KTH Engineering Sciences

Gröna Tåget
Trains for tomorrow's travellers

Eco-driving and use of regenerative electric brakes for the Green Train

The effect on travel time, energy consumption and brake wear

by

Mikael Sjöholm

Stockholm 2011
KTH Railway Group
Royal Institute of Technology

Publication 1101
ISBN 978-91-7501-070-0
www.railwaygroup.kth.se

Postal address
Royal Institute of Technology (KTH)
Aeronautical and Vehicle Engineering
Div. of Rail Vehicles
SE-100 44 Stockholm, Sweden

Visiting address
Teknikringen 8
Stockholm

Telephone
+46 8 790 84 76
Fax
+46 8 790 76 29

E-mail
mabe@kth.se

Preface and acknowledgements

This is a continuation of the outcome of my Master of Science thesis at the Aeronautical and Vehicle Engineering programme at the Royal Institute of Technology (KTH) in Stockholm, Sweden. It is part of “Gröna Tåget” (Eng: Green Train) research and development programme and has been carried in cooperation between Bombardier Transportation, Sweden and the Royal Institute of Technology.

I would like to thank my supervisor at Bombardier Transportation; Christina Larsson for all her efforts and invaluable help.

I would also like to thank my supervisor at KTH; Evert Andersson for his great interest and help in this study.

Thanks also to Johan Palm and Peder Flykt, at Bombardier Transportation for all their help. Also all other great people at Bombardier Transportation who have consistently been helping me with information and valuable advises.

Thanks also to the people at KTH; especially Oskar Fröidh for his valuable assistance regarding the economic investigation.

The financial support from the Swedish Transport Administration (Trafikverket) and Bombardier Transportation is gratefully acknowledged.

Västerås, July 2011

Mikael Sjöholm

Abstract

This study is a part of “Gröna Tåget” (Eng: “Green Train”) research and development programme that is preparing for new high-speed trains in Sweden. The purpose of this study is to investigate the effects of regenerative braking and eco-driving with regard to energy consumption and wear of the mechanical brakes as well as the possible economic benefits.

New sophisticated “eco-driving” systems could help train drivers to run as energy efficient and economically as possible. Combined with powerful drive systems this could lead to more regenerated energy and reduced wear on mechanical brakes. The electric regenerative brakes can thus be used as normal service brake with minimum time loss.

The first part of the study aims at developing a method to calculate wear on train brake pads. This is done by using a reformulated version of Archard’s wear equation with a temperature dependent wear coefficient and a temperature model to predict the brake pad temperature during braking. Generally the temperature dependence is found to be relatively low at normal operational braking.

By performing simulations in the program STEC (Simulation of Train Energy Consumption), energy consumption for different cases of high-speed train operations is procured and significant data for the wear calculations are found. Simulations include both “normal driving techniques” and “eco-driving”. The driving styles were decided through interviews with train drivers and experts on energy optimized driving systems.

The simulations show that more powerful drive systems reduce both energy consumption and travel time by permitting higher acceleration and energy regeneration. Also, with a high degree of electric regenerative braking, the wear of the mechanical brakes becomes lower.

Eco-driving techniques can help to further reduce the average energy consumption and mechanical brake wear. This driving style can require some time margins though, since it takes slightly longer time to drive when using coasting and avoiding speed peaks. However, if used properly this should not have to affect the scheduled travel time, partly because some time margins are always included in the timetable.

Even if new, more powerful, trains would have the ability to reduce energy consumption and brake wear it is also necessary to have an appropriate slip control system for the electric brakes, making it possible to use them also under slippery conditions. In this context it is important that the adhesion utilisation is modest, about 12 – 15 % for speeds up to 100 km/h and lower at higher speeds.

For a 6-car high-speed train in long-distance service (at speeds usually in the range of 190 – 250 km/h) with approximately 280 occupied seats the economical investigation showed that the operator’s cost for brake pad maintenance can be reduced by up to 70 % (with maintained retardation). This if favouring a more powerful drive system (20 kW/ton short-time power instead of 14 kW/ton). The energy cost can be reduced by 4 – 5 % and the reduced travel time would render extra economical benefits of about 0.9 MSEK (per minute of decreased travel time) per year and train, due to improved acceleration. The energy cost will likely be more important for each year since the energy prices are expected to increase significantly.

In fast regional service with more frequent stops and speeds up to 250 km/h, the economical benefits are estimated to be 25 – 70 % higher than for long-distance with few stops.

Sammanfattning

Denna studie är en del av forsknings- och utvecklingsprogrammet “Gröna Tåget” (Eng: Green Train) som förbereder för nya höghastighetståg i Sverige. Syftet med detta arbete är att undersöka vilka effekter som återmatande broms och ”eco-driving” har på energiförbrukningen och slitaget på de mekaniska bromsarna.

Nya sofistikerade system för ”eco-driving” kan hjälpa tågförare att köra så energisnålt och ekonomiskt som möjligt. Detta i kombination med kraftfulla drivsystem (hög effekt) kan leda till mer återmatad energi och minskat slitage på det mekaniska bromssystemet. Elektrisk återmatande broms kan då användas som normal driftsbroms med minimal tidsförlust.

Den första delen av studien syftar till att utveckla en metod för att beräkna slitaget på tågens bromsbelägg. Detta görs genom att använda en omformulerad variant på Archards slitageekvation med en temperaturberoende slitagekoefficient och en temperaturmodell för att approximativt kunna beräkna beläggens temperatur vid inbromsning. Generellt är temperaturberoendet relativt lågt vid normal driftsbroms.

Genom att göra simuleringar i programmet STEC (Simulation of Train Energy Consumption) beräknades energiförbrukning och körtider för olika intressanta körfall och viktiga data för slitageberäkningarna togs fram. Simuleringarna inkluderade både ”normal körstil” och ”eco-driving”. De olika körstilarna togs fram med hjälp av en enkätundersökning bland tågförare och intervjuer med experter på energioptimerande körsystem.

Simuleringarna visar att både energiförbrukningen och restiden kan minskas med hjälp av högre effekt i drivsystemet. Detta medger högre acceleration och retardation och därigenom mer energiåtermatning vid bibehållen bromssträcka och bromstid. Beräkningar visar också att en hög andel elektrisk återmatande broms minskar slitaget på de mekaniska bromsarna.

Teknik för ”eco-driving” kan ytterligare hjälpa till att, i medeltal, minska energiförbrukningen och det mekaniska bromsslitaget. Det fordrar dock att man har en viss tidsmarginal då det tar något längre tid att köra när man utnyttjar frirullning och undviker hastighetstoppar. Använt på rätt sätt behöver dock inte detta påverka den tidtabellslagda restiden, delvis på grund av att vissa tidsmarginaler alltid finns inkluderade i tidtabellen.

Även om nya tåg, med hög driveffekt, skulle ha möjligheten att sänka både energiförbrukning och bromsslitage så är det också nödvändigt med reglersystem som motverkar slirning även vid elektrisk broms. De regenerativa bromsarna bör fungera tillfredsställande även när spåret inte är torrt. Det är i detta sammanhang också viktigt att adhesionsutnyttjningen vid elektrisk bromsning är modest, förslagsvis 12 – 15 % i hastigheter upp till ca 100 km/h och lägre vid högre hastigheter.

För ett 6-vagnars höghastighetståg (190 – 250 km/h) i långdistanstrafik med ungefär 280 belagda platser så visar den ekonomiska undersökningen att operatörernas kostnader för slitage på bromsbelägg kan minskas med nästan 70 % (vid bibehållen retardation). Detta om man väljer ett tåg med högre driveffekt (20 kW/ton korttids driveffekt istället för 14 kW/ton). Energikostnaderna kan sänkas med 4 – 5 % och den reducerade restiden kan öka intäkterna med 0.9 MSEK (per minut som restiden minskas) per år och tåg, på grund av ökad acceleration. Energikostnaderna kommer troligtvis att bli allt viktigare eftersom elpriserna beräknas stiga kraftigt i framtiden.

I snabb regionaltrafik med mera frekventa stopp och hastigheter upp till 250 km/h beräknas de ekonomiska fördelarna bli 25 – 70 % högre än för långdistanstrafik med få stopp.

Table of contents

Nomenclature

In order of appearance

V	Wear volume [m^3]
s	Sliding distance [m]
F_T	Tangential friction force [N]
τ	Constant that characterizes the shear stress of the sliding bodies
ΔW	Wear [m^3]
k	Wear rate coefficient [m^3/Nm]
F_N	Contact normal force [N]
v	Speed [m/s]
t	Sliding time [s]
a, b, c	Friction material specific parameters
T	Operative temperature [°C]
T^*	Melting point of the brake pad material [°C]
P_1, P_2, P_3	Parameters related to the friction coefficient of the material
K	Dimensionless wear coefficient
H_s	Hardness of the softer material [N/m^2] (Vicker’s hardness test)
A	Area [m^2]
Δh	Wear displacement [m]
$\Delta \dot{h}$	Wear displacement rate [m/s]
v_M	Mean value of slide rate [m/s]
t_r	Running time [s]
$\dot{w}$	Wear rate [m/s]
p	Contact pressure [Pa]
k_w	Wear coefficient
E	Mechanical brake energy [J]
k_0	Wear coefficient at reference temperature
T_{crit}	Temperature from which the wear increases exponentially [°C]
H	Heaviside function
c_1, c_2, c_3	Dimensionless constants
T_P	Brake pad temperature [°C]
c_{SB}	Start brake coefficient
c_{SL}	Start leakage coefficient
t_b	Time of braking [s]
t_s	Start of braking [s]
t_d	Time delay [s]
T_{PE}	Achieved temperature at end of braking [°C]
c_{EL}	End leakage coefficient
t_e	End of braking [s]
F_r	Running resistance [N]
A, B, C	Parameters related to the running resistance
F_t	Traction force [N]
a_t	Train acceleration [m/s^2]
m_e	Equivalent mass [kg]
P	Power [W]
r	Discount rate [%]
n	Number of periods (years)

Definitions and explanations

In alphabetical order

Adhesion	Part of friction between wheel and rail that can be used for traction or braking.
Adhesive mass	Part of train mass supported by driven (powered) axles.
Brake disc	A disc that is usually mounted on the wheel axle or the wheel itself, used in combination with a brake pad in order to brake the train.
Brake pad	Part of disc brake system that by a link mechanism is pressed against the brake disc. When pressed against the disc it produces friction and a brake force.
Catenary	Cable over the track that supplies trains with electric power via the current collector (pantograph) on the train roof.
Coasting	Running the train with no tractive or brake force.
Degree of regeneration	Percentage of full regeneration since it is sometimes not possible for the train to regenerate all available power back to the catenary.
Eco-driving	In the context of this study it is an eco-efficient driving style focused on minimizing, or reducing, energy consumption and brake wear, while still trying to keep the timetable.
Load factor	Relation between the number of passenger-km and the offered number of seat-km.
Motor coach	Type of train with no locomotive; instead the traction equipment is distributed throughout the train.
Pantograph	Device that is collecting electrical current and voltage from the overhead wiring (also known as catenary). Usually located on the roof of the train.
Regeneration	In the context of this study it is the percentage of the accumulated input energy regenerated to the catenary.
Regenerative braking	Using the electric motors as generators, transforming the train’s kinetic energy to electricity and, with the exception of losses, feed it back to the catenary.

Speed peak	In the context of this study it is when accelerating right before a speed reduction or stop.
Wear	The loss or displacement of material from a solid surface due to mechanical action.
Wear index	In the context of this study it reflects the relative brake pad wear per seat-km.

Abbreviations and names

In alphabetical order

ATP/ATC	Automatic Train Protection system that applies the brakes of the train automatically if the driver does not apply brakes in due time before a stop or speed restriction. The Swedish ATP system is called ATC (Automatic Train Control).
Bombardier Transportation	Train supplier. (www.bombardier.com)
EMU	Electrical Multiple Unit, train with the traction equipment distributed amongst the coaches.
ERTMS	European Rail Transport Management System, an initiative within the European Union to create a European standard for train control and command systems.
ETCS	European Train Control System, a train protection system for in-cab control and signalling.
Green Train	Swedish “Gröna Tåget” research and development programme which prepares for high-speed trains in Sweden and the Nordic countries. (www.gronataget.se)
Gröna Tåget	See Green Train.
GT	Abbreviation for ”Green Train” or ”Gröna Tåget”.
GT-250	Train concept in the Green Train research programme with top speed of 250 km/h, normally with car body tilt.
GT-VHST	Very High-Speed Train; concept in the Green Train research programme with top speed of 280 – 320 km/h.
KTH	Royal Institute of Technology (Kungliga Tekniska Högskolan), Stockholm, Sweden. (www.kth.se)
Regina	An electrically powered wide-body motor coach train (EMU) for fast regional passenger services, operating in different areas of Sweden.

SJ AB	Swedish train operator. (www.sj.se)
STEC	Simulation of Train Energy Consumption. Simulation software for calculating train energy consumption and running times.
TGV	Train á Grande Vitesse, French high-speed train.
Trafikverket	The Swedish Transport Administration. (www.trafikverket.se)
UIC	International Union of Railways.
Västtrafik	Transit authority in western Sweden.
X2 (X2000)	High-speed train, using a tilting car body allowing higher speed on Swedish conventional main lines. Top speed of 210 km/h, utilized at maximum 200 km/h.
X-Trafik	Transit authority in middle Sweden.

1. Introduction

Background

”Gröna Tåget” (Eng. “Green Train”) is a research and development programme preparing for future high-speed trains in Sweden. The Division of Rail Vehicles at the Royal Institute of Technology (KTH) is actively participating in this project together with the industry (Bombardier Transportation), the Swedish Transport Administration (Trafikverket, former Banverket), SJ AB and other actors.

This study includes and continues the previous study “Benefits of regenerative braking and eco driving for high-speed trains” [1]. The major addition is the economic investigation that aims at giving an indication of the economic impact for operators.

Trains have, among other benefits, the advantage of being able to regenerate energy to the feeding power line (known as catenary) when braking. This saves energy and reduces wear on the mechanical brakes.

The electric regenerative brakes used by the trains have a great potential in this area. However, in most trains today it cannot be used to the extent that might be desirable. They do not have the capability to brake fast enough to be used as the main service brake, especially not at higher speeds and in urgent braking cases, with short braking distance. The deceleration will usually be too low and the train will risk running late. There is simply a conflict where a more ecological and economic driving will result in longer travel times which will risk making the railway system less attractive for passengers. Also, the braking distance may be too long to suit the pre-warning distance in the signalling system. To solve this it would be necessary to make the electric regenerative brakes more efficient and practical both at higher speeds and for cases involving harder braking.

This study aims to immerse on the benefits of this technology, especially when running at higher speeds. Would it, for instance, be more economical to have a more powerful drive system which allows for more regeneration and less wear on mechanical brakes compared to most trains today?

Purpose

The purpose of this study is to show the benefits of the regenerative braking and energy optimized driving technology, eco-driving, when looking at energy consumption and brake wear. This includes the economical aspects of three different versions of a high-speed long-distance train with regard to reduced brake wear, energy consumption and reduced travel time in relation to the increased cost for additional power.

Objectives

- Make an inventory of existing mathematical models that describe the wear of brake pads (as function of braking characteristics) and select the most suitable for the present work.
- Perform a survey and a review among train drivers to learn more about different driving techniques and the cause of these techniques.
- Perform simulations of energy consumption when using a “normal driving style” with different braking styles compared to using eco-driving with almost only regenerative braking on representative routes for the Green Train.
- Perform calculations of the brake pad wear.

- Make a comparison of the energy consumption and wear between different driving and braking styles.
- Find factual figures of the economic impact of the brake wear suitable for this study.
- Perform economic calculations of the actual cost for brake wear and energy consumption.
- Economic impact of possibly reduced travel time.
- Draw conclusions with regard to the trains pay-off with the main alternative of pay back in 10 years. Also, an alternative with pay back in 5 years is investigated.

Limitations

- The mathematical model used for the wear calculations is an approximation.
- No separate model for brake disc wear is developed. However, disc wear is assumed to be close to proportional to brake pad wear, at least in normal operational braking with modest braking power dissipation and energy. The discs are designed to have approximately the same life span as the wheels (and are changed at the same time) which makes them less important with respect to the economical impact.
- The brake pad wear with respect to mechanical brake energy will be based on organic brake pads and thus not sintered brake pads.
- The brake pad wear with respect to mechanical brake energy will be based on 3-car Regina trains in four different routes in Sweden. It is possible that the wear does not completely match the wear that the Green Trains may have in reality.

Methods

The study is carried out through literature studies, calculations and simulations, as well as a review of driver’s experience and opinion. The economic part is based on figures from maintenance personnel, statistics and simulations.

Further studies

It would be an advantage to be able to perform experiments or measurements for validation purposes, both for the brake pad temperature calculations as well as for wear of brake pads and brake discs.

2. General information concerning brake wear

2.1 General background

There are three main principles of braking a running train. Using the adhesion between wheels and rails is the most common; these brakes are called adhesion brakes. There are also brakes which use the friction between the track and brake shoes on the train known as track brakes. Track brakes are in principle only used as emergency brakes. The third principle is the eddy current brake that instead of friction uses electromagnetic current to create resistance between the track and the brake shoes.

The adhesion brakes can in turn be divided into three sub-principles: tread brakes, disc brakes (which are mechanical brakes) and electrical brakes. Some trains use all three, with an additional track brake as emergency brake:

- the tread brakes are used to clean the wheel treads and improve the adhesion;
- disc brakes as the main mechanical brake and
- electrical brakes to perform as much of the braking as possible to save energy and mechanical brake wear.

Each disc brake set consists of two pairs of brake pads which press against both sides of a brake disc. The pads are pressed against the disc by a link mechanism, which normally is controlled by a pneumatic cylinder. The discs can be placed on the wheel axle (usually between the wheels) or on the wheels themselves. The pads are usually made of an organic or sintered material; the latter makes them able to withstand higher temperatures. The discs are usually made of steel, but they can also be made of an aluminium alloy to save weight.

Principally the electrical brake can be either rheostatic or regenerative and produces brake force by using the traction motors as generators. In both cases a braking torque on the wheel axle is produced, which in turn produces a braking force between the wheels and rails. If it's rheostatic the kinetic energy is transformed into heat in resistors. If it's regenerative the electrical energy can be returned to the catenary and used by other trains or sometimes it is even possible to feed it back to the public grid. A big advantage of regenerative brakes is thus the possibility to re-use the electrical energy that otherwise would have been transformed into heat when using either rheostatic electrical brakes or mechanical brakes. This benefits both the environment and the economy for the operator. There is also another advantage as the wear of the mechanical brakes becomes lower which prolongs the maintenance intervals. [2]

For safety reason the mechanical brakes must be capable to stop the train running at full speed at a maximum distance. This means that each brake disc must be able to dissipate a large amount of energy in a very short time, in some cases up to 25 MJ (about 7 kWh) per disc in less than two minutes (TGV train braking from 310 km/h). [3]

The pad material is sometimes depending on whether they are used for a locomotive, motor coach or a trailing car. Locomotives and motor coaches usually have sinter pads which can withstand higher temperatures while trailing cars sometimes are equipped with organic pads, mainly for economic reasons. [4]

The size of the discs varies depending on type and use but usually has an outer diameter of 610 – 680 mm and an inner diameter of 330 – 390 mm. The pads have a contact area of about 200 – 300 cm^2 and there are usually four pads per brake disc.

2.2 Existing wear models

Wear can be defined as the loss or displacement of material from a solid surface as a result of mechanical action (friction). A lot of the work on this subject has been done with the aid of finite element simulations or by experimental studies. Many models also include parameters and constants that need to be determined by experiments and are strictly valid for specific materials and operations. There is no “magic formula” available as a simplified mathematical model for calculating wear on train disc brakes. There are however a few models that are more suitable than others.

Reye’s hypothesis, sometimes referred to as the energy dissipative hypothesis, states that the volume of the removed material is proportional to the work (dissipative energy) done by the tangential force. [5]

$$\frac{V}{s} = \frac{F_T}{\tau} \tag{1}$$

where

V = Wear volume [m^3]
s = Sliding distance [m]
F_T = Tangential friction force [N]
τ = Constant that characterizes the shear stress of the sliding bodies

One formula that is also often mentioned, when speaking of mechanical wear in brakes, is Rhee’s wear formula [6]:

$$\Delta W = kF_N^a v^b t^c \tag{2}$$

where

ΔW = Wear [m^3]
k = Wear rate coefficient [m^3/Nm]
F_N = Contact normal force [N]
v = Speed [m/s]
t = Sliding time [s]
a, b, c = Friction material specific parameters

None of these is however taking into account the temperature dependence; they assume a constant temperature which could be a major weakness if not investigated properly. Neither can they be used without knowing details about the materials in the brake pads and discs.

One formula which was developed to be able to calculate the wear on aircraft brakes [7] is:

$$\Delta W = k_w \frac{T}{T^* - T} \tag{3}$$

where

ΔW = Wear [m^3]
k_w = Wear coefficient
T = Operative temperature [°C]
T^* = Melting point of the brake pad material [°C]

The melting point is suggested to be related to the base material of the air plane brake pads, which in this case was copper with melting temperature at 1083° C. The disc was made of steel.

Accordingly, a way to calculate the surface temperature was suggested:

$$T = P_1 F^{P_2} t^{P_3} \tag{4}$$

Where P_1, P_2 and P_3 are parameters that are related to the friction coefficient of the material and other properties also depending on the materials. The wear was reported to increase dramatically when the surface temperature reached over 600 °C. [7].

The equation's weakness is that it only considers cases where the speed is constant.

A general theory is Archard's wear equation [8], or different interpretations of it. It was developed through experimental tests. In [5] it is used to calculate wear volume:

$$\frac{V}{s} = \frac{KF_N}{H_s} \tag{5}$$

where
V = Wear volume [m^3]
s = Sliding distance [m]
K = Dimensionless wear coefficient
F_N = Contact normal force [N]
H_s = Hardness of the softer material [N/m^2] (According to Vicker's hardness test)

Archard's wear equation is sometimes written with the aspect of wear displacement, which from a design view can be convenient. With $\Delta h = V/A$, where A is the area subjected to wear, and contact pressure $p = F_N/A$ it is stated as:

$$\Delta\dot{h} = \frac{\Delta h}{t_r} = \frac{K}{H_s} p v_M \tag{6}$$

where
v_M = Mean value of slide rate [m/s]
t_r = Running time [s]

Archard's wear equation in local form is stated as in [9]:

$$\dot{w} = k_w p v \tag{7}$$

where
$\dot{w}$ = Wear rate [m/s]
k_w = Wear rate coefficient [m^3/Nm]
p = Contact pressure [Pa]
v = Sliding speed [m/s]

If this equation is reformulated according to the following:

$$\dot{w} = k_w p v \Rightarrow \dot{w} = k_w \frac{F_N}{A} v \Rightarrow \dot{w} \cdot A = k_w P \Rightarrow \tag{8}$$

$$\Rightarrow V = k_w E \tag{9}$$

where

$\dot{w}$ = Wear rate [m/s]
V = Wear volume [m^3]
k_w = Wear coefficient [m^3/Nm]
E = Mechanical brake energy [J]

It is then possible to use the mechanical brake energy to calculate the wear volume of the brake pads.

One way to introduce temperature dependency is to state the wear coefficient as temperature dependent. $k_w(T)$ would mean that the coefficient changes with the temperature, as in [9] and [10].

$$k_w = k_{w0}\left[1 + c_1 T + H(T - T_{crit}) c_2 \left(e^{c_3 (T - T_{crit})} - 1\right)\right] \tag{10}$$

where

k_{w0} = Wear coefficient at reference temperature [m^3/Nm]
T = Temperature [°C]
T_{crit} = Temperature from which the wear increases exponentially [°C]
H = Heaviside function
c_1, c_2, c_3 = Dimensionless constants

According to Vernersson and Lundén [9], the wear of the pad, when dependent of the temperature, would be as in Figure 1 below. The expected temperature in normal service is below 200 °C, see Section 8.1.

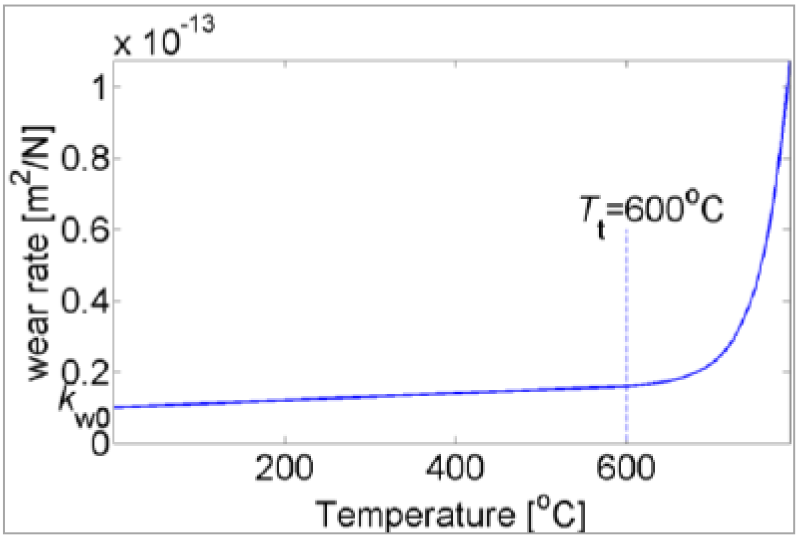

Figure 1. Wear coefficient as function of temperature. [9]

2.3 Tribology and third body

Calculations of the sliding between friction surfaces are highly complex, in particular when considering high-speed cases. The reason for this, among many, is because most friction brakes are functioning in the thermoelastic instability regime. In this regime the interface pressure distribution, heat generation, temperature and wear vary both in space and time. Thermoelastic instabilities are introduced as a cause of the absence of homogeneity in the contact pressure distribution. This results in increased frictional heating and temperatures in regions with higher pressure. As the temperature rises the expansion of the material will increase, resulting in a further concentration of contact pressure and wear. [9]

Another reason for the very complex behaviour is because of the so-called third body. The third body, also known as friction layer, is an expression for the wear debris and other contaminations that gather up between the contact surfaces, i.e. between the other two bodies of contact. The sliding wears down weaker material leaving plateaus of more resistant materials which will make up the primary contact zones between the two bodies. The third body will act as a film between the two bodies where the materials no longer are subjected to all the stresses and displacements. The third body in the interface can withstand shear without serious degradation which is not the case for the two solid bodies. [11]

3. Simulation software (STEC)

In 2009 the Royal Institute of Technology (KTH), Division of Rail Vehicles, identified the need for a new train energy simulation software with an easy to use interface. This resulted in the Microsoft-Excel-based STEC (Simulation of Train Energy Consumption) software [12] developed by Johan Öberg (MiW Konsult AB) for KTH. The main purpose of the program is to calculate the energy consumption and running times after that the user have defined the train and track with a number of parameters.

The program has earlier been used in the EU funded project "TOSCA" (Technology Opportunities and Strategies toward Climate-friendly trAnsport), which deals with transport energy efficiency and reduced environmental impact. This project is carried out by a consortium of seven organizations across Europe with expertise in areas related to transportation and environment.

The main advantages of the program, and the reasons why it is used in this study, are the user-friendly interface and the flexibility that allows for a build-on customization.

A few changes were actually made for this specific study, where the added output of mechanical brake energy is vital. The new version was tested and verified before it was used on a regular basis. One limitation that still could need some improvements is the coasting function. It did nonetheless deliver satisfactory results for this study.

3.1 Input

To be able to simulate different train type's energy consumption and performance, one must first state their properties in the program. Train data, like maximum speed, needs to be defined together with train mass, adhesive mass, number of seats, load factor and so forth. Coefficients of train resistance, traction characteristics and limitations, braking characteristics and limitations, as well as information about the comfort and auxiliary systems are other examples of what information is necessary to be able to perform simulations.

The railway line also needs to be defined. Line gradients and target speeds need to be entered along the line, together with information on locations of stations, as well as dwell time on each station. Information of total track length and desired step length of the calculations are also necessary.

Further, a realistic number of unplanned stops and speed restrictions have to be defined. The final step before it is possible to perform a simulation is to define the run, which means to specify braking mode, coasting, and the output.

3.2 Output

Once a successful simulation has been performed the program instantly shows information about total travel time, details about energy consumption and brake characteristics. It is also possible to see plots of "Speed and target speed as function of position", "Train forces as function of position", "Acceleration as function of position" and "Adhesion coefficient as function of position".

4. Model for brake pad wear

The following chapter describes the different stages of the temperature estimations and the subsequent brake wear calculations done in this study.

4.1 Pad material and temperature dependence

Archard's reformulated wear equation, see Equation 9, was chosen for this study with the temperature dependent wear coefficient (10) proposed by Thuresson [10] and further developed for this explicit use by Vernersson and Lundén [9]. This will make the equation both temperature and speed dependent. Coefficients from Vernersson and Lundén [9] ($k_{w0} = 10 \cdot 10^{-15}$ and $c_1 = 0.001$) will be used and the critical temperature when the wear increases exponentially will be set to 600 °C as in [9], [10]. This is also proven for a certain line-up by Ho and Peterson [7]. This value also coincides with Seidenschwang [13] which leads to the conclusion that 600 °C as a critical temperature is a good approximation. This will have the consequence of being well above the temperatures reached in the cases of this study. In the report "Brake disc – temperature calculation" [13] there is also a highest temperature of 380 °C stated for the brake disc of a Regina motor coach decelerating from 200 km/h to stop at 1.17 m/s^2 (approx. 9.56 ton braked mass per brake disc). This could be seen as an emergency braking with use of the disc brakes only. This data was calculated for a four-car Regina on a demanding route between Uppsala and Gävle in Sweden. Trains that run at higher speeds are usually fitted with more brake discs to make sure the temperature of the braking equipment is held at an acceptable level. No "normal working temperature" can be stated as it largely depends on the actual line and the applied braking. Many stations and speed restrictions lead to a higher mean temperature while a fairly straight track with few stations will allow the brake discs and pads to cool down between braking events.

UIC declares in "Brakes – Disc brakes and their application" [14] that "*The brake pad shall withstand the thermal loading within the limits of the approval program without burning, melting, or forming large deposits on the brake disc or wearing unusually quickly.*

The frictional material shall be able to withstand without worsening of its properties the following temperatures, measured on the rubbing surfaces of the brake discs:

- *for organic brake pads: 400°C,*
- *for sintered brake pads: 550°C.*"

The brake pad material which is used in this work is "Becorit BM 40", which is a sintered pad material for high thermal loads. It is approved for speeds up to 350 km/h.

4.2 Temperature calibration

In order for the wear formula to work properly the temperature must be known at any moment. This can be done by a series of heat dissipation and convection formulas. It could also be done by the use of an equation which could deliver resembling results regarding temperature as function of brake energy. If the parameters are trimmed properly a good adaptation can be achieved, which is the method used in this study.

Data from full scale testing [15] was first used for the calibration. In the beginning this method was considered to be a good approximation. The measured temperature in the test was collected with thermocouples located inside the brake pad, one millimetre from the interface surface, see Figure 2.

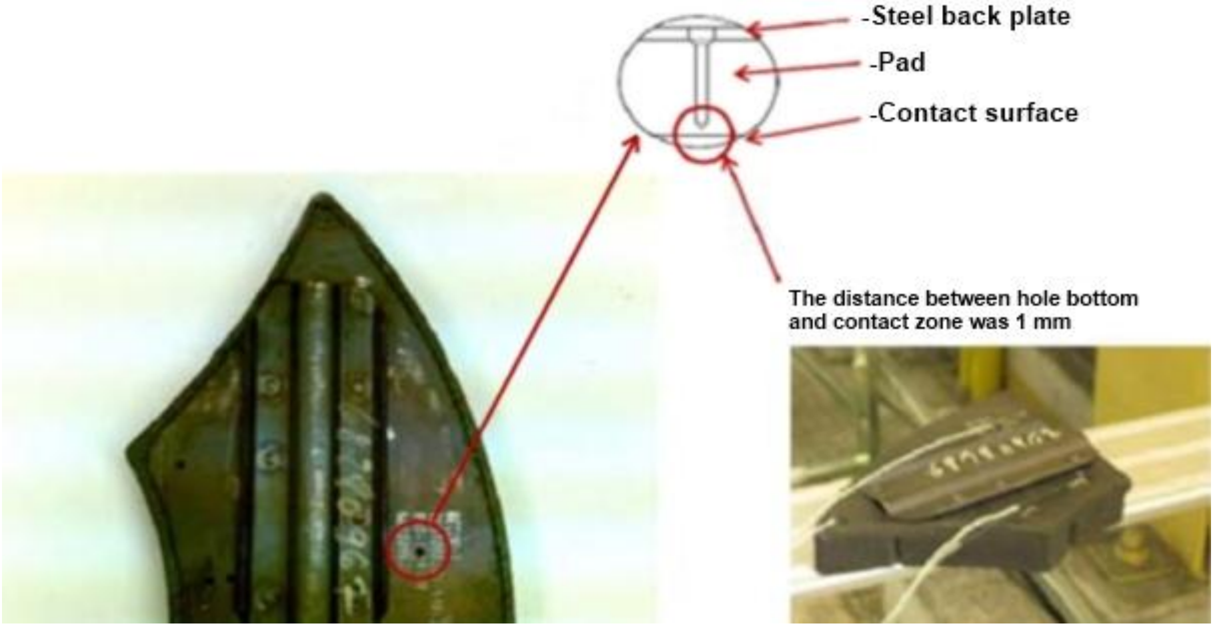

Figure 2. Brake pad with installed thermocouples. [Photo – Courtesy of Saeed Abbasi, KTH]

Since the temperature is measured at a specific point in the pad at a specific moment it is possible that the temperature just millimetres away from the thermocouples is significantly higher. For a better conformity with reality one should perform new tests with the sole purpose of measure the pad surface temperature.

To be able to make an equation that can resemble both the temperature increase and decrease, the “Net dose model” was used. Förstberg used it to predict motion sickness [16] but it can also be used to predict brake pad temperatures. The mathematical formula uses two sets of equations to predict rising and falling temperatures, with the help of a few parameters. Instead of using parameters associated with motion sickness, brake energy and brake coefficients were used together with the braking time.

To do this a steady state (ambient) and starting temperature of 40 °C was approximated, considering and including heat radiation from the train. When the braking starts the first formula sets in and stepwise calculates the temperature rise. When the pressure of the brake pads is reduced and the pad temperature starts to decrease the second formula sets in and calculates (also stepwise) the temperature fall. The calculation ends when the steady state temperature is reached again.

For the braking sequence the following equation was used:

$$\Delta T_P(E_{Mech.brake}) = \frac{c_{SB} \cdot \Delta E}{c_{SL}} \cdot \left(1 - e^{-c_{SL} \cdot (t_b - t_s - t_d)}\right) \qquad (11)$$

where

ΔT_P = Brake pad temperature increment [°C]
ΔE = Mechanical brake energy input [J]
c_{SB} = Start brake coefficient
c_{SL} = Start leakage coefficient
t_b = Time of braking [s]
t_s = Start of braking [s]
t_d = Time delay [s]

If no further brake energy is supplied, i.e. the pads are no longer in contact with the discs or the train has completely stopped, the temperature will start to fall. The following equation is used to calculate the decrease in temperature:

$$T_P(E_{Mech.brake}) = T_{PE} \cdot e^{-c_{EL}\cdot(t_b - t_e - t_d)} \qquad (12)$$

where

T_{PE} = Achieved temperature at end of braking [°C]
c_{EL} = End leakage coefficient
t_e = End of braking [s]

The three coefficients c_{SB}, c_{SL} and c_{EL} thus need to be calibrated, as well as the time delay t_d, in order for the final formula to work properly. The leakage coefficient during the cooling period would need to vary depending on ambient temperature and speed due to convection and radiation.

A comparison between the measured temperature and the calculated temperature, with the above mentioned model, is visualized in Figure 3.

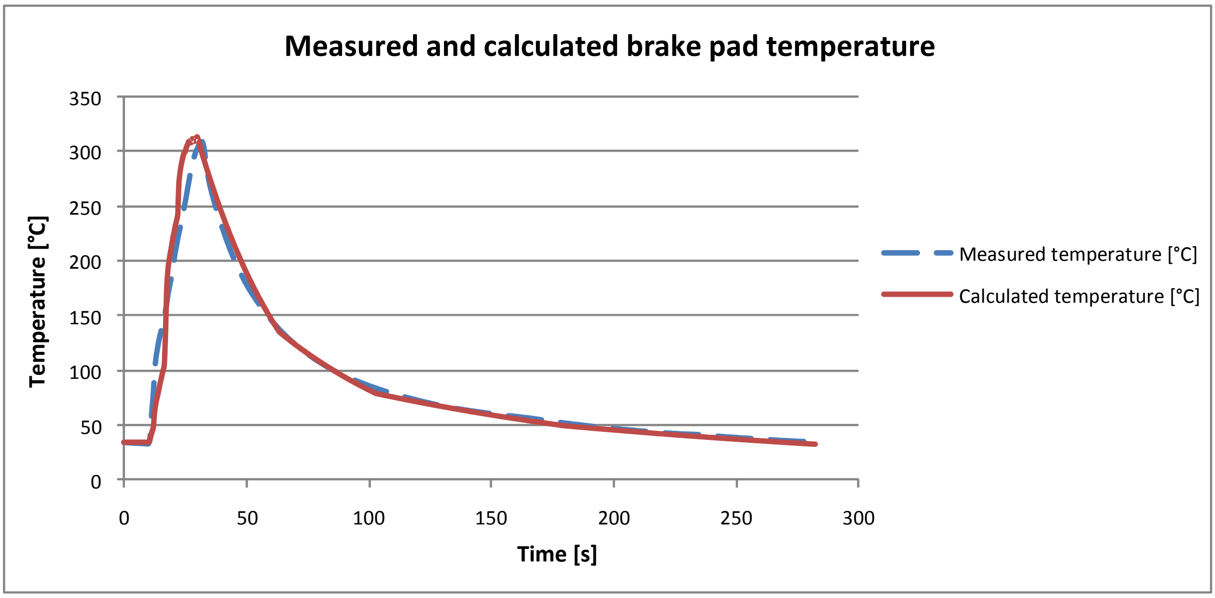

Figure 3. Comparison between measured [15] and calculated brake pad temperature when braking a Regina train from 200 km/h to stop using only disc brakes.

However, though a very good result was achieved in one particular case, when tested for other cases the adaptation was mediocre at best. In some cases the measurements gave different results compared to the calculations regarding the increase in temperature, which also led to an incorrect decrease of the temperature. This might be the cause of the measured temperatures in the field test being figurative but for this study a better approximation of the temperatures was needed. However, the decrease in temperature was recognized as a good approximation.

By adapting the rise of the temperature according to the results of Seidenschwang [13] instead, a more consistent result was obtained. For the decrease in temperature, the earlier approximation also seemed to work well for these cases. The adaptation of the case of braking from 200 km/h at 1.17 m/s^2 is shown in Figure 4. The diagram only shows the results for the temperature rise. The cool down would have to use Equation 12 which was not applied in this figure. The calibrated model was also tested for braking at 0.6 m/s^2, 0.4 m/s^2 and 0.3 m/s^2 with pleasing results.

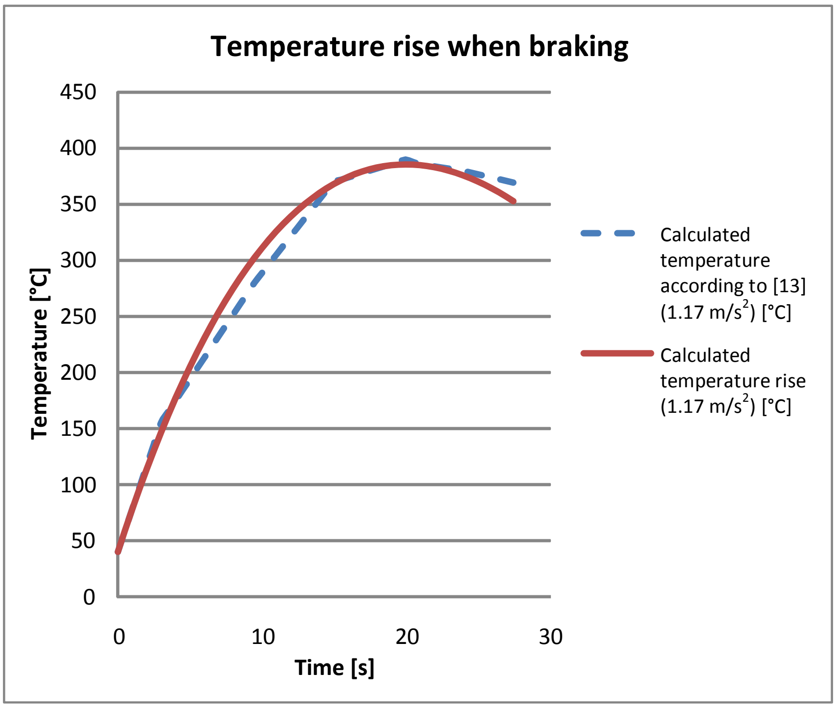

Figure 4. Calculated temperature rise when braking to stop from 200 km/h with a four-car Regina EMU. This can be seen as an emergency braking using only disc brakes.

4.3 Temperature calculations

To further validate the temperature model, calculations with the above calibration was done for a blended brake case with a deceleration of 1.16 m/s^2. The results coincide well with the results of Seidenschwang [13].

The calibrated parameters are as follows:

c_{SB} = 495
c_{SL} = 0.033
c_{EL} (above 145 °C) = 0.025
c_{EL} (81 – 144 °C) = 0.0135
c_{EL} (66 – 80 °C) = 0.006
c_{EL} (0 – 65 °C) = 0.004

The expected temperatures in this study are well below 200 °C in normal operational braking. This is also confirmed in Chapter 8. These predictions gave reason to believe that using an average temperature for wear predictions in each case might simplify the wear calculations and still give a good estimation. According to Vernersson and Lundén [9] the wear only increases 60 % when temperature rises from 0 °C to 600 °C. Therefore an average temperature in this span based on above calculations is believed to give equally good results as a variable one.

4.4 Final wear model

By the above discussion the following calculation path is determined:

1. Increase in brake pad temperature is calibrated using results from Seidenschwang [13] and Equation 11.
2. Decrease in brake pad temperature is calibrated using field test data [15] and Equation 12.
3. Brake pad temperature for the cases in this study is calculated using Equations 11 and 12, the average temperature for a blended braking sequence is then extracted for each case.
4. By using the average brake pad temperatures, the wear coefficients relevant to this study can be determined by Equation 10.
5. With the wear coefficients the actual brake wear can be calculated using Archard's reformulated wear equation (Equation 9) with simulated mechanical brake energy as input.

The brake wear calculations for the cases of this study are further described in Chapter 8.

4.5 Brake wear as function of mechanical brake energy

The operations for the economic study are chosen to fit the results from maintenance statistics regarding 3-car Regina trains. The trains that the statistics are referring to, operate on four lines with station stops identical to the stops in this study, see Table 1. In the "Västtrafik" case the actual trains operate more than just these two lines, but the chosen lines are judged to be representative for all operations.

Table 1. Average speed includes dwell time at station stops as well as time margins.

Operator	**X-Trafik**		**Västtrafik**	
Operation	**Gävle – Sundsvall**	**Gävle – Ljusdal**	**Göteborg – Strömstad**	**Göteborg – Nässjö**
Stations	Gävle C	Gävle C	Göteborg C	Göteborg C
	Axmarby	Ockelbo	Ytterby	Alingsås
	Ljusne	Mo grindar	Kode	Vårgårda
	Söderhamn V:a	Döljebro	Stora Höga	Herrljunga
	Losesjön	Lingbo	Stenungsund	Floby
	Boda	Holmsveden	Svenshögen	Falköping
	Iggesund	Kilafors	Ljungskile	Sandhem
	Hudiksvall	Bollnäs	Uddevalla Ö:a	Mullsjö
	Via	Arbrå	Uddevalla C	Habo
	Gnarp	Vallsta	Munkedal	Bankeryd
	Maj	Järvsö	Dingle	Jönköping C
	Svartvik	Ljusdal	Hällevadsholm	Huskvarna
	Sundsvall C		Rabbalshede	Tenhult
			Tanum	Forserum
			Överby	Nässjö C
			Skee	
			(Strömstad)[1]	
No. of stations	13	12	16	15
Length of line	221 km	162 km	173 km	226 km
Av. speed	94 km/h	95 km/h	68 km/h	85 km/h

---

[1] The tracks between Skee and Strömstad are being upgraded during 2009 – 2012 and are not currently operated, they are excluded from this study.

The Regina train is an electrically powered EMU train running fast regional services in different areas of Sweden. It is officially designated as X50 – X55 and has a wide car body.

The basic track data for simulations have been collected from Trafikverkets line books (2010) regarding speed and station locations and data from Banverket (2000) regarding gradients. Additional data was collected from Trafikverket (2011) regarding additional gradients and duration of station stops as well as other sources within Bombardier Transportation and KTH regarding some additional track data and track upgrades.

Values regarding energy consumption and regeneration for the trains originated from Gävle and Göteborg (Gothenburg) were collected during 2010.

The energy consumption and regeneration results have been validated with data from the measurements taken in 2010. In these measurements a reduction of 8 % of the energy consumption have been made to remove the approximate effects of energy consumption during parking (day time and over night) and planned traffic turnarounds due to a previous investigation. [17] The actual amount of consumption due to these factors may however depend on the train and the use of the train.

The simulations were done as averages for the operations according to the operators' timetables for the actual lines to give as accurate result as possible. The operations were simulated for both directions of each line. The STEC program [12] was used for the simulations.

The trains are of the same type and travel approximately the same distance each year, average values of these trains are used for comparison. The difference between the simulated results and the measurements are, regarding energy consumption and regeneration, less than two percent, see Table 2. The simulated results for the mechanical brake energy are therefore assumed to be equally accurate, as an average.

Table 2. Average values regarding measurements for energy consumption, regeneration and travel time compared to values from simulations made in STEC. The simulations include losses in supply system and 90% degree of regeneration.

	Energy consumption (kWh/km)	**Regeneration (%)**	**Travel time (s)**
Measurements	6.34	20.7	8351
Simulations	6.43	20.7	8342
Match	98.6 %	100 %	100.1 %

The brake pads on the trains of the selected lines have a measured lifespan of about 328 000 km (as an average between two motor cars and one trailing car per train) and travels about 240 000 km per year as an average. With the calculated mechanical brake energy of 8.3 Wh/km per brake pad (0.5 – 0.6 kWh/km for the whole train) on these operations this means that each pair of brake pads can brake off 5400 kWh before needing to be replaced.

5. Train driver survey and review

In order to learn about the driving style in actual high-speed operations and to understand more of the reasons behind the way of driving, a survey was made among professional train drivers (see Appendix A; in Swedish). The survey was sent out to instruction drivers at SJ AB. The results of the survey was also discussed and clarified by Furukrona and Berndtsson at SJ AB [18] [19].

According to the survey the drivers usually plan their driving to be able to make most speed reductions with the electric regenerative brake. More than 50 % of the reductions at higher speeds are made with this brake. Some drivers are able to make more than 75 % of the reductions with the regenerative brake.

The main reasons of not being able to use the regenerative brake are the following:

- Slippery track (poor adhesion).
- Not sufficient electric brake capabilities when urgent speed reduction is needed.
- Not sufficient electric brake capabilities at higher speeds.

When the rails are slippery, for example during the winter, the electric regenerative brake sometimes suffers from slow control. When the motors are braking the wheels and they start to slide, the system must release the brake and restart the braking. This is not always done fast enough and the braking sequence becomes very uncomfortable, resulting in the driver using the mechanical brakes instead. It should be mentioned that improvements have been made in more recent trains compared to the X2, which also can be negatively influenced by its high adhesion utilisation (only 20 – 25 % of the total mass is on powered axles).

High adhesion utilisation increases the risk of entering into a "slippery" region of operation. Slippery conditions will most likely limit the use of electric regenerative brakes, leading to more extensive use of mechanical brakes. This is because the latter have inherently a lower adhesion utilisation; mechanical brakes are usually active on all axles in the train.

In normal passenger operations it is sometimes hard to keep the timetable if only using the electric regenerative brakes. When braking to a stop it is therefore uncommon to only use the regenerative brakes on present trains. It is also very common today that unexpected events delay the trains for a few minutes, forcing the drivers to try to gain time. Since the mechanical brakes allow for quicker braking drivers have to use these if they want to regain time.

The insufficient brake capabilities in today’s electric regenerative brakes when reducing speed urgently, in particular at higher speeds, are mainly due to relatively low power of the traction system.

Coasting (running without traction or braking) is commonly used but is harder to perform on regional lines where the operations are “tougher”, with higher accelerations and decelerations.

To be able to drive more eco efficient the drivers would like:

- System that makes it possible for planning the driving ahead.
- Realistic timetables, i.e. more time margins.
- Improved braking equipment (more electric braking power that also is tuned for slippery conditions).
- Independent control of electric and mechanical braking.

If the drivers had a system that could show if a train is close ahead of their proximity they could maintain a safe distance without having to stop. This would reduce the energy consumption and brake wear. It would also result in a smoother driving which would be more comfortable for the passengers. A step in the right direction is the new ERTMS (European Rail Transport Management System) including ETCS (European Train Control System) that are successively introduced in Europe. This system determines the position of the trains on the lines which gives real-time updates for the train dispatcher and the drivers.

A more generous timetable would give the drivers more opportunities to coast and to use the regenerative brakes. It would also make sure that any unforeseen events that are slowing down the train would not cause too much delay to be able to use the eco efficient driving techniques. This is, however, not desirable from a customer and revenue perspective as it will increase travel time in most cases. Further, possibility to use the regenerative brake only, independent of the mechanical brake, would allow for a more controlled braking.

Improved braking equipment (high electric braking power etc.) would make sure that even at higher speeds and in high-deceleration braking the electric regenerative brakes would be possible to use without losing too much time. If the control equipment was better tuned the electric brakes would be able to perform well during slippery conditions. This also includes that the adhesion utilisation should be kept sufficiently low.

6. Trains and operational cases

Four different types of trains are studied in this project. The X2 (also known as X2000) is a common high-speed train in Sweden that has been operating since 1990. The X2 is set as reference train, since all its specifications and energy consumption etc. are widely documented, see for example Lukaszewicz and Andersson [20].

The other three trains are different versions of the Green Train: the GT-250 and GT-250 Regional with a top speed of 250 km/h and the GT-VHST with a top speed of 320 km/h. VHST is an abbreviation of Very High-Speed Train. A lot of effort has been put into the Green Train research programme and its specification has been thoroughly investigated even though no full train has been built. Each version of the Green Train will also be simulated with 30 % reduced traction power.

In this study the Green Train configurations will be simulated with regenerative electric brakes and disc brakes as the main mechanical brake. These are the standard brake systems on most trains of today. X2 also uses disc brakes and regenerative electric brakes. No emergency braking will be simulated.

6.1 Train specifications

For the reference train X2 as well as the GT-250 Regional, most information in this study emanates from Andersson [21] and the report "Green Train energy consumption" by Lukaszewicz and Andersson [20]. In [20], most information about the Green Trains GT-250 and GT-VHST was found and is presented in Table 3 together with data for X2. In [20] the coefficients *A*, *B* and *C* for train running resistance are derived as well.

Table 3. Train specifications. Mass is incl. passengers in accordance to load factor. All Green Trains are, as mentioned earlier, also tested for a 30 % reduction of power.

Train	Mass (ton)	Length (m)	Power/ mass (kW/ton)	Max power (MW)	Starting acc. (m/s^2)	Load factor (%)	No. of seats	A (kN)	B (Ns/m)	C (Ns^2/m^2)
X2	380	165	9 – 11	3.2 – 4.0	0.4	55	309	2.35	43	7.5
GT-250	360	160	20	7.2	0.6	60	465	2.4	60	6.1
GT-250 Reg.	360	160	20	7.2	0.6	45	530	2.4	60	6.1
GT-VHST	360	160	25	9.0	0.6	60	465	2.5	80	4.7

The *A*, *B* and *C* parameters in Table 3 are related to the running resistance on horizontal track, thus without gradients. Somewhat simplified the resistance can be written as

$$F_r = A + Bv + Cv^2 \tag{13}$$

where *v* is the train speed. The *A*-coefficient is speed independent and expresses mechanical (running) resistance. The *B*- and *C*-coefficients represent (mainly) the aerodynamic drag of the train where a big part of the *B*-coefficient represents the impulse resistance due to ventilation and cooling purposes.

X2

The X2, see Figure 5, is a locomotive propelled train, which means that one locomotive unit is providing the propulsion for all the trailing cars. In the end of the train there is a so-called driving trailer with a cabin so the train can be driven from both ends without having to put the locomotive at the opposite end. The trailing cars have tilting car bodies which allow higher speeds than the track originally was built for. Since it has a locomotive the number of powered axles are limited, this means that the amount of energy that can be regenerated at braking is limited as well. The train is built for 210 km/h, but maximum allowed speed in traffic is 200 km/h. In this study the X2 is simulated for one locomotive and six trailing cars.

Figure 5. The X2 train. [Photo - Courtesy of Evert Andersson]

GT-250 and GT-250 Regional

The GT-250 trains, see Figure 6, are so called EMU:s (Electrical Multiple Units) which means that their traction equipment is distributed amongst the cars and half of the trains' axles are assumed to be powered in the basic configuration. This makes it possible to regenerate a lot of energy when braking. The end cars of the trains are equipped with driver cabins. Compared to the X2 the GT-250 trains have improved running resistance, in particular, the air drag is reduced (at the same speed). The Green Trains have extra wide car bodies, which makes it possible to fit with extra seats. The Green Trains have 3+2 seating compared to the traditional 2+2 seating in 2nd class. The maximum speed is 250 km/h and the train is assumed to include tilting car bodies for enhanced speed in most curves. In this study all the Green Trains will be simulated for a total of six cars. The trains are proposed to be designed for a four-car set as a basic unit but the need for longer trains are recognised and the idea is to multi-link two train sets making an eight-car train in busy hours. The average train set is therefore assumed to have six cars.

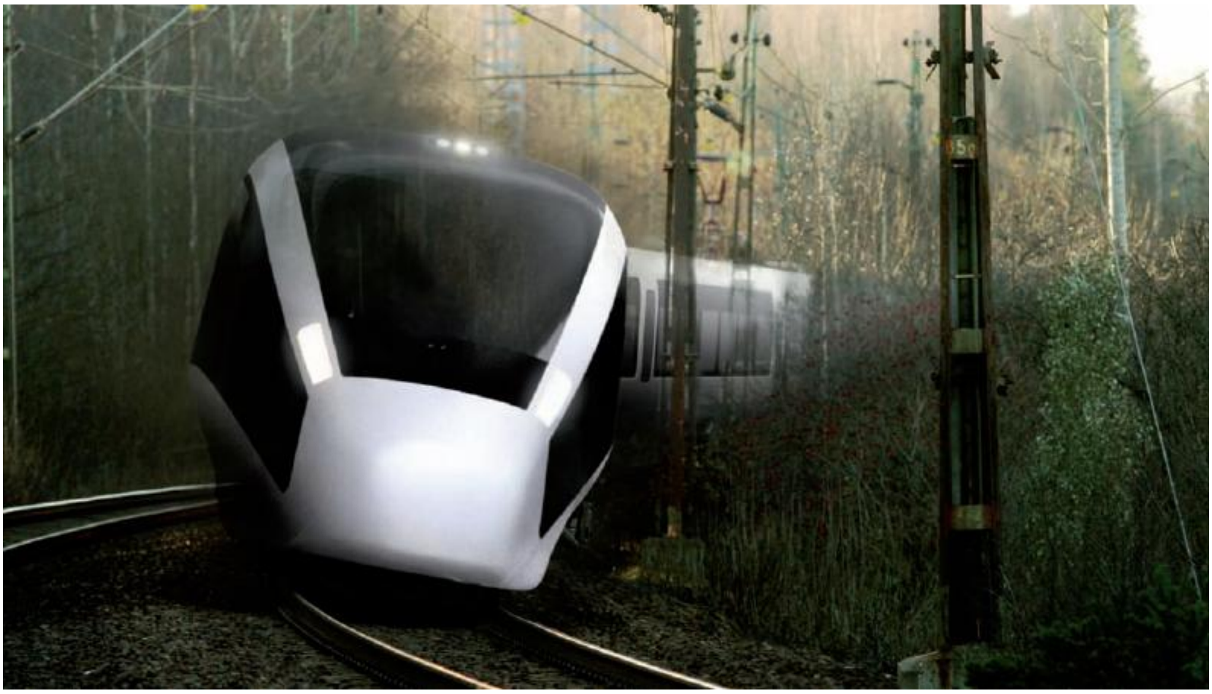

Figure 6. Computer model of the Green Train.

GT-VHST

This train is very similar to the GT-250 except for further improved running resistance and more powerful drive system, which allows for a maximum speed of 320 km/h.

Traction force vs. speed

One particular property, the available traction force at a specific speed, could not be found in the literature for the Green Trains and needed to be calculated. This was done by producing a force-speed diagram for each train type, see Figure 7 and 8.

The first part of the diagram is limited by the train's traction motors', maximum torque output and the available adhesion, the second part by the train's power/speed ratio and the last part by the maximum speed at the selected gear ratio. In each part the train also needs to overcome the running resistance (which differ whether it is a horizontal track or a gradient).

1. The first part of the diagram, usually shown as a horizontal line, is calculated by:

$$F_t = a_t \cdot m_e + F_r \tag{14}$$

where
F_t = Traction force
a_t = Train acceleration
m_e = Equivalent mass
F_r = Running resistance

2. The second part is obtained by dividing the available power at the wheels with the speed (in m/s), acting as a gradually decreasing slope in the diagram, and mathematically described as:

$$F_t = \frac{P}{v} \tag{15}$$

where

P = Power (assumed to be constant throughout part 2)

It should be noted that the traction force characteristics refer to the short-time performance (i.e. the time needed for acceleration to top speed, or electric braking from top speed to stop). The continuously delivered r.m.s. power may be lower.

3. The final part of the chart is related to the train's maximum speed (sometimes with a small margin) and is shown as a vertical line where the traction force is instantly decreased to zero.

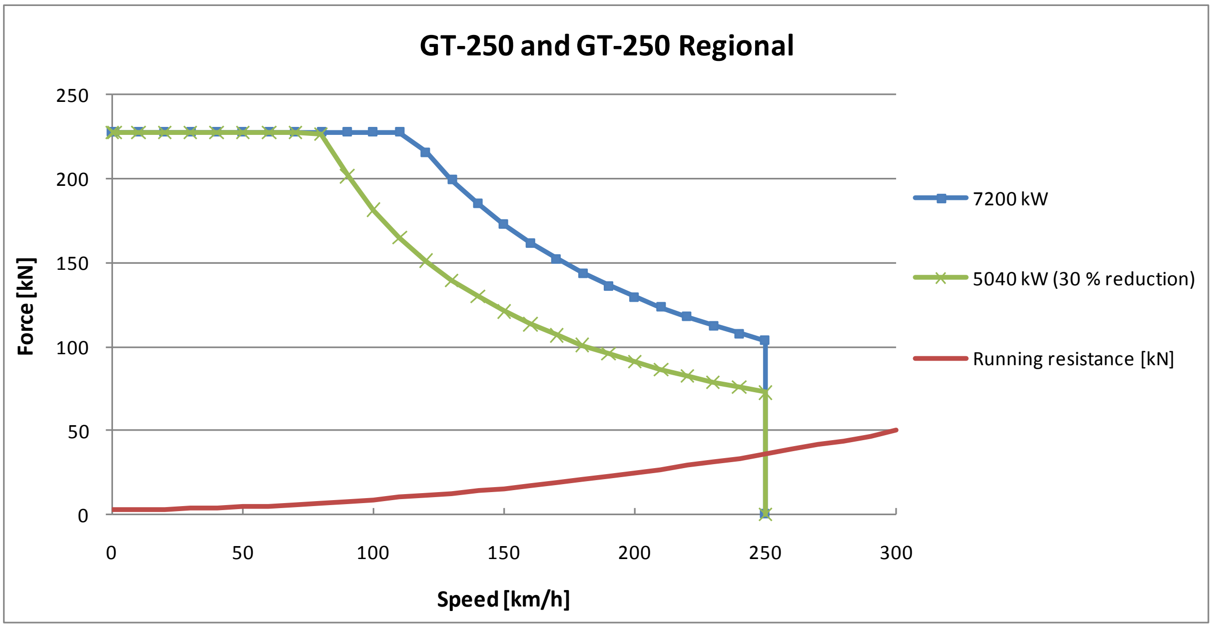

Figure 7. Traction force vs. speed for GT-250 and GT-250 Regional. Maximum speed: 250 km/h.

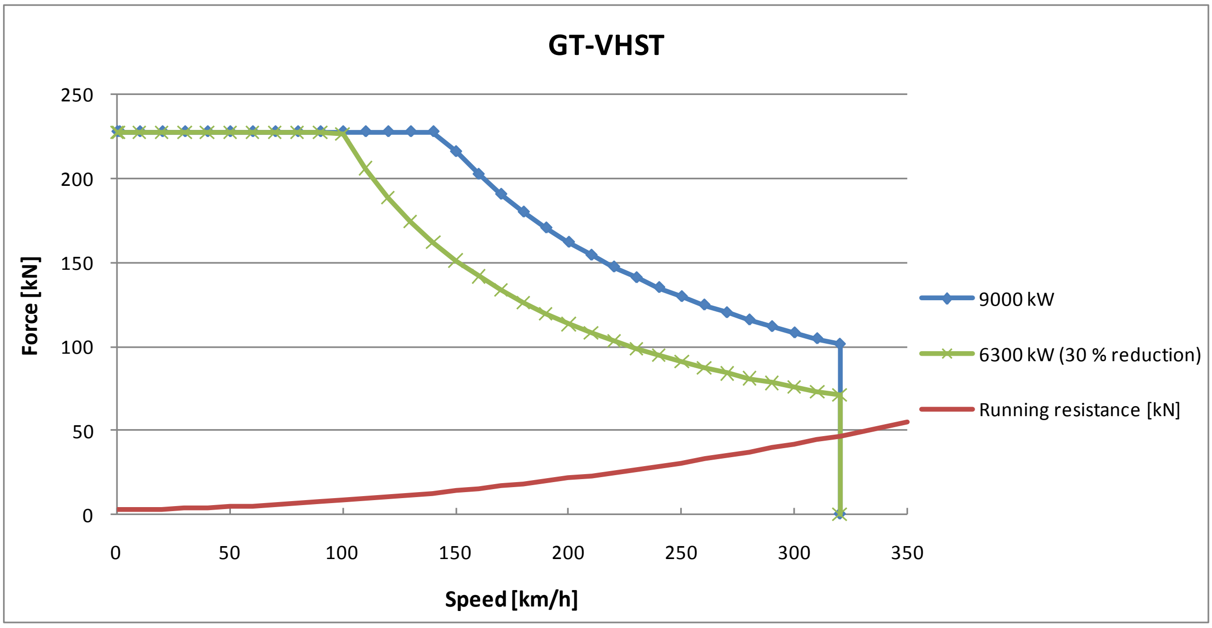

Figure 8. Traction force vs. speed for GT-VHST. Maximum speed: 320 km/h.

6.2 Braking

Just as the traction system has limitations so does the braking system. Generally, the available adhesion between wheel and rail is the limiting factor. If there is not enough adhesion the wheels will lock and slide along the rails, resulting in wheel flats. On modern trains there are anti-lock braking systems preventing this. Also passenger ride comfort should limit the degree of deceleration. In normal passenger high-speed operations the deceleration is usually limited to about 0.6 m/s^2 (at least for Swedish rail operations).

The electric regenerative brake is also limited by the adhesion, but under normal conditions it is the electric motors and the possibility to regenerate energy back to the catenary that is the main limitation. The motors' braking capability are assumed to be 103 % of their tractive capability (although it sometimes can be higher) it is convenient to visualize them in the same manner. In Figures 9 - 11 the X2:s braking diagrams, for three different braking modes, are shown.

- **Blended braking**, where the decelerating is strictly 0.6 m/s^2, using as much regenerative braking as possible and adding mechanical braking as needed.
- **Dynamic braking**, with an electric braking at higher speeds and blended braking at lower speeds. The mechanical brakes are used up to about 130 km/h in the X2, GT-250 and GT-250 Regional. For the GT-VHST it is used up to about 180 km/h, above the electric regenerative brakes is used for all braking. For the powerful Green Trains this means that their drive systems can do almost all of the braking down to about 30 km/h. This differs from the Green Trains with a 30 % power reduction, see next page.
- **Electric braking**, with almost only regenerative braking (except for the lowest speeds).

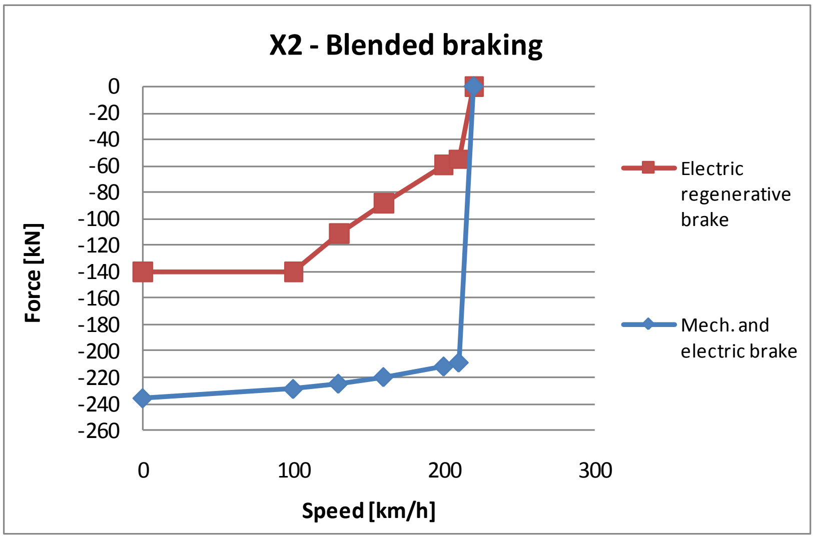

Figure 9. Brake force as function of speed. Braking diagram for X2 which represents blended braking with strictly 0.6 m/s^2.

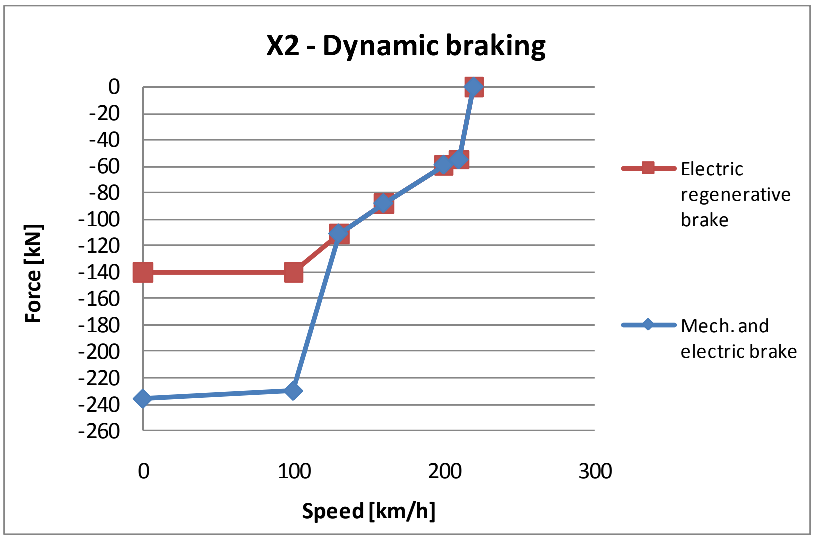

Figure 10. Brake force as function of speed. Braking diagram for X2 which represents dynamic braking with blended braking up to 130 km/h from where only electric braking is used

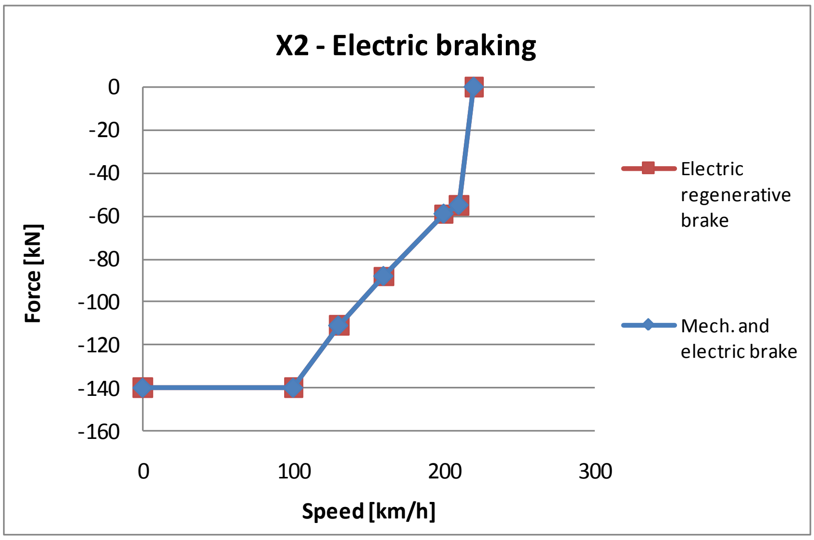

Figure 11. Brake force as function of speed. Braking diagram represents strictly electric regenerative braking.

The GT-250, GT-250 Regional and GT-VHST have the same type of charts as the X2, however, the electric brake has higher forces since the motor power is higher. There is one big difference between the Green Trains with full power and those with a 30 % reduction with respect to dynamic braking. For this study the less powerful trains are simulated to have the same braking distances as the more powerful versions. This means that they will have to use more mechanical braking at higher speeds compared to the more powerful trains. The powerful Green Trains are able to use the electric brakes to such an extent that they basically do not need to use the mechanical brakes in this braking mode, see Figures 12 and 13.

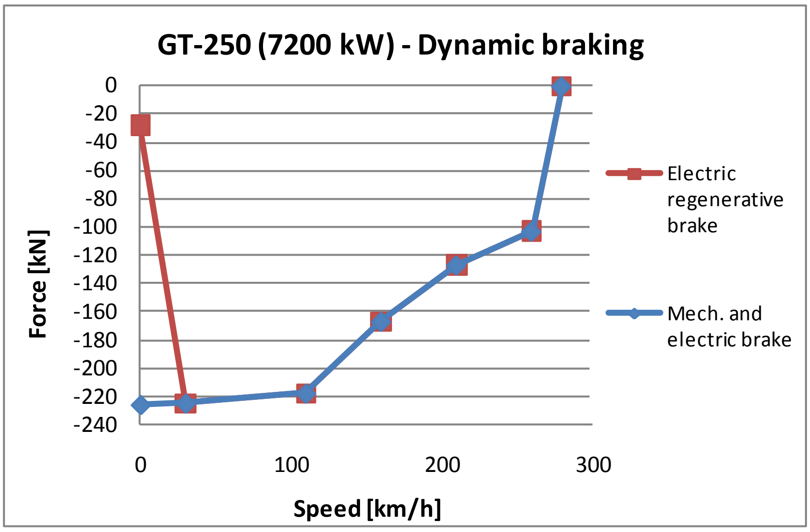

Figure 12. Brake force as function of speed. The diagram represents dynamic braking for the GT-250.

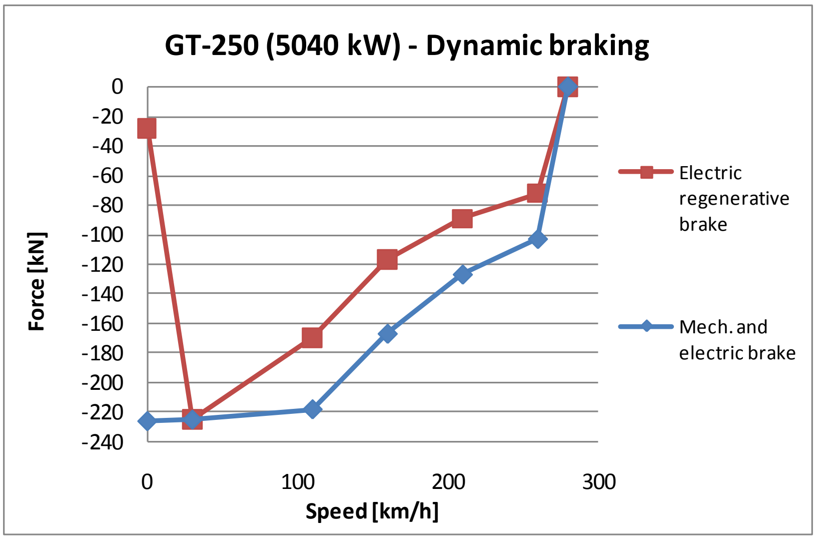

Figure 13. Brake force as function of speed. The diagram represents dynamic braking for the GT-250 with a 30 % power reduction.

6.3 Electric supply system

All electrical systems have losses which make them less than 100 % efficient. In this case the supply both has losses due to resistance in the electrical wires as well as losses in the converter stations. These losses are included in the simulation results as well as the energy consumption due to the comfort and auxiliary systems.

The efficiency assumptions of this study can be seen in Table 4 below.

Table 4. Efficiency assumptions.

Train	Efficiency in train's traction and electric braking system	Efficiency in railway's supply system	Comfort and auxiliary power efficiency
X2	82 %	88 %	90 %
Green Trains	84 %	88 %	90 %

6.4 Operational scenarios

Each train is simulated on a specific railway line.

The reference train X2 is simulated to run on “Västra stambanan” [22], the main line between Stockholm and Göteborg (Gothenburg). The top speed is set to 200 km/h with four intermediate stops at stations and one additional unplanned stop. There are also unplanned reductions in speed in three areas. Total track length is 455 km. Target speed and track altitude profile are shown in Figures 14 and 15.

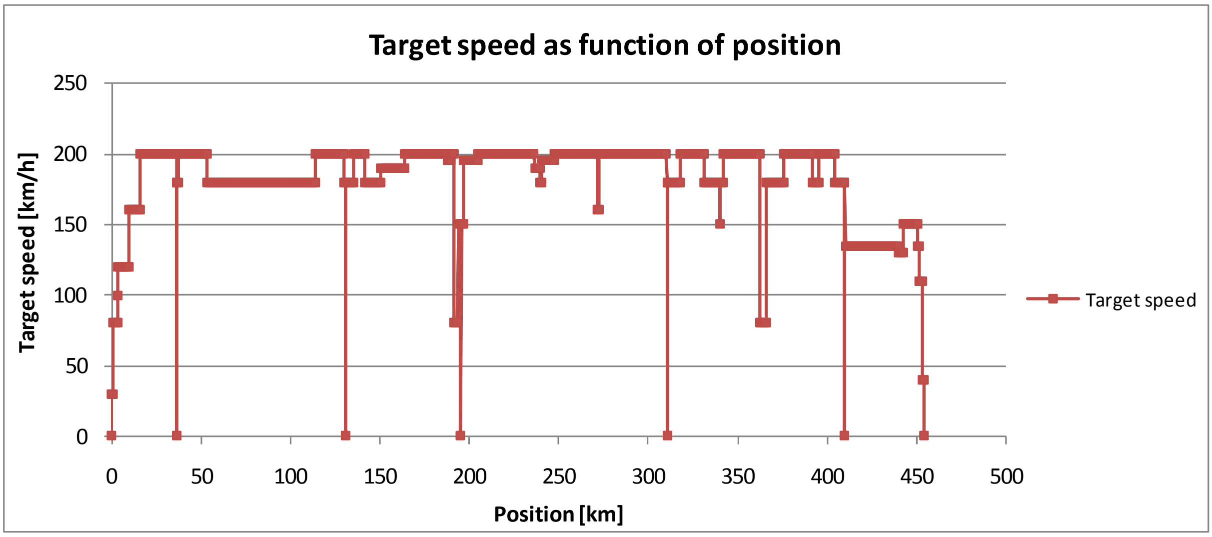

Figure 14. Target speed along "Västra stambanan" for X2.

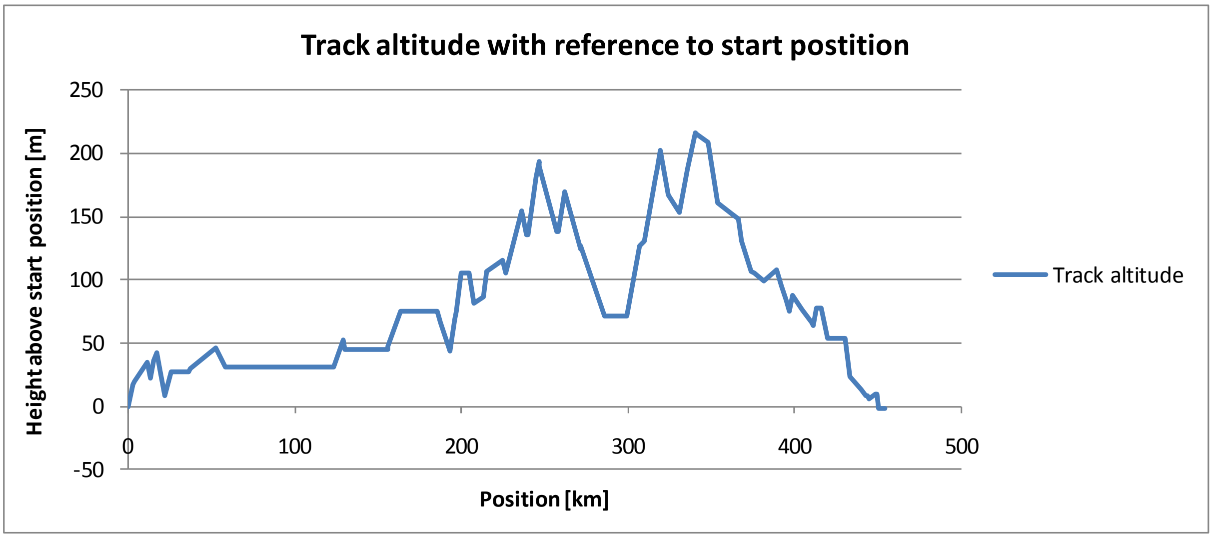

Figure 15. Track altitude profile for "Västra stambanan" for X2 (as well as for GT-250 and GT-250 Regional), with reference to the start position.

The GT-250 was also simulated to run on "Västra stambanan", but with higher target speed. The top speed is partly up to 250 km/h. It was simulated with four stations, one unplanned stop and three speed reductions. Target speed can be seen in Figure 16, track altitude is the same as for X2. Most of the speed reductions can be derived to the many horizontal curves along the track, limiting the speed.

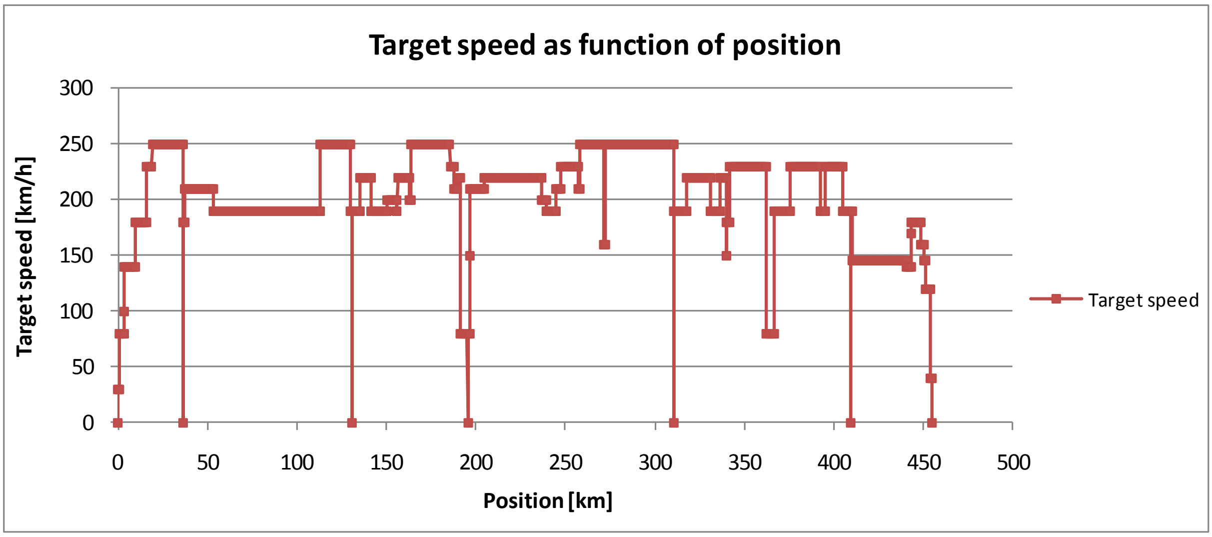

Figure 16. Target speed on "Västra stambanan" for the GT-250.

The GT-250 Regional operation of the "Västra stambanan" case consists of 14 stops at stations, two unplanned stops and another three speed reductions, being typical for an average of fast regional railway lines in Sweden. The regional line has station stops every 30 km, as an average. The target speed can be seen in Figure 17 below, track altitude is the same as for X2.

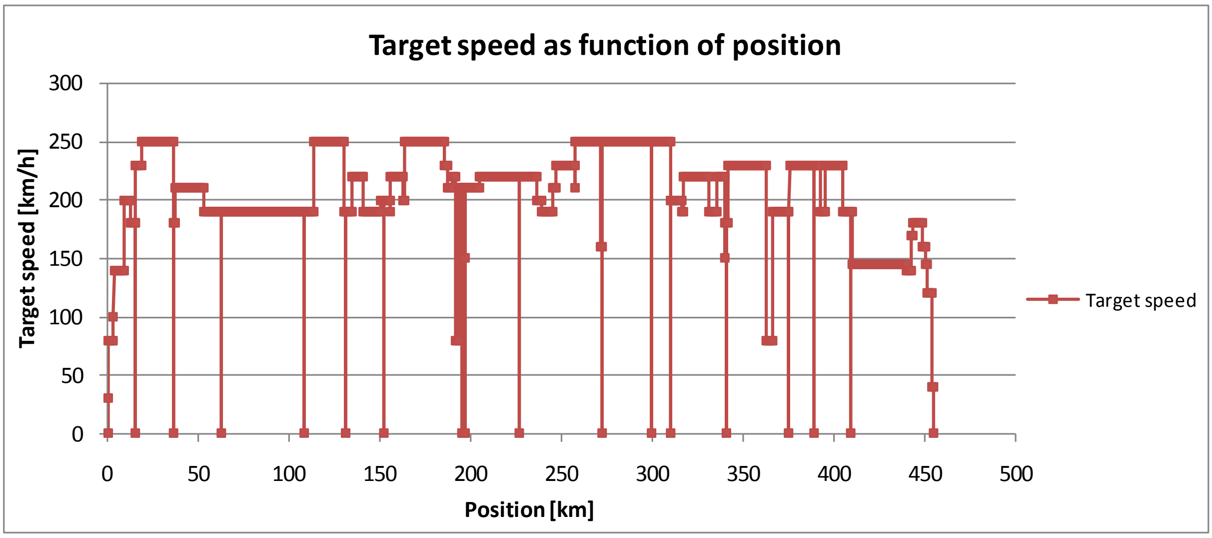

Figure 17. Target speed of the GT-250 Regional on "Västra stambanan regional".

For comparability reasons GT-250 will also be tested on “Västkustbanan” between Göteborg (Gothenburg) and Köpenhamn (Copenhagen) for a few cases as well [23]. “Västkustbanan” is considered to be a much “tougher” regional track than “Västra stambanan regional”. The tracks top speed is party up to 305 km/h but is limited by the train to 250 km/h. The operations on “Västkustbanan” will be simulated with 14 intermediate station stops without any additional unplanned stops. There are several speed reductions throughout the operation. Total track length is 341 km with station stops every 23 km as an average. Target speed can be seen in Figure 18 and track altitude in Figure 19.

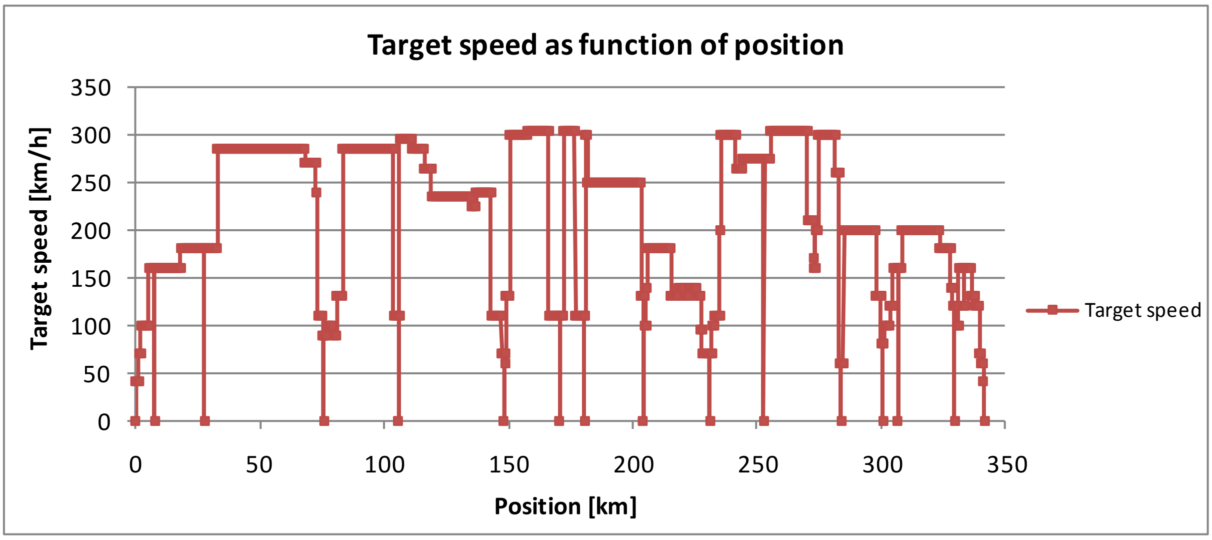

Figure 18. Target speed along “Västkustbanan”, note that the GT-250 Regional is limiting the top speed to 250 km/h.

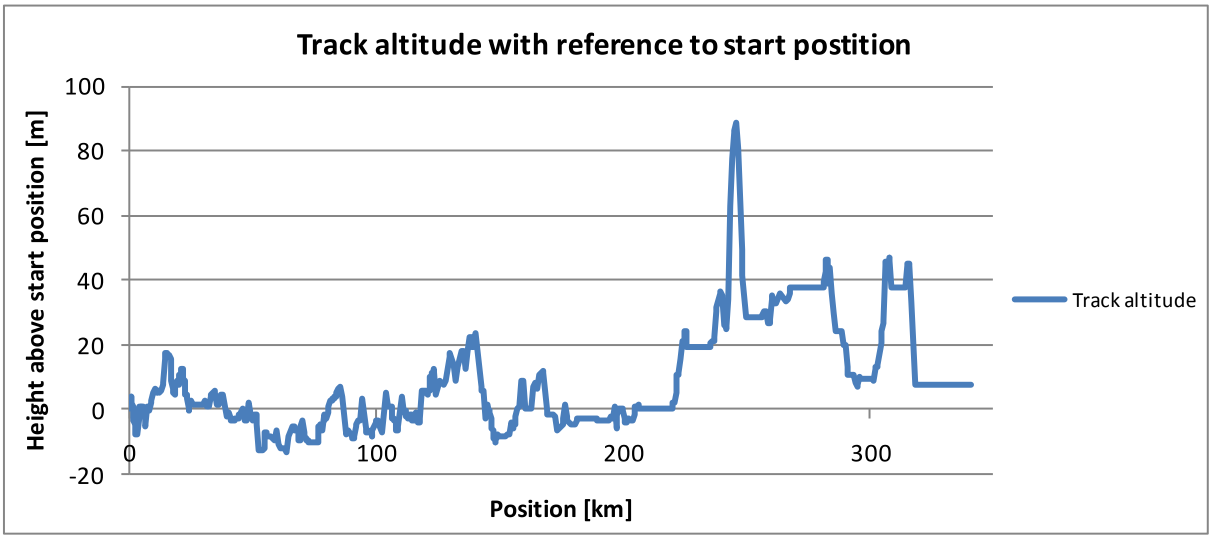

Figure 19. Track altitude profile for “Västkustbanan” for GT-250 Regional with reference to the start position.

The GT-VHST is simulated to run on a new discussed high-speed line called “Götalandsbanan”, which in this study also includes the planned “Ostlänken” from Stockholm to Linköping [22], [24]. GT-VHST travels from Stockholm to Göteborg (Gothenburg) with seven stops at stations, one unplanned stop and three unplanned speed reductions. The extra three station stops, compared to the X2 and GT-250 operations, should be taken into account when considering the final results. The maximum speed for this operation is set to 320 km/h. Total track length is 467 km. The target speed and track altitude profile are shown in Figures 20 and 21. A new high-speed track, such as this, would most likely be built to avoid most speed-limiting curves.

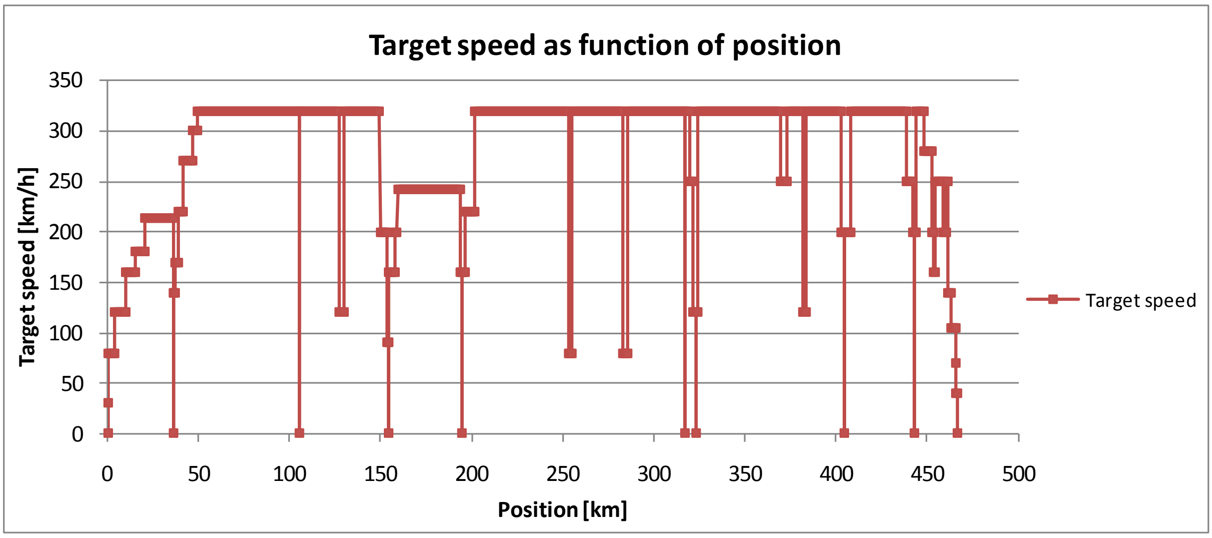

Figure 20. Target speed of the GT-VHST on “Götalandsbanan”.

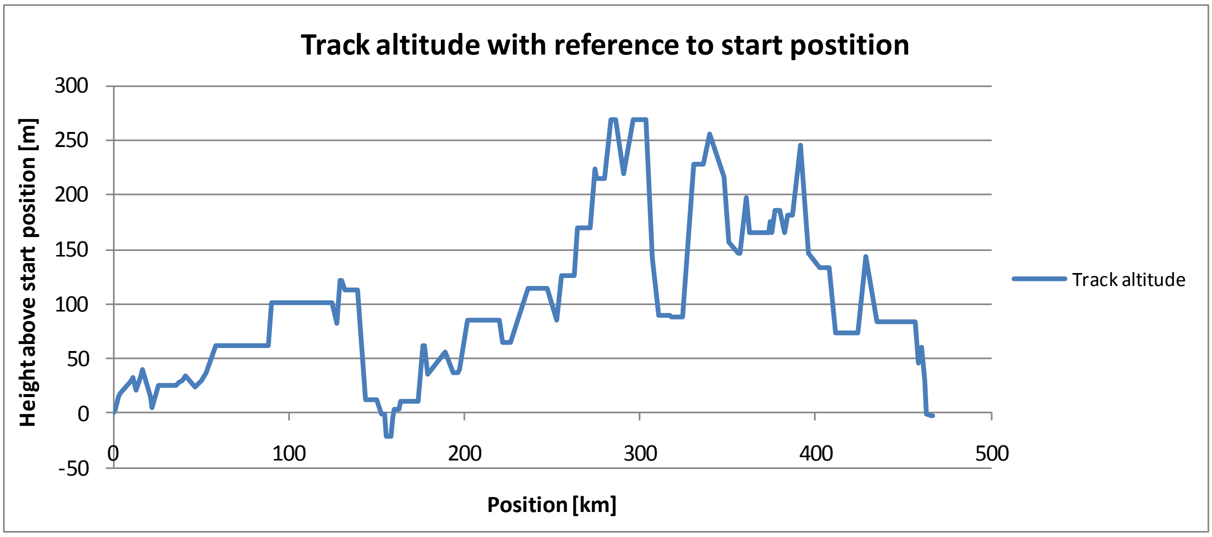

Figure 21. Track altitude profile of "Götalandsbanan" for GT-VHST with reference to the start position

6.5 Additional train specifications

In addition to the trains described above, there are, for the economic viewpoint two important versions of the GT-250. The train data and estimated approximate difference in purchasing price compared to the more powerful train is presented below, see Table 5.

Table 5. Train mass includes a load factor of 60 %. Top speed of 250 km/h.

Train	No. of cars	No. of powered axles	No. of seats	Train length (m)	Max power (kW)	Top speed (km/h)	Power/ weight (kW/ton)	Train mass (ton)	Purchase price (MSEK)
GT-250 A	6	12 (50 %)	465	160	7200	250	20	360	Base value
GT-250 B	6	12 (50 %)	465	160	5040	250	14.2	355	- 4
GT-250 C	6	8 (33 %)	465	160	5040	250	14.5	348	- 8

As seen above, there are two ways to limit the trains' power. It is possible to use less powerful electric motors and for that reason also be able to use less powerful transformers. The other way is to use a reduced number of powered axles and for that reason reduce the number of electric motors and as a result also reducing the number of line converter modules (LCM) and motor converter modules (MCM).

If reducing the number of powered axles, more train mass and costs are reduced but at the same time the adhesion utilisation is affected negatively. A higher adhesion utilisation (at a fixed braking deceleration as well as acceleration at low speed) will make the trains more sensitive towards slippery tracks, with a higher risk for wheel and track wear as a result. For comparison it should be mentioned that most modern high-speed trains in Europe and Japan have adhesion utilisation of 12 – 15 % at speeds up to 100 km/h and lower at higher speeds.

Another downside with high adhesion utilisation is that the possible acceleration is reduced at higher speeds which can lead to longer travel times as well as limited regenerative braking capabilities. The differences in travel time and energy consumption due to the lower mass are, according to simulations, very small and will be disregarded.

As seen in "Benefits of regenerative braking and eco driving for high-speed trains" [1], (and also in this report), if maintaining the retardation with reduced regenerative braking power, the amount of possible regeneration is also limited, leading to a higher energy consumption and brake wear. What is not included in these simulations is the difference in train mass which would very slightly favour the more powerful train, GT-250 A. At the same time the difference in adhesion utilisation is not included either, which would favour the "C" version of the train compared with reality.

7. Driving styles

To confirm the simulations made with STEC with respect to energy, regeneration and running time, several test simulations were made to verify the program for the intended purpose. The simulations were compared with simulations in [20] and with some tuning, mostly regarding speeds, the results were in line with the previous study.

All cases used a 3 % lower maximum speed than the train's permissible speed; this was to make up for different reasons why the speed is sometimes lower than the target speed.

7.1 "Normal" driving style

Each train was simulated for a "normal" driving style, verified by the driver survey. The trains were tested with the three different modes of braking described in Section 6.2: blended, dynamic and electric braking. They were also simulated with both 90 % and 100 % degree of regeneration.

"Normal" driving style was defined, in cooperation with Furukrona and Berndtsson [18] [19] at the operator SJ AB, as a driving style similar to the ones commonly used in passenger operations with a tight schedule. Essentially this means to quickly accelerate to the target speed and to keep it for as long as possible before braking when approaching the next stop. Coasting was not considered during these simulations even though train drivers also use this technique.

7.2 Eco-driving

A more ecological and economical driving style, called eco-driving, was also simulated where the same trains used as much electric regenerative braking as possible. A total of four eco-driving simulations were made for each train. It is estimated that the drivers are able to use 2 – 3 % of the timetabled travel time for eco-driving, as an average over all operations, according to Andersson [21]. Timetables have, in passenger operations, usually about 8 – 10 % of the estimated travel time added for unforeseen events, sometimes more.

Coasting is a normal procedure to save energy, which means that the driver can turn off the traction and let the train continue to roll, though the train will slowly decelerate due to the running resistance. The coasting used in STEC follows Equation 16, at least initially, since coasting to a stop would take too much time.

$$Distance\ of\ coasting = \frac{(v_2 - v_1)^2}{100^2} \cdot d \tag{16}$$

where

d = Preferred distance of coasting from 100 km/h [km]

v_2 = Speed at start of coasting [km/h]

v_1 = Speed at end of coasting [km/h]

Two different settings of coasting were tested during the eco-driving simulations.

- Setting 1 meant d = 3 km coasting, before starting to use the brakes, at a speed of 100 km/h. When driving faster the program added coasting distance quadratically by speed, which means 12 km coasting from 200 km/h and so forth.
- Setting 2 meant d = 6 km coasting from 100 km/h also increasing quadratically with the speed.

The first two eco-driving simulations were done with either coasting setting 1 or setting 2. A third simulation was done with a reduction of speed peaks and a fourth simulation with both reduced speed peaks and coasting setting number one.

The eco-driving was simulated as a response to investigate what effect some new systems, which are being developed by train manufacturers, can have on energy consumption and brake wear. One of these systems is the EBI Drive 50 by Bombardier Transportation; this system is giving suggestions to the driver on the ideal speed at any time on the current line. Taking advantage of the extra time margin that is provided for any unforeseen events, the operator can save energy and reduce brake wear by not driving the trains at their maximum speed. These types of systems aim to take as much advantage as possible of regenerative braking and not to accelerate right before a speed reduction or stop. Figure 22 shows how it is possible to use a time margin to reduce the top speed and by that reducing the energy consumption and brake wear.

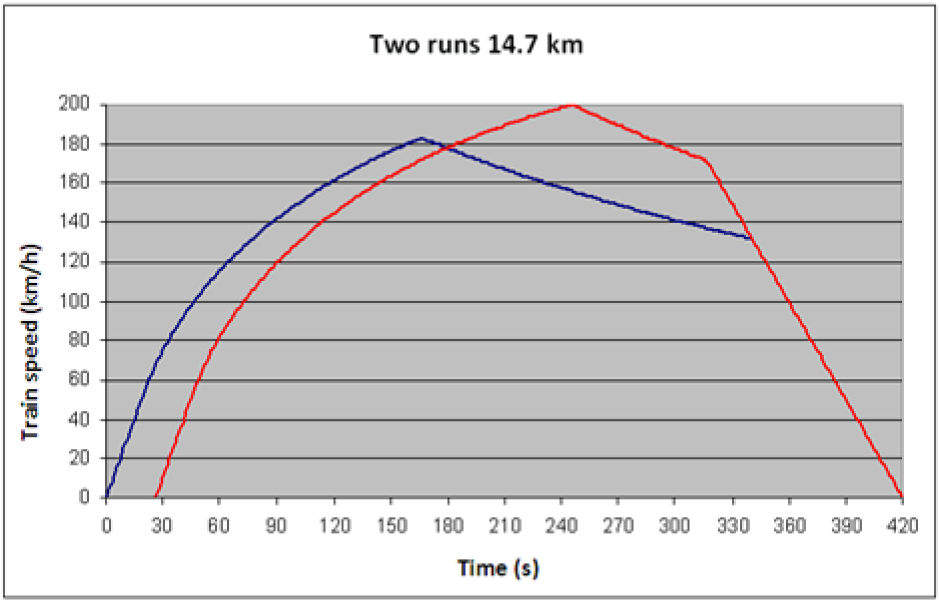

Figure 22. The train with eco-driving system (blue line) uses a time margin and starts earlier. Train not using the system (red line) has to drive faster to reach the destination at the same time. (Figure - Courtesy of Bombardier Transportation)

By reducing the brake wear the operator can save money on maintenance and also reduce the air pollution due to airborne particles from the brake pads.

8. Calculation of brake wear

In this chapter the calculation of brake wear is further described and some results used for the final simulations and calculations are presented. All final results for the different operational cases are presented in Chapter 9 and in Appendix B.

8.1 Brake pad temperatures and wear coefficients

The temperature in the brake pads for each train type braking from maximum speed to stop was calculated using the temperature model described in Chapter 4. The results are shown in Figure 23.

The parts of the braking where the regenerative brakes perform all the work are excluded, since they do not add to the wear. The average temperature for these cases was calculated to 115.8 °C for the X2, 96.3 °C for the GT-250 and 86.9 °C for GT-VHST. The lower temperature for the GT-VHST is due to the fact that this train has three brake discs per axle compared to the X2 and GT-250 which have two brake discs per axle. The more powerful GT-VHST is also able to regenerate more power back to the catenary.

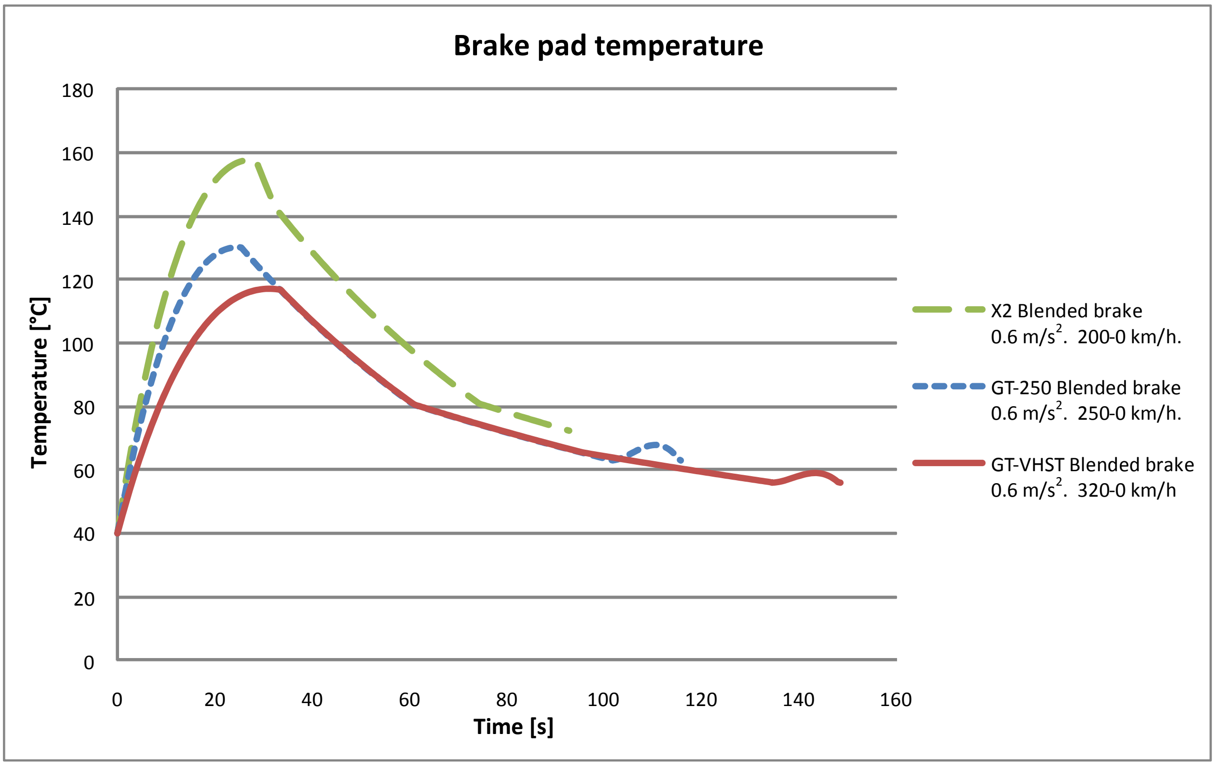

Figure 23. Brake pad temperature for X2, GT-250 and GT-VHST. Temperature for the GT-250 Regional is the same as for the GT-250.

One of the benefits of this wear model is that a pretty rough estimate of the temperature still gives an almost exact wear result, according to the model. As an example, if the temperature dependence of the wear coefficient in reality would be 50 % higher for the Green Train cases shown above, the difference in wear is still only 4 %.

The resulting average temperatures are presented in Table 6 together with the corresponding wear coefficients.

Table 6. Brake pad mean temperatures and wear coefficients for the different trains. The temperature relates to the obtained mean temperature at brake pad surface when using mechanical disc brakes in blended braking (at 0.6 m/s^2). Brake pad data for GT-250 Regional is the same as for the GT-250.

Train	Max speed	Mean temperature (brake pads)	Wear coefficient k_w
X2	200 km/h	115.8 °C	$11.158 \cdot 10^{-15}$
GT-250	250 km/h	96.3 °C	$10.963 \cdot 10^{-15}$
GT-VHST	320 km/h	86.9 °C	$10.869 \cdot 10^{-15}$

8.2 Wear contribution for one blended braking sequence

By using Archard's reformulated wear equation, Equation 9, with the train's brake pad average temperature during braking and the corresponding mechanical brake energy, taken from STEC, the wear can be calculated.

The following results are corresponding to the cases in this study and are stated both as volume and weight removal of sintered brake pads (Becorit BM 40) with the density of 5.120 g/cm^3. No information to validate these figures has been found so they should only be considered as relative to each other.

X2 braking from 200 km/h to a full stop using blended brakes at 0.6 m/s^2 generates a wear of 0.064 cm^3 or 0.328 grams per brake disc which adds up to 3.59 cm^3 or 18.39 grams for the whole train.

GT-250 braking from 250 km/h to a full stop with blended braking at 0.6 m/s^2 generates a wear of 0.043 cm^3 or 0.220 grams per brake disc which adds up to 2.06 cm^3 or 10.46 grams for the whole train.

GT-VHST braking from 320 km/h to a full stop with blended braking at 0.6 m/s^2 generates a wear of 0.039 cm^3 or 0.201 grams per brake disc which adds up to 2.83 cm^3 or 14.49 grams for the whole train.

The results are also presented in Table 7, below. Note that braking several times without letting the brakes cool down would render in a much higher temperature, and consequently higher brake wear.

Table 7. Approximate brake pad wear of the different trains when braking with blended brakes from top speed to stop. The brake pad wear of the GT-250 Regional is in this case the same as for the GT-250. Note that the trains have different number of seats.

Train	Speed (km/h)	Deceleration (m/s^2)	Brake pad wear/disc (cm^3)	Brake pad wear/disc (gram)	Brake pad wear/train (cm^3)	Brake pad wear/train (gram)
X2	200	0.6	0.064	0.328	3.59	18.39
GT-250	250	0.6	0.043	0.220	2.06	10.46
GT-VHST	320	0.6	0.039	0.201	2.83	14.49

9. Simulation results

In this chapter the results from the simulations (regarding energy consumption, travel time etc.) and corresponding brake wear calculations are provided. Additional results of energy consumption and brake wear are found in Appendix B.

Thanks to the results of the simulations in the program STEC and calculations made in earlier chapters the brake wear of the different cases can be calculated. The wear data are presented to allow for a comparison between the different cases in this study and should be seen as relative. To be able to give precise figures of the wear it is necessary to validate them through experimental studies or full scale testing.

For the simulations, a limited number of driving characteristics has been chosen. The types of braking that is used during the simulations are:

- Blended braking; means that maximum available regenerative braking is used and that the mechanical brakes are used as a supplement to make the desired deceleration of 0.6 m/s^2.
- Dynamic braking; uses mechanical brakes as a supplement below a certain speed, thus at higher speeds only electric regenerative braking is used. When using only regenerative brakes it is not always possible to reach 0.6 m/s^2.
- Electric braking; means that only the regenerative brakes are being used.

The specific energy consumption is stated in Wh/seat-km. These figures include all losses in the electric systems in the train and the railway's electric supply system as well as comfort and auxiliary systems energy consumption.

Two different settings of the degree of regeneration have been tested, i.e. 90 % and 100 %. This is because it is sometimes not possible for the train to regenerate all available power back to the catenary, or that for some reason the emergency brakes are applied. The degree of regeneration is stated in percent of full regeneration in all operational cases.

The regeneration of the accumulated input energy is also stated and is simply called "Regeneration", or "Regen." for short, in Tables 8 – 23. This value indicates how much energy that the electric regenerative brakes really feed back to the catenary in relation to the input energy, taking losses in the train's propulsion system as well as the assumed degree of regeneration into account.

A nominal value of the brake pad wear is made available, where the wear of X2 on "Västra stambanan" (4+1 stops) with blended braking (case 001 in Table 8) is set to index 100. All other cases have a value compared to this. The nominal value is based on the wear/seat-km which means that the length of the track does not interfere, it does however favour trains with more seats.

In Sections 9.1 – 9.9 the results for the different trains, in their respective operations in this study, are shown. Several, for this study, important comparisons are made and in Chapter 10 some of these are clarified graphically.

9.1 X2 on "Västra stambanan"

The first simulations were made for the reference case X2 along "Västra stambanan" with 4 + 1 intermediate stops. The results are shown in Table 8.

Table 8. Simulation of X2 on "Västra stambanan" using a normal driving style.

Sim. (no.)	Braking type	Degree of regen. (%)	Travel time (hh:mm)	Spec-energy (Wh/seat-km)	Regen. (%)	Mech. brake energy (kWh)	Brake pad wear (index)
001	Blended	90	02:57	46.3	6.7	710.2	100.0
002	Blended	100	02:57	46.0	7.5	651.1	91.7
003	Dynamic	90	02:58	43.1	12.2	253.7	**35.7**
004	Dynamic	100	02:58	42.5	13.7	153.6	21.6
005	Electric	90	03:01	42.2	14.1	113.4	**16.0**
006	Electric	100	03:01	41.5	16.0	0.0	0

The eco-driving simulations, Table 9, did not add much travel time compared to only using the regenerative brakes. Although the coasting settings are activated, the train could not use this function to the full extent due to the low speed.

Table 9. Simulation of X2 on "Västra stambanan" using eco-driving techniques. All eco-driving runs use the regenerative electric braking with as little mechanical braking as possible. Only 90 % degree of regeneration is used and the remaining 10 % have to be covered by the mechanical brakes.

Sim. (no.)	Coasting setting (no.)	Speed peaks	Travel time (hh:mm)	Spec-energy (Wh/seat-km)	Regen. (%)	Mech. brake energy (kWh)	Brake pad wear (index)
007	1	Full	03:01	41.7	13.2	104.7	14.7
008	2	Full	03:01	41.3	12.6	99.3	14.0
009	0	Reduced	03:01	41.7	13.4	106.5	15.0
010	1	Reduced	03:01	41.2	12.5	97.0	**13.7**

For X2 the eco-driving resulted in reductions of brake wear by up to 14 % relative to normal driving in the electric braking mode and still being within the time margin. Relative to the dynamic braking mode the wear was reduced by over 60 % and was also slightly reducing the energy consumption.

9.2 GT-250 (7200 kW) on “Västra stambanan”

For the same track as X2 (with 4 + 1 intermediate stops), but with increased speed limits, the GT-250 was simulated. Both energy consumption and wear are considerably lower than for the X2, see Table 10. Compared to the dynamic braking case in normal driving for X2 (case 003) the wear was reduced by over 50 % for the corresponding case of GT-250. The energy consumption was reduced by over 30 % and the travel time by 18 minutes. This is despite the higher speed and is due to the increased traction power as well as the higher number of seats.

Table 10. Simulation of GT-250 (7200 kW) on "Västra stambanan" using a normal driving style.

Sim. (no.)	Braking type	Degree of regen. (%)	Travel time (hh:mm)	Spec-energy (Wh/seat-km)	Regen. (%)	Mech. brake energy (kWh)	Brake pad wear (index)
101	Blended	90	02:39	30.8	17.2	596.0	55.2
102	Blended	100	02:39	30.3	19.5	447.5	41.4
103	Dynamic	90	02:40	29.0	23.0	188.2	**17.3**
104	Dynamic	100	02:40	28.2	26.2	2.4	0.2
105	Electric	90	02:40	29.0	23.0	186.0	**17.1**
106	Electric	100	02:40	28.2	26.2	0.0	0.0

The eco-driving simulations shows that the energy consumption and brake wear can be even lower if only a few minutes of travel time are invested, see Table 11 below.

Table 11. Simulation of GT-250 (7200 kW) on "Västra stambanan” using eco-driving techniques. All eco-driving runs use the regenerative electric braking with as little mechanical braking as possible. Only 90 % degree of regeneration is used and the remaining 10 % have to be covered by the mechanical brakes.

Sim. (no.)	Coasting setting (no.)	Speed peaks	Travel time (hh:mm)	Spec-energy (Wh/seat-km)	Regen. (%)	Mech. brake energy (kWh)	Brake pad wear (index)
107	1	Full	02:40	27.8	19.8	154.0	14.1
108	2	Full	02:42	26.8	18.5	138.6	12.7
109	0	Reduced	02:43	27.5	20.1	154.5	14.3
110	1	Reduced	02:43	26.7	17.9	132.4	**12.3**

When using eco-driving techniques the wear can be further reduced by almost 30 % compared to normal driving and also have a positive effect on the energy consumption.

9.3 GT-250 (5040 kW) on "Västra stambanan"

The GT-250 is again tested for "Västra stambanan" but with 30 % reduced power. The simulations, see Table 12, show that both energy consumption and brake wear are increased while the travel time is slightly longer. According to the dynamic braking cases the wear is increased by almost 60 % compared to X2 and over 300 % compared to the stronger GT-250. It is still more energy efficient than the X2 but not compared to the GT-250 using full power.

Table 12. Simulation of GT-250 (5040 kW) on "Västra stambanan" using a normal driving style.

Sim. (no.)	Braking type	Degree of regen. (%)	Travel time (hh:mm)	Spec-energy (Wh/seat-km)	Regen. (%)	Mech. brake energy (kWh)	Brake pad wear (index)
111	Blended	90	02:40	31.8	12.5	917.8	84.9
112	Blended	100	02:40	31.4	14.1	806.7	74.7
113	Dynamic	90	02:41	30.4	16.2	613.5	**56.8**
114	Dynamic	100	02:41	29.8	18.3	476.2	44.1
115	Electric	90	02:42	28.3	22.4	176.9	**16.4**
116	Electric	100	02:42	27.6	25.5	0.0	0.0

Though the energy consumption and wear of the eco-driving simulations are comparable with those of the more powerful GT-250 the travel times are longer, Table 13.

Table 13. Simulation of GT-250 (5040 kW) on "Västra stambanan" using eco-driving techniques. All eco-driving runs use the regenerative electric braking with as little mechanical braking as possible. Only 90 % degree of regeneration is used and the remaining 10 % have to be covered by the mechanical brakes.

Sim. (no.)	Coasting setting (no.)	Speed peaks	Travel time (hh:mm)	Spec-energy (Wh/seat-km)	Regen. (%)	Mech. brake energy (kWh)	Brake pad wear (index)
117	1	Full	02:42	27.5	20.0	154.0	14.3
118	2	Full	02:43	26.4	18.3	133.6	12.4
119	0	Reduced	02:45	27.0	19.7	148.5	13.7
120	1	Reduced	02:45	26.4	17.8	129.8	**12.0**

Compared to normal driving the wear is reduced by over 25 % in the cases of electric braking and by almost 80 % compared to the dynamic case. Compared to the eco-driving of the more powerful GT-250 it has 2 minutes longer travel time but approximately the same energy consumption and brake wear.

9.4 GT-250 Regional (7200 kW) on “Västra stambanan regional”

The regional operation, with 14 + 2 intermediate stops, extends the travel time, however, the energy consumption and brake wear is only moderately affected, see Table 14. This is because of the powerful drive system. Since a lot of the braking can be done by the regenerative system, which regenerates energy back to the power-lines, the wear of the mechanical brakes is still moderate, despite the large number of stops. Consequently the regeneration becomes high, especially with 100 % degree of regeneration. This is a good feature and can be credited to the powerful drive system.

Table 14. Simulation of GT-250 (7200 kW) on "Västra stambanan regional" using a normal driving style.

Sim. (no.)	Braking type	Degree of regen. (%)	Travel time (hh:mm)	Spec-energy (Wh/seat-km)	Regen. (%)	Mech. brake energy (kWh)	Brake pad wear (index)
201	Blended	90	03:14	31.6	27.5	909.6	73.9
202	Blended	100	03:14	30.6	31.5	632.5	51.4
203	Dynamic	90	03:15	29.3	35.3	336.7	**27.3**
204	Dynamic	100	03:15	28.1	40.9	7.0	0.6
205	Electric	90	03:16	29.3	35.4	330.3	**26.8**
206	Electric	100	03:16	28.1	40.9	0.0	0.0

If comparing case 207, which uses coasting, with 209, with reduced number of speed peaks, see Table 15, both energy and wear can be saved by choosing to coast rather than by avoiding speed peaks. The added time is equal for both of these cases. By looking at case 208 which uses higher amount of coasting, the reduction in energy consumption and brake wear is even higher. The travel time, however, exceeds the permitted time margin of 2 – 3 % of the total travel time. Case 210, with both coasting and reduced number of speed peaks, reduces energy consumption and brake wear even further compared to case 207, although with a comparatively long time delay (3.6 % more than case 201).

Table 15. Simulation of GT-250 (7200 kW) on "Västra stambanan regional" using eco-driving techniques. All eco-driving runs use the regenerative electric braking with as little mechanical braking as possible. Only 90 % degree of regeneration is used and the remaining 10 % have to be covered by the mechanical brakes.

Sim. (no.)	Coasting setting (no.)	Speed peaks	Travel time (hh:mm)	Spec-energy (Wh/seat-km)	Regen. (%)	Mech. brake energy (kWh)	Brake pad wear (index)
207	1	Full	03:18	27.0	30.3	257.7	20.9
208	2	Full	03:24	23.6	25.9	193.9	15.7
209	0	Reduced	03:18	28.3	33.5	302.3	24.5
210	1	Reduced	03:21	26.2	28.5	235.7	**19.1**

By using eco-driving the wear can be reduced by over 28 % compared to normal driving with electric braking mode. Even more brake wear can be saved if compared to the dynamic braking.

9.5 GT-250 Regional (5040 kW) on "Västra stambanan regional"

Downsizing the drive system power by 30 % will increase the brake wear, Table 16. This can be avoided by only using the regenerative brakes, but this will, however, increase the travel time instead.

The wear of the dynamic braking case is increased by over 300 % compared to the more powerful train and 2 extra minutes are necessary for the run. If only using the electric brakes the time difference is increased to 5 minutes, the wear and energy consumption are however slightly reduced.

Table 16. Simulation of GT-250 (5040 kW) on "Västra stambanan regional" using a normal driving style.

Sim. (no.)	Braking type	Degree of regen. (%)	Travel time (hh:mm)	Spec-energy (Wh/seat-km)	Regen. (%)	Mech. brake energy (kWh)	Brake pad wear (index)
211	Blended	90	03:17	32.9	19.8	1449.3	117.7
212	Blended	100	03:17	32.2	22.5	1241.3	100.8
213	Dynamic	90	03:17	31.2	24.5	1035.5	**84.1**
214	Dynamic	100	03:17	30.3	28.0	791.8	64.3
215	Electric	90	03:21	28.2	34.5	309.7	**25.1**
216	Electric	100	03:21	27.1	39.9	0.0	0.0

By using the eco-driving techniques the wear can be reduced. The travel time is however beyond what can be seen as acceptable, see Table 17, compared to normal driving and the more powerful train.

Table 17. Simulation of GT-250 (5040 kW) on "Västra stambanan regional" using eco-driving techniques. All eco-driving runs use the regenerative electric braking with as little mechanical braking as possible. Only 90 % degree of regeneration is used and the remaining 10 % have to be covered by the mechanical brakes.

Sim. (no.)	Coasting setting (no.)	Speed peaks	Travel time (hh:mm)	Spec-energy (Wh/seat-km)	Regen. (%)	Mech. brake energy (kWh)	Brake pad wear (index)
217	1	Full	03:22	25.9	29.1	239.4	19.4
218	2	Full	03:28	22.7	25.3	182.3	16.9
219	0	Reduced	03:23	27.4	32.9	287.0	26.6
220	1	Reduced	03:24	25.2	27.5	220.5	**20.4**

If accepting 3 minutes longer travel time the wear is reduced by over 18 % compared to the electric braking style in case 215. Compared to the more powerful train's eco-driving in Section 9.4, the wear is increased by 7 % and the travel time is increased by 3 minutes.

9.6 GT-VHST (9000 kW) on "Götalandsbanan"

On a new high-speed line, with 7 + 1 intermediate stops, the very powerful GT-VHST delivers a short travel time. Consequently, compared to GT-250 the energy consumption is higher and the brake wear as well. Even though it is 120 km/h faster compared to the X2, the GT-VHST has a very similar brake wear and 5 – 10 % lower energy consumption, see Table 18. It should also be mentioned that the GT-VHST has three more station stops and about 12 km longer distance to travel compared to the X2 and GT-250 (which adds at least 10 minutes of travel time). The powerful drive system can for this operation, in dynamic and electric braking modes, ensure a high amount of regenerated energy.

Table 18. Simulation of GT-VHST (9000 kW) on "Götalandsbanan" using a normal driving style.

Sim. (no.)	Braking type	Degree of regen. (%)	Travel time (hh:mm)	Spec-energy (Wh/seat-km)	Regen. (%)	Mech. brake energy (kWh)	Brake pad wear (index)
301	Blended	90	02:31	43.2	26.1	1116.0	99.5
302	Blended	100	02:31	41.9	32.2	767.7	68.5
303	Dynamic	90	02:31	39.9	35.8	413.1	**36.9**
304	Dynamic	100	02:31	28.3	41.4	3.9	0.4
305	Electric	90	02:32	39.9	35.8	410.2	**36.6**
306	Electric	100	02:32	38.3	41.4	0.0	0.0

If accepting a slightly longer travel time, significant improvements can be made in energy consumptions and brake wear with the eco-driving techniques, Table 19. With eco-driving 18 – 20 % energy can be saved compared to X2, despite the much higher speeds.

Table 19. Simulation of GT-VHST (9000 kW) on "Götalandsbanan" using eco-driving techniques. All eco-driving runs use the regenerative electric braking with as little mechanical braking as possible. Only 90 % degree of regeneration is used and the remaining 10 % have to be covered by the mechanical brakes.

Sim. (no.)	Coasting setting (no.)	Speed peaks	Travel time (hh:mm)	Spec-energy (Wh/seat-km)	Regen. (%)	Mech. brake energy (kWh)	Brake pad wear (index)
307	1	Full	02:34	34.7	30.4	302.5	27.0
308	2	Full	02:42	28.1	31.5	253.8	22.6
309	0	Reduced	02:33	38.7	34.0	378.5	33.8
310	1	Reduced	02:35	33.5	28.1	269.9	**24.1**

If accepting 2 – 4 minutes of added travel time, eco-driving can reduce the brake wear with up to 34 % and the energy consumption with up to 16 %.

9.7 GT-VHST (6300 kW) on "Götalandsbanan"

If the power of the GT-VHST is reduced by 30 %, the energy consumption in the dynamic braking mode increases. The wear also increases; in the dynamic braking simulation (90 % regeneration) it increased by almost 300 %. The travel time is also longer, see Table 20 below. Regarding the electric braking mode the energy consumption and the brake wear is slightly improved, but at a cost of 4 minutes travel time.

Table 20. Simulation of GT-VHST (6300 kW) on "Götalandsbanan" using a normal driving style.

Sim. (no.)	Braking type	Degree of regen. (%)	Travel time (hh:mm)	Spec-energy (Wh/seat-km)	Regen. (%)	Mech. brake energy (kWh)	Brake pad wear (index)
311	Blended	90	02:34	43.8	20.7	1712.7	152.8
312	Blended	100	02:34	42.7	24.0	1452.0	129.5
313	Dynamic	90	02:35	41.1	25.5	1193.7	**106.5**
314	Dynamic	100	02:35	40.0	29.2	891.9	79.6
315	Electric	90	02:36	37.3	35.1	376.2	**33.6**
316	Electric	100	02:36	35.9	40.6	0.0	0.0

By using eco-driving techniques the wear can be decreased but the travel time becomes longer and the conserved is energy quite low, see Table 21 below. When using both coasting and reduced number of speed peaks the time delay became too long, the best result was instead case 317 with coasting setting 1.

Table 21. Simulation of GT-VHST (6300 kW) on "Götalandsbanan" using eco-driving techniques. All eco-driving runs use the regenerative electric braking with as little mechanical braking as possible. Only 90 % degree of regeneration is used and the remaining 10 % have to be covered by the mechanical brakes.

Sim. (no.)	Coasting setting (no.)	Speed peaks	Travel time (hh:mm)	Spec-energy (Wh/seat-km)	Regen. (%)	Mech. brake energy (kWh)	Brake pad wear (index)
317	1	Full	02:39	33.0	30.0	284.2	**25.4**
318	2	Full	02:47	26.6	29.6	226.2	20.2
319	0	Reduced	02:38	36.4	33.9	354.2	31.6
320	1	Reduced	02:40	32.4	28.6	266.3	23.8

When using the eco-driving technique the brake wear is reduced by almost 24 %, if compared to the electric braking mode at normal driving. Considerably more is saved if compared to the dynamic braking. The energy consumption is also reduced; compared to the electric braking case by 11 % and even more compared to the dynamic braking case.

9.8 GT-250 Regional (7200 kW) “Västkustbanan” vs ”Västra stambanan regional”

This section contains a comparison between GT-250 on “Västkustbanan” and “Västra stambanan regional”. The comparison is limited to the normal driving style. The main focus is on differences in the energy that is braked off by the mechanical brakes and the brake pad wear index. “Västkustbanan” is known to be a very tough regional operation with frequent stops, while “Västra stambanan regional” is gentler, see Section 6.4.

“Västkustbanan” has 14 intermediate station stops but no additional unplanned stops and the top speed is party up to 250 km/h.

Compared to ”Västra stambanan regional” this operation is 114 km shorter. Cases 401, 403 and 405 compared to 201, 203 and 205 however, are showing a larger wear index in “Västkustbanan” operations, (approximately 1 % – 9 %), see Table 22. The mechanical brake energy is consistently lower for “Västkustbanan” compared to “Västra stambanan”, which is due to the shorter track. The wear index in the blended braking case with 90 % degree of regeneration is the only one showing a higher brake pad wear index for “Västra stambanan regional” (approximately 4 %).

Table 22. Simulation of GT-250 Regional (7200 kW) on "Västkustbanan" using a normal driving style.

Sim. (no.)	Braking type	Degree of regen. (%)	Travel time (hh:mm)	Spec-energy (Wh/seat-km)	Regen. (%)	Mech. brake energy (kWh)	Brake pad wear (index)
401	Blended	90	2:40	31.6	23.7	691.9	74.8
402	Blended	100	2:40	30.5	26.4	457.2	49.3
403	Dynamic	90	2:41	29.3	28.0	277.5	**30.0**
404	Dynamic	100	2:41	28.0	31.1	5.3	0.6
405	Electric	90	2:41	29.3	28.0	272.8	**29.5**
406	Electric	100	2:41	28.0	31.2	0.0	0.0

9.9 GT-250 Regional (5040 kW) “Västkustbanan” vs ”Västra stambanan regional”

The wear of the less powerful train increases in all cases except the operation which uses only electric regenerative brakes (thus using less of the mechanical brakes). The increase in brake pad wear is, according to index, 67 % between cases 403 and 413, while it actually is decreased by 8 % between cases 405 and 415. When reducing the power in the drive system the travel time is increased by 2 – 5 minutes, see Table 23.

Table 23. Simulation of GT-250 Regional (5040 kW) on "Västkustbanan” using a normal driving style.

Sim. (no.)	Braking type	Degree of regen. (%)	Travel time (hh:mm)	Spec-energy (Wh/seat-km)	Regen. (%)	Mech. brake energy (kWh)	Brake pad wear (index)
411	Blended	90	2:42	32.9	18.4	1145.1	123.8
412	Blended	100	2:42	32.1	20.4	968.0	104.6
413	Dynamic	90	2:43	31.1	21.5	827.7	**89.5**
414	Dynamic	100	2:43	30.2	23.8	624.4	67.5
415	Electric	90	2:46	27.8	27.5	252.1	**27.3**
416	Electric	100	2:46	26.7	30.5	0.0	0.0

Compared to “Västra stambanan regional” the mechanical brake energy is consistently lower due to the shorter track. The wear index, however, is higher (approximately 3 % – 8 %, cases 216 and 416 excluded) which gives a hint of the influence of the tougher operation with more frequent stops.

10. Graphical presentation

The simulations in Chapter 9 show that a more powerful electric drive system reduces both the energy consumption and the brake wear even though the trains run faster; resulting also in reduced travel time. See Figure 24, below.

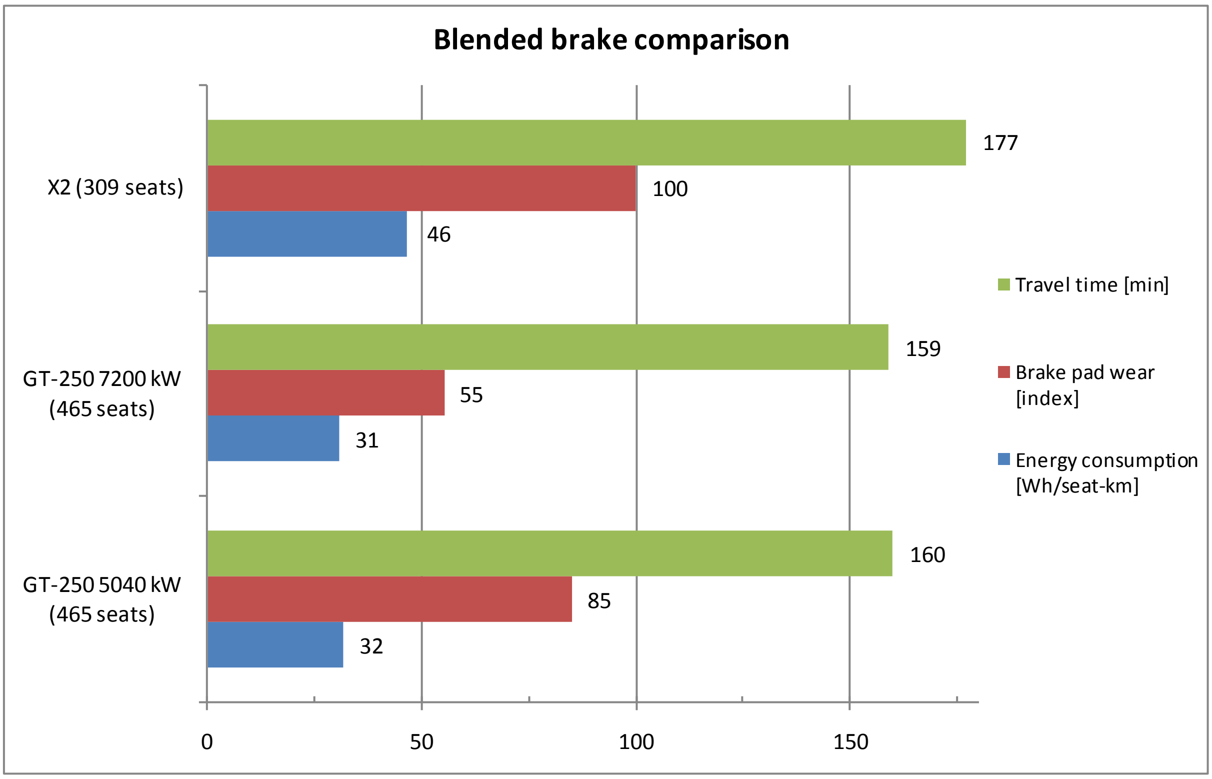

Figure 24. Simulations of blended braking (cases 001, 101 and 111) with 90 % degree of regeneration.

When comparing the GT counterparts with dynamic braking, the trains with less power add in travel time, energy consumption and mechanical brake wear, see Figure 25 below.

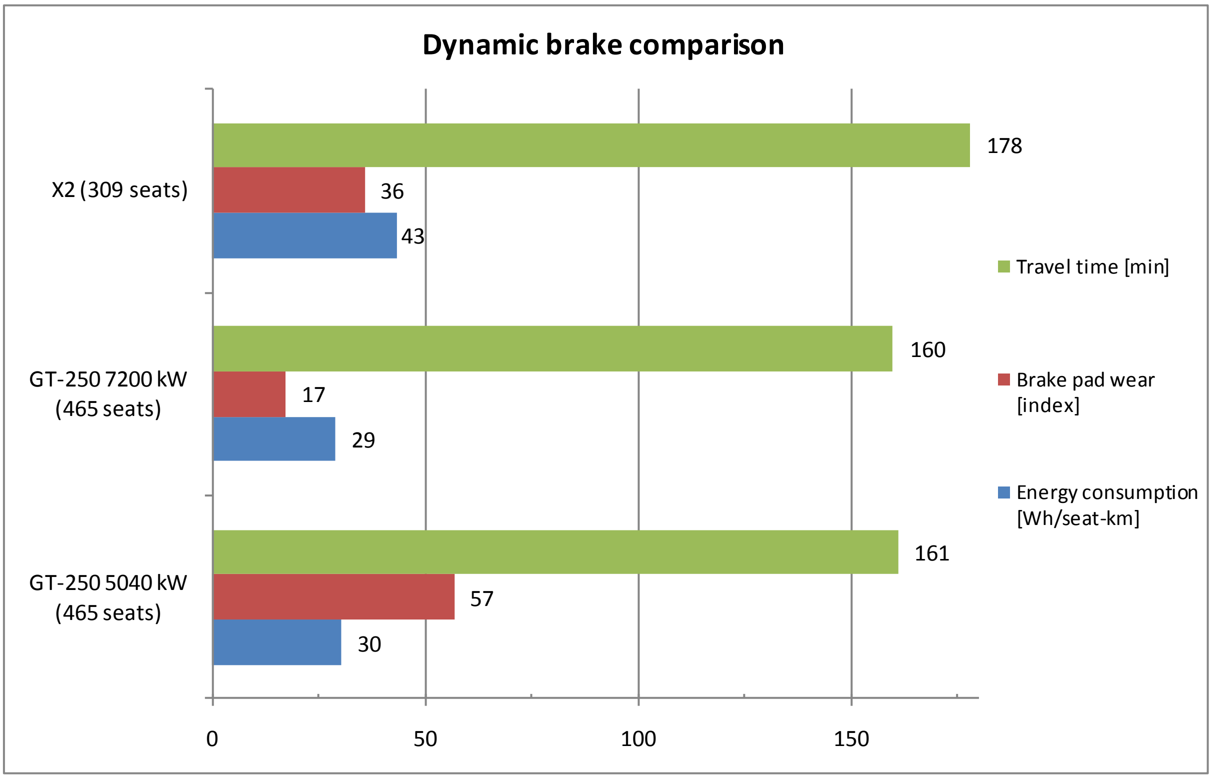

Figure 25. Dynamic brake comparison (cases 003, 103 and 113) with 90 % degree of regeneration.

An operation with many station stops and thus a lot of accelerations and decelerations makes it possible to regenerate more energy. However, to be able to decelerate fast enough using the electric regenerative brakes it is necessary with a powerful drive system. This does not mean however that energy consumption is reduced by having many station stops; the net usage is still higher than compared with an operation with few stops.

The differences between the GT counterparts can with the use of eco-driving techniques be minimized. The loss in time is still an issue though, see Figure 26 below. It is likely that the results of the eco-driving can be further improved. In this study two different techniques are used and tested, in reality more can be done, for example a system for the drivers to plan ahead and be able to avoid unplanned stops.

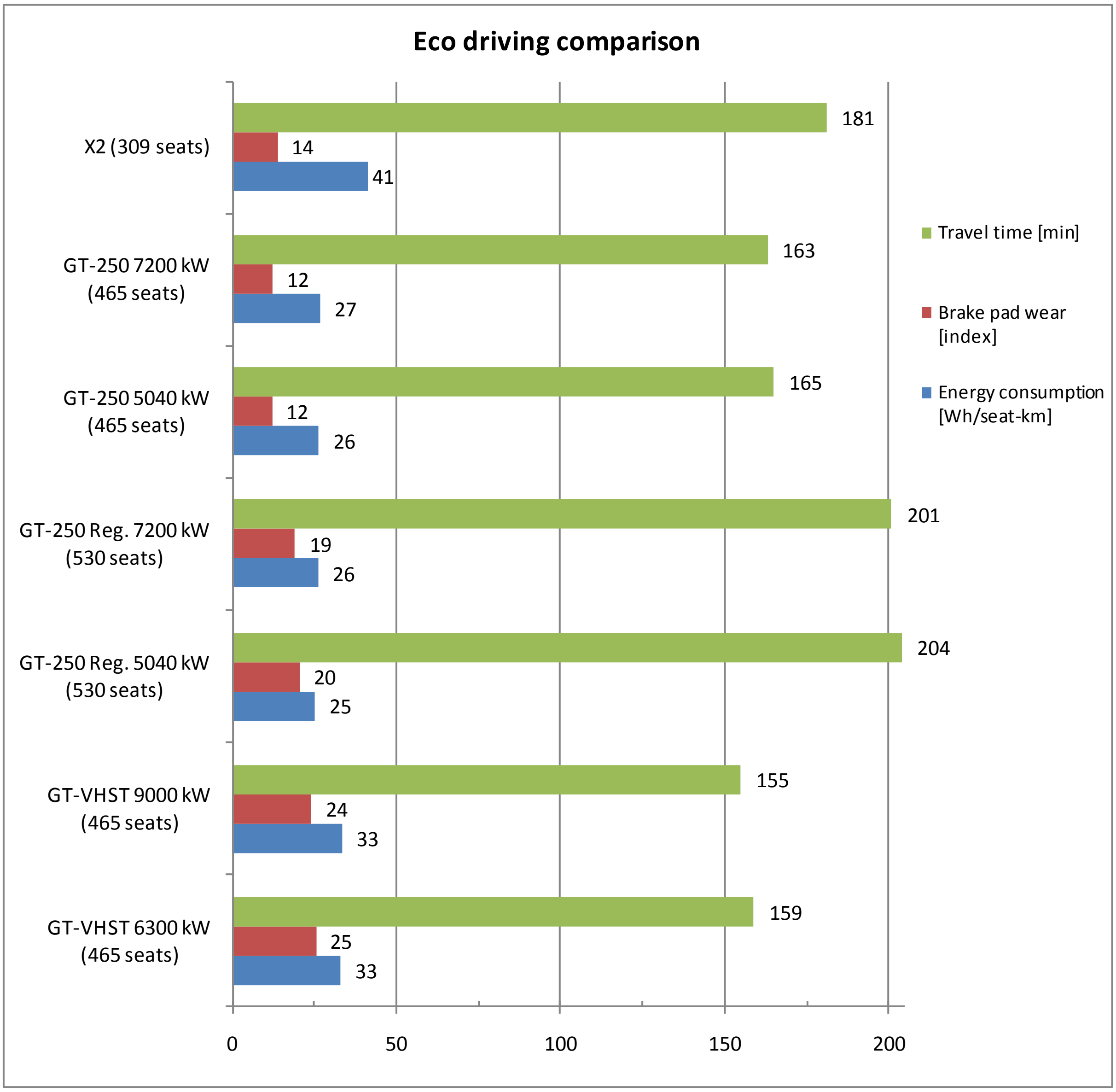

Figure 26. Differences between trains when using eco-driving techniques (cases 010, 110, 120, 210, 220, 310 and 317).

Coasting setting 2 was extreme and its usefulness could be questioned since it could not be used properly by any of the trains. Sometimes setting 2 caused the trains to stop before the oncoming station. Also the travel time is usually longer than acceptable.

It can be pointed out that for the more powerful Green Trains the cases of dynamic braking and electric braking, the results became very similar.

The above presented results, Figure 26, are for a realistic eco-driving with only 2 – 3 % of increased travel time and for 90 % degree of regeneration.

A comparison between the most important cases regarding GT-250 is shown in Figure 27 below. In this figure the significance of the more powerful electric drive systems, regarding especially brake wear, is visualized. It also shows how the eco-driving can reduce this difference except for the travel time which is increased.

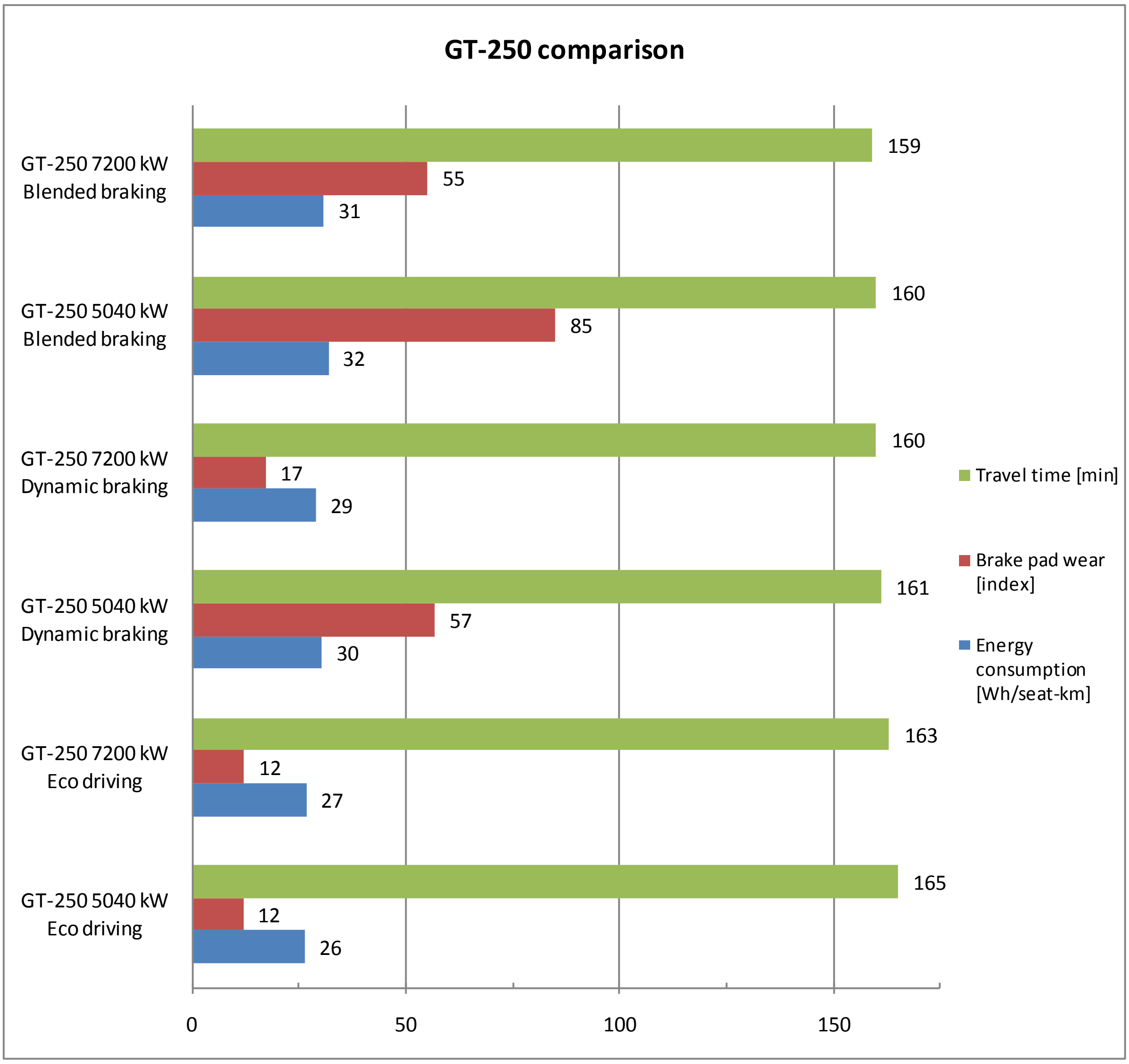

Figure 27. Comparison between the most important simulations regarding GT-250 (cases 101, 111, 103, 113, 110 and 120).

11. Economical aspects

In this section the economical aspects of the different versions of the GT-250 (full power and 30 % reduction) will be discussed.

11.1 Brake maintenance cost

In present Swedish regional and long-distance train operations there is usually an ocular safety inspection made on all trains in regular intervals, for example every two weeks. [25] Even if the brake wear would decrease dramatically this inspection would not become less frequent, due to other safety reasons. The pads or discs, for example, could still become damaged by macadam or other external causes making it necessary for the inspector to call the train in for service. Most important in these inspections is to make sure that the train will not risk derailing and that the brakes are fully functional. If the inspector finds any indication of safety problems the train will be declared unfit for operations and it will be immediately banned from traffic.

The main reasons to call in for extra service are external influences due to ballast pick-up damage, accidents with wild animals and vandalism.

The wear of the brake discs is not included directly in this study. The discs are aimed to have approximately the same lifespan as the wheels and are usually changed at the same time. A used brake disc is never put back to work together with a new set of wheels, according to current practice. If the brake wear is reduced however, an increased margin for the risk that the disc would wear out before the wheels is ensured. This has the potential to reduce the costs for the operator. There is also the possibility that if the mechanical brake wear is considerably reduced the brake disc could be re-used with a new set of wheels. This possibility has however not been investigated and therefore the economic value of low brake wear is possibly underestimated for the type of operations that is relevant for the Green Train.

The trains are usually out of traffic for service when the operators don’t have to replace the train with a spare or rent one to cover its operations. This means that the maintenance is done, when possible, over night when the train is idle and not scheduled for traffic or in other low-traffic periods.

When replacing the brake pads there are two costs involved (except the possible, but unlikely, cost for having the train out of traffic). The first cost is for the new brake pads themselves, the material costs. A new pair (they are changed in pairs) of organic brake pads costs the operator about 700 SEK. There are two brake pad pairs per brake disc (or calliper) and it takes an experienced service personnel about five minutes to change two pair of pads in one calliper. The total amount of time to change all the pads on one bogie is therefore approximately 20 minutes. The cost for labour is about 650 SEK/hour for service personnel. This cost includes the overhead cost for workshop etc. The costs are also presented in Table 24.

Table 24. Cost for labour and material.

Cost for labour (SEK/hour)	Cost for brake pads (SEK/pair)
650	700

If all brake pads are replaced on a GT-250 train with 6 cars the cost for labour adds up to 2 600 SEK (4 hours à 650 SEK) and the material to about 67 000 SEK (96 pairs of brake pads à 700 SEK). All in all, assuming that maintenance service is made over night or at least when the train is not scheduled for traffic, about 70 000 SEK. However, even if the wear is reduced, the number of service occasions would not be reduced. As previously mentioned, it is usually not the brake pad wear that is limiting the service intervals. [25]

As mentioned in Section 4.5 each pair of brake pads can brake off 5400 kWh before needing to be replaced. The cost for material and labour is calculated to 0.135 SEK/kWh.

11.2 Energy costs

According to Trafikverket the expected energy price will only increase slightly until 2015. Since Trafikverket, which negotiates prices and secure energy in advanced, have some control over the prices during the near future these predictions are usually quite accurate, see Table 25. During the next 20 years however, a longer period of time, the energy costs are less sure. [26]

Table 25. Average price forecast by Trafikverket for train operators in Sweden, 2011. The "Total" column excludes the increment for losses.

Price forecast 2011 (SEK/kWh)	Grid cost (SEK/kWh)	Increment for losses[2] (%)	Certificate (SEK/kWh)	Total (SEK/kWh)
0.461	0.088	16	0.045	0.594

The energy price is known to change both rapidly and severe, the increase or decrease of the average market spot price can be over 70 % from one year to another. [27]

According to The Northwest Power and Conservation Council in America [28] the whole sale price of energy can increase with over 114 % until 2030. This prognosis is however based on American conditions and the relevance to the conditions in Europe and Sweden is unclear.

The prognosis used in the TOSCA project [29] on future energy use and greenhouse gas emissions from the European transport sector suggests that the European market price for electricity will increase considerably until 2030 and further until 2050. Table 26 below presents the average expected price development from 2010 up to 2030 based on three European scenarios, see [29] for further information.

Table 26. European electricity price prognosis.

	2010	2020	2030
EUR/kWh	0.118	0.147	0.151
SEK/kWh	1.062	1.323	1.359

If the prices reaches 0.151 EUR/kWh in 2030 this means an increase of about 28 % compared to 2010. Compared to the prices of 2011 in Sweden, this means an increase of 129 % (from 0.594 SEK/kWh (2011) to 1.359 SEK/kWh (2030)) which is slightly higher than the American prognosis but in the same range. It is expected that Swedish (and Nordic) prices move towards the higher prices common in most of Europe due to the internationalisation of the electric power market.

These figures are an estimate and the prices do not necessarily have to increase to this level. It gives however reason to believe that an average increase of 50 % in the period 2015 – 2030 is on the conservative side when used in the economic calculation.

---

[2] Losses are already included in the simulations and this increment is therefore obsolete and will not be taken into account in the calculations.

11.3 Value of travel time

If a train is designed with a higher amount of power it could have the effect of decreasing the travel time. According to a SIKA report [30] the value of decreased travel time for private long-distance travellers is 102 SEK/h and 275 SEK/h for long-distance business travellers, see Table 27. In this study 60 % private travellers and 40 % business travellers is assumed for “Västra stambanan”. [31]

Table 27. Value of travel time for private and business travellers.

Value of travel time average	Value of travel time private	Value of travel time business
171 SEK/h	102 SEK/h	275 SEK/h

With an estimated load of about 280 passengers in a 6-car train (for example a load factor of about 60 % of 465 seats, depending on the interior layout) the value in an operation equal to “Västra stambanan” would be about 171 SEK/h per occupied seat in potential increased ticket revenues, alternatively increased patronage (increased number of travellers).

According to the cost model of “Resande och trafik med Gröna Tåget, Oskar Fröidh, 2010” [31] an operation equal to GT-250 on “Västra Stambanan”, but a 4-car unit, would cost about 123 SEK/min (capital costs, cost for onboard staff and part of maintenance costs) and an additional 32 SEK/train-km (energy, maintenance and track access costs). Translated to a 6-car average train the cost would be 185 SEK/min and additional 48 SEK/train-km. Divided over 280 occupied seats the amount becomes 0.66 SEK/min and an additional 2.85 SEK/min in value of travel time.

This means that the value of decreased travel time would become about 40 SEK/h in reduced cost per occupied seat (increased productivity due to improved utilisation of trains and crew).

All in all the value of decreased travel time would be 3.51 SEK/min per occupied seat for GT-250 on “Västra stambanan”. Note that this refers to timetable time with an average value for turnarounds and service etc. If calculated per train unit and year the amount would be over 0.9 MSEK for each minute of reduced travel time for this operation. This can be derived from an approximate yearly travel work of 425 000 km per train [31] with operation length of 455 km which gives an estimation of 935 trips per year for each train.

If the relationship were to be linear it would look as in Figure 28 (more than 0.9 MSEK in increased revenues for each minute of decreased travel time), however, the more the travel time is reduced the higher the effect. In this time range (below 10 minutes) and assuming 100 % producer surplus the linear approximation is still valid. The socioeconomic value is not considered in this study.

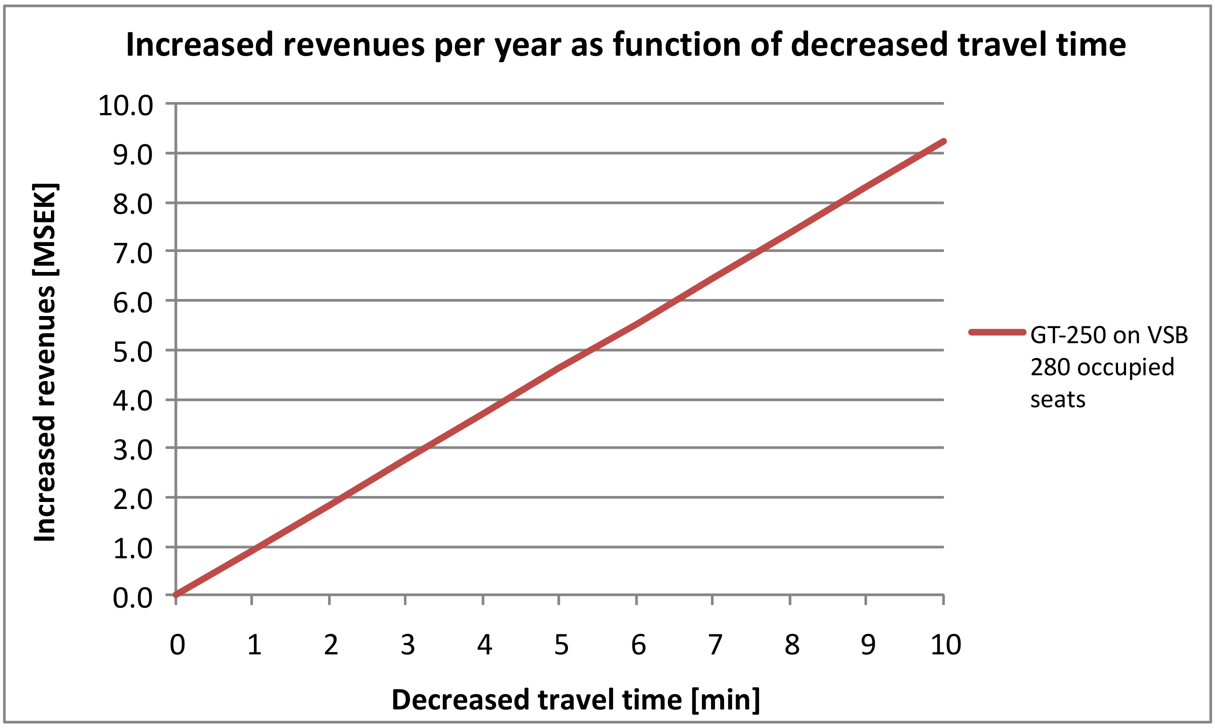

Figure 28. The figure shows the possible increase in revenues per train and year when travel times are decreased on "Västra stambanan" between Stockholm and Göteborg (Gothenburg) on a GT-250 train with 280 occupied seats.

11.4 Economical summary

The GT-250 (A, B and C) in this study, regarding the dynamic braking cases with 90 % degree of regeneration and assuming that it travels 425 000 km/year (which is a realistic estimation based on calculations of future traffic work for the Green Train). [31]

The costs regarding brake pad maintenance for a train similar to the 6-car GT-250 are as shown in Table 28. The brake pads are changed in pairs and are for that reason rounded up to the closest even number. Cost per year includes both parts and labour.

Table 28. Estimated cost per year for brake pad maintenance of the different versions of GT-250 on "Västra stambanan" with 4 station stops.

Train	Power (kW)	Operation	Changed brake pads/year	Cost/year (SEK)
GT-250 A	7200	VSB-4	66	24 900
GT-250 B/C	5040	VSB-4	212	79 500

Costs regarding energy consumption from 2011 – 2030 are shown in Table 29.

Table 29. Energy cost per year and train in MSEK for GT-250 operating "Västra stambanan". Note that energy cost is assumed to increase by 50 % between 2015 and 2030 as an average.

	2011	2012	2013	2014	2015	~2030
GT-250 A	3.41	3.53	3.64	3.64	3.76	5.11
GT-250 B/C	3.56	3.69	3.81	3.81	3.93	5.34

Differences in revenues due to shorter travel time are shown in Table 30.

Table 30. Financial gain in regard to value of travel time for GT-250 A compared to GT-250 B/C versions. The more powerful train saves 1 minute of travel time each trip, according to simulations.

	Trips/year	Saved minutes/year	Increased revenue/year
GT-250 A	935	935	923 000 SEK
GT-250 B/C	935	-	-

A summary of the differences in costs and revenues due to differences in drive system layout are shown in Table 31. These figures are based on the first year of traffic.

Table 31. Calculation of cost and revenue differences the first year of traffic due to differences in drive system. It is assumed that only 1 minute of travel time is gained.

	Decreased purchase price (MSEK)	Decreased maintenance costs (SEK)	Decreased energy costs (SEK)	Increased revenues (SEK)	Total (MSEK)
GT-250 A	-	55 000	150 000	923 000	1.13
GT-250 B	4	-	-	-	4
GT-250 C	8	-	-	-	8

When looking at a longer period of time it is preferable to calculate a present value based on the expected future income, see Equation 17.

$$Present\ value\ of\ annuities\ factor = \frac{1-(1+\mathrm{r})^{-\mathrm{n}}}{\mathrm{r}} \tag{17}$$

where

r = discount rate [%]

n = number of periods (years).

With a discount rate of 6.5 % and a pay back period of 5 years the present value of annuities factor becomes 4.16 which multiplied by 1.13 MSEK becomes 4,7 MSEK. This assumes a fixed energy cost which, as earlier shown, is not the case. The actual present value will therefore be slightly higher.

Based on 10 years pay back time the present value of annuities factor will be 7.19 which multiplied by 1.13 MSEK becomes 8.1 MSEK.

5 and 10 years pay back time are the shortest possible pay back time where the A version of the GT-250 becomes more profitable than the other versions. This gives an idea of the economic characteristics of the different versions.

The value of one single minute of decreased travel time and its importance for operators when deciding what train type to invest in can be discussed. These calculations do however show that if this minute is used for shorter travel time; it can have considerable economical effects in revenues and if the chance is that the travel time reduction is more than one minute, the effect is even more considerable. If the minute is not counted for in the timetable, it can however benefit punctuality and the possibilities to recover perturbations, which has a value as well.

If instead considering “Västkustbanan” with 14 stops, or “Västra stambanan regional”, the travel time difference between GT-250 A compared to the “B” and “C” versions is at least 2 minutes. The regional operations are estimated to have an average of 240 passengers and a value of 4.11 SEK/min per occupied seat [31]. If assuming similar pay back time as for the GT-250 it will render the same present value of annuities factors. Assuming that trains of this type travels 265 000 km per year it will add up to between 582 – 777 trips each year for “Västra stambanan regional” and “Västkustbanan”. Consistently, the amount of decreased travel time adds up to between 1 160 – 1 550 minutes.

Each year the decreased travel time is worth 1.15 – 1.53 MSEK depending on operation.

The present value based on 5 years pay back time is calculated to 4.8 MSEK for “Västra stambanan” and 6.4 MSEK for “Västkustbanan”. Based on 10 years pay back time the present value becomes 8.3 MSEK for “Västra stambanan” and 11.0 MSEK for “Västkustbanan”. This only takes account for the value of decreased travel time, not any other factors.

12. Conclusions and discussion

In this study, one of the main achievements was the development of a model for brake pad wear. As a result, four different trains with different levels of tractive power have been investigated regarding energy consumption, brake wear and travel time:

- X2 (up to 4000 kW), as reference;
- GT-250 (7200 and 5040 kW);
- GT-250 Regional (7200 and 5040 kW);
- GT-VHST (9000 and 6300 kW).

Each train has been simulated for three different braking modes, (1) blended, (2) dynamic and (3) electric and also for two different driving styles; (A) normal and (B) eco-driving.

GT-250 with the powerful drive system is superior regarding energy consumption, brake wear and travel time compared to X2. Also the GT-250 with a 30 % power reduction shows better results than X2, regarding travel time and energy consumption. This is not necessarily the case with brake wear which in the dynamic brake mode actually is worse for the weaker GT-250 than for X2. This shows the necessity of sufficient power.

Amongst the Green Trains, those with more powerful drive systems are superior to the trains with 30 % power reduction, regarding energy consumption and brake wear in normal driving.

The GT-250 Regional, with many station stops and accelerations along the line, loses, depending on the braking mode, 2-5 minutes in travel time for "Västra stambanan" if the power is reduced by 30 %. If using eco-driving it loses even more, compared to the more powerful version, particularly in blended and dynamic braking modes.

Comparing two regional operations like "Västra stambanan regional" and "Västkustbanan" it clearly shows the influence in wear that the more frequent stopping pattern can have. In most cases the wear index increased with several percent in "Västkustbanan" compared to "Västra stambanan regional".

If the new high speed line "Götalandsbanan" were to be introduced in Sweden with a similar train as the GT-VHST, we could expect similar brake wear as today for the X2 (X2000) on "Västra stambanan" but reduced energy consumption, in particular for eco-driving. This is even though GT-VHST has a 120 km/h higher top speed and cuts the travel time by around 30 minutes between Stockholm and Göteborg (Gothenburg) (455 – 467 km). Consider also that the GT-VHST has a somewhat longer travel distance and three more station stops.

Eco-driving can further reduce energy consumption and brake wear. If using 2-3 % of the total travel time (about one third of the total time margin) as an average, the scheduled travel time in passenger operations will likely not be affected. If using only electric braking, powerful drive systems constitute an extra strong advantage, enhancing faster acceleration and braking as well as more energy regeneration.

If energy consumption and brake wear are to be kept at a minimum it is also crucial that the regenerative system works properly in all conditions. As the train driver survey showed, this is not always the case today. Some particularly important properties were pointed out:

- high electric braking power;
- modest adhesion utilisation (i.e. high share of powered axles);
- a slip control system tuned also for electric braking under slippery conditions and
- possibility to use the electric brake only, independent of the mechanical brake.

The results in this report should be adequate regarding the energy consumption, since the results of the software STEC have been validated through comparison with earlier work. According to the present study the brake pad wear is nearly proportional to the mechanical brake energy in normal operational cases with modest deceleration and use of electric braking. This should be sufficient as a relative measure.

After conducting an investigation of actual trains in regular regional services, a cost for brake pad wear of 0.135 SEK/kWh (mechanical brake energy) is concluded.

The economical effects of the difference in power for the GT-250 consist of four base areas:

- Purchase price of train.
- Cost due to brake wear (maintenance).
- Energy cost.
- Value of travel time.

These areas render a present value that can be compared to the higher purchase price of the more powerful version of the train. In consideration of a pay back time of 10 years the estimated present value is 8.1 MSEK for a future long-distance operation; in this time span the more powerful train is more profitable. If instead considering a pay back time of 5 years the estimated present value is 4.7 MSEK which makes the more powerful train (GT-250 A) more profitable than the “B” version but less profitable than the “C” version (see Section 6.5 for definition). GT-250 A:s pay back time compared to the “B” and “C” versions are shown in Table 32. This is however strongly dependent of the operation. An operation with few stops is favouring the weaker trains.

Table 32. The expected pay back time for GT-250 A compared to “B” and “C” versions of the same train on an operation equal to “Västra stambanan” with 4 station stops.

	Compared to GT-250 B (years)	Compared to GT-250 C (years)
Pay back time for GT-250 A	5	10

The study shows that if conducted right, it is possible to reduce the energy consumption and brake wear which in turn reduces the energy and maintenance costs while also reducing the travel time. Shorter travel time opens up for higher revenues for the operator which according to the study (together with reduced maintenance and energy costs) can compensate for a higher purchase price.

It should be mentioned that fast regional operations with more frequent stops favour the more powerful versions of the train even more, as the savings in travel time, energy consumption and brake wear is higher than for long-distance services with relatively few stops.

Further studies should be made in order to validate the brake wear, in particular through full scale tests. It would also be of value to know what economical effects the operators could expect in regard to reduced energy consumption, reduced brake pad wear and reduced travel time for the other train types as well. Moreover, it would be of value to look into additional types of operations and driving styles as well as further analyze what effects different eco-driving techniques have. Most likely there are driving techniques that work better than others with respect to reduced energy consumption and wear as function of added travel time.

References

[1] M. Sjöholm: Benefits of regenerative braking and eco driving for high-speed trains, Master of Science thesis, KTH, Stockholm, 2011.

[2] E. Andersson and M. Berg: Railway systems and rail vehicles (in Swedish: Spårtrafiksystem och spårfordon), KTH Rail Vehicles, Stockholm. ISBN 978-91-7178-743-9, 2007.

[3] Y. Desplanques, O. Roussette, G. Degallaix, R. Copin and Y. Berthier: Analysis of tribological behaviour of pad-disc contact in railway braking - Part 1, Wear, 262, pp. 582-591, 2007.

[4] A. Lönnermo, Bombardier Transportation: Personal communication. Autumn 2010.

[5] P. Flores: Modeling and simulation of wear in revolute clearance joints in multibody systems, Mechanism and Machine Theory, 44, pp. 1211–1222, 2009.

[6] S. K. Rhee: Wear equation for polymers sliding against metal surfaces, Wear, 16, pp. 431-445, 1970.

[7] T. L. Ho and M. B. Peterson: Wear formulation for aircraft brake material sliding against steel, Wear, 43, pp. 199-210, 1977.

[8] J. F. Archard: Contact and rubbing of flat surfaces, Journal of Applied Physics, 24, pp. 981-988, 1953.

[9] T. Vernersson and R. Lundén: Wear of disc brakes and block brakes – Influence of design on modelled wear for repeated brake cycles.

[10] D. Thuresson: Influence of material properties on sliding contact braking applications, Wear, 257, pp. 451-460, 2004.

[11] N. Fillot, I. Iordanoff and Y. Berthier: Wear modeling and the third body concept, Wear, 262, pp. 949-957, 2007.

[12] STEC: MS Excel based software for Simulation of Train Energy Consumption (version 2.7), Div. of Rail Vehicles, KTH, Stockholm, 2010.

[13] A. Seidenschwang: Brake disc – Temperature calculation, Knorr-Bremse, report 701-70/08-2, 2010.

[14] UIC code 541-3: Brakes – Disc brakes and their application – General conditions for the approval of brake pads, 6th edition, 2006.

[15] S. Abbasi, KTH: Personal communication. Autumn 2010.

[16] J. Förstberg: Ride comfort and motion sickness in tilting trains, Doctoral thesis, KTH Railway Technology, Stockholm, 2000.

[17] P. Flykt, Bombardier Transportation: Personal communication. Spring 2011.

[18] P. Furukrona, SJ AB: Personal communication. February 2011.

[19] S. Berndtsson, SJ AB: Personal communication. February 2011.

[20] P. Lukaszewicz and E. Andersson: Green Train energy consumption, KTH Rail Vehicles, Stockholm. ISBN 978-91-7415-257-9, 2009.

[21] E. Andersson, KTH: Personal communication. Autumn 2010, spring 2011.

[22] PM Infrastrukturmodell av Götalandsbanan i RailSys. Banverket/Railize, Mats Gunnervall 2006-01-03.

[23] H. Sipilä: Calculations of Travel Times for the Green Train (in Swedish: Körtidsberäkningar för Gröna Tåget), KTH Railway Group, Stockholm. ISBN 978-91-7415-133-6, 2010.

[24] Bandata Götalandsbanan 070515. KTH Internal document, Oskar Fröidh.

[25] M. Göransson, Bombardier Transportation: Personal communication. Spring 2011.

[26] The Swedish Transport Administration, Report on energy prices, 2011-05-30 (in Swedish: Trafikverkets elprisrapport, 2011-05-30)

[27] Nord Pool and Svensk Energi, available at: http://www.svenskenergi.se/sv/Om-el/Fakta-om-elmarknaden/Spotprisets-utveckling-sedan-1996/

[28] Northwest Power and Conservation Council, Sixth Northwest Conservation and Electric Power Plan, Appendix D: Wholesale Electricity Price Forecast, available at: http://www.nwcouncil.org/energy/powerplan/6/final/SixthPowerPlan_Appendix_D.pdf

[29] A. Perimenis, et al: Lifecycle Assessment of Transportation Fuels, TOSCA, 2010.

[30] Socio-economic principles and calculation values for the transport sector (in Swedish: Samhällsekonomiska principer och kalkylvärden för transportsektorn): ASEK 4 (2008). SIKA rapport 2008:3.

[31] O. Fröidh: Travelling and traffic with Gröna Tåget (in Swedish: Resande och trafik med Gröna Tåget), KTH Railway Group, Stockholm. ISBN 978-91-7415-684-3, 2010.

Appendix A

Survey regarding train driving styles
(Enkät angående körsätt hos tågförare)

De flesta moderna tåg har återmatande elektrisk broms (elbroms) – t ex X2, X30, X40, X50. Vid användning av elbroms återmatas en del av energin till andra tåg eller (i vissa fall) till elnätet. Detta sparar energi. En annan effekt av elbroms är att man sparar slitage och underhållskostnader för den mekaniska bromsen.

Det finns även andra sätt att köra på för att spara energi.

Namn (frivilligt): Titel:	Främst förare för lok/tågtyperna:
Har jobbat som tågförare i (antal år):	
PLANERAR DU DIN KÖRNING FÖR ATT DU SKA KUNNA GÖRA HASTIGHETSNEDSÄTTNIGNAR ENBART ELLER HUVUDSAKLIGEN MED ELBROMS?	
X2 Ja, delvis, nej Kommentar	**X30, X40, X50** Ja, delvis, nej
HUR OFTA OCH HUR MYCKET ANVÄNDER DU ELBROMSEN VID **HASTIGHETSNEDSÄTTNINGAR**?	
X2 (0->100 %) Kommentar	**X30, X40, X50** (0->100 %)
HUR OFTA OCH HUR MYCKET ANVÄNDER DU ELBROMSEN VID **BROMSNING TILL STOPP** ELLER NÄRA STOPP?	
X2 (0->100 %) Kommentar	**X30, X40, X50** (0->100 %)
VILKA ÄR DE TRE FRÄMSTA **ORSAKERNA** TILL ATT DU ANVÄNDER **MEKANISKA BROMSEN** HELT ELLER DELVIS, D V S ATT DU INTE ENBART ANVÄNDER ELBROMS ?	
• • •	
HÄNDER DET ATT DU HELT STÄNGER AV ELBROMSEN FÖR ATT KUNNA BROMSA MED ENBART DEN MEKANISKA BROMSEN? VILKA FÖRDELAR SER DU I SÅ FALL MED DETTA?	
• Kommentar	

I VILKEN UTSTRÄCKNING NYTTJAR DU MEDVETET **FRIRULLNING** FÖRE HAST-NEDSÄTTNING ELLER STOPP?

X2 (0->100 %) **X30, X40, X50** (0->100 %)

Kommentar

VAD SKULLE KRÄVAS FÖR ATT DU SKULLE **KÖRA MER ENERGIEFFEKTIVT** (T.EX. UTBILDNING, TEKNISKA HJÄLPMEDEL…)?

-
-
-

OM DU KÖR EN LÄNGRE STRÄCKA MED X2000, T. EX. MELLAN STOCKHOLM OCH GÖTEBORG, HUR MÅNGA OPLANERADE TILLFÄLLIGA STOPP ELLER HASTIGHETSNEDSÄTTNINGAR TROR DU ATT DU FÅR?

-

Kommentar

Appendix B

Below is detailed data apprehended from simulations using STEC v. 2.7 and calculations of the mechanical brake wear, cf Chapters 9 and 10.

X2 (up to 4000 kW)

(One locomotive and six trailing cars)

Normal driving style on "Västra stambanan", maximum 200 km/h, 4 stops at stations, 1 unplanned stop and 3 speed reductions during the run.

Sim. (no.)	Braking type	Degree of regen. (%)	Coasting setting (no.)	Travel time (hh:mm)	Energy (kWh/train-km)	Spec-energy (Wh/seat-km)	Spec-energy (Wh/pass-km)	Regen. (%)	Mech. brake time (s)	Mech. brake energy (kWh)	Brake pad wear (cm^3)	Brake pad wear (g)	Brake pad wear (mm^3/ seat-km)	Brake pad wear (index)
001	Blended	90	0	02:57	14.3	46.3	84.2	6.7	1198	710.2	28.3	145.1	0.2020	100.0
002	Blended	100	0	02:57	14.2	46.0	83.6	7.5	1198	651.1	26.0	133	0.1852	91.7
003	Dynamic	90	0	02:58	13.3	43.1	78.4	12.2	1570	253.7	10.1	51.8	0.0721	35.7
004	Dynamic	100	0	02:58	13.1	42.5	77.3	13.7	1570	153.6	6.1	31.4	0.0437	21.6
005	Electric	90	0	03:01	13.0	42.2	76.7	14.1	0	113.4	4.5	23.2	0.0323	16.0
006	Electric	100	0	03:01	12.8	41.5	75.5	16.0	0	0	0	0	0	0

Eco-driving on "Västra stambanan", maximum 200 km/h, 4 stops at stations, 1 unplanned stop and 3 speed reductions during the run.

Sim. (no.)	Braking type	Degree of regen. (%)	Coasting setting (no.)	Travel time (hh:mm)	Energy (kWh/train-km)	Spec-energy (Wh/seat-km)	Spec-energy (Wh/pass-km)	Regen. (%)	Mech. brake time (s)	Mech. brake energy (kWh)	Brake pad wear (cm^3)	Brake pad wear (g)	Brake pad wear (mm^3/ seat-km)	Brake pad wear (index)
007	Electric	90	1	03:01	12.9	41.7	75.8	13.2	0	104.7	4.2	21.4	0.0297	14.7
008	Electric	90	2	03:01	12.8	41.3	75.1	12.6	0	99.3	4.0	20.3	0.0282	14.0
009	Electric	90	0	03:01	12.9	41.7	75.8	13.4	0	106.5	4.3	21.8	0.0303	15.0
010	Electric	90	1	03:01	12.7	41.2	74.8	12.5	0	97.0	3.9	19.8	0.0276	13.7

GT-250 (7200 kW)
(EMU, six cars)

Normal driving style on “Västra stambanan”, maximum 250 km/h, 4 stops at stations, 1 unplanned stop and 3 speed reductions during the run.

Sim. (no.)	Braking type	Degree of regen. (%)	Coasting setting (no.)	Travel time (hh:mm)	Energy (kWh/train-km)	Spec-energy (Wh/seat-km)	Spec-energy (Wh/pass-km)	Regen. (%)	Mech. brake time (s)	Mech. brake energy (kWh)	Brake pad wear (cm^3)	Brake pad wear (g)	Brake pad wear (mm^3/ seat-km)	Brake pad wear (index)
101	Blended	90	0	02:39	14.3	30.8	51.4	17.2	1250	596.0	23.5	120.4	0.1114	55.2
102	Blended	100	0	02:39	14.1	30.3	50.4	19.5	1250	447.5	17.7	90.4	0.0837	41.4
103	Dynamic	90	0	02:40	13.5	29.0	48.3	23.0	1430	188.2	7.4	38.0	0.0349	17.3
104	Dynamic	100	0	02:40	13.1	28.2	47.0	26.2	1430	2.4	0.1	0.5	0.0004	0.2
105	Electric	90	0	02:40	13.5	29.0	48.3	23.0	0	186.0	7.3	37.6	0.0345	17.1
106	Electric	100	0	02:40	13.1	28.2	47.0	26.2	0	0	0	0	0	0

Eco-driving on “Västra stambanan”, maximum 250 km/h, 4 stops at stations, 1 unplanned stop and 3 speed reductions during the run.

Sim. (no.)	Braking type	Degree of regen. (%)	Coasting setting (no.)	Travel time (hh:mm)	Energy (kWh/train-km)	Spec-energy (Wh/seat-km)	Spec-energy (Wh/pass-km)	Regen. (%)	Mech. brake time (s)	Mech. brake energy (kWh)	Brake pad wear (cm^3)	Brake pad wear (g)	Brake pad wear (mm^3/ seat-km)	Brake pad wear (index)
107	Electric	90	1	02:40	13.0	27.8	46.4	19.8	0	154.0	6.0	31.1	0.0286	14.1
108	Electric	90	2	02:42	12.5	26.8	44.6	18.5	0	138.6	5.4	28.0	0.0257	12.7
109	Electric	90	0	02:43	12.8	27.5	45.8	20.1	0	154.5	6.1	31.2	0.0289	14.3
110	Electric	90	1	02:43	12.4	26.7	44.5	17.9	0	132.4	5.2	26.8	0.0248	12.3

GT-250 (5040 kW)

(EMU, six cars)

Normal driving style on "Västra stambanan", maximum 250 km/h, 4 stops at stations, 1 unplanned stop and 3 speed reductions during the run.

Sim. (no.)	Braking type	Degree of regen. (%)	Coasting setting (no.)	Travel time (hh:mm)	Energy (kWh/train-km)	Spec-energy (Wh/seat-km)	Spec-energy (Wh/pass-km)	Regen. (%)	Mech. brake time (s)	Mech. brake energy (kWh)	Brake pad wear (cm^3)	Brake pad wear (g)	Brake pad wear (mm^3/ seat-km)	Brake pad wear (index)
111	Blended	90	0	02:40	14.8	31.8	53.1	12.5	1241	917.8	36.2	185.5	0.1716	84.9
112	Blended	100	0	02:40	14.6	31.4	52.3	14.1	1241	806.7	31.8	163	0.1508	74.7
113	Dynamic	90	0	02:41	14.1	30.4	50.6	16.2	1419	613.5	24.2	124	0.1147	56.8
114	Dynamic	100	0	02:41	13.9	29.8	49.7	18.3	1419	476.2	18.8	96.2	0.0890	44.1
115	Electric	90	0	02:42	13.2	28.3	47.1	22.4	0	176.9	7.0	35.8	0.0331	16.4
116	Electric	100	0	02:42	12.8	27.6	46.0	25.5	0	0	0	0	0	0

Eco-driving on "Västra stambanan", maximum 250 km/h, 4 stops at stations, 1 unplanned stop and 3 speed reductions during the run.

Sim. (no.)	Braking type	Degree of regen. (%)	Coasting setting (no.)	Travel time (hh:mm)	Energy (kWh/train-km)	Spec-energy (Wh/seat-km)	Spec-energy (Wh/pass-km)	Regen. (%)	Mech. brake time (s)	Mech. brake energy (kWh)	Brake pad wear (cm^3)	Brake pad wear (g)	Brake pad wear (mm^3/ seat-km)	Brake pad wear (index)
117	Electric	90	1	02:42	12.8	27.5	45.9	20.0	0	154.0	6.1	31.1	0.0288	14.3
118	Electric	90	2	02:43	12.3	26.4	44.0	18.3	0	133.6	5.2	10.6	0.0250	12.4
119	Electric	90	0	02:45	12.5	27.0	44.9	19.7	0	148.5	5.9	30.0	0.0278	13.7
120	Electric	90	1	02:45	12.3	26.4	43.9	17.8	0	129.8	5.1	26.2	0.0243	12.0

GT-250 Regional (7200 kW)
(EMU, six cars)

Normal driving style on “Västra stambanan”, maximum 250 km/h, 14 stops at stations, 2 unplanned stops and 3 speed reductions during the run.

Sim. (no.)	Braking type	Degree of regen. (%)	Coasting setting (no.)	Travel time (hh:mm)	Energy (kWh/train-km)	Spec-energy (Wh/seat-km)	Spec-energy (Wh/pass-km)	Regen. (%)	Mech. brake time (s)	Mech. brake energy (kWh)	Brake pad wear (cm^3)	Brake pad wear (g)	Brake pad wear (mm^3/ seat-km)	Brake pad wear (index)
201	Blended	90	0	03:14	16.8	31.6	70.2	27.5	2095	909.6	35.9	184	0.1492	73.9
202	Blended	100	0	03:14	16.2	30.6	68.1	31.5	2095	632.5	25.0	128	0.1038	51.4
203	Dynamic	90	0	03:15	15.5	29.3	65.1	35.3	2347	336.7	13.3	68.0	0.0552	27.3
204	Dynamic	100	0	03:15	14.9	28.1	62.5	40.9	2347	7.0	0.3	1.41	0.0012	0.6
205	Electric	90	0	03:16	15.5	29.3	65.1	35.4	0	330.3	13.0	66.7	0.0542	26.8
206	Electric	100	0	03:16	14.9	28.1	62.5	40.9	0	0	0	0	0	0

Eco-driving on “Västra stambanan”, maximum 250 km/h, 14 stops at stations, 2 unplanned stops and 3 speed reductions during the run.

Sim. (no.)	Braking type	Degree of regen. (%)	Coasting setting (no.)	Travel time (hh:mm)	Energy (kWh/train-km)	Spec-energy (Wh/seat-km)	Spec-energy (Wh/pass-km)	Regen. (%)	Mech. brake time (s)	Mech. brake energy (kWh)	Brake pad wear (cm^3)	Brake pad wear (g)	Brake pad wear (mm^3/ seat-km)	Brake pad wear (index)
207	Electric	90	1	03:18	14.28	27.0	59.9	30.3	0	257.7	10.2	52.1	0.0423	20.9
208	Electric	90	2	03:24	12.52	23.6	52.5	25.9	0	193.9	7.7	39.2	0.0318	15.7
209	Electric	90	0	03:18	14.99	28.3	62.9	33.5	0	302.3	11.9	61.1	0.0496	24.5
210	Electric	90	1	03:21	13.86	26.2	58.1	28.5	0	235.7	9.3	47.6	0.0387	19.1

GT-250 Regional (5040 kW)

(EMU, six cars)

Normal driving style on “Västra stambanan”, maximum 250 km/h, 14 stops at stations, 2 unplanned stops and 3 speed reductions during the run.

Sim. (no.)	Braking type	Degree of regen. (%)	Coasting setting (no.)	Travel time (hh:mm)	Energy (kWh/train-km)	Spec-energy (Wh/seat-km)	Spec-energy (Wh/pass-km)	Regen. (%)	Mech. brake time (s)	Mech. brake energy (kWh)	Brake pad wear (cm^3)	Brake pad wear (g)	Brake pad wear (mm^3/ seat-km)	Brake pad wear (index)
211	Blended	90	0	03:17	17.4	32.9	73.1	19.8	2067	1449.3	57.2	293	0.2377	117.7
212	Blended	100	0	03:17	17.1	32.2	71.5	22.5	2067	1241.3	49.0	251	0.2036	100.8
213	Dynamic	90	0	03:17	16.5	31.2	69.3	24.5	2310	1035.5	40.9	209	0.1699	84.1
214	Dynamic	100	0	03:17	16.1	30.3	67.4	28.0	2310	791.8	31.3	160	0.1299	64.3
215	Electric	90	0	03:21	14.9	28.2	62.6	34.5	0	309.7	12.2	62.6	0.0508	25.1
216	Electric	100	0	03:21	14.4	27.1	60.2	39.9	0	0	0	0	0	0

Eco-driving on “Västra stambanan”, maximum 250 km/h, 14 stops at stations, 2 unplanned stops and 3 speed reductions during the run.

Sim. (no.)	Braking type	Degree of regen. (%)	Coasting setting (no.)	Travel time (hh:mm)	Energy (kWh/train-km)	Spec-energy (Wh/seat-km)	Spec-energy (Wh/pass-km)	Regen. (%)	Mech. brake time (s)	Mech. brake energy (kWh)	Brake pad wear (cm^3)	Brake pad wear (g)	Brake pad wear (mm^3/ seat-km)	Brake pad wear (index)
217	Electric	90	1	03:22	13.7	25.9	57.5	29.1	0	239.4	9.4	48.4	0.0393	19.4
218	Electric	90	2	03:28	12.0	22.7	50.4	25.3	0	182.3	7.2	36.8	0.0341	16.9
219	Electric	90	0	03:23	14.5	27.4	60.8	32.9	0	287.0	11.3	58.0	0.0537	26.6
220	Electric	90	1	03:24	13.4	25.2	56.0	27.5	0	220.5	8.7	44.5	0.0412	20.4

GT-VHST (9000 kW)
(EMU, six cars)

Normal driving style on "Götalandsbanan", maximum 320 km/h, 7 stops at stations, 1 unplanned stop and 3 speed reductions during the run.

Sim. (no.)	Braking type	Degree of regen. (%)	Coasting setting (no.)	Travel time (hh:mm)	Energy (kWh/train-km)	Spec-energy (Wh/seat-km)	Spec-energy (Wh/pass-km)	Regen. (%)	Mech. brake time (s)	Mech. brake energy (kWh)	Brake pad wear (cm^3)	Brake pad wear (g)	Brake pad wear (mm^3/ seat-km)	Brake pad wear (index)
301	Blended	90	0	02:31	20.1	43.2	72.0	26.1	2015	1116.0	43.7	223.6	0.2011	99.5
302	Blended	100	0	02:31	19.5	41.9	69.8	32.2	2015	767.7	30.0	153.8	0.1383	68.5
303	Dynamic	90	0	02:31	18.5	39.9	66.4	35.8	2226	413.1	16.2	82.8	0.0744	36.9
304	Dynamic	100	0	02:31	17.8	38.3	63.8	41.4	2226	3.9	0.2	0.8	0.0007	0.4
305	Electric	90	0	02:32	18.6	39.9	66.5	35.8	0	410.2	16.1	82.2	0.0739	36.6
306	Electric	100	0	02:32	17.8	38.3	63.9	41.4	0	0	0	0	0	0

Eco-driving on "Götalandsbanan", maximum 320 km/h, 7 stops at stations, 1 unplanned stop and 3 speed reductions during the run.

Sim. (no.)	Braking type	Degree of regen. (%)	Coasting setting (no.)	Travel time (hh:mm)	Energy (kWh/train-km)	Spec-energy (Wh/seat-km)	Spec-energy (Wh/pass-km)	Regen. (%)	Mech. brake time (s)	Mech. brake energy (kWh)	Brake pad wear (cm^3)	Brake pad wear (g)	Brake pad wear (mm^3/ seat-km)	Brake pad wear (index)
307	Electric	90	1	02:34	16.1	34.7	57.8	30.4	0	302.5	11.8	60.6	0.0545	27.0
308	Electric	90	2	02:42	13.1	28.1	46.7	31.5	0	253.8	9.9	50.9	0.0457	22.6
309	Electric	90	0	02:33	18.0	38.7	64.5	34.0	0	378.5	14.8	75.8	0.0682	33.8
310	Electric	90	1	02:35	15.6	33.5	55.8	28.1	0	269.9	10.6	54.1	0.0486	24.1

GT-VHST (6300 kW)
(EMU, six cars)

Normal driving style on “Götalandsbanan”, maximum 320 km/h, 7 stops at stations and 1 unplanned stop during the run.

Sim. (no.)	Braking type	Degree of regen. (%)	Coasting setting (no.)	Travel time (hh:mm)	Energy (kWh/train-km)	Spec-energy (Wh/seat-km)	Spec-energy (Wh/pass-km)	Regen. (%)	Mech. brake time (s)	Mech. brake energy (kWh)	Brake pad wear (cm^3)	Brake pad wear (g)	Brake pad wear (mm^3/ seat-km)	Brake pad wear (index)
311	Blended	90	0	02:34	20.4	43.8	72.9	20.7	1916	1712.7	67.0	343.1	0.3086	152.8
312	Blended	100	0	02:34	19.9	42.7	71.2	24.0	1916	1452.0	56.8	290.9	0.2616	129.5
313	Dynamic	90	0	02:35	19.1	41.1	68.6	25.5	2116	1193.7	46.7	239.1	0.2151	106.5
314	Dynamic	100	0	02:35	18.6	40.0	66.6	29.2	2116	891.9	34.9	178.7	0.1607	79.6
315	Electric	90	0	02:36	17.4	37.3	62.2	35.1	0	376.2	14.7	75.4	0.0678	33.6
316	Electric	100	0	02:36	16.7	35.9	59.8	40.6	0	0	0	0	0	0

Eco-driving on “Götalandsbanan”, maximum 320 km/h, 7 stops at stations and 1 unplanned stop during the run.

Sim. (no.)	Braking type	Degree of regen. (%)	Coasting setting (no.)	Travel time (hh:mm)	Energy (kWh/train-km)	Spec-energy (Wh/seat-km)	Spec-energy (Wh/pass-km)	Regen. (%)	Mech. brake time (s)	Mech. brake energy (kWh)	Brake pad wear (cm^3)	Brake pad wear (g)	Brake pad wear (mm^3/ seat-km)	Brake pad wear (index)
317	Electric	90	3	02:39	15.4	33.0	55.0	30.0	0	284.2	11.1	56.9	0.0512	25.4
318	Electric	90	6	02:47	12.4	26.6	44.3	29.6	0	226.2	8.9	45.3	0.0408	20.2
319	Electric	90	0	02:38	16.9	36.4	60.6	33.9	0	354.2	13.9	71.0	0.0638	31.6
320	Electric	90	3	02:40	15.1	32.4	53.9	28.6	0	266.3	10.4	53.4	0.0480	23.8

GT-250 Regional (7200 kW)

(EMU, six cars)

Normal driving style on “Västkustbanan”, maximum 250 km/h, 14 stops at stations and no unplanned stops during the run.

Sim. (no.)	Braking type	Degree of regen. (%)	Coasting setting (no.)	Travel time (hh:mm)	Energy (kWh/train-km)	Spec-energy (Wh/seat-km)	Spec-energy (Wh/pass-km)	Regen. (%)	Mech. brake time (s)	Mech. brake energy (kWh)	Brake pad wear (cm^3)	Brake pad wear (g)	Brake pad wear (mm^3/ seat-km)	Brake pad wear (index)
311	Blended	90	0	2:40	16.7	31.6	70.1	23.7	2103	691.9	27.3	139.8	0.1511	74.8
312	Blended	100	0	2:40	16.1	30.5	67.7	26.4	2103	457.2	18.0	92.4	0.0996	49.3
313	Dynamic	90	0	2:41	15.5	29.3	65.0	28.0	2276	277.5	11.0	56.1	0.0606	30.0
314	Dynamic	100	0	2:41	14.8	28.0	62.2	31.1	2276	5.3	0.2	1.1	0.0012	0.6
315	Electric	90	0	2:41	15.5	29.3	65.0	28.0	0	272.8	10.8	55.1	0.0595	29.5
316	Electric	100	0	2:41	14.8	28.0	62.2	31.2	0	0	0	0	0	0

GT-250 Regional (5040 kW)

(EMU, six cars)

Normal driving style on "Västkustbanan", maximum 250 km/h, 14 stops at stations and no unplanned stops during the run.

Sim. (no.)	Braking type	Degree of regen. (%)	Coasting setting (no.)	Travel time (hh:mm)	Energy (kWh/train-km)	Spec-energy (Wh/seat-km)	Spec-energy (Wh/pass-km)	Regen. (%)	Mech. brake time (s)	Mech. brake energy (kWh)	Brake pad wear (cm^3)	Brake pad wear (g)	Brake pad wear (mm^3/ seat-km)	Brake pad wear (index)
311	Blended	90	0	2:42	17.5	32.9	73.2	18.4	2054	1145.1	45.2	231.4	0.2500	123.8
312	Blended	100	0	2:42	17.0	32.1	71.4	20.4	2054	968.0	38.2	195.6	0.2114	104.6
313	Dynamic	90	0	2:43	16.5	31.1	69.1	21.5	2218	827.7	32.7	167.3	0.1808	89.5
314	Dynamic	100	0	2:43	16.0	30.2	67.0	23.8	2218	624.4	24.6	126.2	0.1363	67.5
315	Electric	90	0	2:46	14.8	27.8	61.9	27.5	0	252.1	10.0	50.9	0.0551	27.3
316	Electric	100	0	2:46	14.1	26.7	59.3	30.5	0	0	0	0	0	0

Appendix C

Extra simulations for comparability

(EMU, six cars)

The following results are presented as an addition to Hans Sipiläs work on travel times for "Gröna Tåget", see [23]. The number after the operation name in the table below represents the number of intermediate stops during the operation. The estimated average load factors are as in previous calculations 60 % (about 280 seated passengers of 465 available seats) for all operations except for the regional operation which has an estimated load factor of 45 % (about 240 seated passengers of 530 available seats).

Driving on shortest possible time (blended braking) on three different tracks, maximum 250 – 320 km/h, both intermediate stops at stations and non-stop travel. The energy consumption includes losses in the electric grid which are always charged to the operators. The travel times are, with one exception (GLB-9), consistent with the results of Hans Sipilä.

Train	Operation	Degree of regen. (%)	Coasting setting (no.)	Travel time (hh:mm)	Energy (kWh/train-km)	Spec-energy (Wh/seat-km)	Spec-energy (Wh/pass-km)	Regen. (%)	Mech. brake time (s)	Mech. brake energy (kWh)	Brake pad wear (cm^3)	Brake pad wear (g)	Brake pad wear (mm^3/ seat-km)	Brake pad wear (index)
GT-250	VSB-0	90	0	2:23	13.69	29.4	49.1	11.4	901	512.2	20.2	103.5	0.0957	47.4
GT-250	VSB-8	90	0	2:49	14.83	31.9	53.2	17.2	15.03	649.6	25.6	131.3	0.1213	60.0
GT-VHST	GLB-0	90	0	1:50	19.25	41.4	69.0	12.8	1028	685.3	26.8	137.3	0.1270	61.1
GT-VHST	GLB-9*	90	0	2:18	20.63	44.4	73.9	18.4	1766	911.7	35.7	182.7	0.1691	81.4
GT-250 R.	VKB-14	90	0	2:40	16.72	31.6	70.1	23.7	2103	691.9	27.3	139.8	0.1293	74.8

* This operation differs from Hans Sipiläs calculation by stopping at Skavsta instead of taking a small detour pass Nyköping. This operation is approximately 7 - 8 minutes faster than running pass Nyköping.