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Effects of Tunnel Related Parameters on Energy Consumption

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Abstract

The growth in railway passenger and freight traffic in Norway is predicted to be considerable towards 2050. This means there will be a need to increase the railway transport capacity. In order to meet this challenge, it is necessary to invest in new infrastructure and utilize both old and new in the best manner. Tunnels are an important part of the railway network in Norway, and has an important role when connecting areas where the topography is challenging. Tunnels could possibly have an impact on energy consumption for trains, and is therefore of interest to study. The main goal of this study is to identify and study the critical parameters affecting the energy consumption. Emphasis will be given to tunnel related parameters.

A literature review is conducted in order to identify parameters. Full factorial design (FFD) is used to design the experiment. A microscopic model is built in the simulation software Opentrack, and run with scenarios combining different parameter levels as designed in the FFD. Output from the simulations is used to identify the critical parameters through use of response surface plots and regression analysis.

The parameters affecting energy consumption in a tunnel are from most critical to least critical gradient, train speed and tunnel resistance factor. Tunnel resistance factor gets increasing importance at higher train speeds. Two-factor interaction between tunnel resistance and gradient was found, but it is deemed to be minor. The results from the study imply that high values of gradient should avoided in combination with tunnels.

Keywords:
Railway, Energy consumption, Tunnel resistance, Track gradient, Parametric study, Response surface plot

Sammendrag

Det er forventet en betydelig vekst i togtrafikken i Norge fram mot 2050. Dette betyr at det er et behov for å øke kapasiteten i jernbanenettet. For å komme i mål med dette er det nødvendig å investere i ny infrastruktur og utnytte både gammel og ny på best mulig måte. Tunneler er en viktig del av jernbanenettet i Norge, og har en betydningsfull rolle i å binde sammen områder med utfordrende topografi. Tunnel kan ha innvirkning på energiforbruket til tog, og er derfor av vitenskapelig interesse å studere. Målet med oppgaven er å identifisere og studere de kritiske parametere som påvirker energiforbruket. Tunnelrelaterte parametere vil bli vektlagt.

Et litteratursøk er gjennomført for å identifisere parametere. Full factorial design-metoden (FFD) er brukt for å utforme eksperimentet. En mikroskopisk modell er bygget i simuleringsprogrammet Opentrack, og kjørt med ulike scenarioer som kombinerer ulike parameternivåer. Data fra simuleringene er brukt til å identifisere de kritiske parametere gjennom bruk av respons flater og regresjonsanalyse.

Parametere som påvirker energiforbruket i en tunnel er fra mest til minst kritisk stigning, toghastighet og tunnelmotstandsfaktor. Tunnelmotstandsfaktor får økende betydning ved høyere toghastigheter. Tofaktorinteraksjon mellom tunnelmotstand og gradient ble oppdaget, men er ansett til å være relativt liten. Studien antyder at bratte stigninger burde unngås i kombinasjon med tunnel.

Preface

This document is the concluding work of Christian Magnus Olsen's master's thesis at the Department of Civil and Environmental Engineering at NTNU. The thesis is written during the spring of 2019 and is worth 30 credits.

The thesis has been supervised by Prof. Elias Kassa at the Department of Civil and Environmental Engineering at NTNU. Thank you for your ideas, discussions and feedback.

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Christian Magnus Olsen

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1 Introduction

1.1 Background

According to Jernbaneverkets (now Bane NOR) analysis “Jernbanen mot 2050”, the predicted growth in railway passenger traffic is 170 % toward 2050 in the four major city areas in Norway. For freight volume on rail, the predicted growth is 100 % in the same time span (Jernbaneverket, 2015). This means there will be a need to increase the railway transport capacity considerably.

In order to meet this challenge, it is necessary to invest in new infrastructure and utilize both old and new in the best manner. Investments done in infrastructure stands for a large amount of a nations expenses. In the 2018-2029 period, approximately 929 billion NOK is to be spent on infrastructure. Approximately 35 %, or 319 billion NOK, is earmarked for investments in the railway sector (Regjeringen, 2017). How the infrastructure is built has implications for many aspects of operating the railway, both for train operators and infrastructure owners. It is therefore important to ensure that the investment done gives the best possible outcome for all parties.

For infrastructure owners, capacity is of great importance. This is because the infrastructure owners revenue comes from selling time slots in the network to the operators. For train operators, the energy consumed by the trains should be as low as possible. This is because the operators pay for the consumed energy and therefore is important to minimize in order to keep operational costs low (Jernbaneverket, 2012).

Mustad et al. (2018) has identified which parameters that have the largest influence on the combined effect of energy consumption and capacity. The study was limited to open track, and therefore the effects of tunnel resistance was not studied. Tunnel resistance may affect energy consumption and journey time. There exists many tunnels and several new are under planning and construction in Norway. The tunnels will both be long and designed for a relatively high line speed. These are parameters that may have a significant impact on resistance and thus capacity and energy consumption. Tunnel resistance is therefore of interest to include in a study on combined effects of track related parameters on energy consumption and capacity.

1.2 Goal and research questions

The goal of the master’s thesis is to identify and study the critical parameters affecting the energy consumption. Parameters related to tunnels will be given extra attention, which is reflected in the research questions and literature review:

1. *What are the parameters that affect energy consumption on a railway line?*
2. *What are the parameters that have the largest impact on energy consumption?*
3. *Does the two-factor response from tunnel resistance and a second track related parameter behave linearly or non-linearly?*

1.3 Global methodology

A literature review has been conducted to identify relevant parameters. The parameters are included in a parameter study where the critical parameters are identified through use of simulation software and full factorial design.

1.4 Limitations

This study has limitations. The studied railway line excludes horizontal and vertical curves. The topics covered are limited to longitudinal movement. The energy consumption calculation is limited to the train traction system, but not on the power supply network level. The focus of the thesis is on the infrastructure side, therefore it will not be given much attention to operational factors such as train driver behaviour. Initially it was planned to study the effects on energy consumption and capacity combined. Some issues regarding the study of capacity was discovered at a late stage, and therefore it was decided to focus on the energy consumption. The capacity part of the literature review is included despite this.

2 Literature review

2.1 Track alignment

The alignment of a railway line can be described as the path the track is built and the train drives along. An alignment consists of a horizontal and vertical alignment. These two types of alignments consist of geometrical elements in the horizontal and vertical plane respectively.

Horizontal alignment refers to longitudinal and lateral elements such as tangents, horizontal curves and transition curves. Trains running through curves is subject to a type of resistance called curve resistance (Esveld, 2001). This resistance will be described later.

Vertical alignment refers to vertical elements such as vertical curves and defines the gradient of the track. The gradient is the vertical elevation relative to the horizontal alignment. It is usually described as one unit rise vertically per thousand units horizontally [‰]. The gradient is positive for a rising track, and negative for a falling track in the movement of traffic. Gradient has an impact on energy consumption and performance for trains (Chandra & Agarwal, 2013).

2.2 Resistance

In order to accelerate and maintain a given speed, the train must overcome the resistance forces it is subjected to. The resistance forces can be divided into several categories. Profillidis (2006) uses the categories running resistance, curve resistance, grade resistance and inertial resistance. Pachl (2015) uses the terms line resistance and train resistance. Line resistance deals with grade and curve resistance, while train resistance deals with rolling, bearing, traction system, dynamic and air resistance. Jernbaneverket (2018) uses the terms basic resistance, curve resistance and gradient resistance. Basic resistance deals with bearing, rolling, air and rail-related resistances. Esveld (2001) states that the most important resistances are running resistance, air resistance, curve resistance, and gradient resistance. Also, tunnel resistance is among others an interesting resistance to be described. In this study, resistances are described similar to the description by Hürlimann (2001) and Opentrack (2017) as they are implemented in the Opentrack software. See Figure 1 for an overview.

The total resistance is the sum of traction resistance and acceleration resistance.

$$R = R_F + R_a \tag{1}$$

Where:

- R = Total resistance
- R_F = Traction resistance
- R_a = Acceleration resistance

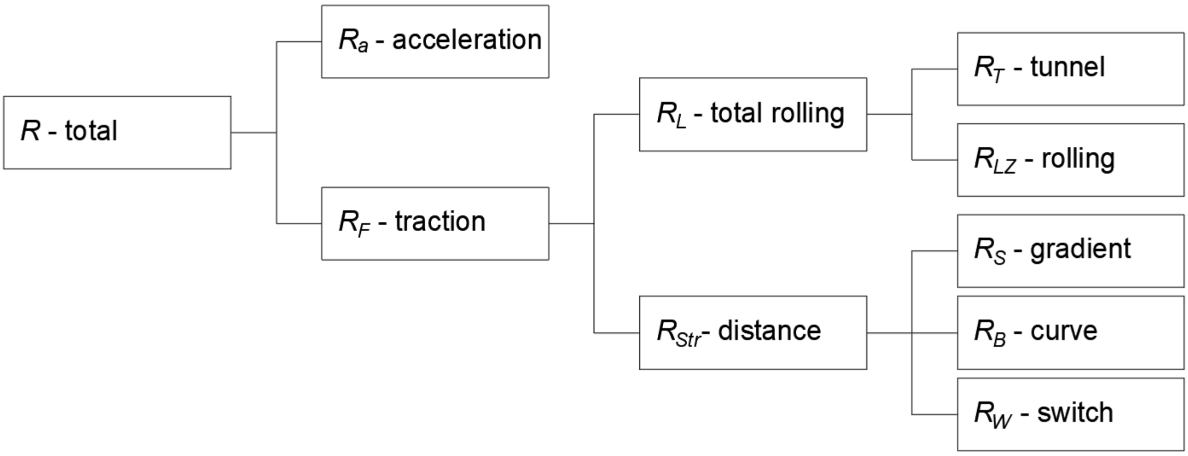


Figure 1: Train resistances

The resistance relative to the weight of the train is called the specific resistance, w:

$$w = \frac{R}{G_T} \tag{2}$$

A brief explanation of the different resistances is given in the following section.

2.2.1 R_a – Acceleration resistance

A train experiences acceleration resistance when it accelerates or decelerates.

$$R_a = m \cdot a \cdot (1 + 0.01 \cdot \rho) \tag{3}$$

- R_a = Acceleration resistance
- m = train mass
- a = acceleration rate
- ρ = empirical mass factor

The mass factor is to account for the rotary inertia of the wheelset. According to Jernbaneverket (2018), the factor is in the interval 3-13 for EMUs (Electric Multiple Units). The BM74E rolling stock used in simulations in this thesis has a value of 8.

2.2.2 R_F – Traction resistance

Traction resistance is divided into total rolling resistance and distance resistance.

$$R_F = R_L + R_{Str} \tag{4}$$

2.2.2.1 R_L – Total rolling resistance

Total rolling resistance is the sum of rolling resistance and tunnel resistance if any.

$$R_L = R_{LZ} + R_T \tag{5}$$

R_{LZ} – Rolling resistance

Rolling resistance consists of air resistance, bearing friction, running resistance and inertial resistance. The Davis formula is one among other formulas used for calculating rolling resistance. The terms A, B and C are parameters associated with a given train.

$$R_{LZ} = A + B \cdot v + C \cdot v^2 \tag{6}$$

The running resistance for a train is relatively low compared to a road running vehicle, approximately 1.5 to 2 ‰ compared to 10 to 30 ‰ (Esveld, 2001). This is due to low friction force that is occurring in the wheel-rail interaction. The friction force is low because of the combination of limited friction of steel-to-steel contact over a relatively small contact area.

The air resistance is dependent on the dimensions and shape of the rolling stock. The air resistance is proportional to the square of the speed, and a possible headwind should also be factored in (Esveld, 2001). The resistance consists of the pressure on the front of the train, air flowing in between train cars, suction on the end of the train, and a friction force on roof, sides and underbody. Due to how the air resistance varies with speed, the resistance will make up a large portion of the total resistance for high speed trains (Jernbaneverket, 2018). The air resistance is considerably larger in tunnels compared to open track.

R_T – Tunnel resistance

Air resistance in tunnels is significantly different from air resistance on open track. Because of this, air resistance in tunnels is referred to as tunnel resistance in this master's thesis. The tunnel resistance acting upon a train is calculated by use of equation (7).

$$R_T = f_T \cdot v^2 \tag{7}$$

Where:

- R_T = tunnel resistance
- f_t = tunnel factor
- v = speed

Vardy (1996) points at two main factors for the difference between air resistance inside and outside of tunnels:

- Generation of pressure waves
- Increased aerodynamic drag

These will be briefly discussed in the following.

Generation of pressure waves

Several authors have discussed the generation of pressure waves, a summary based on Raghunathan, et al. (2002), Schetz (2001) and Vardy (1996) will be presented. When a high-speed train enters a tunnel, a compression wave is formed at the head of the train. This wave propagates along the tunnel at nearly the speed of sound. The pressure wave is reflected from the tunnel exit as an expansion wave. Similarly to the head of the train, the tail of train also generates a wave. Unlike the head, an expansion wave is generated when the tail enters the tunnel. The expansion wave is reflected as a compression wave from the tunnel exit. These pressure waves causes a complex wave interaction due to their successive reflection from the entry and exit of the tunnel. As a result, pressure fluctuations occur that may cause passenger discomfort. The pressure rise in front the train causes additional aerodynamic drag if either the train runs at a high speed or the cross section area of the tunnel is small.

Increased aerodynamic drag

The overall aerodynamic drag may be regarded as the sum of skin friction drag and pressure drag (Vardy, 1996). This holds true for operation in both open air and inside a tunnel. However, the magnitude of the factors are different in the two cases. The skin friction drag is higher in the tunnel case because of the second no-slip condition that is the tunnel wall. As a result, the velocity gradient at the train surface is different and thus the shear force is different. The pressure drag will increase because of the confinement around the nose and tail of the train. This alters the contribution of the nose and tail to the pressure drag.

Schetz (2001) points at following factors as being the main contributors to the increased aerodynamic drag:

- Blockage ratio (the ratio of cross-sectional area of train to tunnel)
- Length of tunnel
- Length of train
- Presence of discontinuities
- Roughness of tunnel wall
- Roughness of train surface
- Presence of other trains in the tunnel

2.2.2.2 R_{Str} – Distance resistance

The distance resistance is a term used for the sum of gradient resistance, curve resistance and switch resistance.

$$R_{Str} = R_S + R_B + R_W \tag{8}$$

Where:

- R_{Str} = distance resistance
- R_S = gradient resistance
- R_B = curve resistance
- R_W = switch resistance

R_S – Gradient resistance

When a train runs on an inclined plane, i.e. there is a non-zero gradient, the gravitational force will have a component parallel to the plane. If the direction of traffic is uphill, the force will act as a resistance, and is called gradient resistance. If the direction of traffic is downhill, the force will not act as a resistance, but rather contribute to the train motion.

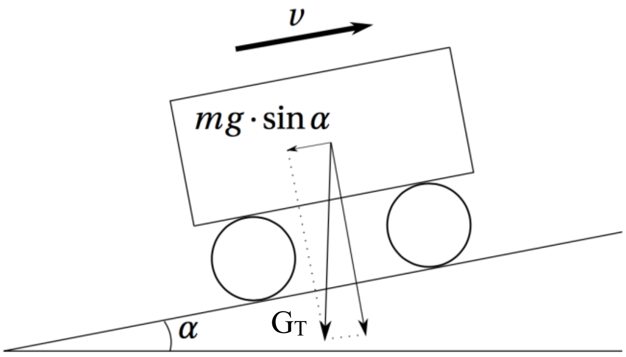


Figure 2: Gradient resistance

Railways are usually built with limited gradients, and therefore the sine can be replaced by the tangent (Pachl, 2015). This leads to the following formula:

$$R_S = m \cdot g \cdot \sin\alpha = m \cdot g \cdot \tan\alpha = m \cdot g \cdot s \tag{9}$$

Consequently, the specific resistance is:

$$r_S = \frac{R_S}{G_T} = \frac{m \cdot g \cdot s}{m \cdot g} = s \tag{10}$$

Where:

- R_S = absolute resistance
- r_s = specific resistance
- m = mass of train
- g = gravitational acceleration
- W = weight of train
- s = gradient
- α = angle between horizontal and inclined plane

R_B – Curve resistance

When the train is travelling through a curve, the outer wheel will cover a greater distance than the inner wheel. The conic wheel profile will help in reducing this, but some slip will occur nevertheless. The flange of the outer wheel may also come in contact with the rail depending on the curve radius, this is referred to as steering force. The curve resistance will be the sum of the slip and steering force.

Røckl's formula (empiric) is often used to calculate the curve resistance (Jernbaneverket, 2018).

$$R_B = \frac{650}{r - 60} \tag{11}$$

Where:

- R_B = curve resistance in ‰
- r = radius in m

At curve radii greater than 1100 m this resistance is neglected.

R_W – Switch resistance

Switch resistance is a small resistance force trains are subject to when running through a switch. Due to the small influence caused by this resistance, it is neglected in the simulations by Opentrack.

2.3 Traction

Trains move forward through transmitting force from wheel to rail. The force that moves a train forward is called the tractive force. In order to maintain a constant speed, the tractive force must be equal to the total resistance force (Steimel, 2008).

$$F = G_T \cdot w \tag{12}$$

The train will lose speed if $F < G_T \cdot w$ and accelerate if $F > G_T \cdot w$.

The specific tractive force of a train is found in a similar way as a trains specific resistance.

$$f = \frac{F}{G_T} \tag{13}$$

There are two factors limiting the maximum tractive effort a train could exert:

- The maximum force that can be transmitted by adhesion
- The maximum force developed by the train

These factors will be briefly discussed in the following sections.

2.3.1 Adhesion

The force generated by the train is transmitted from wheel to rail through adhesion. The adhesion coefficient μ specifies how much tractive force that can be applied relative to the weight on the driving wheels. The adhesion coefficient decreases with increasing speed. The weather has also a significant impact, a wet rail has a lower adhesion coefficient than a dry rail. Icy conditions and leaves on the rail leads to a low adhesion coefficient (Jernbaneverket, 2018). A low adhesion coefficient and weight on driving wheels will limit the tractive force.

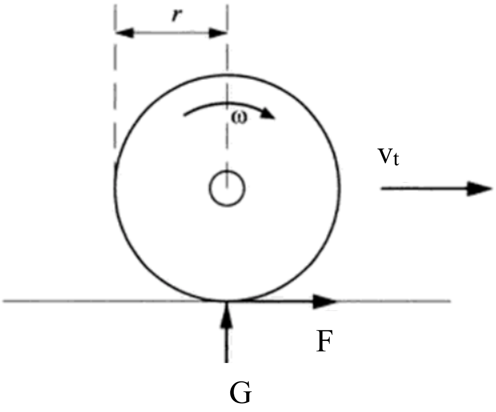


Figure 3: Forces, train speed and wheel circumferential speed (Steimel, 2008)

Figure 3 shows relevant abbreviations related to traction. Below is a set of equations related to traction. Slip can occur in two cases. When driving slip occurs when the wheel circumferential speed is higher than the train speed. When braking slip occurs when the train speed is higher than the wheel circumferential speed.

$$\mu = \frac{F}{G_T} \tag{14}$$

$$v_w = \omega \cdot r \tag{15}$$

$$\Delta v = v_w - v_t \tag{16}$$

$$s_d = \frac{\Delta v}{v_t} \ (v_w > v_t) \tag{17}$$

$$s_b = \frac{\Delta v}{v_w} \ (v_t > v_w) \tag{18}$$

Where:

- μ = adhesion coefficient
- F = traction force
- G_T = train weight
- v_w = wheel circumferential speed at contact point
- v_t = train speed

- s_d = slip when driving
- s_b = slip when braking

2.3.2 Power of train

A train using the power, P, at the speed, v, generates the force, F.

$$P = F \cdot v \tag{19}$$

As the equation shows, the generated tractive force will decrease as the speed increases (Jernbaneverket, 2018).

2.3.3 Relation between traction and resistance

Figure 4 shows the relation between the specific traction force and specific rolling resistance force for a freight train (a) and a passenger train (b) (Jernbaneverket, 2018). This implies that there are no horizontal curves or gradients. It can be seen that the tractive force decreases as the speed increases. For some trains, like a freight train, the curves for resistance and traction will meet before the line speed is reached. This is the case for (a), and the train speed will be v_g. For other trains, the line speed is reached before the resistance curve meets the traction curve. This is the case for (b), where the train speed will be v_{max}. This tells us that (b) will, unlike (a), have excess traction force at v_{max}. This excess force can be used for traversing horizontal curves and overcoming gradients at v_{max}. If the given gradient or curve resistance exceeds the excess force, the train will start to slow down.

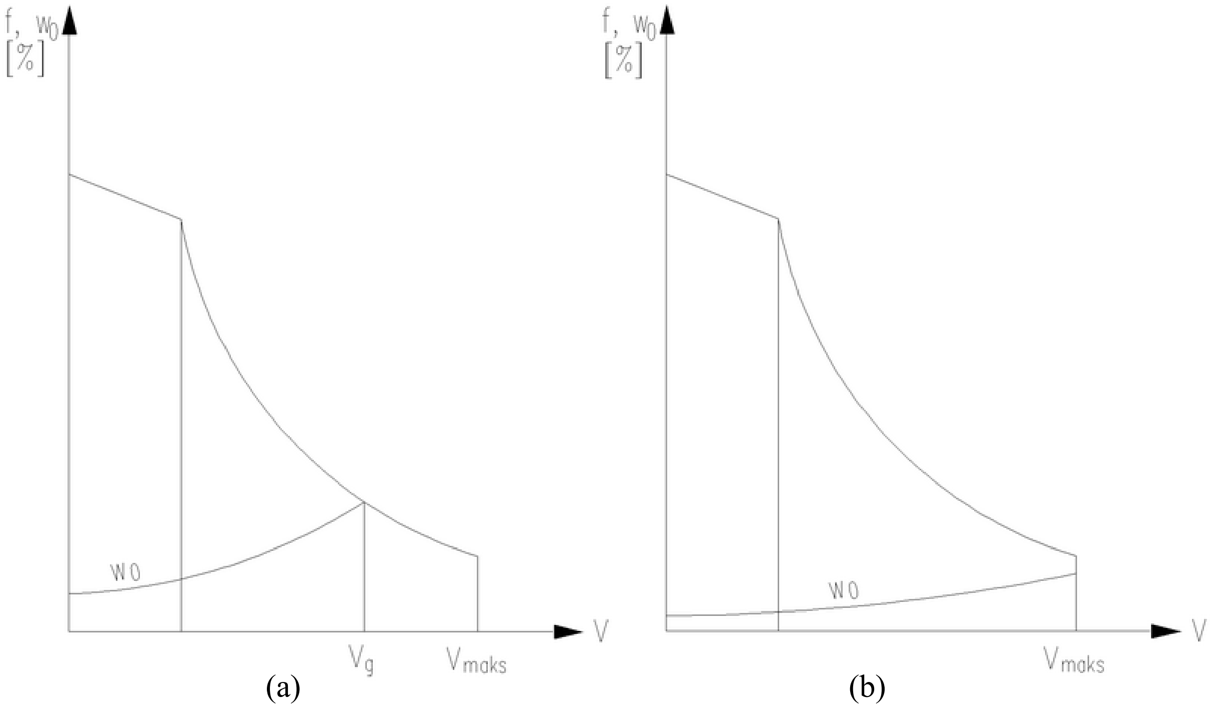


Figure 4: Relation between specific traction force and basic specific resistance for freight train (a) and passenger train (b).

2.3.4 Train movement

Pachl (2015) refers to four elements of a trains movement between two stops.

- Acceleration
- Cruising
- Coasting
- Braking

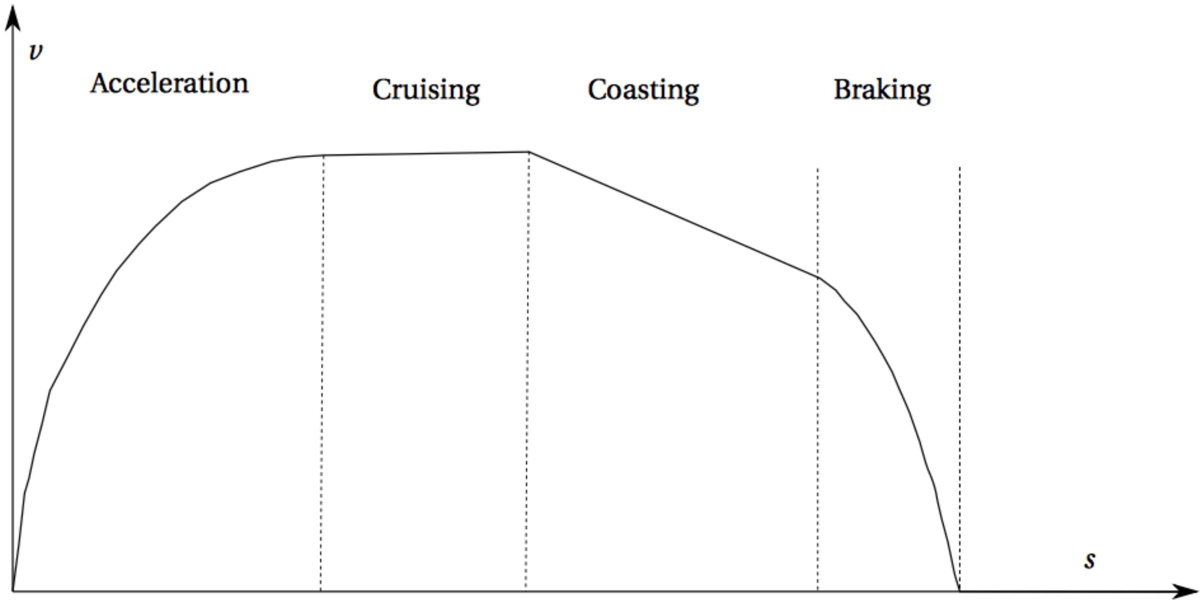


Figure 5:Elements of a trains movement (Pachl, 2015).

The train is subject to different forces during movement. These are found in Table 1.

Table 1: Forces acting on a train during movement

Acceleration	Cruising	Coasting	Braking
$F = R + F_a$	$F = R$	$R_{inertia} = R$	$R_{inertia} = R + F_b$

Where:

- F = tractive effort
- R = total resistance
- F_a = accelerating force
- $R_{intertia}$ = inertial force
- F_b = braking force

Due to the train's tractive characteristics and possible change of line resistance, acceleration will be non-constant. Because of this, deriving the running time is not done in a simple manner.

2.4 Running time calculations

Running time calculations are important because they tell us how long a train will use to traverse a railway line without experimenting in the field. Based on running time calculations one can create timetables, calculate minimum headway times, design of power supply and signaling systems etc.

Pachl (2015) describes a two-step way of determining the running time.

1) Calculation of the speed curve
2) Calculation of running time through integration of the speed curve

A step-by-step approximation of the speed curve in form of a sequence of straight line portions is presented. The accuracy is dependent on the point density of the polygon. The calculation can be based on both fixed speed interval (Δv) or fixed distance interval (Δs).

The running time can then be found be integration of the speed curve.

$$T = \int \frac{1}{v(s)} ds \tag{20}$$

2.5 Energy consumption

The energy consumption by a train is directly linked to the tractive effort. The connection between the power of a train, traction force and speed is found in equation (19).
The relation between power and energy consumption is defined as:

$$P = \frac{dE}{dt} = \dot{E} \tag{21}$$

For a train running fra point A to point B, the energy used is given as:

$$E = \int_{t_A}^{t_B} P(t)\,dt = \int_{t_A}^{t_B} F \cdot v(t)\,dt \tag{22}$$

Where:

- E = consumed energy
- t_i = time at point i
- F = tractive force
- v = speed

In addition to the energy used for moving the train, the auxiliary systems such as heating, cooling and lighting will contribute to the total energy consumed by the train. These factors are not taken into account in this paper.

2.6 Capacity

Capacity is defined as the maximum traffic flow a piece of infrastructure (line, interlocking, terminal, yard) can handle under specified operating conditions (Pachl, 2015). For a railway section, this definition translates to number of trains per time unit. A higher capacity gives room to run more trains, an important factor in order to meet the demand.

2.6.1 Train separation

In order to operate a railway line in a safely manner, the trains must be separated to not come in conflict with each other. The three basic principles of train separation is the following (Pachl, 2015):

- Train separation in relative braking distance
- Train separation in absolute braking distance
- Train separation in fixed block distance

Separation in relative braking distance means that the distance between the trains are equal to the difference in the braking distance plus an additional safety distance. This way of spacing the trains gives the highest utilization of the network, but comes with two major problems. First, there is a problem related to moving through points. If a point is to be operated, the following train must be able to come to a full stop until the point is safely locked in its new position. This is not possible when the trains are separated in this way. Second, if the preceding train has an accident, the following train will not be able to stop before colliding with the first train.

Separation in absolute braking distance means that the distance between the trains are equal to the braking distance of the following train plus an additional safety distance. This way of separating the trains is also known as “moving block”.

When separation in fixed block distance is used, the railway line is divided into block sections. Each block may only be occupied by one train at any given time. The separation distance between two trains is equal to the braking distance of the following train plus the length of the block plus an additional safety distance. Separation in fixed block distance is the most commonly used principle of train separation worldwide.

2.6.2 Blocking time

The time interval related to the allocation of a track section to a given train, is called blocking time. During this time interval, the track section (usually a block) is exclusively allocated for this given train. The blocking time consists of six parts (Pachl, 2015):

- Signal clearing time
- Signal watching time
- Approach time between distant signal and block signal
- Running time inside the block
- Clearing time
- Release time

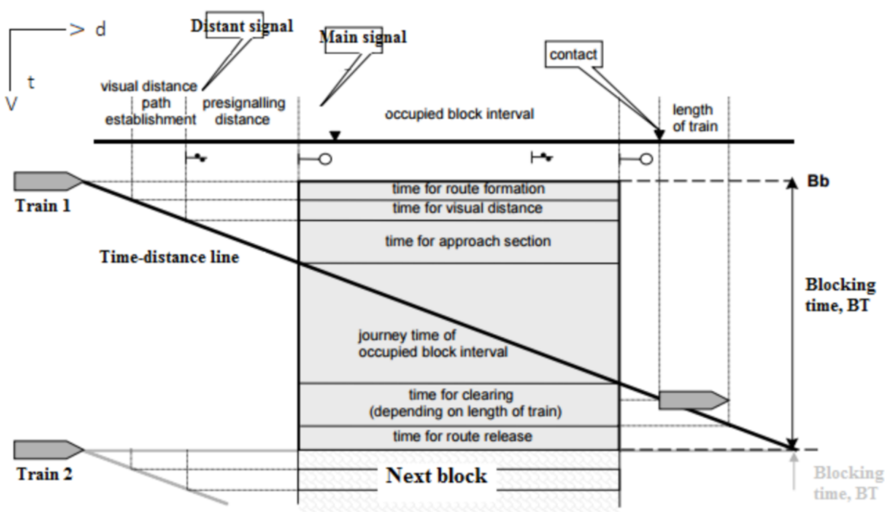


Figure 6:Blocking time diagram (Eggum, 2017)

A railway line usually consist of multiple blocks. By drawing the blocking times of all the blocks into a “distance-time diagram” one can create the “blocking stairway”. The blocking stairway visualizes the operational use of the line. Softwares like Opentrack can generate blocking stairways.

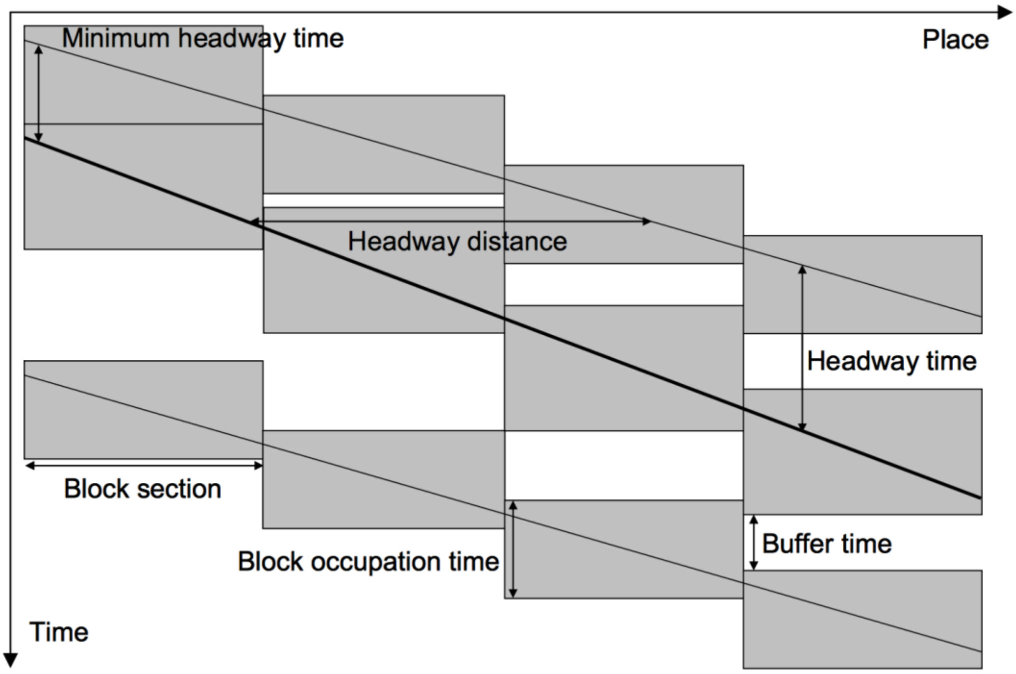


Figure 7: Distance-time diagram with key definitions related to capacity (Landex, 2006)

2.6.3 Minimum headway time

The headway time is the time interval between two following trains (Pachl, 2015). With use of the blocking stairway, the minimum headway time on a line can be found. The minimum headway, or line headway, is the minimum time interval between two trains considering the whole line. This can be found by compressing the blocking stairways of two trains until they touch. The block where they touch is called the “critical block section”. The minimum headway can then be derived from the start position of the line by subtracting the dispatching time for the following train from the proceeding train. In a strictly theoretical view, the minimum headway time is what limits the capacity on a railway line.

The line headway will vary depending on what types of trains that are running. This is because different types of trains may have different performance characteristics that affects the running time. For a line where different types of trains are running, the average minimum line headway is of interest. This is a weighted value that represents what the line headway will be on average when the different types of trains and headway between these are known.

$$t_h = \sum_{i,j} t_{h,ij} \cdot f_{ij} \tag{23}$$

Where:

- t_h = the average line headway
- $t_{h,ij}$ = the minimum headway between train i and j
- f_{ij} = the relative frequency of combination train j following train i

If the frequency is unknown, it can be estimated based on the number of trains.

$$f_{ij} = \frac{n_i \cdot n_j}{N^2} \tag{24}$$

Where:

- f_{ij} = the relative frequency of combination train j following train i
- n_i = the number of train i
- n_j = the number of train j
- N = the number of all trains

2.6.4 Theoretical and practical capacity

There are different types of capacity related to a railway section (Abril, et al., 2008).

Theoretical capacity

The theoretical capacity represents the upper limit of the capacity on a line. This type of capacity is only achievable in a perfect, mathematical environment where all trains run permanently and ideally at minimum headway. Effects related to variances in operations and traffic is ignored, and thus it does not reflect the reality.

Practical capacity

The practical capacity represents the realistic level of capacity on a line. The term is used for the capacity achievable at a reasonable level of reliability. This means a realistic assumption regarding operations and system quality is used. The relation between reliability and theoretical and practical capacity is found in Figure 8.

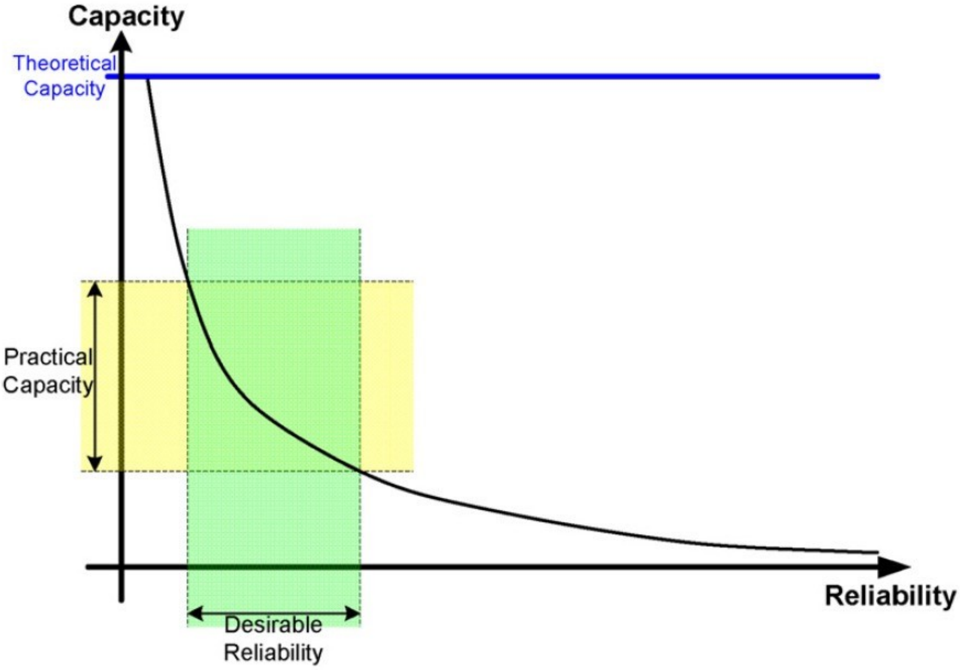


Figure 8: Relationship between capacity and reliability (Abril, et al., 2008)

A high level of utilization will lead to a reduced level of reliability (Pachl, 2015). UIC 406 has recommended limits regarding the consumed capacity on a line.

Table 2: Recommended limits of consumed capacity in UIC 406

Type of line	Peak hour	Daily period	Comment
Dedicated suburban passenger traffic	85%	70%	The possibility to cancel some services allows for high levels of capacity utilisation.
Dedicated high-speed line	75%	60%	
Mixed-traffic lines	75%	60%	Can be higher when number of trains is low (smaller than 5 per hour) with strong heterogeneity.

2.7 State of the art

This chapter will include a summary of different studies on energy consumption of trains. Studies related to the goal of this thesis is given the most weight.

2.7.1 Energy consumption

A comparison between two different vertical alignment profiles connecting two rail transit stations has been done by Kim, et al. (2013). Key findings from this paper is that a dipped vertical alignment can significantly reduce travel time, energy use, brake wear, operating cost and total cost. The study shows that factors such as station spacing, maximum gradients, maximum acceleration/deceleration rate and relative power has an impact.

Schetz (2001) points out that the aerodynamic drag, and thus total resistance, of a train in a tunnel is larger than that of a similar train in open air. Factors relevant to the increased resistance has been discussed previously in this paper. Resistance is directly linked to the energy consumption of a train.

Mustad (2018) has found that gradient will considerably increase the energy consumption of a train running uphill. Higher train speed and heavy freight trains further increases the energy consumption at an inclined line.

3 Methodology

3.1 Literature review

A literature review has been conducted and can be found in chapter 2. Reason for the study was to refresh or gain knowledge and outline the main basis for the thesis. The process of searching was threefold:

1) Online search independently conducted through use of search tools such as Google Scholar (https://scholar.google.no) and Oria (https://www.oria.no). Keywords used in the search are found in Table 3.
2) Study of academic books based on recommendations from supervisor and the Architecture and Civil Engineering Library at NTNU.
3) Snowballing from relevant literature.

Table 3: Keywords used in literature search

Subject	**Keywords**
Energy consumption	Energy consumption train, energy consumption railway
Capacity	Railway capacity, vertical alignment railway capacity, parameters railway capacity

3.2 Parameter identification

Parameters for the study are chosen based on the literature review and discussion with the supervisor. Due to the scope of the thesis, parameters related to operation are excluded. The parameters will be presented and briefly discussed. A summary of the chosen parameters and their levels is found in Table 5.

Train speed

Train resistance is dependent on train speed, thus it will have an impact on energy consumption. Of major interest is how the energy consumption is affected by train speed in a tunnel environment. Reason for this is that air resistance and tunnel resistance, varies with speed squared. Three levels of speed are chosen based on usual levels of train speed in Norway; 100, 150 and 200 km/h. It was initially desired to have a higher level of speed, 250 km/h, due to certain IC lines being planned for this level. However, the present rolling stock trafficking the IC network does not run faster than 200 km/h. The same rolling stock is used in the simulation model, so the same constraint applies there. A solution could have been to use a model with a higher maximum speed. However, the rolling stock used to measure the tunnel resistance factor is the model used in the IC network today. Using a different model could potentially distort the effect of tunnel resistance. It was chosen to use the correct rolling stock rather than using a model with higher speed. This was decided in order to comply with the model used to measure train resistance.

Tunnel wall roughness

The parameter is chosen based on Vardy (1996). Friction drag, and thus resistance, is said to be influenced by the surface roughness.

Blockage ratio

According to Raghunathan et. al (2002), pressure variation, flow velocity and aerodynamic drag increases with increasing blockage ratio. The blockage ratio is the ratio of cross-sectional area of train to tunnel.

Tunnel resistance factor

It was discovered that Opentrack does not have a tool to calculate the tunnel resistance factor based on rolling stock, tunnel wall roughness and blockage ratio. Therefore, “Tunnel wall roughness” and “Blockage ratio” was merged into this parameter “Tunnel resistance”. Four levels of tunnel resistance (f_t) for the desired rolling stock was chosen based on findings by Hansen et al. (2017) presented in Table 4. Opentrack has predefined values for tunnel resistance, but these are found to be exaggerated and therefore avoided (Hansen, et al., 2017).

Table 4: Tunnel resistance factors

Tunnel name	Aerodynamic cross section $[m^2]$	No. of tracks	Length [km]	Surface	V_{max} [km/h]	f_t [kg/m]	f_t grouped
Romeriksporten	87	Double	14,6	Smooth	200	2.4	2.4
Bærumstunnelen	87	Double	5,4	Smooth	160	5.3	
Tanumtunnelen	79	Double	3,5	Smooth	160	3.5	3.6
Skaugumtunnelen	79	Double	3,8	Smooth	160	3.8	
Lieråstunnelen	58	Double	10,7	Rough	130	8.8	8.8
Kvinesheitunnelen	27	Single	9,1	Rough	130	14.8	15.2
Siratunnelen	27	Single	3,1	Rough	130	16.0	
Tronåstunnelen	27	Single	3,2	Rough	130	14.3	
Hægebostadtunnelen	27	Single	8,5	Rough	130	15.8	
Gylandtunnelen	27	Single	5,7	Rough	130	12.1	

Open track / tunnel mix

While tunnel resistance was the main focus of the thesis, it could also be of interest to study cases without any tunnel resistance present. Therefore, a parameter was added that would make simulations without tunnel resistance possible. Three levels were chosen; 0 % (open track), 50% (half part in tunnel and half in open track) and 100% of the line in tunnel.

Gradient

Resistance due to the gradient is part of the total resistance acting on a train. It will be interesting to see how energy consumption is affected by the combination of gradient and tunnel.

Summary

Table 5 makes up a summary of the chosen parameters and their associated levels.

Table 5: Parameters and their levels

Parameter	**Designation**	**Level 1**	**Level 2**	**Level 3**	**Level 4**
Train speed	X1	100 km/h	150 km/h	200 km/h	
Tunnel resistance f_t [kg/m]	X2	2.4	3.6	8.8	15.2
Open track/ tunnel mix	X3	30 km open	15 km tunnel/ 15 km open	30 km tunnel	
Gradient	X4	0 ‰	12.5 ‰	20 ‰	25 ‰

3.3 Simulation model

A microscopic model is built in the simulation software Opentrack by OpenTrack Railway Technology Ltd. The model is built as a deterministic environment, which means that the result is solely dependent on input and has no room for random variations. The reason for using simulation is to be able to analyze a set of parameters in a deterministic setting. Moreover, it will give the opportunity to study the relative differences between the parameters without outside interaction. Output from the simulations has been used as input for the parameter influence study.

3.3.1 Infrastructure model – components

The basic components of a infrastructure model in Opentrack is presented in the subsequent subchapter.

3.3.1.1 Worksheet

The track layout is created and edited in a file called the worksheet. In the worksheet, the infrastructure elements (such as rails, signals and stations) are graphically placed. The worksheet is not to scale, and the spacing between elements has no connection to the actual distance between them.

3.3.1.2 Vertex

A vertex is a point where attributes (gradient, speed) may be changed and a signal may be located.

3.3.1.3 Edge

An edge is a connection between two vertices, and is a representation of railroad track. An edge has numerous attributes associated to it. The most important are length, gradient, radius, tunnel attributes and speed limit. Edges are direction dependent, this for example means that the value of gradient is in the direction of which the edge was drawn.

3.3.1.4 Signal

Signals are placed at vertices and forms the basis of train operation management. There are two types of signals; signals with changing information (light signals, beacons) and halt position indicators. Light signals are further divided into main signals (can show stop), distant signals (shows aspect of the next main signal), combined signals (combination of main and distant signals) and shunting signals. Main signals are further divided into home, exit and block signals.

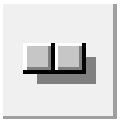


Figure 9: Vertex

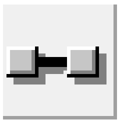


Figure 10: Edge

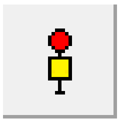


Figure 11: Signal

3.3.1.5 Safety elements

Safety elements are sections of track that can only be occupied by one train at any time. In Opentrack, a safety element consists of one or several edges. Opentrack automatically creates safety elements based on the elements placed in the worksheet, and they are not visible to the user.

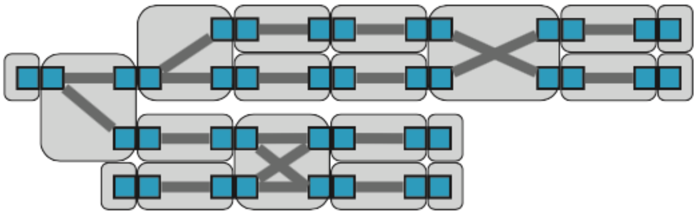


Figure 12: Safety elements in Opentrack (Opentrack, 2017)

3.3.1.6 Station

Every station in the Opentrack model must have a reference point, a Station Vertex. This is a normal vertex that has been given a station status. General practice is to place the Station Vertex at the location of the station building, and at every track at the station. Opentrack has a station database where stations are defined with their attributes. A station icon is placed on the worksheet and linked to a station in the station database to create a functional station in the model. Any number of vertices, edges, signals and one station icon can be grouped into a Station Area for visualization and to ease management.

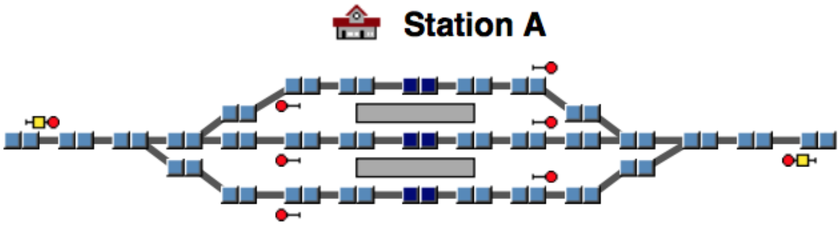


Figure 13: Opentrack station. Station vertices in dark blue (Opentrack, 2017)

3.3.2 Infrastructure model – train operation management

The basic elements of train operation management in Opentrack is presented in the subsequent subchapter.

3.3.2.1 Route

A route is the lowest level of train operation management and consists of 2-to-n vertices of one direction of travel. Routes always begin and end at a main signal, and routes belong to the vertex at which the main signal where the route begins is located.

3.3.2.2 Path

The next level is called a path. This is merely an organizational structure, and does not correspond to any real life railway element. A path consists of 1-to-n routes of one direction of travel. A set of routes that are often used together is an example of what can form a path (all the routes from the exit signal of one station to exit signal of the next station).

3.3.2.3 Itinerary

The top level of train operation management is called an itinerary. An itinerary consists of 1-to-n successive paths. A train is given a list of itinerary with a priority to each itinerary. The list consists of all itineraries of which the train may use to reach its goal. The actual route the train takes is chosen during simulation. The highest prioritized itinerary that is also available is selected and determines the route.

3.3.2.4 Course

A course is a service operated by a train. To each course, a set of itineraries are listed as described above. Each course also has an entry in the timetable where the stopping pattern is to be determined. Other characteristics such as driver behavior and speed restrictions may also be set.

3.3.3 Description of model used in simulations

The model used for the simulations is presented in this subchapter. It was focused on creating a model as simple as possible without losing any functionality. Therefore, a one-way single line was created to mimic one track of a double track line. This removed the need for having switches and crossings. Only one platform was created at each station as this effectively simulates what a train operation looks like. The model is not necessarily meant to reflect an existing line, but rather be suitable for analyzing effects of different track related parameters. A screenshot of the model in Opentrack is shown in Figure 14.

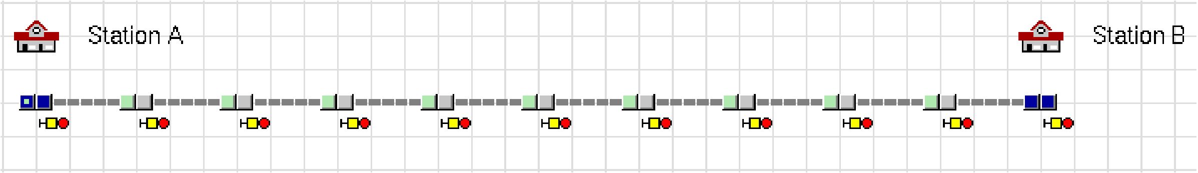


Figure 14: Opentrack simulation model

3.3.3.1 Components

Two stations, Station A and Station B, were built at each side of the worksheet. Station A at km 0, and Station B at km 30. The stations was connected using edges between a set of vertices. Kilometer point at each vertex was set to the value of the previous vertex plus the block section length of 3000 m. Calculations for block section length are found in appendix B. Table 6 gives an overview of the infrastructure model. Values of gradient and tunnel were changed to each simulation accordingly.

Table 6: Infrastructure model components overview

Km	**Object**	**Signal**	**Gradient [‰]**	**Tunnel (f_t)**
0.0	Station	Exit (main/distant)		
	Edge		0	0
3.0	Vertex	Exit (main/distant)		
	Edge		0	0
6.0	Vertex	Exit (main/distant)		
	Edge		0	0
9.0	Vertex	Exit (main/distant)		
	Edge		0	0
12.0	Vertex	Exit (main/distant)		
	Edge		0	0
15.0	Vertex	Exit (main/distant)		
	Edge		0	0
18.0	Vertex	Exit (main/distant)		
	Edge		0	0
21.0	Vertex	Exit (main/distant)		
	Edge		0	0
24.0	Vertex	Exit (main/distant)		
	Edge		0	0
27.0	Vertex	Exit (main/distant)		
	Edge		0	0
30.0	Station	Exit (main/distant)		

3.3.3.2 Train operation management

Routes

Routes along every edge.

Path

One path from Station A to Station B containing all routes.

Itinerary

One itinerary using the path described above.

Course

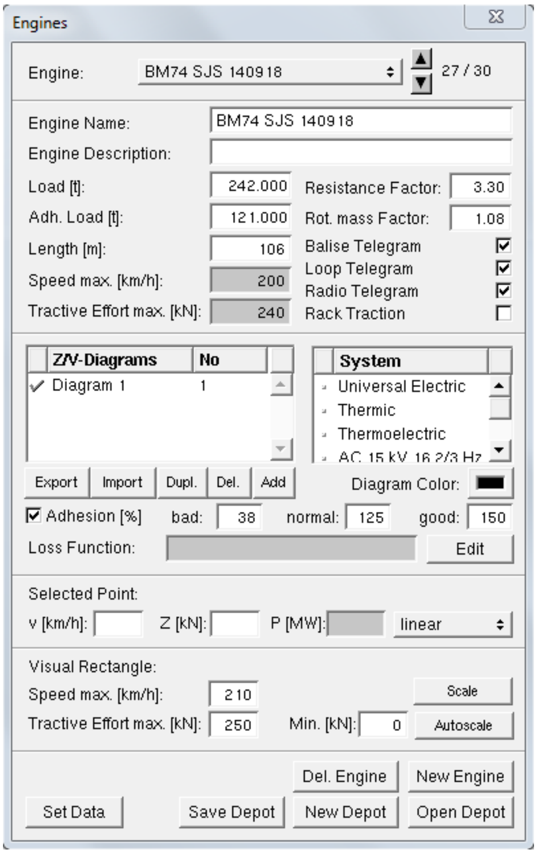
One course using the itinerary described above.

3.3.4 Rolling stock characteristics

The rolling stock used in the simulations is the NSB BM74E, a variant of the FLIRT series delivered by Stadler Rail. The train type is EMU (Electric Multiple Unit), and the model is primarily used for Intercity service in the Oslo-area. Figure 15 shows the rolling stock.

Figure 15: BM74E (Norske Tog, 2019)

Data regarding performance and characteristics is shown below. Figure 16 shows engine performance, Figure 18 shows the F/V-diagram, while Figure 17 shows train characteristics. The data is supplied by NSB.


Engines

Engine: BM74 SJS 140918 27 / 30

Engine Name: BM74 SJS 140918

Engine Description:

Load [t]: 242.000 Resistance Factor: 3.30

Adh. Load [t]: 121.000 Rot. mass Factor: 1.08

Length [m]: 106 Balise Telegram ☑

Speed max. [km/h]: 200 Loop Telegram ☑

Tractive Effort max. [kN]: 240 Radio Telegram ☑

Rack Traction ☐

Z/V-Diagrams	No
✓ Diagram 1	1

System
Universal Electric
Thermic
Thermoelectric
AC 15 kV 16 2/3 Hz

☑ Adhesion [%] bad: 38 normal: 125 good: 150

Loss Function:

Selected Point:

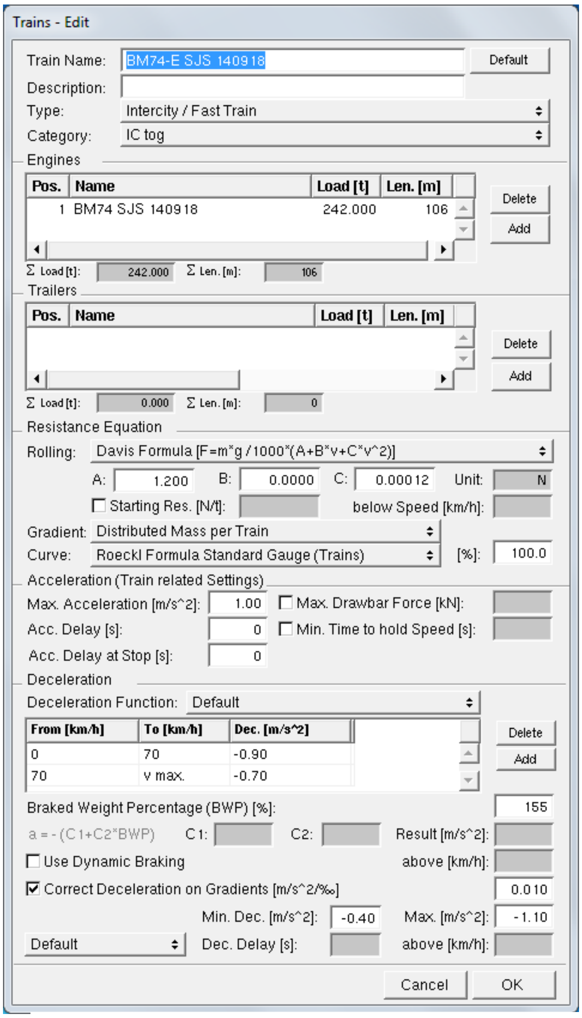
v [km/h]: Z [kN]: P [MW]: linear

Visual Rectangle:

Speed max. [km/h]: 210

Tractive Effort max. [kN]: 250 Min. [kN]: 0

Figure 16: Engine performance for BM74E


Trains - Edit

Train Name: BM74-E SJS 140918

Description:

Type: Intercity / Fast Train

Category: IC tog

Engines

Pos.	Name	Load [t]	Len. [m]
1	BM74 SJS 140918	242.000	106

Σ Load [t]: 242.000 Σ Len. [m]: 106

Trailers

Pos.	Name	Load [t]	Len. [m]

Σ Load [t]: 0.000 Σ Len. [m]: 0

Resistance Equation

Rolling: Davis Formula [F=m*g / 1000*(A+B*v+C*v^2)]

A: 1.200 B: 0.0000 C: 0.00012 Unit: N

☐ Starting Res. [N/t]: below Speed [km/h]:

Gradient: Distributed Mass per Train

Curve: Roeckl Formula Standard Gauge (Trains) [%]: 100.0

Acceleration (Train related Settings)

Max. Acceleration [m/s^2]: 1.00 ☐ Max. Drawbar Force [kN]:

Acc. Delay [s]: 0 ☐ Min. Time to hold Speed [s]:

Acc. Delay at Stop [s]: 0

Deceleration

Deceleration Function: Default

From [km/h]	To [km/h]	Dec. [m/s^2]
0	70	-0.90
70	v max.	-0.70

Braked Weight Percentage (BWP) [%]: 155

a = - (C1+C2*BWP) C1: C2: Result [m/s^2]:

☐ Use Dynamic Braking above [km/h]:

☑ Correct Deceleration on Gradients [m/s^2/‰]: 0.010

Min. Dec. [m/s^2]: -0.40 Max. [m/s^2]: -1.10

Default Dec. Delay [s]: above [km/h]:

Figure 17: Train characteristics for BM74E

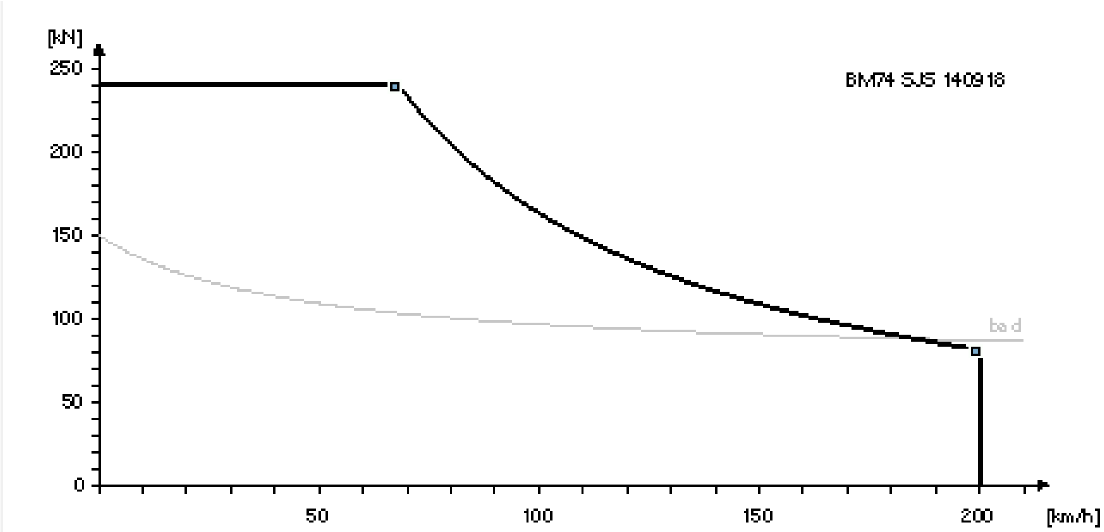


Figure 18: F/V diagram for BM74E

3.3.5 Outputs

The outputs of a simulation come in a numerous amount of files. The *.tsvP file is one of the files that contains the desired data. This file contains a table with values for time, distance, speed, acceleration, tractive effort, resistance, mechanical power, and cumulative power consumption.

3.4 Parameter influence

The influence of different parameter levels on energy consumption was analyzed in two ways; qualitative and quantitative. Response surface curves was used for the qualitative study, while regression analysis was used for the quantitative study.

3.4.1 Response surface curves

Response surfaces are used to study the relationship between several variables and one or more responses. The response is visualized as a 3d-plane where the response value determines the height at any given xy-coordinate. By using this methodology, one can illustrate how a response is affected by different variables and visually determine which parameters that have a big impact. In addition, the relationship of the studied parameters with the output can be seen whether it is linear or non-linear. Matlab is used to generate the surface plots. The used code is found in appendix D.

3.4.2 Single parameter regression analysis

For each parameter and the parameters' different levels, averages was calculated based on equations (25)-(28). The notations used are presented below.

- X1 parameter levels: $I = \{1, 2, 3\}$
- X2 parameter levels: $J = \{1, 2, 3, 4\}$
- X3 parameter levels: $K = \{1, 2, 3\}$
- X4 parameter levels: $L = \{1, 2, 3, 4\}$
- $\bar{E}(m_a)$ average energy consumption of all runs where parameter m is at level a
- E_{ijkl} energy consumption for run where respective parameters are at level i, j, k, l.
- $V(m_a)$ value of parameter m at level a (e.g. 150 km/h for parameter X1 at level 2)
- $V(m_{max})$ value of parameter m at the highest level (e.g. 200 km/h for parameter X1)

$$\bar{E}(X1_i) = \frac{\sum_{j,k,l} E_{ijkl}}{j \cdot k \cdot l} \tag{25}$$

$$\bar{E}\left(X2_j\right) = \frac{\sum_{j,k,l} E_{ijkl}}{i \cdot k \cdot l} \tag{26}$$

$$\bar{E}(X3_k) = \frac{\sum_{j,k,l} E_{ijkl}}{i \cdot j \cdot l} \tag{27}$$

$$\bar{E}(X4_l) = \frac{\sum_{j,k,l} E_{ijkl}}{i \cdot j \cdot k} \tag{28}$$

The difference between the average energy consumption for a parameter at level *a* and *b* is calculated according to equation (29).

$$\bar{E}(m)_{a \to b} = \bar{E}(m_b) - \bar{E}(m_a) \tag{29}$$

To get the slope, the values from equation (29) was divided by the normalized values of the related parameter levels as shown in equation (30).

$$S(m)_{a \to b} = \frac{\bar{E}(m)_{a \to b}}{U(m_b) - U(m_a)} = \frac{\bar{E}(m_b) - \bar{E}(m_a)}{U(m_b) - U(m_a)} \tag{30}$$

Where the normalized values $U(m_a)$ and $U(m_b)$ are calculated as for the respective subscripts:

$$U(m_a) = \frac{V(m_a)}{V(m_{\max})} \tag{31}$$

It was chosen to use the normalized values of the parameters for one particular reason. If the non-normalized values were to be used, the effect on energy consumption of changing the parameter value of one parameter could not be compared to the effect of changing the parameter value of a different parameter. By using normalized values, one can study the relative importance between the different parameters.

The value of *S* tells us the slope of the effect, i.e. how much energy consumption change per change of normalized parameter value. The value of *S* for different parameters and between the parameters' levels can be directly compared. Thus, the relative importance between the parameters can be studied.

3.4.3 Combined parameter regression analysis

The notations used to calculate the two-factor effect is similar to what used for the single parameter effect. Equation (32) gives the general idea on how the average energy consumption was calculated when two parameters were kept at a certain level.

$$\bar{E}(X3_k X4_l) = \frac{\sum_{i,j} E_{ijkl}}{i \cdot j} \tag{32}$$

4 Results

4.1 Response surface curves

4.1.1 Tunnel mix 0 % and train speed third variable

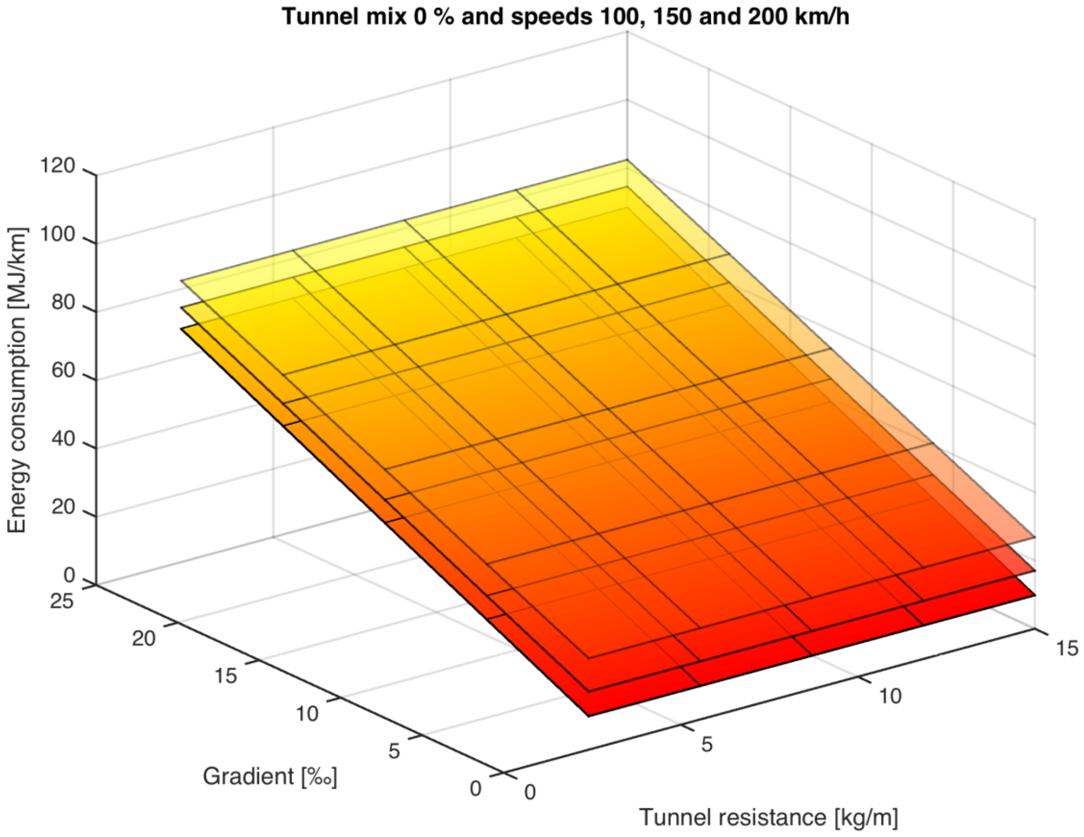


Figure 19: Energy consumption with different levels of gradient, tunnel resistance and train speed (one level for each surface) while the tunnel mix is at 0 % level

Tunnel mix level at 0 % implies that there are no tunnel on the line, tunnel resistance will obviously have no effect on response. As a result, the surface will only have curvature around the gradient axis. It can be observed that the effect from gradient is linear, which is expected. The effect is relatively large, approximately 2.5 MJ/km per unit change of gradient.

4.1.2 Tunnel mix 100 % and train speed third variable

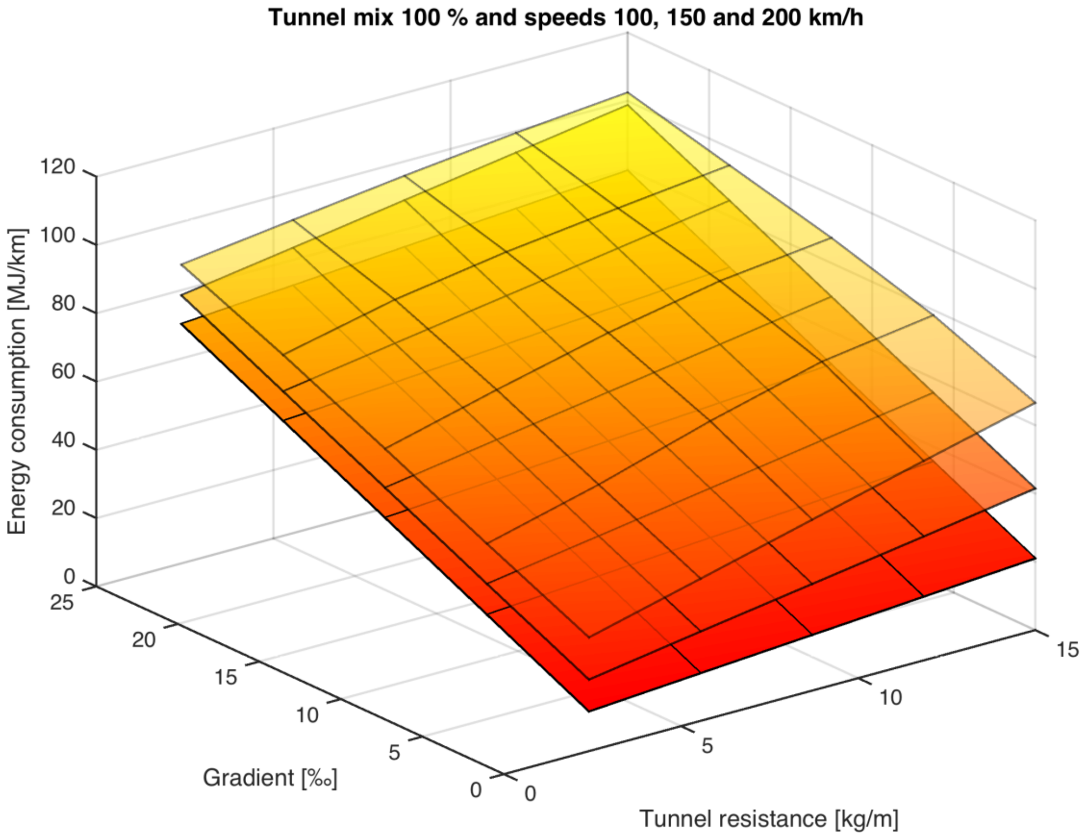


Figure 20: Energy consumption with different levels of gradient, tunnel resistance and train speed (one level for each surface) while the tunnel mix is at 100 % level

At tunnel mix 100 %, the entire line is inside a tunnel. Now it can be observed that tunnel resistance has an effect on the response. At low speed (bottom surface) gradient seems to be a much larger contributor compared to tunnel resistance to the energy consumption. However, when the speed increases (two highest surfaces) the effect from tunnel resistance is considerably increased.

At 200 km/h (top surface), a slightly double curvature can be observed that gives the impression of that the energy consumption converges. It was found that the train does in fact not reach its target speed at certain combinations of parameter levels. The flattening of the surface is a result of the train reaching its maximum power output at approximately 4500 kW. As long as there is an equilibrium between tractive effort and resistance and the train is not running at its target speed, higher levels of parameters (and therefore resistance) will result in a speed decrease.

4.1.3 Tunnel mix 100 % and gradient third variable

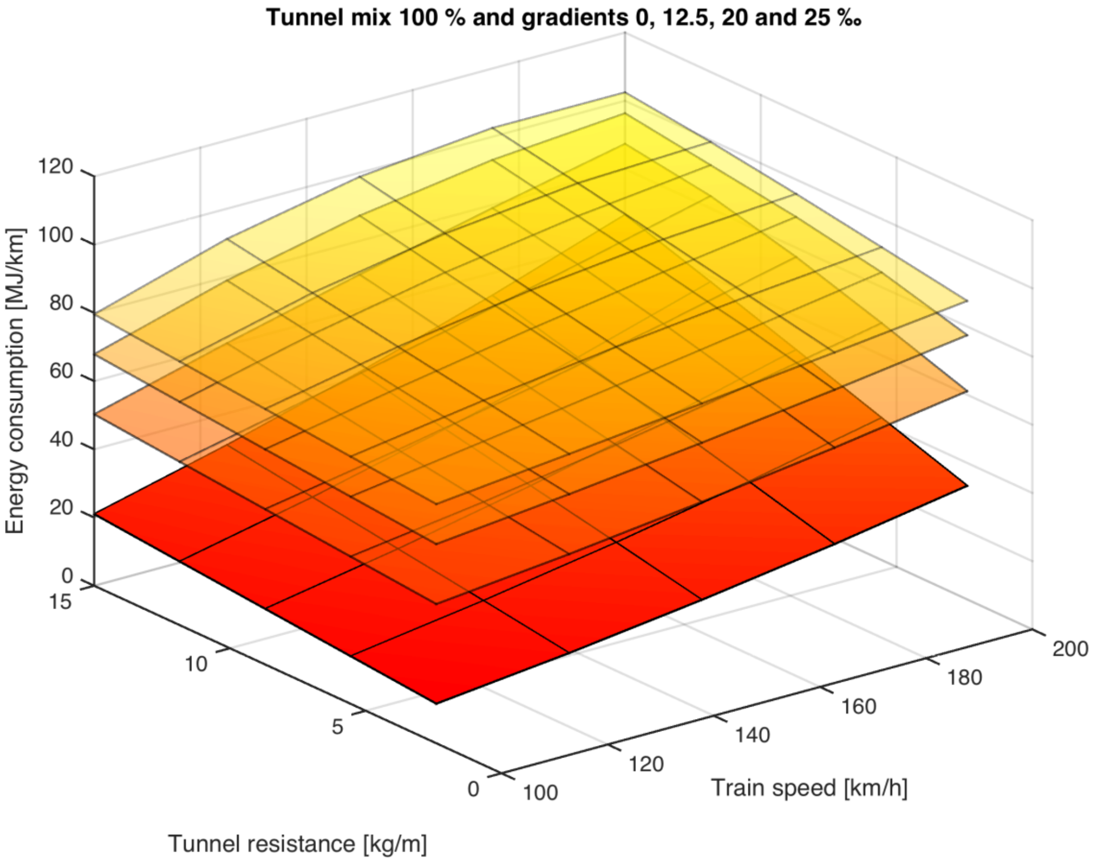


Figure 21: Energy consumption with different levels of gradient (one level for each surface), tunnel resistance and train speed while the tunnel mix is at 100 % level

Again, the effect of the train reaching its maximum power output is clear, especially for gradient 20 and 25 ‰ (top two surfaces). The bottom surface (0 ‰ gradient) gives the best insight in train speed vs. tunnel resistance importance. It can be observed that train speed is the dominating factor, but tunnel resistance is gaining importance at higher speed.

4.1.4 Tunnel mix 100% and tunnel resistance third variable

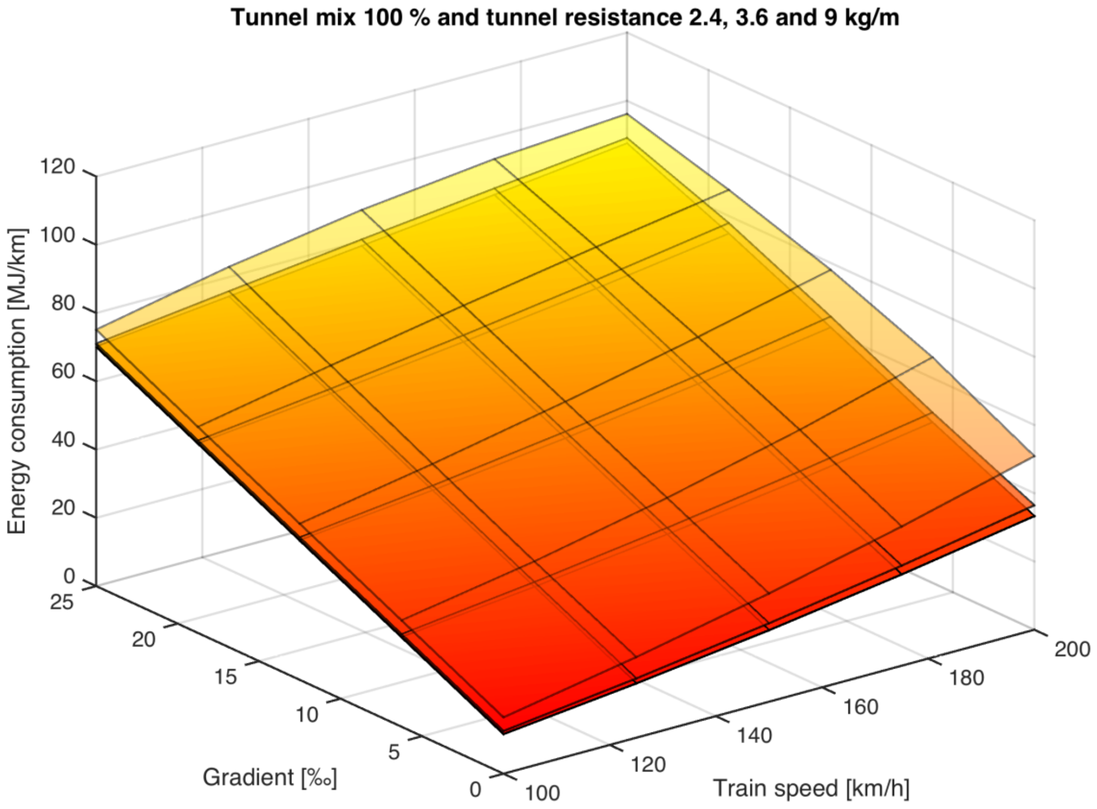


Figure 22: Energy consumption with different levels of gradient, tunnel resistance (one level for each surface) and train speed while the tunnel mix is at 100 % level

Here is the response based on gradient and train speed presented at different levels of tunnel resistance factor. Gradient seems to have a bigger influence compared to train speed, although the balance changes as tunnel resistance increases. This is in line with theory on how tunnel resistance varies with train speed, while gradient does not.

4.2 Single parameter analysis

Table 7 summarizes the average energy consumption for each parameter at the parameters' different levels. These values are results of equation (25) through (28) used on the data gathered through the simulations. These values tells us what the average energy consumption in MJ/km is when one parameter is kept at a permanent level while the other parameters are varied in all possible combinations. E.g.; the value in the top left corner is the sum of the energy consumption of all simulations where the train speed is 100 km/h divided by the number of simulations where this applies.

An important observation can be done here. For gradient 0 ‰, the average energy consumption is relatively low compared to all the other entries in the table. This indicates that trains running at no gradient use considerably less energy than trains that do not.

Table 7: Average energy consumption values. Values in MJ/km.

	Level 1	**Level 2**	**Level 3**	**Level 4**
$\bar{E}$(X1)	47.17	58.23	69.47	
$\bar{E}$(X2)	52.71	55.09	61.07	67.08
$\bar{E}$(X3)	50.74	56.44	62.03	
$\bar{E}$(X4)	26.31	54.38	70.83	81.63

In order to understand how the change in energy consumption is relative to change in parameter value, the value of the slope has to be studied. The data from Table 7 are used to find the slope by use of equation (30). The results are summarized in Table 8. A slightly elaborated description of the process of calculating the values in Table 8 is found in appendix C.

Table 8: Slope values

	1→2	**2→3**	**3→4**	**1→3**	**1→4**
$S(X1)_{a\to b}$	44.2	45.0	-	44.6	-
$S(X2)_{a\to b}$	29.8	16.6	15.0	-	17.1
$S(X3)_{a\to b}$	11.4	11.2	-	11.3	-
$S(X4)_{a\to b}$	56.1	54.8	54.0	-	55.3

As seen in the table, the slope is calculated for several changes in parameter value. Parameter X1 and X3 have three parameter levels, while parameter X2 and X4 have four levels. In addition to the intermediate slope values, the slope for minimum parameter value to maximum parameter value is calculated. In this way, the step from minimum to maximum can be compared to the intermediate steps to discover if there are any differences. Different values indicate that the change in energy consumption is not linear. The values are organized in a column chart in Figure 23.

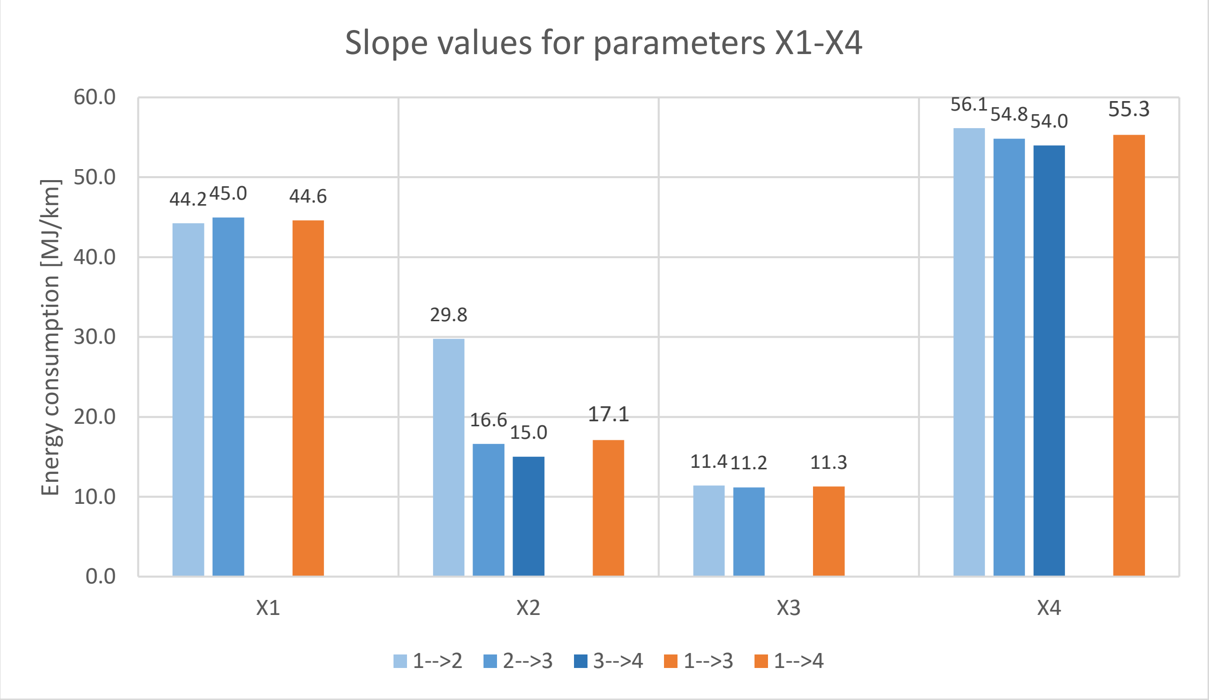


Figure 23: Slope values for parameters X1-X4

4.2.1 Parameter X1 – train speed

Train speed seems to have a relatively large impact on the energy consumption. The slope is bigger going from 150 km/h to 200 km/h than going from 100 km/h to 150 km/h. This result confirms that the model predicts as in the theory stating that air resistance and tunnel resistance increases with speed squared. Certain parameter combinations with 200 km/h led to the train actually not reaching 200 km/h due to limited power output. If the train could exert more power, an even higher slope value for 150 km/h to 200 km/h would likely be found.

4.2.2 Parameter X2 – tunnel resistance

Difference in slope values seems to be especially prominent for parameter X2. A large increase in energy consumption is observed going from 2.4 kg/m to 3.6 kg/m tunnel resistance compared to the other steps. However, one must be cautious when looking at these numbers. As previously discussed, the train reaches its maximum power output for certain combinations of parameters.

For high values of tunnel resistance this was the case. This leads to a small increase in energy consumption going from parameter level 2 to 3 and 3 to 4 simply because the train cannot use more power. This will be further treated in the discussion chapter.

4.2.3 Parameter X3 – tunnel mix

This parameter must be studied slightly differently from the three others and cannot be directly used in a comparison. Reason for this is that the parameter values are in percent. However, it gives the opportunity to compare tunnel to non-tunnel cases. For no tunnel, the average energy consumption is 50.74 MJ/km. For 100 % tunnel, the average energy consumption is 62.03 MJ/km. In this regard, we can see that the energy consumption is approximately 20 % higher when the line is inside a tunnel compared to open track.

4.2.4 Parameter X4 – gradient

Of the four parameters, gradient seems to have the biggest effect on energy consumption. Having a line with 12.5 ‰ increases the energy consumption by approximately 100 % compared to 0 ‰. The slope values are declining most likely due to the maximum train power output being reached as previously discussed. A linear relationship, i.e. equal values, is to be expected based on gradient resistance theory.

4.3 Combined parameter analysis

The combined parameter effect was analyzed for the X3 and X4 combination as this was deemed to be of highest interest. In many railway projects, train speed is usually determined by the government and not a matter of design. Similarly, the tunnel design (which implicates the tunnel resistance factor) is done based on the train speed in line with national requirements. Therefore it is mainly tunnel and gradient that the designer of the alignment can have a say in. Thus, it is important to discover any two-factor interaction between the two.

Table 9: Average energy consumption for combined parameter cases. Values in MJ/km

	No tunnel & 0 ‰ gradient	**100 % tunnel & 12.5 ‰ gradient**	**100 % tunnel & 20 ‰ gradient**	**100 % tunnel & 25 ‰ gradient**
$\bar{E}$(X3X4)	17.86	58.40	74.44	84.81

Table 9 is a summary of the combined parameter results. The average energy consumption increases by approximately 39.5 MJ/km when going from no tunnel and no gradient to 100 %

tunnel and 12.5 ‰ gradient. This is approximately an increase of 230 %. From no tunnel and no gradient to 100 % tunnel and 20 ‰ gradient the value increases by 56.6 MJ/km, approximately 320 %. From no tunnel and no gradient to 100 % tunnel and 25 ‰ gradient the value increases by 67.0 MJ/km, approximately 370 %.

In order to reveal any two-factor interaction the numbers must be compared to the sum of the single parameter effects, see Table 11.

Table 10: Change in average energy consumption for single parameter effects [MJ/km]

	1→2	**1→3**	**1→4**
$\bar{E}(X3)_{a\rightarrow b}$	-	11.3	-
$\bar{E}(X4)_{a\rightarrow b}$	28.1	44.5	55.3

Table 11: Comparison of average energy consumption between sum of single parameters and combined parameters [MJ/km]

	Sum of single parameters	**Combined parameters**
No tunnel and no gradient to 100 % tunnel and 12.5 ‰ gradient	39.4	39.5
No tunnel and no gradient to 100 % tunnel and 20 ‰ gradient	55.8	56.6
No tunnel and no gradient to 100 % tunnel and 25 ‰ gradient	66.8	67.0

From no tunnel to 100 % tunnel there is an increase of approximately 11.3 MJ/km. From no gradient to 12.5 ‰ gradient there is an increase of approximately 28.1 MJ/km. In sum, this equals an increase of 39.4 MJ/km. This is more or less equal to the two-factor results, only off by 0.1 MJ/km which could be a result of rounding error.

From no gradient to 20 ‰ gradient there is an increase of approximately 44.5 MJ/km. Adding this value to the 11.3 MJ/km from single parameter tunnel effect gives an increase of 55.8 MJ/km. The two-factor increase equal to 56.6 MJ/km is 0.8 MJ/km higher than the sum of the single parameter effects. Although a small number, this indicates a minor two-factor interaction.

From no gradient to 25 ‰ gradient there is an increase of approximately 55.3 MJ/km. Adding this value to the 11.3 MJ/km from single parameter tunnel effect gives an increase of 66.8 MJ/km. The two-factor increase equal to 67.0 MJ/km is 0.2 MJ/km higher than the sum of the single parameter effects. In other words, a minor difference.

The results are ambiguous. The first case does not indicate a two-factor interaction. The second case indicates a two-factor interaction. A small two-factor interaction is seen in the third case. It is hard to make a conclusion based on this, but the results indicates there is a two-factor interaction. However, it is considered to be minor.

5 Discussion

5.1 Results

Some of the results got slightly distorted due to reaching the maximum train power for certain combinations of parameter levels. This was not anticipated when designing the simulations and came as a surprise to the author. The topic will be further elaborated in subchapter 5.4. Furthermore, the energy calculations was done based on the different parameter levels having equal weight. This might be false compared to the reality.

The fact that gradient had the biggest effect on energy consumption is not surprising, this has been proved earlier by Mustad (2018) among others. Trains are heavy objects and moving them against gravity requires considerable amounts of energy. Gradients are usually determined by the topography, but effort should nevertheless be made to avoid unnecessary gradient due to its effect on energy consumption.

The study showed that by running through a tunnel there was an approximate increase in energy consumption by 20 %. This number is assumed to be too high compared to reality. Reason for this is that there are regulations applying to tunnel resistance for high train speeds which were not respected for some parameter combinations. As a result, the value for average energy consumption might be too high due simulations where the train is running in a tunnel that is smaller (thus resistance too high) than what is allowed. This is further discussed in subchapter 5.3.2.

Two-factor interaction between tunnel and gradient was studied. The results indicate a minor two-factor interaction which answers one of the research questions.

5.2 Methodology

5.2.1 Simulation model

The Opentrack software worked well for this type of research. Although it has a steep learning curve, it was able to do what was planned. However, it may not have been necessary to use a simulation software for energy consumption calculations. It might have been adequate to use a set of equations to get the desired data. On the other hand, it can be said that the software already has implemented the set of equations. Therefore, another source of error is eliminated by using an acknowledged software instead of setting up the calculations.

5.2.2 Regression analysis

The methodology regarding regression analysis was most likely not optimal to study the effect on parameter change. It would most likely be more beneficial to study the average of changes rather than change in averages. This was however found to be difficult with the amount of parameter levels, and time started to run out before this methodology was developed.

5.3 Parameter levels

5.3.1 Train speed

Three levels of speed were chosen; 100, 150 and 200 km/h. Although not exactly being the regular speed restrictions, these values are considered to be in the range of what trains are realistically running at in Norway today. Some parts of the Intercity network currently being developed are designed for speeds up to 250 km/h. It could therefore have been interesting to study how higher speeds than 200 km/h, and even higher than 250 km/h for an international applicability, affects the energy consumption. Due to some resistances varying with the speed squared, a clearer nonlinear response are assumed to be found.

5.3.2 Tunnel resistance factor

An important topic in this thesis has been tunnel resistance. The tunnel resistance factors used to calculate the tunnel resistance have been based on findings by Hansen et al. (2017). The values depend on a numerous amount of factors, including aerodynamic cross section of the tunnel, tunnel wall roughness, tunnel length, train shape, interference with other trains, local weather conditions. In other words, not only tunnel design influences the tunnel resistance factor. This has consequences for the validity of some findings in this thesis. The tunnel resistance factors used are based on real life measurements done in tunnels in Norway. As previously stated, the BM74E rolling stock is used in this thesis in order to comply with the rolling stock used to carry out the measurements. However, the rolling stock used to measure the tunnel resistance factor for the 27 m^2 tunnels are not the same used for the other tunnels. This is due to the BM74E simply not using that line. As a result, the tunnel resistance factors for the 27 m^2 may not be as correct as the others for the BM74E rolling stock. This could lead to incorrect tunnel resistance calculations and energy consumption. The errors are assumed to be low due to the train shapes not being too different. Also, the actual values are not truly of interest, but rather how the energy consumption is affected by the change of tunnel resistance factor.

Another important matter is which combinations of train speed and tunnel resistance are realistic. The size of tunnel, and thus tunnel resistance factor, might be limiting for train speed. Lieråstunnelen is limited to 130 km/h due to its small aerodynamic cross section for being a double track tunnel. Especially the combinations of 200 km/h train speed and tunnel resistance factors above 3.6 kg/m are assumed to be unrealistic (Jernbaneverket, 2018).

5.3.3 Gradient

The four levels of gradient are based on technical requirements for the Norwegian railway by Bane NOR (Bane NOR, 2019). The highest value used is 25 ‰ which is restricted to passenger traffic lines only. Even the second highest value of 20 ‰ cannot be used on mixed traffic lines without extra considerations. Few lines in Norway today are restricted to passenger traffic only. Reason for investigating such irregular values is that some lines in future may be designed for passenger traffic only, and therefore the effect of using such high values of gradient should be known.

5.4 Power consumption and train power limitation

During simulations it was found that the maximum power output for the train was reached for certain combinations of parameter levels. This applied to 200 km/h train speed in combination with high levels of gradient and/or tunnel resistance. Because of this, the results became slightly distorted. Some response surface plots showed that the energy consumption would reach a maximum value, and any higher levels of the parameters would not result in a higher energy consumption. This is both a true and false result, as the energy consumption does in fact reach a maximum value, but not as an effect of parameter levels increasing. If the train could exert more power, the surface plots would not have this shape. This result can be viewed as a confirmation of the current requirements for these track related parameters.

Regenerative braking was not included for the energy consumption calculations in this study. By including this feature the energy consumption would be lower, although the effect is assumed to be negligible due to the length of the railway line. The effect on a line with a more realistic stopping pattern would be more noticeable.

6 Conclusion and further research

6.1 Conclusion

The thesis has provided insight into which parameters and to what extent they affect a trains energy consumption on a railway line. A literature study has been conducted to identify parameters. A simulation model has been used to extract data from scenarios where the parameters have been combined at different levels. The data has been analyzed to find the critical parameters and if there is a two-factor interaction. The core findings are:

- The parameters affecting energy consumption in a tunnel are from most critical to least critical gradient, train speed and tunnel resistance factor. Tunnel resistance factor gets increasing importance at higher train speeds.
- Two-factor interaction between tunnel resistance was found, but it is deemed to be minor.
- A passenger trains energy consumption is approximately 20 % higher when the line is inside a tunnel compared to open track.

6.2 Further research

It is of interest to conduct such a study for higher train speeds. With an increasing focus on environmental friendly transport, high speed railway might be more prevalent than it is today. Theory and this thesis has shown that air and tunnel resistance, and thus energy consumption, is affected by speed squared. Train speed might therefore have increasing importance at higher speeds.

Bibliography

Abril, M. et al., 2008. An assessment of railway capacity. *Elsevier,* 44(5), pp. 774-806.

Antony, J., 2003. *Design of Experiments for Engineers and Scientists.* 1st red. s.l.:s.n.

Bane NOR, 2017. *Bane NOR.* [Internett]
Available at: https://www.banenor.no/Nyheter/Nyhetsarkiv/2017/----historisk-jernbanesatsing/
[Accessed 11 10 2018].

Bane NOR, 2018. *Bane NOR.* [Internett]
Available at: https://www.banenor.no/Prosjekter/prosjekter/Arna-Bergen/mer-om-prosjektet/
[Accessed 3 December 2018].

Bane NOR, 2019. *Teknisk Regelverk.* [Internett]
Available at: https://trv.banenor.no/wiki/Forside
[Accessed 5 July 2019].

Box, G. E. P., Hunter, J. S. & Hunter, W. G., 2005. *Statistics for Experimenters: design, innovation and discovery.* s.l.:s.n.

Chandra, S. & Agarwal, M., 2013. *Railway Engineering.* 2nd Edition red. s.l.:Oxford University Press.

Eggum, D., 2017. *Effekten av stigningsgrad på jernbanekapasitet,* s.l.: s.n.

Esveld, C., 2001. *Modern Railway Track.* 2 red. s.l.:MRT-productions.

Hansen, H. S., Nawaz, M. U. & Olsson, N., 2017. Using operational data to estimate the running resistance of trains. Estimation of the resistance in a set of Norwegian tunnels. *Elsevier.*

Hürlimann, D., 2001. *Objektorientierte Modellierung von Infrastrukturelementen und Betriebsvorgängen im Eisenbahnwesen,* Zürich: s.n.

Hu, S.-R. & Huang, S.-S., 2014. Effects of Vertical Alignment on Rail Line Capacity Loss for HSR Operation. *IEEE 17th International Conference on Intelligent Transportation Systems (ITSC).*

Jernbaneverket, 2012. *Slik fungerer jernbanen,* Oslo: s.n.

Jernbaneverket, 2015. *Jernbanen mot 2050,* s.l.: Jernbaneverket.

Jernbaneverket, 2018. *Jernbanekompetanse.* [Internett]
Available at: http://jernbanekompetanse.no

Kim, M., Schonfeld, P. & Kim, E., 2013. Comparison of verticle track alignments for rail transit. *Journal of transportation engineering.*

Landex, A., 2006. Evaluation of railway capacity. *Proceedings of Trafficdays.*

Landex, A., 2014. Rail Traffic Engineering. I: s.l.:s.n.

Lindahl, M., 2001. *Track geometry for high-speed railways,* s.l.: s.n.

Mustad, B., 2018. *Combined effects of track gradient related parameters on energy consumption and capacity,* s.l.: s.n.

Norske Tog, 2019. *Norske Tog.* [Internett]
Available at: https://www.norsketog.no/tog/type74
[Accessed 11 June 2019].

Opentrack, 2017. *Opentrack User Manual,* Zürich: s.n.

Pachl, J., 2015. *Railway Operation and Control.* 3rd Edition red. s.l.:s.n.

Profillidis, V., 2006. *Railway Management and Engineering.* 3rd Edition red. s.l.:s.n.

Raghunathan, R., Kim, H.-D. & Setoguchi, T., 2002. Aerodynamics of high-speed railway train. *Elsevier.*

Regjeringen, 2017. *Regjeringen.* [Internett]
Available at: https://www.regjeringen.no/no/dokumenter/meld.-st.-33-20162017/id2546287/sec1#KAP1-2
[Accessed 11 10 2018].

Schetz, J. A., 2001. Aerodynamics of high-speed trains. *Annual review of fluid mechanics.*

Steimel, A., 2008. *Electric Traction - Motive Power and Energy Supply.* Munich: Oldenbourg Industrieverlag.

Vardy, A., 1996. Aerodynamic drag on trains in tunnels Part 1. *SAGE.*

Appendix

Master`s Agreement

Faculty	IV - Fakultet for ingeniørvitenskap
Institute	Institutt for bygg- og miljøteknikk
Programme code	MTBYGG
Course code	194_TBA4955_1

Personal information

Family name, first name	Olsen, Christian Magnus
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The Master`s thesis

Starting date	15.01.2019
Submission deadline	11.06.2019
Thesis working title	Combined Effects of Tunnel Related Parameters on Energy Consumption and Capacity
Thematic description	The goal of the master thesis is to identify the critical parameters for the combined effect of capacity and energy consumption. Parameters related to tunnels will be given extra attention. 1) What are the parameters that affect capacity and energy consumption on a railway line? 2) What are the parameters that have the largest impact on the combined effect of capacity and energy consumption? 3) Does the two-factor response from tunnel resistance and a second track related parameter behave linearly or non-linearly?

Supervision and co-authors

Supervisor	Elias Kassa
Any co-supervisors	
Any co-authors	

Topics to be included in the Master`s Degree (if applicable)

Guidelines – Rights and Obligations

Purpose

Agreement on supervision of the Master's thesis is a cooperation agreement between the student, supervisor and the department that governs the relationship of supervision, scope, nature and responsibilities.

The master's program and the work of the master's thesis are regulated by the Act relating to universities and university colleges, NTNU's study regulations and current curriculum for the master's program.

Supervision

The student is responsible for

- Agre upon supervision within the framework of the agreement
- Set up a plan of progress for the work in cooperation with the supervisor, including the plan for when the guidance should take place
- Keep track of the number of hours spent with the supervisor
- Provide the supervisor with the necessary written material in a timely manner before the guidance
- Keep the institute and supervisor informed of any delays

The supervisor is responsible for

- Explain expectations of the guidance and how the guidance should take place
- Ensure that any necessary approvals are requested (REC, ethics, privacy)
- Provide advice on the formulation and demarcation of the topic and issue so that the work is feasible within the standard or agreed upon study time
- Discuss and evaluate hypotheses and methods
- Advice on professional literature, source material / data base / documentation and potential resource requirements
- Discuss the presentation (disposition, linguistic form, etc.)
- Discuss the results and the interpretation of them
- Stay informed about the progression of the student's work according to the agreed time and work plan, and follow up the student as needed
- Together with the student, keep an overview of the number of hours spent

The institute is responsible for

- Make sure that the agreement is entered into
- Find and appoint supervisor(-s)
- Enter into an agreement with another department / faculty / institution if there is a designated external supervisor
- In cooperation with the supervisor, keep an overview of the student's progress, an overview of the number of hours spent, and follow up if the student is delayed by appointment
- Appoint a new supervisor and arrange for a new agreement if
  - supervisor will be absent due to research term, illness, travel, etc., and if the student wishes
  - student or supervisor requests to terminate the agreement because one of the parties does not follow it
  - other circumstances make the parties find it appropriate with a new supervisor
- Notify the student when the guidance relationship expires.
- Inform supervisors about the responsibility for safeguarding ethical issues, privacy and guidance ethics

- Should the cooperation between student and supervisor become problematic for one of the parties, a student or supervisor may ask to be freed from the Master`s agreement. In such case, the institute must appoint a new supervisor

This Master`s agreement must be signed when the guidelines have been reviewed.

Signatures

Elin Tøust

Institute	**Supervisor**	**Student**
21/1-19		
place and date	place and date	place and

date

Trondheim 15.01.19

Christian Olsen

Trondheim 14.01.19

Appendix B

Calculation of block lengths

According to Bane NOR (Bane NOR, 2019), equation (1) is used to calculate the length of the block sections.

$$MA = \frac{L}{3{,}6}T + \frac{L^2 - MH^2}{2R \cdot 3{,}6^2} \tag{1}$$

Where:

- MA = block section length [m]
- L = line speed [km/h]
- T = sum of reaction time and safety factor [s]
- MH = target exit speed [km/h]
- R = retardation [m/s^2]

MH is 0 km/h as full stop is considered. T is 8 seconds when considering signal balises. The retardation is calculated using the following formula.

$$R = -0{,}2 \cdot \frac{L - 150}{150} - \frac{C}{100} + 0{,}7 \tag{2}$$

Where:

- C = negative gradient [‰] (= 0 if line has 0 or positive gradient)

The first term which includes the line speed should only be used when $L > 150$ km/h. If the train is running at less than 150 km/h and is moving at 0 or positive gradient, the retardation is simply 0,7 m/s^2.

Based on these constraints, the block lengths for different line speeds are calculated and found in Table 1. Due to only considering a line with positive gradient, values for C are left out.

Table 1: Block lengths for different line speeds

L [km/h]	**160**	**200**	**250**
T [s]	8		
MH [km/h]	0		
R [m/s^2]	0,69	0,63	0,57
MA [m]	1794	2881	4811

Appendix C

Regression method explanation

1) For each parameter and the parameters' different levels, averages was calculated based on equations (25) to (28) in the methodology chapter. The results are found in the table below.

	Level 1	**Level 2**	**Level 3**	**Level 4**
$\bar{E}$**(X1)**	47.17	58.23	69.47	
$\bar{E}$**(X2)**	52.71	55.09	61.07	67.08
$\bar{E}$**(X3)**	50.74	56.44	62.03	
$\bar{E}$**(X4)**	26.31	54.38	70.83	81.63

2) The value of each parameters' level is found below.

	Level 1	**Level 2**	**Level 3**	**Level 4**
V(X1)	100 km/h	150 km/h	200 km/h	
V(X2)	2.4 kg/m	3.6 kg/m	8.8 kg/m	15.2 kg/m
V(X3)	30 km open	15 km tunnel/ 15 km open	30 km tunnel	
V(X4)	0 ‰	12.5 ‰	20 ‰	25 ‰

3) Equation (31) is used on the values in order to calculate the normalized values shown in following table.

	Level 1	**Level 2**	**Level 3**	**Level 4**
U(X1)	0.5	0.75	1	
U(X2)	0.16	0.24	0.6	1
U(X3)	0	0.5	1	
U(X4)	0	0.5	0.8	1

4) Last, equation (30) is used to find the slopes.

	1→2	**2→3**	**3→4**	**1→3**	**1→4**
S(X1)$_{a\rightarrow b}$	44.2	45.0	-	44.6	-
S(X2)$_{a\rightarrow b}$	29.8	16.6	15.0	-	17.1
S(X3)$_{a\rightarrow b}$	11.4	11.2	-	11.3	-
S(X4)$_{a\rightarrow b}$	56.1	54.8	54.0	-	55.3

Appendix D

D.1 Response surface plots

```
close all
clear all

load datay.mat %import vector Y containing all data from simulations; [X1
X2 X3 X4 E]
k = 1;

X1 = [100 150 200];
X2 = [2.4 3.6 9 15];
X3 = [0 50 100];
X4 = [0 12.5 20 25];

v1 = X1; %variable parameter 1
v2 = X2; %variable parameter 2

f1 = 4; %constant parameter 1
c = 4; %= set equal to f1
f1l = 3; %constant parameter 1 level

f2 = 3; %constant parameter 2
d = 3; %= set equal to f2
f2l = 3; %constant parameter 2 level

a = length(v1);
b = length(v2);


W1 = Y(Y(:,c)==1 & Y(:,d)==f2l & Y(:,2)<=length(X2) & Y(:,4)<=length(X4),
:)
W2 = Y(Y(:,c)==2 & Y(:,d)==f2l & Y(:,2)<=length(X2) & Y(:,4)<=length(X4),
:)
W3 = Y(Y(:,c)==3 & Y(:,d)==f2l & Y(:,2)<=length(X2) & Y(:,4)<=length(X4),
:)
W4 = Y(Y(:,c)==4 & Y(:,d)==f2l & Y(:,2)<=length(X2) & Y(:,4)<=length(X4),
:)

while k <= a*b
    for i = 1:b
        for j = 1:a
            Z1(i,j) = W1(k,5);
            Z2(i,j) = W2(k,5);
            Z3(i,j) = W3(k,5);
            Z4(i,j) = W4(k,5);
            k
            k = k+1;
        end
    end
end

nn = 5;

v1i = linspace(min(v1), max(v1), nn);
v2i = linspace(min(v2), max(v2), nn);

[v1i, v2i] = meshgrid(v1i, v2i);
```

```
Zi1 = interp2(v1, v2, Z1, v1i, v2i, 'spline');
Zi2 = interp2(v1, v2, Z2, v1i, v2i, 'spline');
Zi3 = interp2(v1, v2, Z3, v1i, v2i, 'spline');
Zi4 = interp2(v1, v2, Z4, v1i, v2i, 'spline');

figure
surf(v1i,v2i,Zi1, 'Linestyle', '-', 'FaceColor', 'interp');
hold on
surf(v1i,v2i,Zi2, 'Linestyle', '-', 'FaceColor',
'interp','FaceAlpha',.6,'EdgeAlpha',.6);
surf(v1i,v2i,Zi3, 'Linestyle', '-', 'FaceColor',
'interp','FaceAlpha',.5,'EdgeAlpha',.5);
surf(v1i,v2i,Zi4, 'Linestyle', '-', 'FaceColor',
'interp','FaceAlpha',.4,'EdgeAlpha',.4);
colormap(autumn)
zlim([0 120])
hold off

title(['Tunnel mix 100 % and gradients 0, 12.5, 20 and 25 ' char(8240) ''])
zlabel('Energy consumption [MJ/km]')

if v1(1) == X1(1)
    xlabel('Train speed [km/h]')
elseif v1(1) == X2(1)
    xlabel('Tunnel resistance [kg/m]')
elseif v1(2) == X3(2)
    xlabel('Tunnel mix [%]')
elseif v1(2) == X4(2)
    xlabel('Gradient')
end

if v2(1) == X1(1)
    ylabel('Train speed [km/h]')
elseif v2(1) == X2(1)
    ylabel('Tunnel resistance [kg/m]')
elseif v2(2) == X3(2)
    ylabel('Tunnel mix [%]')
elseif v2(2) == X4(2)
    ylabel(['Gradient [' char(8240) ']'])
end
```

D.2 Parameter influence single parameter

```
close all
clear all

load dataz.mat %import vector Z containing data from simulations; [X1 X2 X3
X4 E]
    %(entries with X3=1 & X2=2:4 removed due to being equal to entries with
X3=1 & X2=1)

B = 0;
a = 2; %investigated parameter (1:4)
b = 1; %investigated parameter level (1:3 if a is 1 or 3, 1:4 if a is 2 or
4)
n = 0;
E = 0;

for z = 1:length(Z)
    if Z(z,a) == b
        B = B+Z(z,5)
        n = n+1
    end
end

E = B/n
```

D.3 Parameter influence combined parameters

```
close all
clear all

load dataz.mat %import vector Z containing data from simulations; [X1 X2 X3
X4 E]
    %(entries with X3=1 & X2=2:4 removed due to being equal to entries with
X3=1 & X2=1)

B = 0;
a = 3; %investigated parameter 1 (1:4)
b = 3; %investigated parameter 1 level (1:3 if a is 1 or 3, 1:4 if a is 2
or 4)
c = 4; %investigated parameter 2 (1:4)
d = 4; %investigated parameter 2 level (1:3 if a is 1 or 3, 1:4 if a is 2
or 4)
n = 0;
E = 0;

for z = 1:length(Z)
    if Z(z,a) == b & Z(z,c) == d
        B = B+Z(z,5)
        n = n+1
    end
end

E = B/n
```