direkte til Skipnes Trykkeri som leverer den trykte oppgaven til instituttkontoret 2-4 dager senere. Instituttet betaler for 3 eksemplarer, hvorav instituttet beholder 2 eksemplarer. Ekstra eksemplarer må bekostes av kandidaten/ ekstern samarbeidspartner.

Masteroppgaven regnes ikke som ferdig levert før kandidaten har levert innleveringsskjemaet (fra DAIM) hvor både Ark-Bibl i SBI og Fellestjenester (Byggsikring) i Sentralbygg II har signert på skjemaet. Innleveringsskjema med de aktuelle signaturene underskrives av instituttkontoret før skjemaet leveres Fakultetskontoret.

Dokumentasjon som med instituttets støtte er samlet inn under arbeidet med oppgaven skal leveres inn sammen med besvarelsen.

Besvarelsen er etter gjeldende reglement NTNUs eiendom. Eventuell benyttelse av materialet kan bare skje etter godkjennelse fra NTNU (og ekstern samarbeidspartner der dette er aktuelt). Instituttet har rett til å bruke resultatene av arbeidet til undervisnings- og forskningsformål som om det var utført av en ansatt. Ved bruk ut over dette, som utgivelse og annen økonomisk utnyttelse, må det inngås særskilt avtale mellom NTNU og kandidaten.

(Evt) Avtaler om ekstern veiledning, gjennomføring utenfor NTNU, økonomisk støtte m.v.
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Faglærer ved instituttet: Elias Kassa
Veileder hos ekstern samarbeidspartner: Anne Christine Torp Handstanger, Infraplan

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Dato: 15.01.2018, (revidert: 31.05.2018)

Underskrift

Elias kassa.
Faglærer

Appendix B

Block section lengths

B.1 Calculations

In Norway, fully equipped ATC is to be utilized when the line speed is larger than 130 km/h. According to Bane NOR (2017e), equation (B.1) should be utilized to find the block lengths.

$$\mathrm{MA} = \frac{L}{3.6} \cdot T + \frac{L^2 - \mathrm{MH}^2}{2R \cdot 3.6^2} \tag{B.1}$$

MA = block section length [m], L = line speed [km/h], MH = desired exit speed [km/h], T = the sum of reaction time and a safety factor [s] and R = the retardation of the train [m/s^2].

MH is in this case 0 km/h as a case to full stop is being considered. For signal balises, $T = 8$ s should be used. If there is a descending gradient, the retardation is found from equation (B.2). If there is no gradient or the train is running uphill, the basic resistance of 0.7 m/s^2 is used.

$$R = -0.2 \cdot \frac{L - 150}{150} - \frac{C}{100} + 0.7 \tag{B.2}$$

L = line speed [km/h], C = the negative gradient [‰] (with a positive sign). The first term should only be used if $L \geq 150$ km/h.

For any piece of infrastructure, the design block section length should correspond to the vehicle with the longest block length.

From this information we calculate the block section lengths for the different profiles.[16] The

---

[16] For the calculations, an average gradient of 18.125 ‰ is used for profile 2.

calculations are presented in Table B.1.

Table B.1: Calculation of block section lengths for descending train with 250 km/h line speed

		Profile 1	Profile 2	Profile 3
T	s	8		
L	km/h	250		
C	‰	20	18.125	12.5
R	m/s^2	0.37	0.39	0.44
MH	km/h	0	0	0
MA	m	7132	6812	6015

For ascending trains, the basic resistance $R = 0.7\ \mathrm{m/s^2}$ is applied. Other values are inserted in equation (B.1).

$$\begin{aligned} \mathrm{MA} &= \frac{250}{3.6} \cdot 8 + \frac{250^2 - 0^2}{2 \cdot 0.7 \cdot 3.6^2} \\ &= 4000 \quad [\mathrm{m}] \end{aligned}$$

The block section lengths used in the infrastructure model are presented in Table B.4

Table B.2: Block section lengths used in infrastructure model

	Descending [m]	Ascending [m]
Profile 1	7200	4000
Profile 2	6900	
Profile 3	6100	

B.2 Alternative situation 200 km/h

For comparison, calculations for a dimension speed of 200 km/h are presented in Table B.3. See discussion regarding this in chapter 5.

Table B.3: Calculation of block section lengths for descending train with 200 km/h line speed

		Profile 1	Profile 2	Profile 3
T	s	8		
L	km/h	200		
C	‰	20	18.125	12.5
R	m/s^2	0.43	0.45	0.51
MH	km/h	0	0	0
MA	m	4006	3858	3480

$$\begin{aligned} MA &= \frac{200}{3.6} \cdot 8 + \frac{200^2 - 0^2}{2 \cdot 0.7 \cdot 3.6^2} \\ &= 2649 \quad [\mathrm{m}] \end{aligned}$$

Table B.4: Block section lengths that could have been used in infrastructure model

	Descending [m]	Ascending [m]
Profile 1	4100	2700
Profile 2	3900	
Profile 3	3500	

Appendix C

Coding

Listing C.1 shows the MATLAB coding for the objective function. This listing also has the input for infrastructure variables from the infrastructure model. Listing C.2 shows MATLAB coding for the genetic algorithm runnings. Listing C.3 shows MATLAB coding for calculations regarding the full factorial design.

Listing C.1: MATLAB coding for objective function

```
% objective function

function [result] = sumerror (B)

% values definition

% X matrix. 128 x 36 matrix consisting of
    % all 1 and -1's. Column 1 is all 1
    % (corresponding to B0)
    % Not included in appendix due to large
    % data amount
% Y matrix with weighting copy pasted from
    % Excel file. NB: Change ',' to '.'
    % Not included in appendix due to large
```

```
    % data amount

% evualtion function starts here

Yhatt=x*B';
% B transposed to row format to match matrix
    %calculation

error =(Yhatt-y).^2;

result = sum(error);

end
```

Listing C.2: MATLAB coding used to minimize the objective function using the genetic algorithm

```
tic % timing starts

clc;
clear;
close all;

% nvars = number of variables
nvars= 36;

% lb = lower bound constraints
lb = zeros([1 36]);

% ub = upper bound constraints
ub = ones([1 36]);

```

```
% modify the option to call for the display
    %while running
options = optimoptions(@ga,'PlotFcn',{@gaplotbestf,@
    ↪ gaplotstopping});

% B = final B values found by optimisation
% fval = final answer
% exitflag = to flag the process if anything goes wrong
    ↪ during the process
% output = to print all the output
% population = all the trials the optimisation tried
% score = an evaluation score uses by the algorithm
% ga = genetic algorithm (optimisation method)
% @sumerror = function to be solved
% [] = empty cell when default options are used
% options = is to call the function to modify the option.

[B,fval,exitflag,output,population,score] = ...
ga(@sumerror,nvars,[],[],[],[],lb,ub,[],[],options);


% for better visualization
column = [1:1:36];
Bout = [column; B];
fprintf('The best function value found was : %g\n', fval);
B'

toc
```

Listing C.3: MATLAB coding used to produce effect analysis figures

```
close all
clear all

% Also X matrix (128x28) and Y matrix (128x3)
    % are defined but, these ~180 code lines are
    % not necessairy to include in this appendix

    % Ymatrix: [Y(100%Cap)      Y(100%EC)       Y(50/50)]

%Define array for X axis labels
Xlabel = {'X1';'X2';'X3';'X4';'X5';'X6';'X7';'X1X2';'X1X3';'X1X4';'X1X5';'X1X6';'X1X7';'X2X3';'X2X4';'X2X5';'X2X6';'X2X7';'X3X4';'X3X5';'X3X6';'X3X7';'X4X5';'X4X6';'X4X7';'X5X6';'X5X7';'X6X7'};

i=1:28;

% Effects on Capacity
Eff_CAP(i) = sum(X(:,i).*Y(:,1))/(length(Y)/2);
% Average effect on Capacity
Eff_Avg(1) = sum(Y(:,1))/length(Y);
% Error
err_cap =sqrt(sum((Eff_CAP-Eff_Avg(1)).^2))/(length(Y)/2);
% Normal probability plot
figure(1)
normplot(Eff_CAP)

figure(2)
bar(Eff_CAP)
```

```
set(gca,'xtick',[1:28],'xticklabel',Xlabel)
hold on
plot([0 length(Eff_CAP)],[err_cap err_cap])
plot([0 length(Eff_CAP)],[-err_cap -err_cap])
hold off
xtickangle(45)

% Effects on Energy
Eff_ENE(i) = sum(X(:,i).*Y(:,2))/(length(Y)/2);
% Average effect on Energy
Eff_Avg(2) = sum(Y(:,2))/length(Y);
% Error
err_ene =sqrt(sum((Eff_ENE-Eff_Avg(2)).^2))/(length(Y)/2);

% Normal probability plot
figure(3)
normplot(Eff_ENE)

figure(4)
bar(Eff_ENE)
set(gca,'xtick',[1:28],'xticklabel',Xlabel)
hold on
plot([0 length(Eff_ENE)],[err_ene err_ene])
plot([0 length(Eff_ENE)],[-err_ene -err_ene])
hold off
xtickangle(45)

% Effects on combined weighted
Eff_COM(i) = sum(X(:,i).*Y(:,3))/(length(Y)/2);
% Average effect on combined weighted
```

```matlab
Eff_Avg(3) = sum(Y(:,3))/length(Y);
% Error
err_com =sqrt(sum((Eff_COM-Eff_Avg(2)).^2))/(length(Y)/2);

% Normal probability plot
figure(5)
normplot(Eff_COM)

figure(6)
bar(Eff_COM)
set(gca,'xtick',[1:28],'xticklabel',Xlabel)
hold on
plot([0 length(Eff_COM)],[err_com err_com])
plot([0 length(Eff_COM)],[-err_com -err_com])
hold off
xtickangle(45)
```

Appendix D

Isolated effects

This appendix shows figures correlating to the isolated effects the identified parameters have on capacity and energy consumption.

The methodology is the same as for the combined effects, but different weighting factors in equation (3.7) are used. In relation to capacity, $w_1 = 1$, while $w_2 = 1$ for energy consumption.

Results are presented briefly in section 4.2.3.

D.1 Capacity

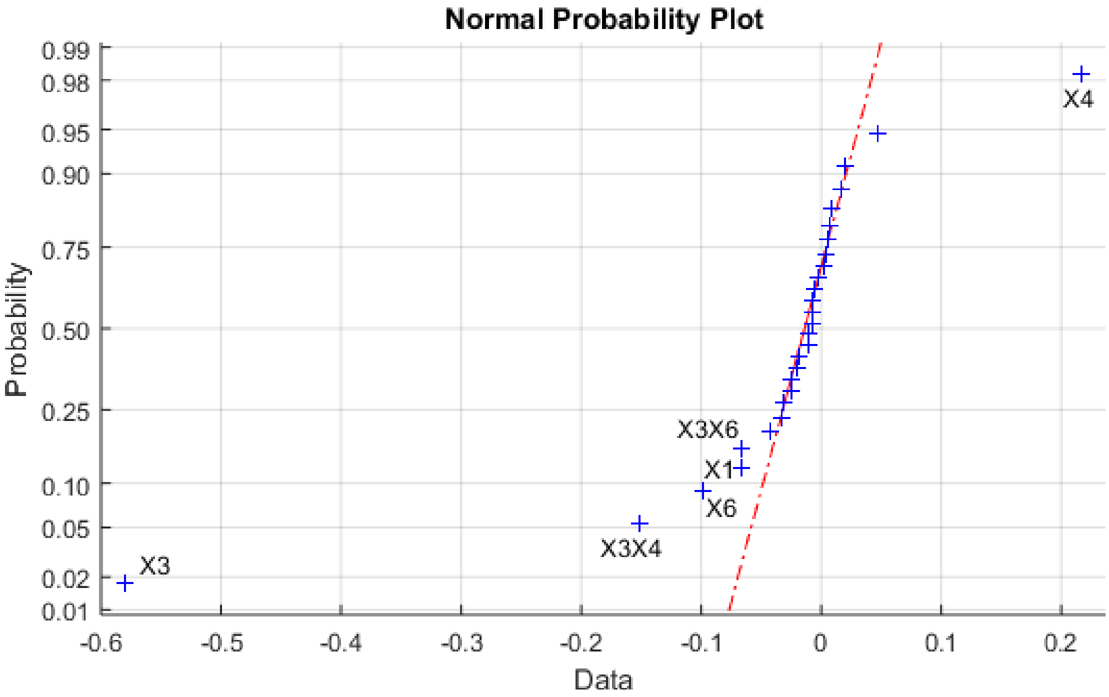

Figure D.1: Normal Probability Plot of the effects of capacity

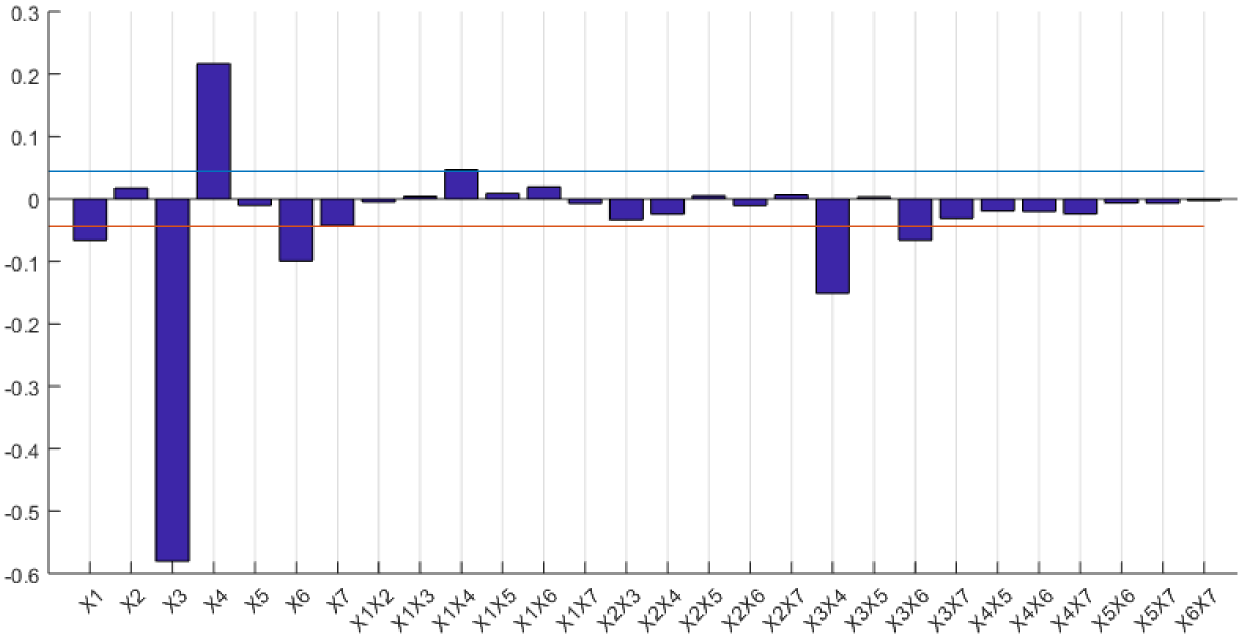

Figure D.2: Bar plot of effects of capacity for each parameter

D.2 Energy consumption

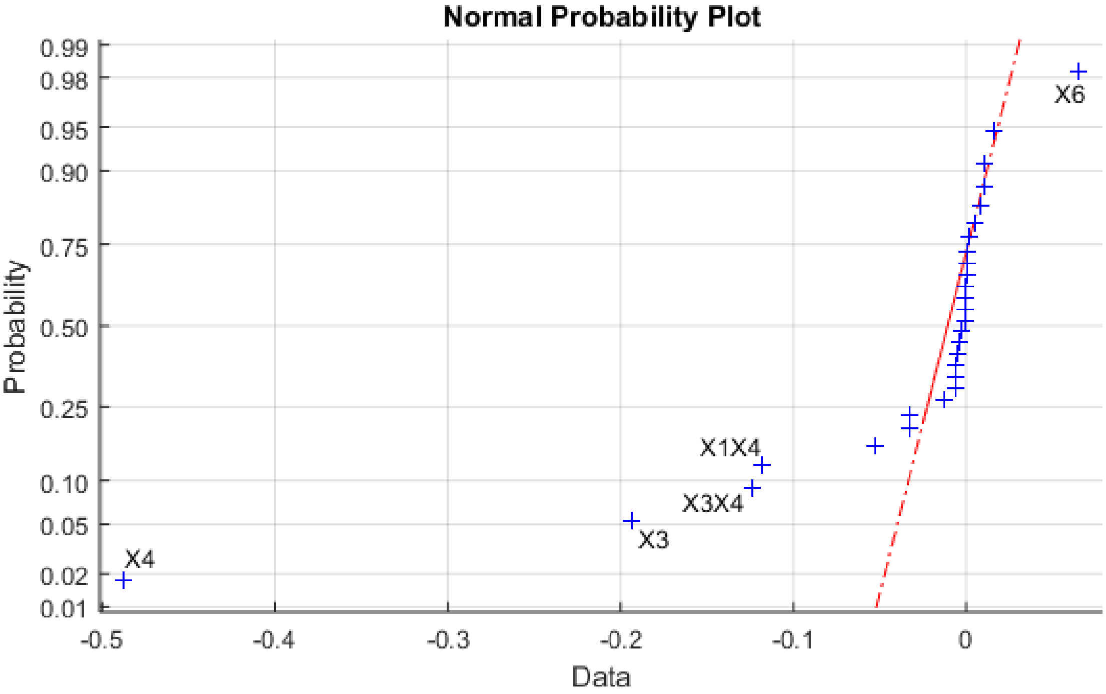

Figure D.3: Normal Probability Plot of the effects of energy consumption

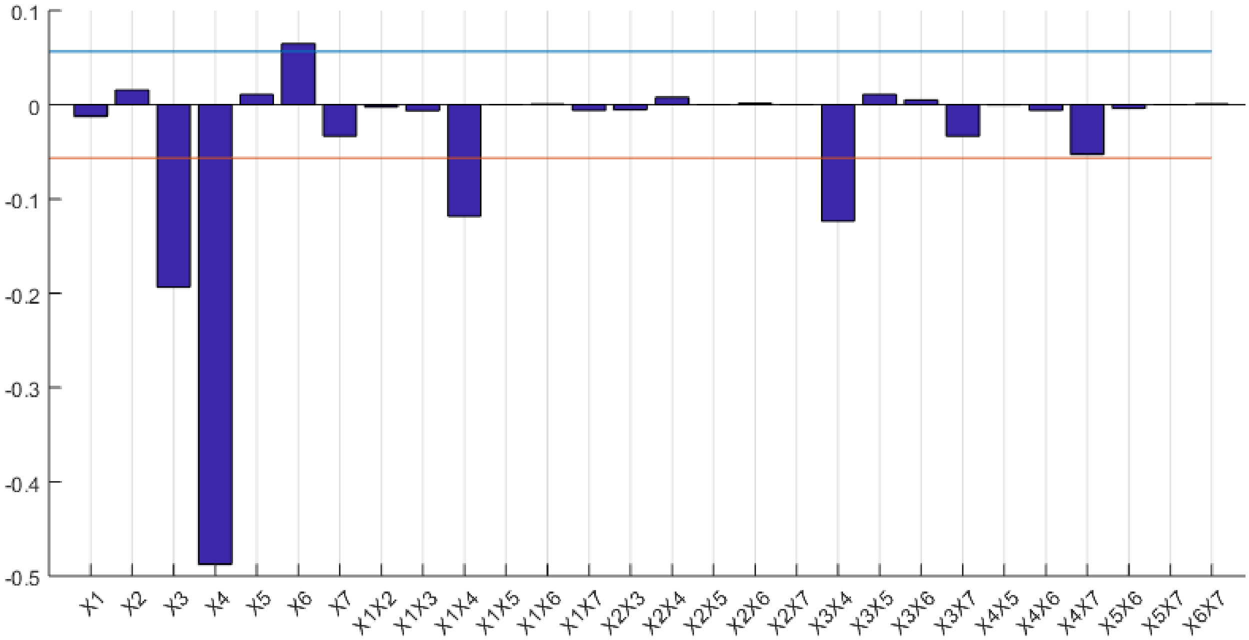

Figure D.4: Bar plot of effects of energy consumption for each parameter

Appendix E

Extended abstract

An extended abstract has been written and sent to *RAILWAYS 2018* – an international conference on railway technology.

The abstract has been accepted for oral presentation at the conference, which will be held September 3rd-7th 2018 in Sitges, Barcelona, Spain.

The document is attached.

Title:

Combined Effects of Track Gradient Related Parameters on Energy Consumption and Capacity

Authors & affiliations:

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Abstract: (Your abstract must use **Normal style** and must fit in this box. The box will 'expand' over 2 pages as you add text/diagrams into it.)

1. Introduction

Towards 2050, it is predicted an increase of between 28-36 % for passenger transport in the four major cities in Norway [1]. In the same time span, the European Union's target is to shift as much as 50 % of road freight travelling over 300 km to more green modes like railway [2].

Because of the predicted growth, it is important that new and existing railway infrastructure is utilized in a sustainable way. When designing an infrastructure section, investment costs are often a major contribution in regard to chosen alternatives.

However, some infrastructural decisions could have a large impact on the operations of a line, from both a train operator's and an infrastructure owner's point of view. For train operators, the energy consumption has a direct correlation to operational expenses. For infrastructure owners, the track capacity is important regarding punctuality and increase productivity of their railway sections.

Track gradient is one of the parameters that seem to have a substantial effect on these measures. Technical specification for interoperability in Europe limits the track gradient values to 35 ‰ for new lines dedicated to passenger traffic [3]. In Norway, the standard requirements for the vertical gradient on a line with mixed traffic is 12,5 ‰, while the maximum allowed gradient on mixed line is 20 ‰ but with restricted length of the gradient [4]. The higher the vertical gradient the larger will be its effects on the accelerating and braking characteristics of trains.

Although steep gradients can be avoided, a trade-off for this is often a longer horizontal alignment which could lead to higher investment costs. It is therefore of scientific interest to study the effects a track gradient has on operational outcomes.

Several researches have been conducted to study the effects of track geometric and operational parameters on energy consumption and in railway capacity as independent topics. Minimization of energy consumption has been exclusively studied to minimize cost for operation on a given track section. Better driving behavior as a result of increased coasting, train control systems, calculating critical points etc. are some of the methods identified to have positive effects on reducing energy consumption on a track section [5]. Most researches in railway capacity (defined in this paper as "the maximum number of trains which may be operated through a line") are related to the economic effects of maximizing the capacity on an existing or designed section.

Several parameters have been studied to identify those with significant effect in limiting track section capacity, as well as maximizing capacity on existing infrastructure. Krueger found train speed, signaling systems and side track capacity as most critical parameters [6]. Hu and Huang has concluded that an increasing gradient increases the capacity loss, while an increasing speed will decrease the capacity loss [7]. Eggum et al. concluded that gradient does not have a significant effect on the capacity, while two parameters namely, the train mix and length of the track section, have been identified to have the biggest impact on the capacity [8].

These researches have contributed to a better understanding on how the energy consumption and capacity are affected by different parameters, including track gradient. However, to the best of the authors' knowledge, there is no research conducted to assess the combined effect of track gradient on railway capacity and energy consumption. These combined effects might even be highly considerable for both operators and infrastructure owners for scenarios with larger axle loads, large mix of train speeds and longer freight trains. Therefore, it is necessary to investigate how track gradient and related parameters affect the capacity and energy consumption, combined.

The main goal of the study is to identify parameters that have the largest influence on the combined effect of energy consumption and capacity on a railway section. To achieve this, the gradient related parameters are identified, and a model is built to study the combined effects of energy consumption and train capacity in relation to the track gradient. Thereafter, the critical parameters with the largest effect are identified and consequences of exceeding limit values for track gradient are studied.

2. Methodology

To assess the combined effects of track gradient in both capacity and energy consumption, several stages have been followed. An infrastructure model for the section to be studied is built using a commercial software, LUKS. Several simulations have been conducted to identify the critical parameters with the highest effect.

2.1 Parameter identification

Track gradient related parameters influencing the combined effects of the railway capacity and energy consumption are identified through literature and interviews with experts in the field. When choosing the relevant parameters, it was important that they are quantifiable, as well as the fact that they should be able to be built in the model. Because of these criteria, some parameters like driving behavior and degree of coasting are excluded, mainly due to the limitation in the software to model and incorporating these parameters. The chosen parameters are presented in Table 1.

.

Table 1: Identified parameters with corresponding upper and lower levels

Parameter	**Abbreviation**	**Upper level, +*l***	**Lower level, -*l***
Track gradient	*X1*	Exceeding normal values	Normal values
Max passenger train speed	*X2*	250 km/h	200 km/h
Train mix	*X3*	Mixed	Uniform
Gradient direction	*X4*	Ascending	Descending
Speed profile	*X5*	Flying start	From stop
Section length	*X6*	30 km	15 km
Freight train weight	*X7*	Heavy (1200 t)	Light (750 t)

2.2 Model

A numerical infrastructure model is built in a microscopic software tool LUKS to assess capacity and energy consumption in the studied section. Two different models are built for the two different section length variables between station A and Station B. Figure 1 shows a sketch of the model section. The infrastructure model contains descriptions of the switches and crossings of the passing loops, stopping positions for both freight and passenger trains, and relevant signals with ETCS level 2 signaling with constant block lengths. The analysis area lies between the exit- and entrance signals for the consecutive passing loops, where the distance between the two signals is 15 km or 30 km.

The infrastructure model represents a double track, where all traffic is defined to be either in an ascending or descending direction. Two different passenger train types (with maximum operating speeds of 250 km/h and 200 km/h) and freight train with heavy or light loadings are described in the model. The model parameters and the traffic composition is simplified in order to study the effects of different parameters on the combined output.

The software is using a deterministic approach to determine the minimum headway time and hence the theoretical capacity of the section studied. The software is also able to determine the tractive effort and resistances for the defined train and track characteristics.

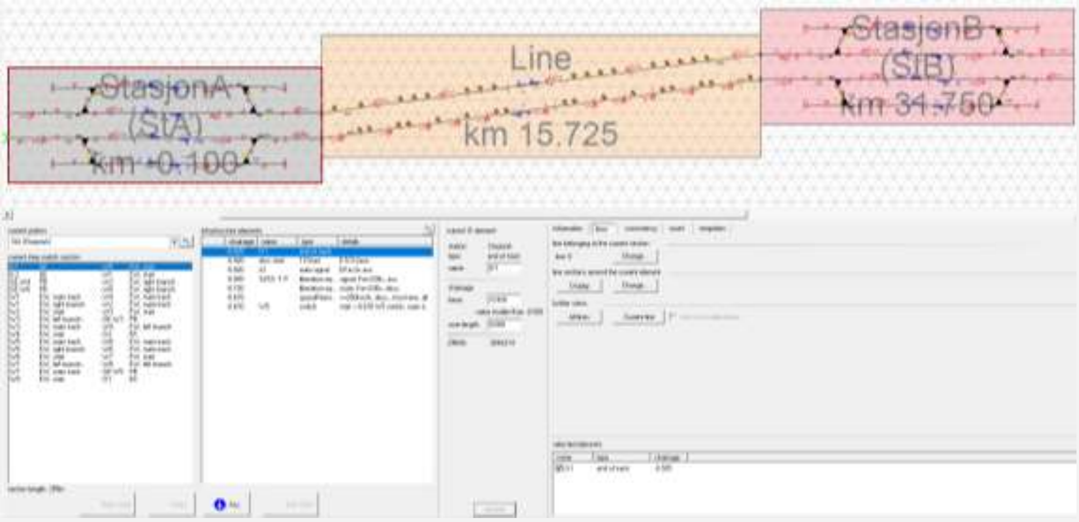

Figure 1: A sketch of the infrastructure model with the infrastructure elements from LUKS

The maximum theoretical capacity, K_{theo}, from the model is found from the mean minimum headway time, $t_{s,min}$, (the minimum headway time is found as shown in Figure 2) using equation (1). T is the observation time.

$$K_{theo} = \frac{T}{t_{s,min}} \qquad (1)$$

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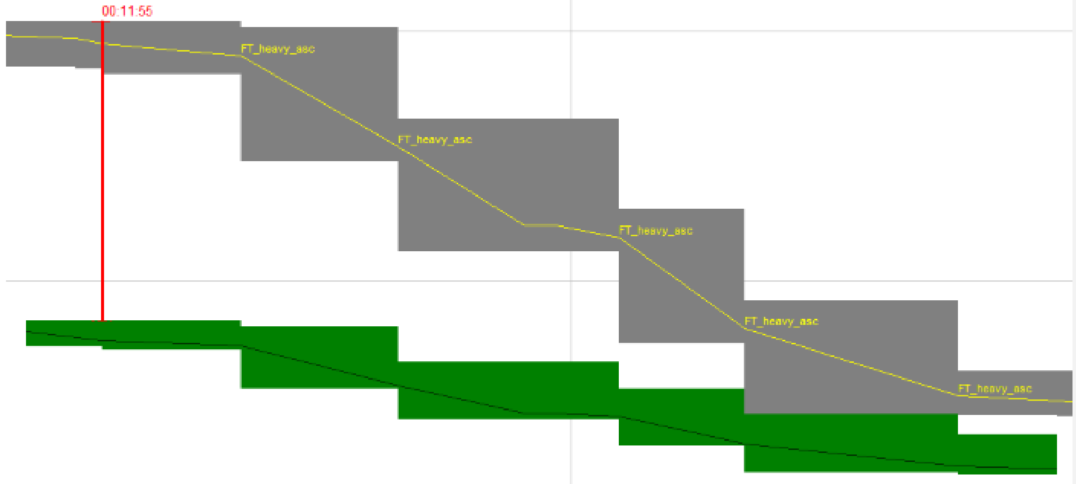


Figure 2: Example of how minimum headway time is read from model

From the tractive effort, *e*, resistances, *W*, length of section, L_s, and the distance covered, *s* (all found in Table 2), the energy consumption per running kilometer, *E*, for a given track and train characteristics is determined. Note that resistances' positive direction is opposite of the driving direction in the table.

The energy consumption for a single train, *E*, is calculated using equation (2). The total response used in the parametric study is the sum of the energy consumption for relevant trains.

$$E = \frac{\sum\left(\frac{(F-W)\cdot s}{3\ 600\ 000}\right)}{L_s} \qquad \left[\frac{\text{kWh}}{\text{km}}\right] \tag{2}$$

Table 2: Extract of table showing tractive effort, resistances and distance

distance [m] [m]	current departure	current arrival	dwell time	V [km/h]	VMax [km/h]	vmaxLine	gradient	tractive effort [N]	resist. vehicle [N]	resist. tract. unit [N]	resist. line [N]
4037	0/00:32:18	0/00:32:18	-	182,00	250,00	250,00	20,0	158000,0	9806,7	0,0	85514,0
4515	0/00:32:28	0/00:32:28	-	186,36	250,00	250,00	20,0	153640,0	10245,6	0,0	85514,0
4515	0/00:32:28	0/00:32:28	-	186,36	250,00	250,00	20,0	153640,0	10245,6	0,0	85514,0
4515	0/00:32:28	0/00:32:28	-	186,36	250,00	250,00	20,0	153640,0	10245,6	0,0	85514,0
4615	0/00:32:30	0/00:32:30	-	187,22	250,00	250,00	12,5	152780,0	10333,3	0,0	53446,2
4674	0/00:32:32	0/00:32:32	-	188,00	250,00	250,00	12,5	152000,0	10413,2	0,0	53446,2
4715	0/00:32:33	0/00:32:33	-	188,54	250,00	250,00	12,5	152000,0	10468,6	0,0	53446,2
4750	0/00:32:33	0/00:32:33	-	189,00	250,00	250,00	12,5	152000,0	10516,0	0,0	53446,2

2.3 Parametric influence

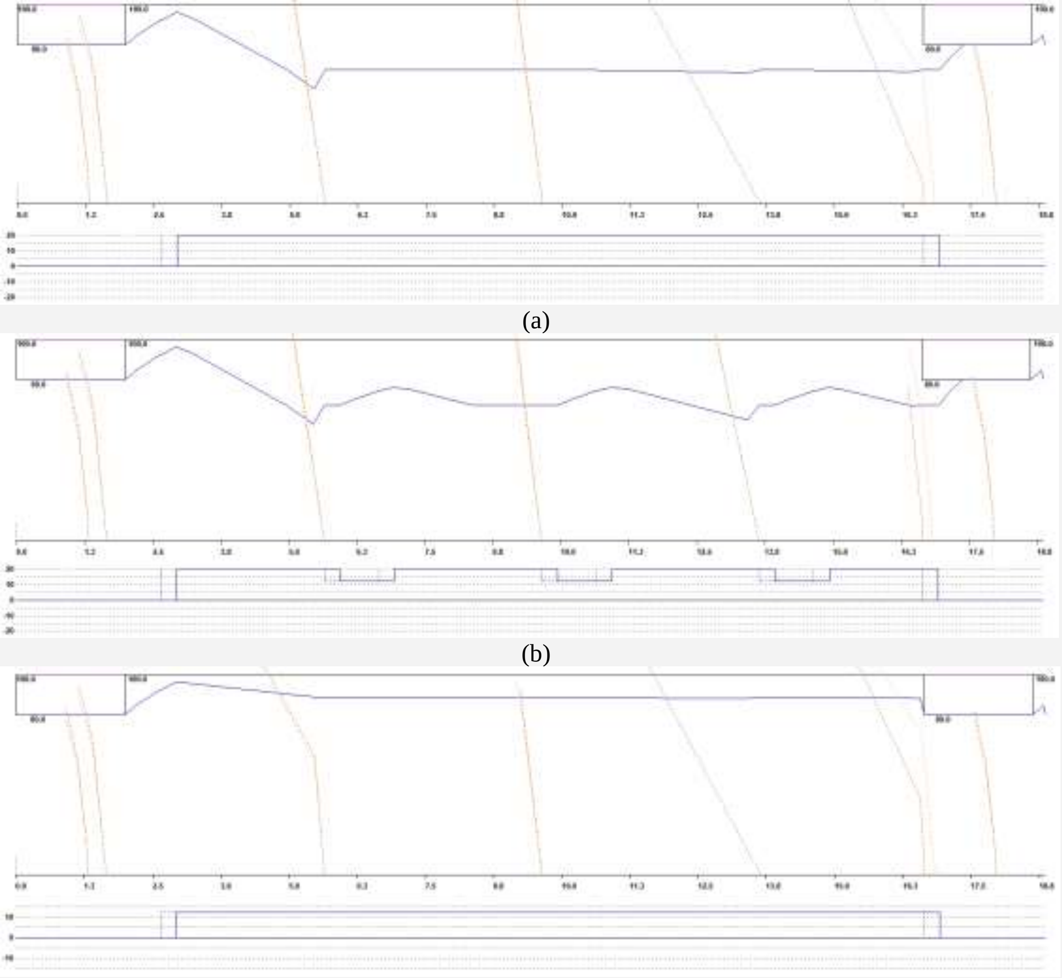
Seven parameters, see Table 1, have been selected and several infrastructure models are developed considering the different variables of the parameters. The effects of changing a single parameter and a combination of the different parameters are studied. The minimum headway times, the tractive effort, resistances and the distance covered are the outputs from the model used for further analysis.

Full factorial design is used to evaluate the most influential parameters that have the largest effect on both energy consumption and line capacity. The values of each parameter are varied to conduct several simulations and to generate the responses. Weighting factors are allocated to each output, namely the energy consumption and the railway capacity, and the combined weighted output is used for the models. A deterministic process is followed to investigate the actual influence of multiple parameters on the energy consumption and the capacity.

3. Results

3.1 Single parameter effects on track gradient

Figure 3 shows velocity diagrams for heavy freight trains over different track gradient profiles. The top part of the diagrams show the speed as a function of distance travelled, while the bottom part of the graph shows the track gradient.



(a)

(b)

(c)

Figure 3: Velocity diagram for ascending heavy freight trains over a track gradient profile (a) exceeding normal values (b) using minimum allowable values (c) using normal values

The corresponding capacity and energy consumption outputs are presented in Table 3.

Table 3: Capacity and energy consumption for different track gradient profiles

	(a)	(b)	(c)	No gradient
Capacity [trains/hour]	10.8	11.1	13.2	13.6
Energy consumption [kWh/km]	517.1	497.1	426.0	301.6

Table 4: Capacity and energy consumption for ascending, descending and no gradient

	Ascending	Descending	No gradient
Capacity [trains/hour]	11.1	11.0	13.6
Energy consumption [kWh/km]	497.1	142.0	301.6

3.2 Combined effects

The energy consumption and capacity are weighted equally, to evaluate the parameters' combined effects. Figure 4 shows a normal probability plot for the calculated effects. For the accumulated normal distribution, points that end up far away from this line are considered having a large effect on the response.

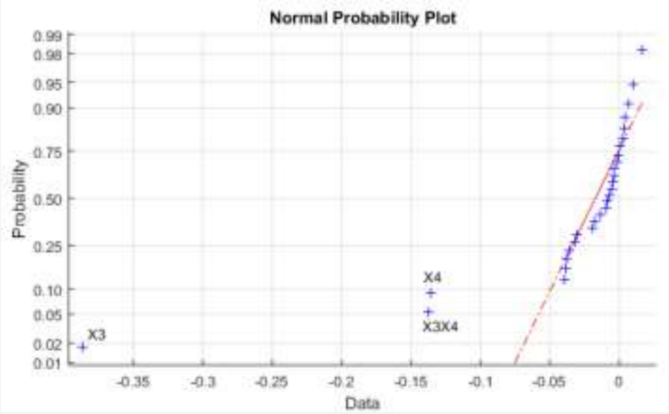


Figure 4: Normal probability plot for combined effects of energy consumption and capacity

The largest significant single effect for the combined outputs is the train mix, *X3*. The single effect gradient direction, *X4*, and the interaction effect between train mix and gradient direction, *X3X4*, have also significant effect on the combined output. These are the only parameters with significant effects that can be clearly seen in the normal probability plot.

Figure 5 and Figure 6 visualize the significant parameters when the isolated effects of energy consumption and capacity are considered, respectively.

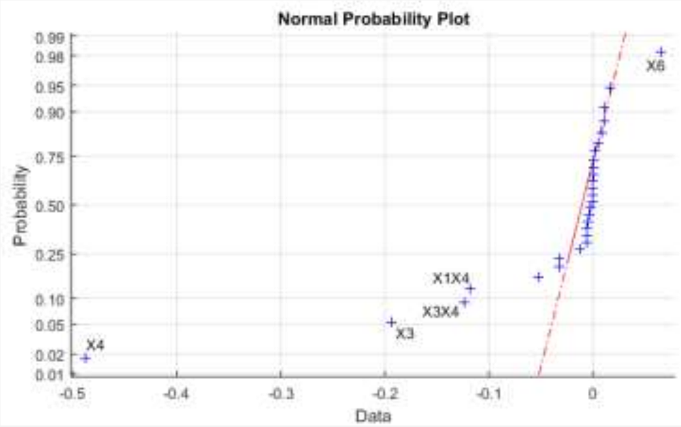


Figure 5: Normal probability plot for isolated effects on energy consumption

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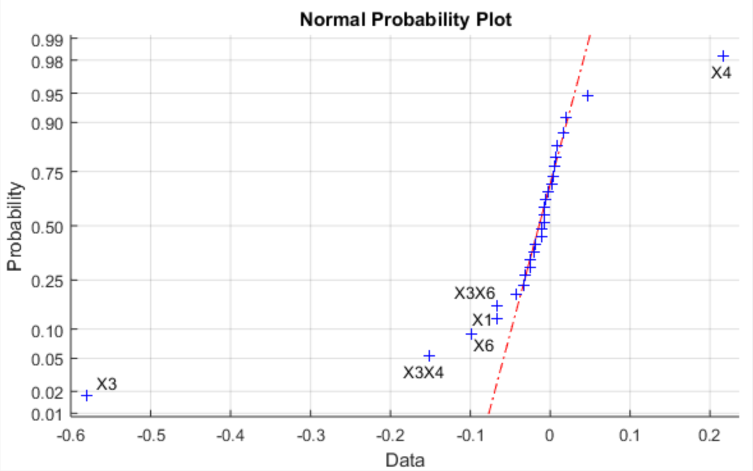

Figure 6: Normal probability plot for isolated effects on capacity

4. Conclusions

The significant parameters effecting combined effects of the energy consumption and capacity are in significance order the train mix, the gradient direction and the two-factor interaction between these two.

Results from the study also imply that an increasing ascending track gradient does not seem to have a significant effect on the track's capacity until heavy freight trains have trouble maintaining a reasonable speed. However, track gradient will considerably increase the energy consumption for a train running uphill, and the effect will be much higher if combined with higher train speed and longer train length, the study implies.

Isolated, the capacity's identified significant parameters are train mix and gradient direction. With preconditions set for this study, gradient direction and train mix are identified as the significant factors for the energy consumption as well.

References

[1] Jernbaneverket, “Jernbanen mot 2050: Perspektiver for transport i byområder og mer gods på skinner,” 2015.

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