Master Thesis

Energy Efficient Train Control in the Netherlands

Analysis of effects on a large scale network with distributed delays

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Picture front page: (SpoorPro.nl, 2012)

Preface

This report represents the conclusion of my master degree in Civil Engineering and Management at the faculty Construerende Technische Wetenschappen at the University of Twente. The report is the result of a study on the effects of energy efficient train control on a network-level. The research is put together with and performed at Royal HaskoningDHV, but could not have been executed without the help of my thesis committee. Rail network are complicated environments that are influenced by many factors. This made it especially difficult to structure the problem at hand and in the same time keep the research manageable within the time available.

I would like to thank my supervisor at RHDHV ir. E.B. (Edo) Nugteren for defining this topic and his feedback on my work during the meetings with the thesis committee. Edo also brought me in contact with the experts in the field, that resulted in valuable insights in energy efficient train control in the Netherlands. On a day to day basis Edo helped me to stay on track of the planning. Because of this the research is finished within a reasonable time-span.

Furthermore I want to thank my daily supervisor ing. K.M. (Kasper) van Zuilekom for the valuable feedback during the meetings, but especially for his help in the early and final stages of this research. His help in structuring the problem and structuring the final report has resulted in helped me in keeping an overview of the research, when I tended to go too much into detail.

Although he says he is not an expert in railways, prof.dr.ir. E.C. (Eric) van Berkum has been very helpful by always asked the right questions during the meetings, revealing the weaker parts of the research. His help has contributed to a better product.

During this research I was assisted by ir. D. (David) Koopman in setting-up and constructing the simulation model. Furthermore he always could provide the data I needed. I want to thank him and also the other colleagues who were always available for questions.

Finally I want to thank my family and friends for their support during my study.

Michiel Jansen van Galen
Velp, July 2016

Summary

Introduction

Energy efficiency is an increasingly popular topic, also in rail transportation. The main operator of trains in the Netherlands NS, aims to reduce its energy consumption by two percent a year, in order to reduce the environmental impact and operational cost of train travel. Around 80 percent of the energy consumed by the rail sector is used for traction (e.g. powering the trains themselves). Not surprisingly, reducing the traction energy is often the starting point in evaluation of energy reduction measures.

One of the most effective means of reducing traction energy consumption is energy efficient train control. In this strategy a coasting regime is added to the traditional control strategy speed profile. Energy efficient train control is a train control strategy executed by the train driver in which running time reserves (called slack times) are used for coasting. During the coasting regime power to the engines is switched off . The train will decelerate under the influence of resistive and gravitational forces and uses the kinetic energy that has been build up during acceleration to roll down the line. By using the kinetic energy to coast, eventually less kinetic energy dissipates under braking, resulting in an energy saving. Coasting is a trade-off between energy savings and increased running time.

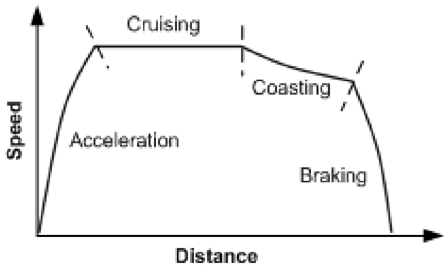


Figure 1 - Regimes energy efficient train control

Problem definition

Extensive research has been conducted on the effects of energy efficient train control in the past. These studies are often limited to the optimization of speed profiles for specific train services on specific sections of track in order to examine the energy saving bandwidth for these services. In these studies, the trains are treated as single entities. These studies recognize the large saving potential of energy efficient train control. Savings found are typically in the range of 5-20 percent, depending on the magnitude and distribution of slack time in the specific case-studies. Also NS has recognized the potential: Energy efficient train control is part of the training of new and current staff.

Little is known about the performance of energy efficient train control, when it is applied to an entire network. A rail network is a highly dynamic environment in which trains interact with each other. Also in every railway network, delays are present, which causes trains to deviate from the in the timetable planned paths. The control strategies influence the position in time and space of all trains within the network. Different control strategies can therefore lead to different patterns of interaction and delay.

Although the effectiveness of energy efficient train control is clear, in the Netherlands it is not a priority in both the timetable design process as well as day-to-day train operation. Safety and punctuality have priority over energy efficiency. Due to the higher priorities the allocation of slack time within the timetable is not optimized for energy efficient train control. In planning practice this means that the slack time is often used as a tool to resolve and/or create a time-buffer for conflicts in the initial timetable design process. These conflicts often occur near critical nodes where train flows from different directions meet (e.g. near large stations). This means that the majority of slack time is situated at the critical nodes in the final timetable.

Because coasting consumes (part of) the slack time before reaching the critical nodes, punctuality can be influenced if a conflict still occurs, which might happen for certain combinations of delay. Without a network-optimized Driver Advisory System or DAS, a train driver cannot foresee a conflict from happening upfront and adapt the control strategy accordingly, because the position of other trains in the network are unknown. This can lead to suboptimal results. Conflicts cannot only affect punctuality, but also safety and energy consumption. At a conflict a braking action is required for one of the trains in the conflict. Conflicts are regarded as an indicator of safety, because approaching a red signal and/or having to stop for a red signal is regarded as potentially unsafe: Missing a red signal can bring a train in an already occupied block section with possible collision as a consequence. Regarding energy consumption conflicts have a negative impact on energy consumption, because acceleration is necessary after the conflict has cleared.

Research scope

In this research the performance of energy efficient train control on the network-level is examined for a part of the rail network of the Netherlands, considering performance on energy saving potential, punctuality and conflicts in order to gain insights on the behavior off energy efficient train control on a network level. It is important that delays are present in the network, in all railway systems delays are present. Without deviation from the planned timetable (e.g. delays) little interaction takes place, because the planned timetable is mostly free of conflicts.

Main research question

The main research question in this research is defined as:

What are the effects of energy efficient train control on a network-level on energy consumption, punctuality and conflicts?

Research strategy

Real world performance of energy efficient train control is very difficult to measure, because the effects of one measure cannot be isolated from other effects influencing the running time of trains. In these cases, simulation is a valuable tool, since it enables the user to examine the effects of one measure by developing scenarios in which only one parameter is changed, in this case the driving control strategy, while all other factors remain constant. This isolates the effects of the topic that is investigated. Therefore, the research strategy used in this study is an experiment by simulation. The tool used for the simulations is OpenTrack. OpenTrack is a micro-simulation tool in which both network and trains are programmed to the smallest detail in order to accurately simulate running times. OpenTrack is a tool that is capable of synchronous simulation, which means that multiple trains can be loaded to the network at once in order to simulate an actual timetable. This enables simulation of interaction of trains within the network.

Scenarios

A number of scenarios are developed to test the performance of energy efficient train control on a network.

- Scenario 1: The traditional train control strategy is assigned to 100 percent of the trips.
- Scenario 2: The energy efficient train control strategy is assigned to 100 percent of the trips. Performance in this scenario is compared to the performance in scenario 1.
- Scenario 3: Traditional train control and energy efficient train control are randomly assigned to the trips 50-50. From this scenario the influence of having different strategies simultaneously on the energy consumption of either traditional train control or energy efficient train control are examined. Traditional train control trips in this scenario are evaluated against scenario 1 and the energy efficient train control trips against scenario 2.
- Scenario 4: The energy efficient train control strategy is assigned to 100 percent of the trips and freight trains are taken out of the model. In this scenario the influence of freight trains on the energy saving potential is evaluated. This scenario is evaluated against scenario 2.

Research area

The research area is a large section of the rail network in the Randstad area of the Netherlands. An important reason for choosing this particular network is the availability of empirical data on delays for this network, but also because this network contains the largest stations in the Netherlands in terms of passengers, these stations also fulfill an important transfer function, which makes punctuality especially important at these stations. On the network the occupations are high, meaning that the buffer times (e.g. the time between two following trains are low). Therefore a slight deviation from the planned timetable gives a high probability of hindering another train. This makes this network especially suitable for examining potential effects of energy efficient train control on punctuality and conflicts. The timetable that is taken as the basis is the 2014 timetable, since the empirical data on delays are gathered during this year

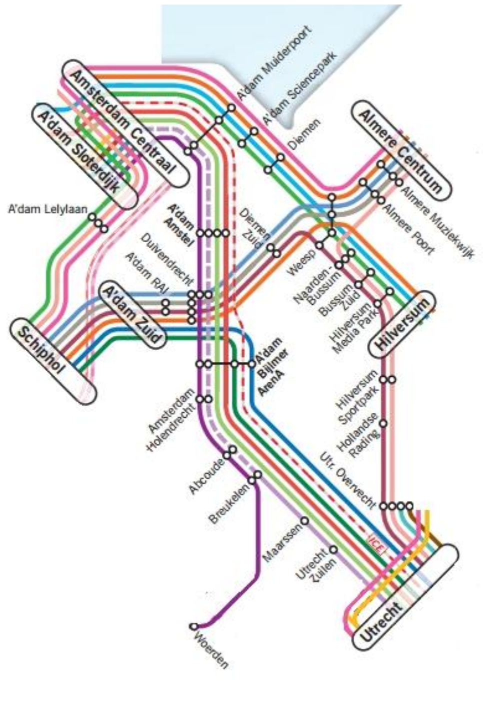


Figure 2 - Research area

Simulation model construction and modeling energy efficient train control

The foundations for the simulation model are a timetable for 2014, an infrastructure model of the research area (OpenTrack) and a train database (OpenTrack). The timetable contains all information regarding planned arrival and departure and dwell times for all services on the network, and also the planned train types that are planned to run the services. The timetable is coupled to the OpenTrack infrastructure model and train database. This forms the basis of the simulation model.

Energy efficient train control is modeled by determining the coasting points for the trains in the timetable. By deterministic asynchronous simulation (deterministic simulation of trains one by one) the technical minimum running times are calculated for every train in the timetable. By comparison of the technical minimum running time to the running time in the timetable, the size and distribution of slack time for all the individual trains are found. These are called the slack time profiles. From the slack time profiles the energy efficient train control speed profiles are constructed for nearly every unique profile, by determining the coasting points (e.g. the locations where the traction should be switched off) in such a way that all slack time available at a certain section of track for a certain train is consumed. This is done by manually by determining the coasting point at which the arrival delay at the next station equals zero (with a margin of five seconds). This is also done for a number of delays a train can take: As long as the delay is smaller than the slack time available, energy efficient train control can be applied to a certain degree without late arrival at the next station. For delays larger than the slack time no coasting point is defined as these trains should make up for the delay by driving as fast as possible. In total over 500 unique coasting points are defined.

Simulations

The scenarios described are stochastically simulated to determine the effects of energy efficient train control in the network. Stochastic simulation means that the value of a number of variables are drawn from probability distributions. The stochastic elements in this research are the dwell time and initial delay, both are drawn from a dwell time distribution and initial delay distribution respectively. The distributions on these parameters are derived from empirical data from timetable 2014 for the stations in the research area. The distributions cause the trains to deviate from the planned timetable, they sustain a certain delay at the stations in the network. In the dynamic environment of the network, trains will interact in a certain pattern based on the pattern of delays drawn from the distributions.

Results

In the Figure 3 a scatter plot of the energy consumption at the wheel for energy efficient train control and traditional train control (scenarios 1 and 2) is displayed. Each sample point represents the energy consumption of an individual train in which the performance of the traditional train control strategy is plotted against the performance under energy efficient train control. Also displayed are the y=x line and the trend line and the trend line based on the least square fit to the sample points. If no differences between the control strategies would exist, the sample points would be plotted on the y=x line. The trend line deviates downwards from the y=x-line, which means that on average the energy consumption under energy efficient train control has decreased relative to the energy consumption under traditional train control. Calculations have shown that the energy consumption is significantly reduced when energy efficient train control is applied. The mean savings are 11.3 percent relative to traditional train control.

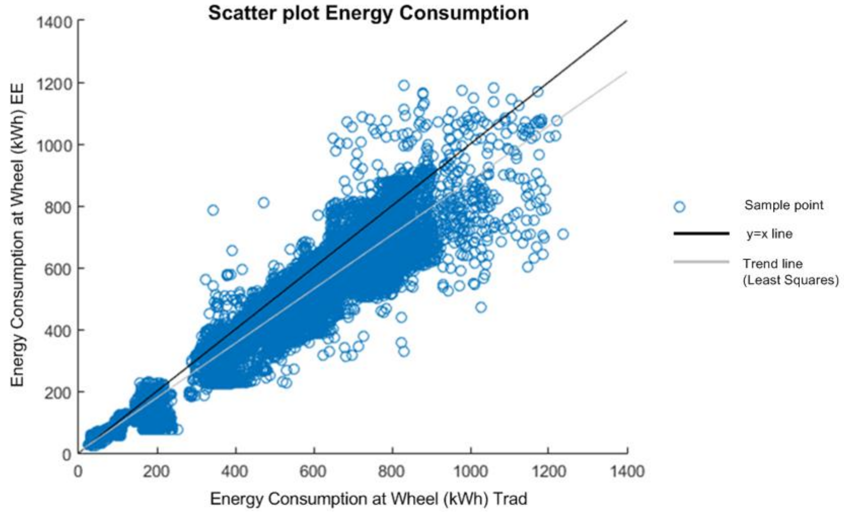


Figure 3 - Scatter plot energy consumption

It is apparent that numerous sample points are situated above the y=x line indicating that the application of the energy efficient train control can lead to an increase in energy consumption, from which it can be concluded that network-wide application of energy efficient train control does not have positive effects on all trains. Energy efficient train control will lead to an energy saving in general, but application of the strategy does not automatically mean that an energy saving is made. Calculations on train series level show that the majority of train series show energy savings, though for individual trains within the series increases can be found.

In Figure 4 the spatial distribution of savings over the network is displayed. Figure 4 represents the difference in energy consumption of energy efficient train control relative to traditional train control all track sections between service control points. The blue/green shades indicate energy savings, the yellow shades an increase in energy consumption. The yellow shaded sections generally indicate the parts of the network where no coasting is applied (e.g. the behavior of trains under energy efficient train control roughly equals to the behavior under traditional train control). Due to a setting of a performance parameter caused trains under energy efficient train control to run slightly faster than trains under traditional train control when no coasting is applied, which explains why slight increases in energy consumption can be found in Figure 4. This is elaborated on in the main report.

Under certain conditions coasting is not applied at a track section:

- Trains on the section of track do not have slack time available for coasting, either because it is not incorporated in the timetable or not available due to delays.
- The track section is not a coasting area and trains are in another regime at this section (acceleration, cruising or braking)
- The permissible line speed is lower than the lower coasting limit. A lower coasting limit is set at 80 km/h (e.g. coasting is never applied below this speed).

Roughly from Amsterdam Sloterdijk up to Amsterdam Muiderpoort/Amsterdam Amstel a permissible

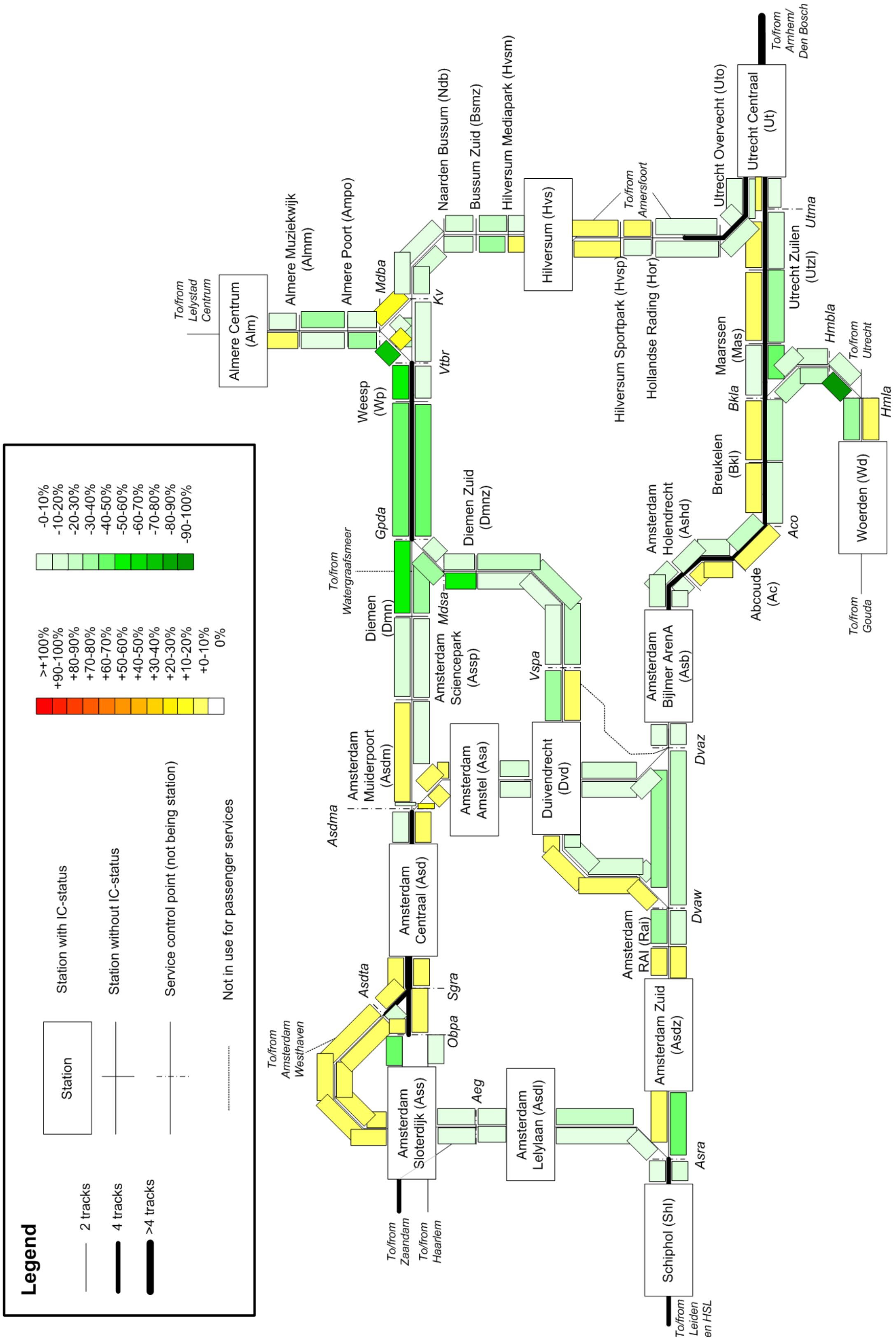


Figure 4 - Spatial distribution of energy savings by energy efficient train control

line speed of 40-80km/h is in place. Slack time between station stops on this section cannot be used for coasting because of a lower coasting limit. An estimation of the lost saving potential is made by measuring the energy savings of the trains not running through this area. For these trains an average saving of 12 percent is found, which means that a lower coasting limit influences the saving potential.

No evidence could be found that having both energy efficient train control trips and traditional control trips in the network simultaneously affects either the energy consumption of energy efficient train control or the energy consumption of traditional train control, which means that total energy savings are proportional to the degree in which energy efficient train control is applied.

Although freight trains potentially can affect the delays within a network, because of slow acceleration and blockage of track sections because of their length, no evidence could be found that the presence of freight trains leads to a lower energy saving potential of energy efficient train control.

In Figure 6 the probability distributions of the arrival delay for both traditional and energy efficient train control are displayed. Arrival delay is a measure of punctuality and is measured deviation in seconds from the planned arrival time. The figure displays the distribution of arrival delays for all stations in the network combined. From Figure 6 and the calculations it is concluded that energy efficient train control does not influence punctuality negatively. The right tails of the distributions overlap. It is shown that in general applying the energy efficient train control strategy does not cause the trains to arrive with a positive delay more often than in the traditional train control strategy even though calculations on the energy consumption have shown that energy efficient train control does not have positive consequences for all trains. In the figure it can be seen that trains can still arrive early in energy efficient train control. This is mainly caused by the arrivals on Amsterdam Centraal. As explained coasting cannot be applied at a low speed zone. Therefore the slack time situated in this area cannot be consumed which means that early arrival is still possible. The Weesp station gives an understanding of the performance in a part of the network in which the largest energy savings are found. The distribution for the Weesp station are displayed in

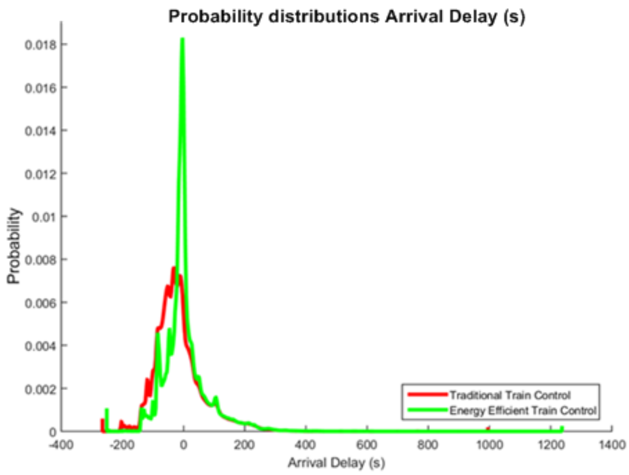


Figure 6 - Arrival delay distributions (all stations)

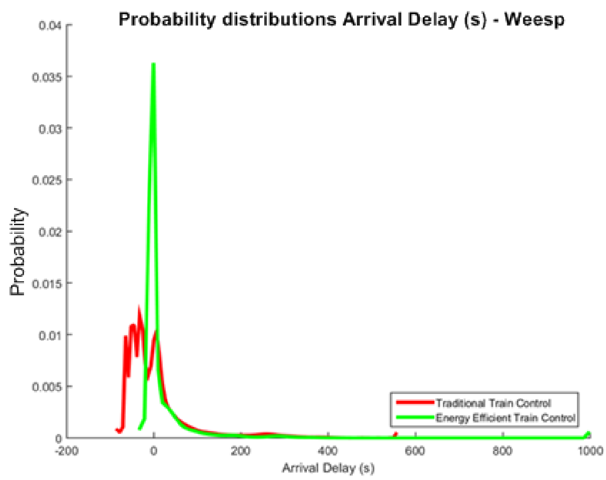


Figure 5 - Arrival delay distributions (Weesp)

Figure 5. In energy efficient train control, the majority of arrivals take place around the zero seconds delay mark, whereas in traditional train control more trains arrive early. Arriving on time, rather than early will not have negative consequences for passengers as long as the transfer times for connecting train services are adequately calculated. This ensures that passengers can make a connection when a train arrives at the planned arrival time. The dispersion in the arrival delay distribution decreases the application of energy efficient train control. This means that trains using this strategy arrive in a smaller time-window. This benefits the capacity of the network.

In Table 1 the results for the calculations on conflicts are displayed. The calculations represent the average number of times a certain braking action is executed per train trip (e.g. The value .22 at red signal aspect (full stop) at traditional train control means that in this control strategy, every train has to stop on average .22 times for a red signal every journey through the model. It should be explained that not every occurrence of a braking action enforced by signaling is caused by a conflict. Some signals are deliberately kept on red, for instance at stop connections which are often found at stations with a level crossing directly behind it. These cases however affect both strategies equally, e.g. the differences between the control strategies described in the last column represent differences in number of braking actions due to conflicts.

Mean occurrences of braking actions at signals per train trip	Traditional Train Control	Energy Efficient Train Control	Difference in %
Red signal aspect (full stop)	0,22	0,19	-10,7
Red signal aspect(approach)	0,57	0,52	-10
Yellow signal aspect	3,12	2,68	-14,3

Table 1 - Mean occurrences of braking actions at signals per train trip

Al types of braking actions at signals are significantly reduced by application of energy efficient train control, which indicates that the number of conflicts are brought down. In energy efficient train control a train generally arrives later at a conflict location, meaning that the conflict often has cleared ones the train arrives. The reduction in number of conflicts has contributed to the energy savings that are found. The number of red signal approaches and stops at red signals have been reduced by 10 percent, meaning that energy efficient train control contributes to the safety in a network.

Conclusions

This study has shown that also on network-level, energy efficient train control significantly reduces the energy consumption of trains. An average saving of 11 percent is calculated. In general application of energy efficient train control leads to an energy saving, but application of the strategy does not guarantee a saving. Some of the trains will experience an increase of energy consumption. The research has also shown that punctuality is not affected negatively. Energy efficient train control causes the trains arrive more around the planned arrival time. Energy efficient train control contributes to safety. The red signal approaches and red stops at red signals are reduced by 10 percent. Because of the great variety in slack distributions it is strongly advised to implement a train based DAS system in order to make the most out of the energy saving potential

Table of Contents

1. Introduction

Rail transportation is an increasingly popular mode of mass transportation. Although rail transportation can be considered a highly efficient means of transportation, due to its high capacity and relatively low energy consumption per passenger, rail transportation is responsible for a large share in the total energy consumption within a country. Together with an increasing demand and intensification of train traffic to satisfy demand, the energy consumption is likely to become even greater in the future. In the mean time train operators face pressure to reduce the energy consumption to achieve efficiency targets.

In the Netherlands, the main operator NS (Nederlandse Spoorwegen) consumes about 1.4 terawatt hour of electricity annually. This equals about one percent of the total annual energy consumption of the Netherlands and equals the total energy consumption of the capital Amsterdam (NS, 2014). Since 2005 NS aims to reduce its energy consumption by two percent every year in order to reduce cost and in the same time reducing the environmental impacts of train travel (Stroecken, 2013), (Luijt R. , 2015b). Since 80 percent of the energy consumption of the rail sector is consumed by traction (e.g. running the trains) , reducing traction energy consumption is often seen as a starting point of evaluation of energy efficiency measures (Douglas, Roberts, Hillmansen, & Schmid, 2015).

1.1. Energy efficient train control

Energy Efficient Train Control is an effective measure to reduce the traction energy consumption.

A traditional train control profile consists of four phases between station stops, called regimes. The acceleration regime, a cruising regime (maintaining a certain speed) and the braking regime. In the energy efficient control strategy a coasting regime is added in between the cruising and braking regime. During the coasting regime power to the engines is switched off by the train driver . The train will decelerate under the influence of resistive and gravitational forces and uses the kinetic energy that has been build up during acceleration to roll down the line. By using the kinetic energy to coast, eventually less kinetic energy dissipates under braking, resulting in an energy saving. This strategy does come at the cost of an increased running time. Energy efficient train control by coasting can therefore be seen as a trade-off between energy savings and increased running time (Douglas, Roberts, Hillmansen, & Schmid, 2015). Because of relatively low resistance a train can coast a relatively long distance for a small increase of running time. According to the theory on optimal train control, the most efficient strategy is: Acceleration at the maximum possible rate, cruising at the permissible line speed, coasting and braking at the maximum possible (comfortable) rate (Albrecht, 2008), (Howlett, Milroy, & Pudney, 1994). By executing all other regimes than coasting at the maximum possible performance, the most slack time remains available for coasting.

To compensate for the increased running time, the energy efficient train control makes use of the running time reserves in the timetable. These running time reserves are called slack time. By consuming all slack time for coasting, the train would theoretically arrive exactly on the planned arrival time (depicted in the timetable) at the next station. The slack time allows for an energy saving, combined with punctual operation. Allowing for energy efficient train control is however not the primary purpose of slack time. The primary purpose of slack time is to ensure that the running times are manageable under unfavorable circumstances and allowing delayed trains to make up (part of) the delay. When a train is punctual and the circumstances are good, the running time reserves can be used for coasting. (Scheepmaker, 2013).

The efficiency of energy efficient train control has been a topic in many studies in the past. These studies consistently show possible savings between 15% and 35% at slack time percentages of 5% to 12% (Douglas, Roberts, Hillmansen, & Schmid, 2015). Since the majority of the energy consumption is consumed by traction, the potential savings are substantial. Also NS has recognized the potential: Energy efficient train control is part of the training of new and current staff.

1.2. Priorities over energy efficient train control

Although the potential of energy efficient train control is recognized by NS. In both timetable design and train operation energy efficiency is not the priority. Safety and punctuality have priority over energy efficient train control. (Scheepmaker, 2013). Due to the higher priorities the timetable design is not optimized for energy efficient train control.

Initially all train movements between stations are assigned 5 percent of slack time over the technical minimum travel time. Planners however add or remove slack time to resolve for conflicts in the initial stages of the timetable planning. Also the timetable is rounded to full minutes. All factors combined mean that the slack time is not evenly distributed. It can even be negative. Generally a uniform distribution of slack time gives a higher saving potential (Scheepmaker, 2013).

Resolving a conflict in de planning is often carried out by adding slack time to one of the conflicting train movements. The train concerned is in this case planned at a lower speed than it is theoretically capable of. This ensures that the timetable will be mostly free of conflicts to assure that trains use shared infrastructure at a safe time-distance. Driving this lower speed resolves the conflict in the planning, the train with the added running time passes behind the other train. Not travelling at the planned speed means the train will arrive early at the critical location and the conflict can occur. The train will be forced to brake and/or stop, and wait until the conflict has cleared. The train driver is enforced to brake/stop by the signaling system. In this case the slack time acts as a time-buffer. It reduces the impact of the conflict. Using the slack time as a tool for resolving conflicts serves both a safety and punctuality purpose. Safety by making sure that in the planning trains follow each-other at a safe time-distance and punctuality by creating a time-buffer for when the conflict occurs.

Punctuality is a measure of on-time performance of the train services for a certain station. It is often described as the fraction of trains that arrive within a margin of the planned arrival time (Hansen, 2001). In Europe generally a 5 minute margin is used. In the Netherlands also a 3-minute margin is measured for a number of large stations. In consultation with the ministry of Infrastructuur en Milieu (Infrastructure and Environment), minimum requirements about the level of punctuality are set. A disadvantage of using the 3- or 5-minute norm for punctuality as performance indicator for on time-performance is that it does not describe delays shorter than the margin of 3 or 5 minutes. Small delays can have a significant impact on the travel time, because relatively small delays can lead to missing a connecting train service. A delay at a transfer often has a larger effect at on travel time at a transfer than at the destination, because at the destination only the delay of the train determines the extra travel time whereas at the transfer also the waiting time for the next train is added to the travel time, the latter depends on the frequency of trains. A solid assessment of punctuality includes analysis of the full distribution of arrival delays, mean and dispersion of arrival delay (Juan, 2008).

Occurrences of conflicts are often used as a measure for the safety of train operation. A conflict between trains results in a required braking action for one of the trains in conflict. This braking action is enforced by the signaling system. The train protection system of the train governs whether the train driver applies a braking input to ensure the train slows down to the required speed. Although constant improvements to the train protection system are made, red signal violations still can and do occur in practice under certain conditions. A red signal violation is potentially unsafe, since it can bring the train in a block that is occupied by another train, with a possible collision as the consequence. Conflicting train movements that result in red signal approaches are therefore considered less safe.

Conflicts also affect the energy consumption of trains, because a train has to accelerate once the conflict has cleared. Acceleration requires the largest input of energy per unit of time. Relevant are all signal aspects that require a braking action. Apart from red signal aspects, this concerns yellow signal aspects as well

1.3. Energy Efficient Train Control and DAS

As with any efficient driving technique the success heavily relies on the ability of the drivers to follow the optimal trajectories. To assist train drivers in driving more energy efficient, numerous Driver Advisory Systems (or DAS) have been developed in the Netherlands.

The earliest versions consisted of general coasting rules in tabular form. The energy savings were estimated to be fairly low, because the train driver had to make some calculations regarding the coasting point (e.g. the location where the traction is switched off). Furthermore this system relied on the craftsmanship and experience of the train driver to know where and when slack time is available. A later version included more specific advice. For a number of train series a specific advise as to where the traction should be switched off was provided. Both systems mentioned have in common that they are static. Static DAS do not provide an advice for when a train is delayed.

Currently NS is experimenting with dynamic train based DAS, called 'Uitrolapp' (Luijt R. , 2016) It is an application on the mobile phone of the train driver. The GPS receiver from the phone itself is used to determine the location of the train in space and time. The position is compared to an energy efficient profile from empirical data and is shown to the train driver. All systems mentioned above have in common that they are train based and therefore only provide advice on the control strategy of the own train. These systems do not necessarily lead to an optimal solution for an entire network. C-DAS or Connected-DAS connects al trains in the network through a GSM-r network with traffic control, where an optimal solution based on the current status of al trains is calculated by a traffic management system and send back to the trains concerned. In the Netherlands such a system is not foreseen in the near future (Luijt R. , 2016), the current level of DAS development in the Netherlands is therefore train based dynamic DAS.

A rail network is a highly dynamical environment in which trains interact with each other. Although the planned timetable is planned almost free of conflicts, delays within the network cause the trains to deviate from the planned timetable, this causes interaction. Delays are present in every rail network and can be caused by numerous factors, both within the network, but also by outside factors such as the weather or incidents (Juan, 2008). Different delay patterns lead to different patterns of interaction within the network. Interaction between trains translate into conflicts. A conflict arises when two trains have to use a shared part of the infrastructure at the same time. Since this is not possible one of the trains in a conflict is required to brake and wait for the conflict to clear. Since train based DAS optimizes the profile for only the own train such a system is not able to foresee conflicts, because the position of other trains is unknown.

1.4. Delays and energy efficient train control

A railway network is a highly dynamic environment in which trains interact with each other. In all networks delays are present, which causes trains to deviate from the in the timetable planned paths. This causes interaction with other trains within the network. The result of interaction is a conflict. In a conflict one of the trains is required to perform a braking action and wait for the conflict to clear. Due to a conflict a train sustains a secondary delay. Two types of delays can be distinguished, primary and secondary delay. Primary delay is a delay is a delay that isn't caused by interaction with other trains, for example a delay on the initial departure. Secondary delays are the result of trains with a primary delay transferring delay to other trains due to interaction on the network (Weeda, Wiggenraad, & Hofstra, 2006). Secondary delays occur because a piece of the infrastructure cannot be shared by two trains at the same time.

The performance within a rail network are determined by both internal and external inputs and include: Network characteristics, train characteristics, timetable, train driver control inputs (e.g. the control strategy) and primary delays (that can be caused by external factors such as bad weather or incidents). These factors together determine the patterns of interaction (e.g. secondary delay), which results in a certain output of performance.

Delays directly influence the saving potential of the energy efficient train control strategy. The energy saving potential of a train trip largely depends on the distribution and magnitude of the slack time that is available. (Scheepmaker, 2013). A delay affects the magnitude of slack time, and therefore the energy saving potential.

The applied control strategy influences the location of a train in space and time. Different control strategies can therefore lead to different patterns of interaction and delay.

1.5. Research outline

In this paragraph the research outline is described. This includes the problem description, research goal, research questions, research scope and the structure of this report

Rail networks are complex environments. The dynamic behavior of trains is affected by many aspects. It is important to set clear boundaries in order to keep the research and manageable.

1.5.1. Problem Description

Energy efficient train control has been the topic in many studies in the past. The energy saving potential of energy efficient train control is widely recognized. Savings found are typically in the range of 15-35 percent, depending on the magnitude and distribution of slack time in the specific case-studies. Also NS has recognized the potential: Energy efficient train control is part of the training of new and current staff and numerous driver advisory systems have been developed to assist train drivers in more efficient driving.

Studies regarding the saving potential are often limited to the optimization of speed profiles for specific train services on specific sections of track in order to examine the energy saving bandwidth for these services. In these studies, the trains are treated as single entities.

Little is known about the performance of energy efficient train control when it is applied to an entire network. A rail network is a highly dynamic environment in which trains interact with each other. Also in every railway network, delays are present, which causes trains to deviate from the in the timetable planned paths. The control strategies influence the position in time and space of all trains within the network. Different control strategies can therefore lead to different patterns of interaction and delay. Therefore it is important to understand the behavior of energy efficient train control within a network.

Although the effectiveness of energy efficient train control is widely recognized, in the Netherlands it is not a priority in both the timetable design process as well as day-to-day train operation. Safety and punctuality have priority over energy efficiency. Because these factors are also related to the train control strategy it is important to include these in an evaluation of energy efficient train control. Because of the higher priorities, the allocation of slack time within the timetable is not optimized for energy efficient train control. In planning practice this means that the slack time is often used as a tool to resolve and/or create a time-buffer for conflicts in the initial timetable design process. These conflicts often occur near critical nodes where train flows from different directions meet (e.g. near large stations). This means that the majority of slack time is situated at the critical nodes in the final timetable. Because coasting consumes (part of) the slack time before reaching the critical nodes, this potentially affects the punctuality when does still occur. At the current level of DAS a conflict cannot be seen beforehand, since train-based DAS optimizes the speed profile for the own train only.

1.5.2 Research Goal

The goal in this research is defined as:

Provide insights in the effects of energy efficient train control on a network-level, assessing energy saving potential, punctuality and conflicts

1.5.3. Research questions

The main research question is defined as:

What are the effects of energy efficient train control on a network-level on energy consumption, punctuality and conflicts?

The sub-research questions are defined as:

1. ***What is the magnitude of the energy savings that can be achieved when energy efficient train control is applied?***
2. ***What is the influence of energy efficient train control on the punctuality of the system?***
3. ***What are the effects of energy efficient train control on conflicts***
4. ***Does having mixed driving strategies on the same network affect the energy consumption of either traditional train control or energy efficient train control?***
5. ***Do freight trains influence the energy saving potential of energy efficient train control?***

1.5.4. Research Scope

Real world performance of energy efficient train control is difficult to measure, because the effects of one measure cannot be isolated from other effects influencing the train movements. In these cases, simulation is a valuable tool, since it enables the user to examine the effects of one measure by developing scenario's in which only one parameter is changed, in this case the driving control strategy, while all other factors remain constant. This isolates the effects of the topic that is investigated. The tool used for the simulations is the program OpenTrack. OpenTrack is a micro-simulation tool in which both network and trains are programmed to the smallest detail in order to accurately simulate running times. OpenTrack is a tool that is capable of synchronous simulation, which means that multiple trains can be loaded to the network at once in order to simulate an actual timetable. This enables simulation of interaction of trains within the network. It is outside the scope of this research to provide a full understanding of interaction related to energy efficient train control. Only the outputs from the network in terms of energy consumption, punctuality and conflicts are measured to determine the effects of energy efficient train control.

Energy efficient train control is the only energy efficiency measure that is considered. Other methods are considered different saving strategies and are outside the scope of this research.

This research is limited to the Dutch rail network. The extent to which energy efficient train control can be applied is largely determined by the way in which slack time is distributed over the network. Since this is done following some timetabling rules, distribution and magnitude of slack time can vary between countries.

The optimization of the energy efficient train control speed profiles is done from the vantage point, that train based-dynamic DAS is the current level of development, regarding driver assistance systems assist train drivers in energy efficient train control. This means that energy efficient train control is optimized on the train level, not considering the positions of other trains in the network.

In order to determine effects of interaction, (e.g. effects on punctuality and conflicts) it is a condition that delays are present in the network. Because of the limited amount of time for this research, already available data are used. Availability of this data is limited to certain parts of the network under certain timetables, which limited the choices on the research area and timetable.

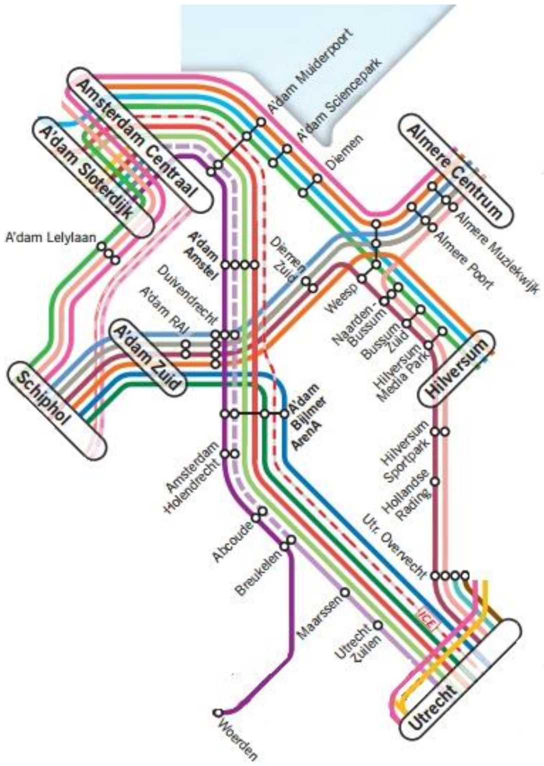


Figure 7 - Research Area

The timetable of 2014 serves as a basis for this research, since the available empirical data on delays are taken from this year. Because the method of assigning slack time in the timetabling process has not changed in recent years it is assumed that the results that are found in general will apply to current timetables. The research area chosen is a large part of the Randstad area displayed in Figure 7. The network contains the largest stations in the

Netherlands in terms of passengers, these stations also fulfill an important transfer function, which makes punctuality especially important at these stations, since it affects a large number of passengers. On the network the occupation is high, meaning that the buffer times (e.g. the time between two following trains are low). Therefore a slight deviation from the planned timetable gives a high probability of hindering another train. This makes this network especially suitable for examining effects on punctuality and interaction (conflicts) that are the result of the strategy energy efficient train control. This network is considered a heavy utilized network. It is assumed that the energy savings found are achievable for parts of the Dutch real network with lower train intensities.

1.5.5. Report structure

In this paragraph the report structure is described. In chapter 2 the theoretical framework is described that functions as the basis for the conceptual model in chapter 3. In this chapter also the research set-up is described. In Chapter 4 the construction of the simulation model is described. In chapter 5 the results of the study are discussed. Conclusions and recommendations of this research are found in Chapter 6

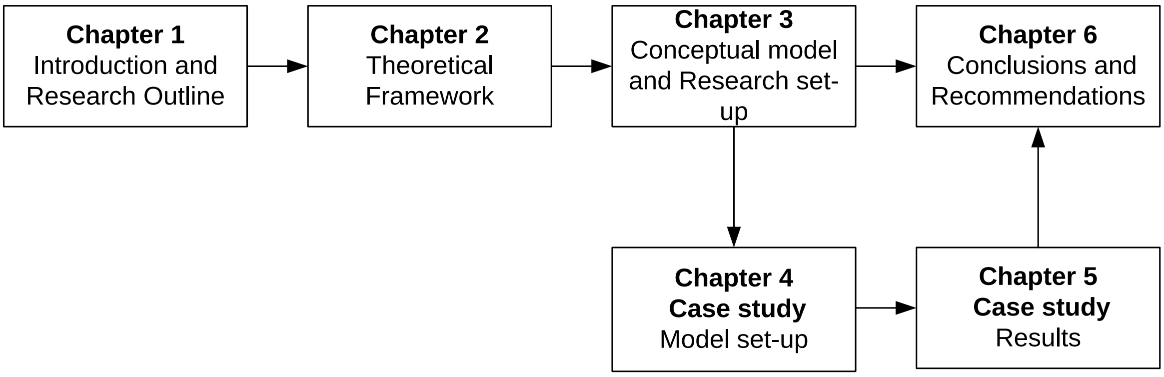


Figure 8 - Report structure

2. Theoretical Framework

2.1. Energy Efficient Train Control

2.1.1. Energy Consumption of Trains

Up to 80 percent of the energy consumption of rail transportation is used to power trains. The remaining 20 percent is used to power stations, depots, switches etcetera (Douglas, Roberts, Hillmansen, & Schmid, 2015) (NS, 2014). When the goal is to reduce the overall energy consumption of train transport it is obvious that the attention is aimed at reducing the energy consumption of the trains themselves.

Trains are usually powered by electric motors in which the power is either supplied by a catenary or a third rail. Less common in the Netherlands are trains powered by an internal combustion engine, which are often diesel-electric or diesel-hydraulic. The efficiency of the electric motor is superior to internal combustion engine. Vehicle is efficiency is a measure of the energy that enters the vehicle is converted into traction at the wheel (Hoffrichter, 2013). In Figure 9 the vehicle efficiencies are displayed for an electric and a diesel-electric locomotive. As is clear, a diesel-electric train less than half as efficient as an electric train.

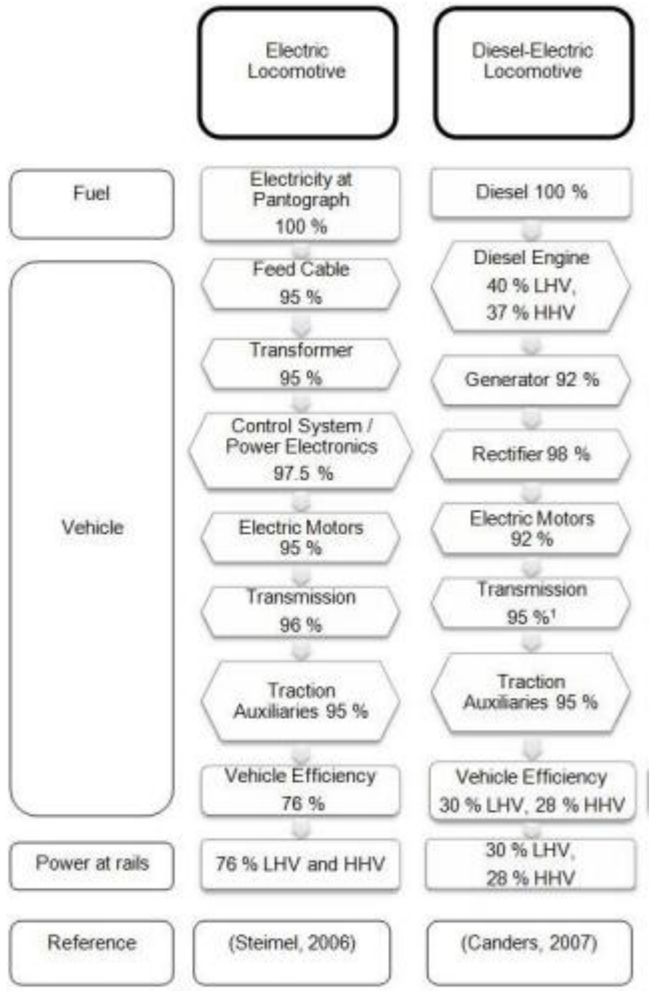


Figure 9 - Vehicle Efficiencies Electric vs. Diesel-electric Trains (Hoffrichter, 2013)

In the Netherlands most of the rail network is equipped with an 1800 Volts DC-current catenary, not surprisingly, most of the trains are electrically powered. Most lines that are not equipped with a catenary are operated by regional operators such as Arriva and Veolia. The operator of the main lines, Nederlandse Spoorwegen (NS), only has two lines within their concession that are operated by diesel-electric trains: Zwolle-Enschede and Zwolle Kampen, both concessions are handed over to regional operator Syntus, which means that the trains that are operated by NS are solely electric-powered in the near future. Since diesel-electric trains are not Diesel-powered trains are not used within the research area, diesel trains are not further discussed.

Apart from the energy consumed by the traction system of a train, from which the efficiency is displayed in Figure 9, passenger trains consume a further 15-20 percent of the energy that is coming in through the pantograph on auxiliary systems from which the most important is the climate system (Gielesen, 2012) (Douglas, Roberts, Hillmansen, & Schmid, 2015). When these auxiliaries are taken into account the energy consumption of the different components of the energy consumption of electric trains look like the division displayed in Figure 10

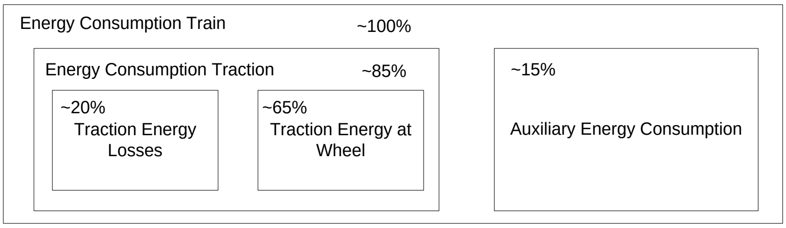


Figure 10 - Energy consumption of Train, Traction and Auxiliary components

2.1.2. Train Dynamics

A train is subjected to numerous forces. These forces van be divided into tractive forces and resistive forces. The tractive force which are determined by the power output of the train must overcome the resistive forces working against the tractive force in order to accelerate. When the resistive forces are smaller than the tractive force the train accelerates, when the resistive forces are greater than the tractive force the train decelerates. The rate of acceleration is described by Newton's second law of motion:

$\sum F = m * a$ or $a = \frac{\sum F}{m}$

The forces working against the movement of a train can be divided into speed dependent and speed independent resistances. The speed dependent resistances, such as air resistance are not constant, but increase quadratic to the speed of the train. Speed independent resistances, such as rolling resistance are constant over speed. The relations of tractive force of the engine, train mass, resistive force with respect to speed and acceleration are described in Figure 11.

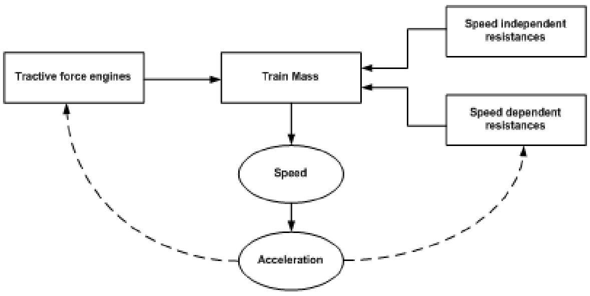


Figure 11 - Relations forces and mass to speed and acceleration. (Gijssen & van den Brink, 2002) - Edited

In Figure 12 a tractive force curve for an electric train is displayed. The tractive force of a train is limited by numerous factors, each of these factors become dominant at a certain speed.

The rate in which a train can initially accelerate is limited by the adhesion limit as long as the adhesion limit is lower a trains maximum tractive force. Due to a limited contact surface between the wheels of the train and the rail and low adhesion between the steel wheel and the steel rail, the adhesion limit for trains is generally low, compared to for instance cars. Exceeding the adhesion limit will result in slipping the wheels. The adhesion limit is described by Coulomb:

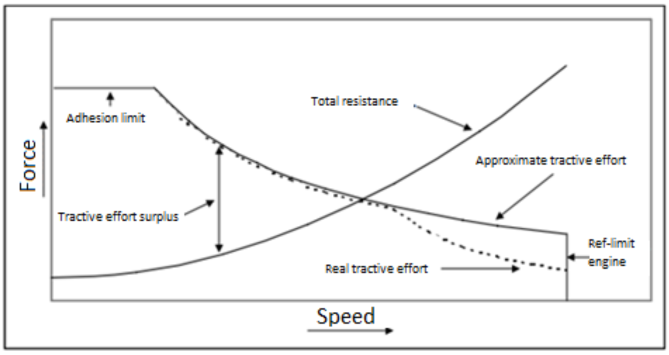


Figure 12 - Tractive effort and Resistances on a train

$F_{ad} \leq \mu * m_{tra}$

where:

$F_{ad} = Adhesion\ force$

$\mu = Friction\ coefficient$

$m_{tra} = Train\ mass\ on\ powered\ axles$

This formula indicates that the more mass is on the axles, the higher the Adhesion limit will be. This is one of the reasons the Nederlandse Spoorwegen are phasing out locomotive-hauled trains, self-powered carriage's or EMU's (Electric Multiple Units) (Scheepmaker, 2013). These trains have more powered axles, which means that a large proportion of the trains mass is over these axles, resulting in a large adhesion limit en therefore ensures better acceleration. The adhesion is also an important factor in bad weather conditions. Rain for instance lowers the friction coefficient, which means that trains tend to slip earlier when the rails are wet. To prevent the train from slipping the acceleration is limited which can make the running times in the timetable harder to achieve.

The tractive force of an electric train is at its maximum at the acceleration from a standstill up to the moment when the train reaches its maximum power. Then the traction force curve follows a hyperbolic line all the way to its maximum speed, which is theoretically determined by the ref-limiter. The ref-limiter prevents the rotating parts in the engine from spinning to fast. Resistive forces working against the tractive force of the train increase with speed. At some point either the sum of resistive forces will equal the tractive effort of the train or the train will reach the ref-limiter. In both situations the train has reached its maximum speed.

The resistances working on a train are generally divided in two types: Train resistance and infrastructure resistance. Train resistance is the sum of resistances working on the train because of movement. Track resistance is the sum of resistances imposed by the infrastructure, such as resistance due to gradients, curves or tunnels. The sum of train resistance and track resistance equal the total resistance that has to be overcome by the train in order to move, the resulting force is described by

$$\sum F = F_{Traction} - (F_{Train\ resistance} + F_{Track\ resistance})$$

Train resistance

Train resistance is the resistance that work on the train because of movement. A general formula is (Brünger & Dahlhaus, 2008):

$$F_{Train\ Resistance}(v) = r_0 + r_1 * v + r_2 * v^2$$

It consists of a constant r_0 which describes the rolling resistance from the contact between the wheel and the rail. The component with a lineair relation to the speed; $r_1 * v$ is the resistance from the rotating components of the train, parts that are responsible for transferring forces. The last component of the formula is air resistance, which is mulltiplied by the square of the speed. These component for instance contains information about the front surface area of the train.

The formula for $F_{Train\ Resistance}(v)$ is a general formula. Resistance formulas for different trains, for instance freight trans, locomotive hauled passenger trains and multiple units, exist.

In the Netherlands the VPT formula for train resistance is developped. The formula is part of the framework VPT, which stands for 'Vervoer per Trein' (Transportation by Train) and is a program to develop a uniform system used by all departments responsible for planning, traffic control etc. in order to synchronize operations (Agricola, 2009). The parameters are calibrated from empirical data for all different train types operating in the Netherlands. The formula is as follows (Van Gigch & Kouyzer, 1996):

$$F_{Train\ Resistance} = (A + N * B) * (V + \Delta V)^2 + M * (C + D * V) + N * E(V + \Delta V)$$

where:

$A = Head - tail\ air\ resistance$

$B = length\ dependent\ air\ resistance(\frac{N}{m/s^2})$

$C = Speed\ independent\ rolling\ resistance\ \left(\frac{N}{kg}\right)$

$D = Speed\ dependent\ rolling\ resistance\ (\frac{N}{kg*m/s})$

$E = Internal\ air\ resistance$

$N = Number\ of\ carriages\ (-)$

$M = Train\ mass\ (kg)$

$V = Train\ speed\ \left(\frac{m}{s}\right)$

$\Delta V = wind\ speed\ \left(\frac{m}{s}\right)$

In the formula the components from the general resistance formula are clearly visible. Notable is the adition of wind speed within the VPT formula. Since the train resistance heavily depends on air resistance, the resistance increases with the square of the speed, wind can have a significant influence, because air resistance becomed dominant at high speeds because of the quadratical relation. For the wind component, often a 10 km/h headwind is assumed. By taking wind into consideration at the calculation of running times, trains can manage to achieve these running times in case of a moderate head wind (Scheepmaker, 2013).

Track Resistance

Track resistance is the resistance imposed by the infrastructure. It concerns resistance due to gradients, curves and tunnels. Both curve resistance and tunnel resistance are often ignored in calculations. The curve resistance, which is the results of the flange of the wheel hitting the rail and thereby increasing resistance is relatively low compared to the resistance of gradients and therefore ignored (Brünger & Dahlhaus, 2008). Tunnel resistances are often ignored because of the lack of general formulae that describe this resistance (Scheepmaker, 2013).

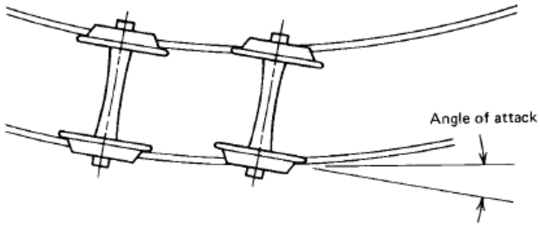


Figure 13 - Curve resistance (Barkan, 2009)

The resistance due to a gradient can be described by the formula (Huerlimann & Nash, 2010):

$F_{slope} = m * g * \sin(\alpha)$

For small gradients there is a different formula (Huerlimann & Nash, 2010):

$F_{slope} = m * g * \tan(\alpha) \approx \mathrm{m} * \mathrm{g} * \frac{\mathrm{I}}{1000}$

$F_{slope} = Gradient\ Resistance\ (N)$

$m = Train\ mass(kg)$

$G = gravitational\ accelerarion\ in\ m/s^2$

$\alpha = Gradient\ (rad.\ or\ degrees)$

$I = Gradient\ (‰)$

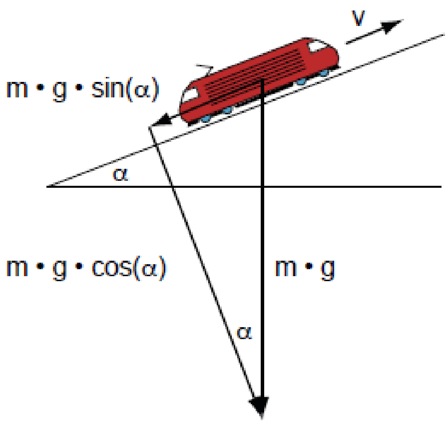


Figure 14 - Gradient resistance (Huerlimann & Nash, 2010)

Although it is often assumed that the Netherlands is a flat country, and gradients are therefore ignored, it is an important resistance. Especially for heavy freight trains the resistance of gradients is noticeable. Because of their weight and relatively high air resistance the resistance curve meets the traction force curve at a relatively low speed, see Figure 12. Which means a freight train often operates near the trains' limit in order to run at a decent speed. This means there isn't any, or little tractive effort surplus, which means they can lose a considerable amount of speed when reaching an incline. Passenger trains often have a large tractive effort surplus. When it is on an incline the train driver can simply apply more traction to maintain its speed. For passenger trains a gradient can be of great influence when energy efficient train control is applied. When a train is coasting and no traction is applied it loses a relatively large amount of speed when driving on an incline, compared to coasting on a flat section of track.

Functions used in the simulations

In the Netherlands the data containing the characteristics of different train types is based on VPT as is explained earlier. The simulation software OpenTrack is however not able to cope with the VPT formula directly. OpenTrack uses the Davis formula, which is described by (Trani, N.Y.):

$$F_{Resistance} = A + Bv + Cv^2$$

The parameter values from VPT are recalculated for the Davis parameters A, B and C are by an excel sheet. The simulation model in this research does not include curve resistance or tunnel resistance. These data are not available. As is mentioned for tunnel resistance no general formulae are available. The influence of curve resistance is small compared to the influence of gradients. The simulation model does contain gradients. A train database is available for all train types that generally operate on the Dutch railway network. This contains information contains the traction curves and the resistances curves based on the Davis equation based on VPT input.

Implications of choosing a resistance function

As is mentioned, many different formulas are available for describing a trains resistance. As is often the case it cannot be said that one formula is the right one to pick. All functions are simplifications of the real resistance, so the outcomes come with some level of uncertainty. Some are more suitable for certain trains than others etc. Ultimately the resistance calculations together with the tractive force of the train determine the tractive effort surplus, which describes at what rate a train can accelerate. This mean that the choice of a resistance function can have

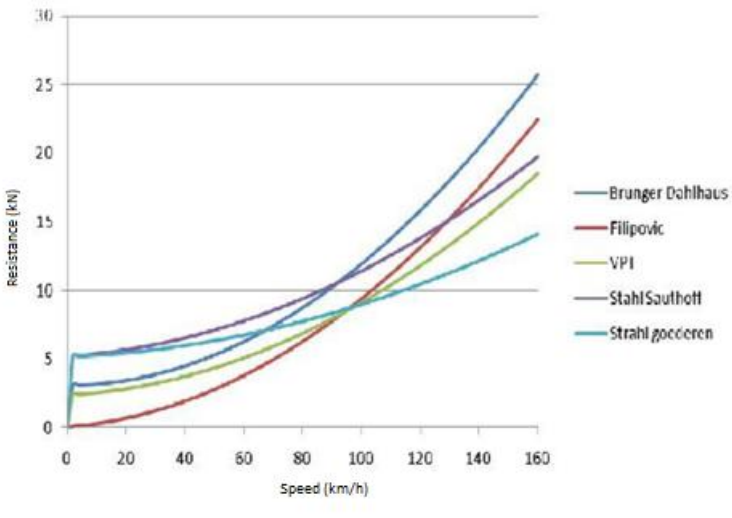


Figure 15 - Speed time relation for different resistance functions (Agricola, 2009)

implications for the running time calculations, but also on the energy consumption. Especially in a coasting regime, because when no traction is applied the rate of deceleration is determined by the resistances only. Overestimating the resistance results in a train losing speed at a higher rate than in reality and underestimating the resistance and the train will lose speed at a lower rate than in reality. In (Agricola, 2009) the effects of different resistances functions on the running time are calculated for a passenger train running on a flat piece of test track. In Figure 15 the relation between the calculated resistance to the speed is displayed. It can be seen that the different formulas do in fact have a great influence on the resistance. In Figure 16 however, it can be seen that this has very little influence on the calculated travel time. It is assumed that the difference is caused by a relatively high tractive effort surplus passenger trains generally have (Agricola, 2009), which mean that passenger trains can cope with resistance relatively easy.

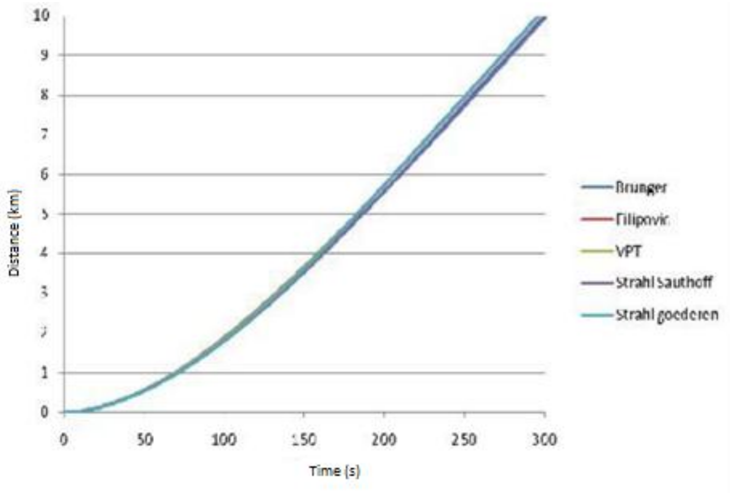


Figure 16 - Distance time relation for different resistance functions (Agricola, 2009)

2.1.3. Energy Flows

A typical speed profile speed profile consists of three phases, also called regimes. Acceleration, Cruising (maintaining a constant speed) and Braking. In energy efficient train control a coasting phase is added in which the traction is set to idle and the train gradually decelerates under the influence of resistive and gravitational forces.

The four phases in a speed profile (Albrecht, 2008):

- Acceleration: Acceleration to a desired or maximum allowed speed.
- Cruising: Maintaining the speed to which is accelerated to
- Coasting: No traction appliance, train decreases speed due to resistive and gravitational forces.
- Braking: Brakes are applied

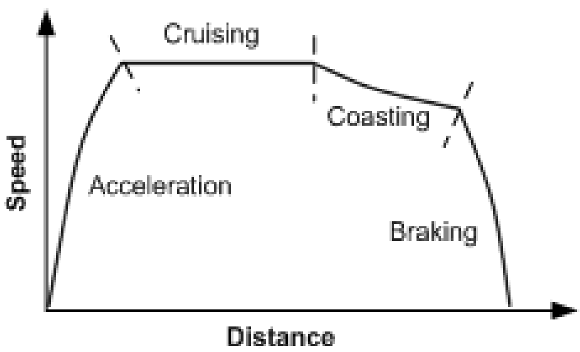


Figure 17 - Four regimes speed profile (Albrecht, 2008)

The law of conservation of energy states that all energy in an isolated system maintains constant. It cannot be created or destroyed, but can only be converted into another state (Guillen, 1999). This means that all energy that is used to move a train over a network is lost somewhere in the journey. Energy is a measure of effort delivered by a power source when moving a mass over a distance. Energy is measured in Joules, but often when it concerns electricity in kilo watt hours (kWh).

In Figure 18 the energy flows involved in train movement are described. In the following it is described how these energy flows are related to the regimes in the speed profile described in Figure 17. In the acceleration regime, the energy from the source, which enters the train via the catenary and the pantograph, is send to the electric motors that power the train. The engine is not 100% efficient, which means that some of the energy coming in is lost. These are the traction losses. During acceleration the train builds op speed and with that kinetic energy. Kinetic energy is the energy an objects possesses due to its motion. Kinetic energy is build op until the moment the acceleration regime is ended and the cruising regime starts. In the cruising regime the speed is maintained, which means that kinetic energy remains constant. In both the acceleration and cruising regime, the engine is delivering power to overcome the resistive forces. So in order to gain or maintain kinetic energy, energy is put in. The effort put in to overcome resistance are resistive losses. Resistive losses are found in every regime, since it is inherent to having speed. In the coasting phase the traction is switched off. The train decelerates due to resistive forces and 'trades' the kinetic energy it has build up for resistive losses. Due to the low resistive forces on a train this process is relatively slow, which means that a train is capable of coasting a relatively large distance for a small decrease in speed. In the braking regime a brake is applied in order to slow the train down. In the process the remaining kinetic energy is converted into a braking loss, which is often mostly heat.

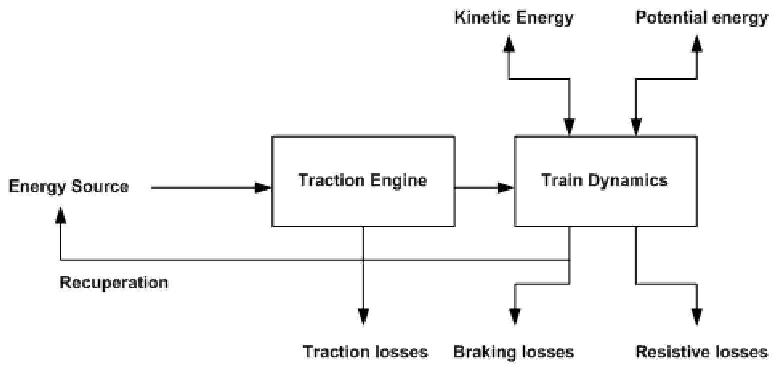


Figure 18 - Energy flows in train movement (Howlett, Milroy, & Pudney, 1994) - Edited

Modern trains are capable of recuperation of braking energy, the motors of the train act as generators. Through the pantograph recuperated energy is delivered back to the catenary. Depending on the current and type of current (AC or DC) it is in some cases possible to transfer the energy back to the main grid. In the Netherlands the efficiency of recuperation is low, because of the low voltage (1800V) DC current. This means that the recuperated energy cannot be fed back to the grid but can only be used by a train in the near vicinity. Approximately only 10% of the recuperated energy can be usefully used (Van Weert, 2014).Recuperation is not part of this research, because it seen as a different strategy. This research only assesses the effects of energy efficient train control, although interaction effects exist: Combining energy efficient train control with recuperation reduces the potential of recuperation, since less braking effort is needed after the coasting regime.

The last element in Figure 18 is potential energy. Potential energy is the energy that is stored because of having height. Energy has been put into the system to gain height and is stored until it is released again when the train is going downhill.

2.1.4. Energy Efficient Train Control Srategy

In Energy efficient train control the slack times that are incorporated in the timetable are used to drive energy efficient. Slack times are running time reserves which are added to the technical minimum running time to be able to make up for delays or in case of unfavorable circumstances, such as bad weather, to still be able to make the running time in the timetable. When a train is not delayed and the circumstances are good, the train driver can use the slack time to drive more energy efficient. Energy efficient train control is a trade-off between energy savings and a longer running time (Douglas, Roberts, Hillmansen, & Schmid, 2015).

There are numerous methods to consume the slack time, but not all of them are energy efficient. Four general methods can be distinguished

- Coasting: Setting the traction to idle well in advance of speed restriction. The train will slowly decelerate due to the resistive and gravitational forces. The biggest speed reduction is a stop at a station. Speed restrictions are also found along a railway line where the permissible line speed is lowered. Coasting reduces the energy consumption by lowering the braking losses.
- Accelerating at lower rate: Accelerate at a certain fraction of the maximum power of the train. In this situation it will take longer to reach the permissible line speed.
- Maintain a cruising speed lower than the maximum permissible line speed.
- Braking at lower rate: Braking at lower force than the maximum comfortable braking force.

The optimal strategy for reducing energy consumption is a acceleration-cruise-coast-brake strategy, unless the track contains gradients in which the cruising must me interrupted by appliance of more power for inclines and coasting or even braking for downhill sections (Albrecht, Howlett, Pudney, & Vu, 2013). To determine the differences in energy consumption with respect to the strategies for consuming the slack time. A simple calculation is made for a section of test track, with a rolling and air resistance. The following train, track and timetable characteristics are used. The train characteristics are derived from (Scheepmaker, 2013).

Train characteristics

Train	SLT-6	
Train mass	198300	kg
Maximum power output	1260000	W
Maximum tractive force	170000	N
Rolling resistance	0,0162	N/kg
Air resistance	3,140958	N/(m/s2)

Table 2 - Train characteristics energy efficiency strategies

Track characteristics

Maximum permissible speed	140	km/h
Length	20	km
Gradient	0	%

Table 3 - Track characteristics energy efficiency strategies

Timetable characteristics

Technical minimum running time (calculated)	577	sec
Slack time proportion	0,05	-
Slack time	29	sec

Table 4 - Timetable characteristics energy efficiency strategies

The results of the calculations are displayed in Table 5. The strategies are compared to a strategy in which the slack time is not consumed, the time-optimal strategy. In this strategy a train accelerates at the maximum rate, cruises at the maximum permissible speed and brakes at the last moment at the maximum comfortable rate.

Strategy	Energy Consumption (kWh)	Energy savings(%)	Braking losses(kWh)	Resistance losses(kWh)
Time-optimal	83,0	-	41,7	41,3
Coasting	64,8	**-21,9**	25,7	39,1
Accelerating at lower rate	81,7	**-1,6**	41,7	40,0
Maintain a lower maximum speed	75,3	**-9,3**	36,5	38,8
Braking at lower rate	81,3	**-2,0**	41,7	39,5

Table 5 - Energy consumption for different strategies consuming the slack time

The calculation confirms that the strategy with a coasting regime is the most efficient strategy, because it significantly reduces the braking losses as can be seen in Table 5. The second best strategy maintaining a lower maximum speed. This also decreases the braking losses albeit less than in the coasting strategy. The resistance losses are about equal for all strategies. Slowly accelerating has almost no effect on the energy consumption at all; per time unit energy is saved when accelerating more slowly, but the acceleration phase takes longer, so in the end only a fraction of energy is saved, because of a lower resistance loss due to a lower average speed compared to a time optimal profile. Braking at a lower rate results in a marginal lower resistance loss for the same reason.

Summarized the energy efficient train control strategy should contain the regimes acceleration, cruising, coasting and braking regime that are defined by (Howlett, Milroy, & Pudney, 1994)**:**

- **Acceleration: Maximum tractive acceleration**
- **Cruising: Tractive acceleration = resistive acceleration**
- **Coasting: Tractive acceleration = 0**
- **Braking: Maximum braking,**

2.1.5. Slack time in the timetable planning process

Every year in December a new timetable is introduced in the Netherlands. Well before the introduction the planners of infrastructure operator ProRail start with the construction of the timetable. This paragraph briefly describes this process. Particularly important is the way in which the slack times are incorporated in the timetable. The timetable for each single train as well as for the whole system influences energy consumption. For a single train the size and distribution of slack times are the main factors determining the potential for energy savings (Albrecht, 2008).

Roughly the following steps are taken in the design process of a new timetable. (Prorail, 2014)

1. Train operators hand in a request for capacity about one year prior to the date the new timetable is effectuated, mentioning the requested services and train type that will be used to run the service
2. The technical minimum running times are calculated by planning tool DONNA for the requested paths. The technical minimum running time is the shortest possible time between two station, given the characteristics of the network and the train.
3. 5% slack time is added to the technical minimum running time.
4. Running times (including slack times) are rounded to full minutes. Rounded up for larger stations and rounded down for smaller stations. Especially at short inter stop distances between stations where the slack time is round down, this could cause the slack time disappears completely or even be negative (Luijt, 2015).
5. Generation of a feasible timetable by DONNA based on the running times including 5% slack time and a set of timetabling rules for sequential and crossover train movements and dwell times.
6. Planners manually add or remove running time for sections of track to resolve conflicts. Conflicts are the result of interaction between trains having to share a common piece of infrastructure at the same time. Conflicts mostly occur on the nodes of the network, because at these locations different corridors and train flows come together. A conflict is often solved by adding running time to one of the conflicting trains. Note that in this case the conflict is only solved when the conflicting train with added running time achieves the running time specified. If it does not follow the speed profile complying with the running time the conflict still arises.

The result of the timetabling process are basic-hour patterns (BUP - BasisUurPatroon). These are time-distance diagrams with a length of one hour containing all trains on the corridor including paths reserved for freight trains. Three different basic-hour patterns are developed; for the morning peak hours, evening peak hours and off-peak hours. A basic hour pattern is an example of a cyclic timetable. A cyclic timetable is repeated every hour (Peeters, 2003). Having a cyclic timetable is beneficial to the passengers, because they only have to remember at which minute a train departs instead of a specific time.

Contrary to passenger train operators, freight train operators request capacity shortly in advance. Because of the great intensity of train traffic on the Dutch network, it is not possible to plan a path for a freight train ad-hoc. For this reason ProRail does reserve capacity for the most common freight corridors in the basic-hour patterns, planned with a long heavy train composition. No slack time is added to the running time of freight paths, because in most cases the actual train has a lower mass than the planned train, which means the actual train does have a running time reserve, because it is able to run faster than the planned profile.

The basic-hour pattern is mainly used for planning processes, the actual timetable used on a specific day is described in a so called 'Dagplan' or timetable of the day. This is in essence a basic-hour pattern in which the freight paths are filled in by the actual freight trains and a number of passenger services are taken out of the plan. For passenger services the timetable of the day especially differs from the basic-hour patterns in the weekends, because the intensity of passenger services is generally lower in weekends compared to weekdays.

As mentioned before, the size and distribution are important for the energy saving potential of a timetable. Unequal distribution of slack time(e.g. putting the majority before the critical situation and removing it from the other sections of the network) may lead lower energy savings compared to an almost equal distribution of slack time (Albrecht, 2008) (Scheepmaker, 2013), because coasting is more efficient at a higher speed. Saving energy implies reducing brake losses (see the previous paragraph). Because all kinetic energy is lost at braking, the most effective strategy is to convert as much kinetic energy into movement (e.g. coasting) as possible in order to not lose it to braking. From the equation for kinetic energy $E_k = \frac{1}{2}mv^2$ it can be seen that at higher speeds more kinetic energy is converted. From an energy efficiency point of view it makes more sense to distribute the slack evenly (in many small portions) than concentrate it (in one large portion).

In Figure 19 the distribution of slack time for the timetable of 2013 is displayed. It can be seen that the slack time is highly dispersed. The average slack time is about 11%. The majority is concentrated around the node stations, whereas the slack time on arrival at stations on along the free track are relatively low or even negative.

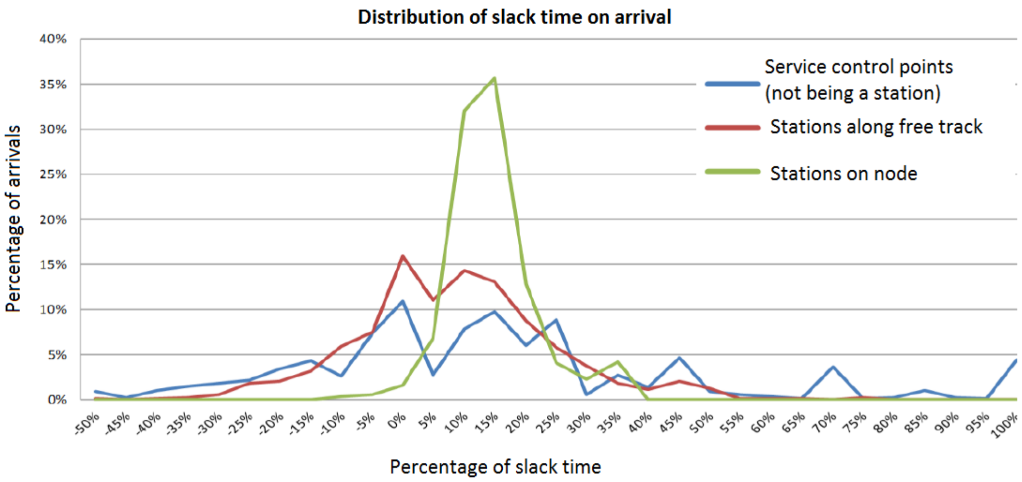


Figure 19 - Distribution of slack times (Van Weert, 2014)

The slack times are not evenly distributed because energy efficiency is not a priority in the timetable design process. Safety and punctuality have priority over energy efficiency (Scheepmaker, 2013). Safety is ensured by minimizing the conflicts in the timetable and ensuring a save time-distance between train movements. The concentration of slack near the nodes in the network serves a punctuality purpose.

The total slack time for a station to station section of track is the difference between the running time described by the timetable (this is the running time that contains all reserves) and the technical minimum running time:

$$\boldsymbol{Total\ slack\ time = Running\ time\ timetable - Technical\ minimum\ running\ time}$$

In Figure 20 the relation between slack time and the planning process is described.

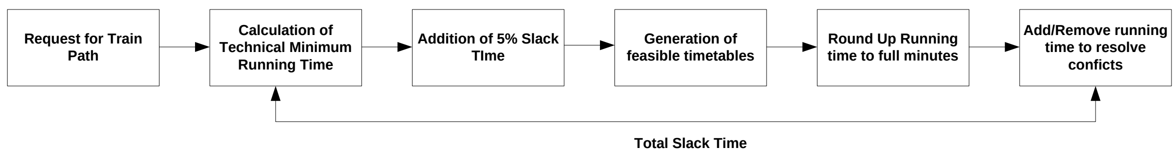


Figure 20 - Slack time in relation to the planning process

2.1.6. Driver Advisory Systems

Energy efficient train control is not the primary task of a train driver. Safety and punctuality are more important (Scheepmaker, 2013). A train operates within a highly dynamic environment in which other trains are present. The driver has to constantly adapt his control strategy (traction, coasting, braking) in order to move safely and punctual through the network. This is described in the driver control loop

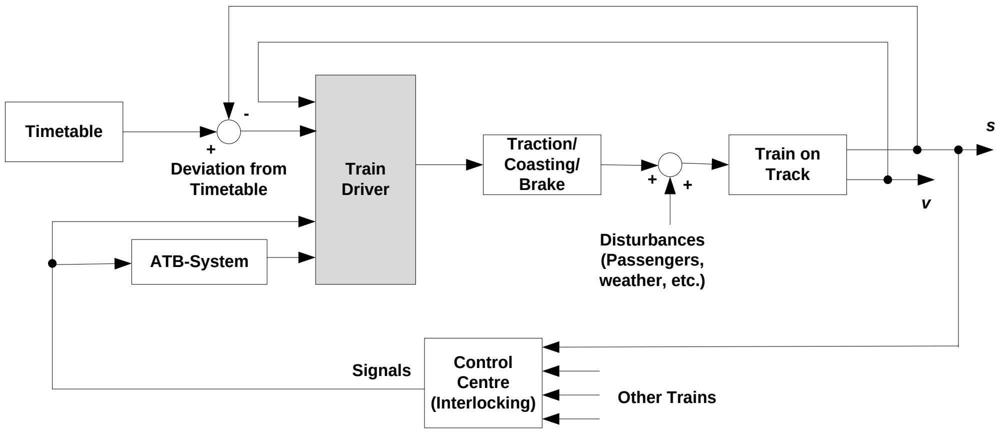


Figure 21 - Train driver control loop (Albrecht, 2008) - edited

Only when a train is punctual the train driver can execute energy efficient train control. Also only when a train is punctual, the driver will have slack time to coast as long as slack time is incorporated in the timetable. In delayed condition there will be no slack time available and so the train driver will apply a time optimal strategy by driving as quickly as possible (Albrecht, 2008).

Energy efficient train is difficult to execute well without any assistance. Without assistance a train driver can only rely on his craftsmanship and route knowledge to know whether there is slack time available at a specific location that can be utilized to drive more energy efficient.

To assist train drivers in driving energy efficient and increase the energy savings numerous Driver Advisory Systems (or DAS) have been developed over time. The earliest methods were all based on a static advice, e.g. universal approaches to drive more energy efficient or approaches based on the slack time that is planned in the timetable. The more modern DAS are dynamic and make use of GPS to determine a trains actual position in space and time in relation to the timetable and provides a tailor-made advice to the train driver how to drive most efficient. The maximum efficiency is reached when the train consumes all the slack time available and therefore arrives exactly at the planned arrival time at the next station (Luijt, 2015).

Al assistance discussed above have in common that the optimization level is train based, which means that the strategy is optimized on the train-level. This not necessarily lead to an optimal solution for the entire system. A train network is a highly dynamic system. A train based DAS cannot foresee conflicts and optimize the strategy to the train driver accordingly, because it doesn't know the position of other trains in the network. C-DAS (Connected DAS) can optimize the advices for the entire network by sending the position of the train to a background system in which the position of all trains is known, an network wide optimal solution is calculated and send back to the trains.

The current level of development in the Netherlands is train based DAS. Currently experiments

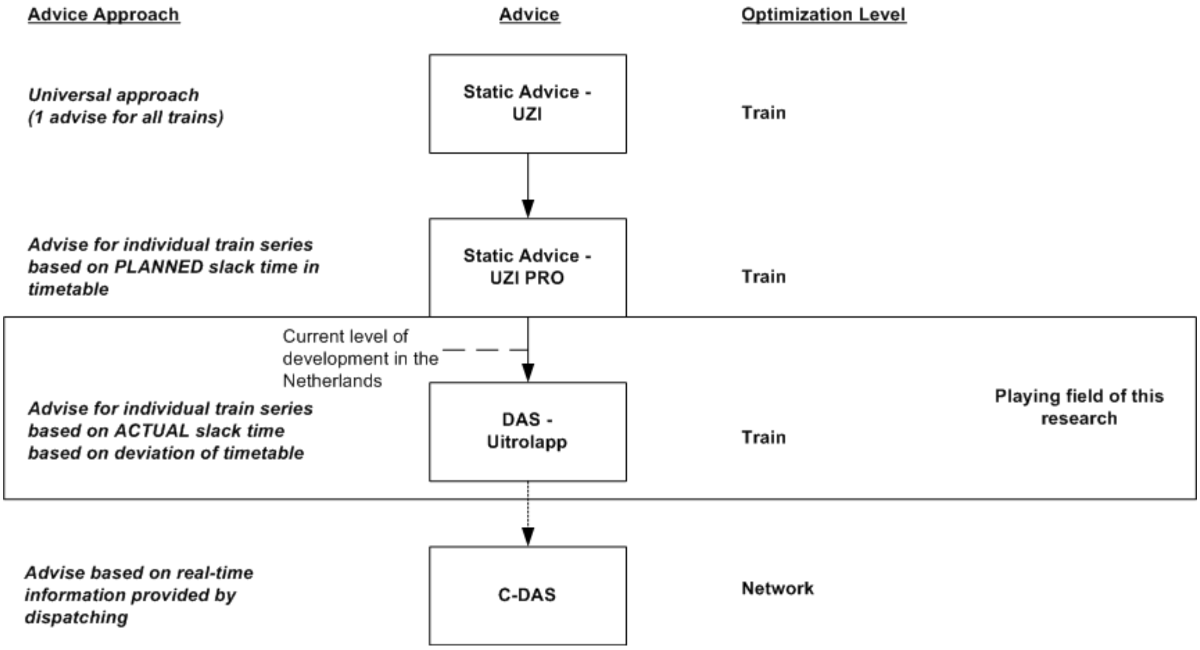


Figure 22 - Different DAS systems in the Netherlands and current level of development

with a small group of train drivers are held. These train drivers use the 'Uitrolapp' or coasting app on their mobile phone. The application calculates the position of the train through the phones GPS receiver with respect to a successful energy efficient speed profile from empirical data.

C-DAS is not planned to be developed for the Dutch rail network in the near future (Luijt R. , 2016) This is probably because energy efficient train control is not considered a priority. The potential extra savings are large which is broadly recognized in literature (Douglas, Roberts, Hillmansen, & Schmid, 2015), (Albrecht, Howlett, Pudney, & Vu, 2013) (Albrecht, 2008). The playing field of this research is train based DAS.

Two earlier Drives Assistance Systems in the Netherlands are UZI basis and UZI pro. Both are examples of train-based static DAS. Examples are presented in Appendix A.

2.2. Punctuality and conflicts

In the Netherlands trains are planned according to a cyclic timetable. A combination of basic hour patterns for peak and off-peak hours form the timetable for the entire day. Although the plan is mostly free of conflicts, deviations from the plan cause delays in the system. Delays can be caused by numerous factors, factors within the train system, but also factors from outside, weather accidents etc. Delays are present in every railway network (Juan, 2008).

To measure delays, punctuality is an often used performance indicator. Punctuality is often defined as the percentage of trains that arrive on a station within a certain margin of delay for which the arrival of a train is considered on-time. The European standard is a 5-minute margin. In the Netherlands also a 3-minute margin is used. Using the 3-or 5 minute norm for punctuality has a few disadvantages (Hansen, 2001):

- Trains with a large delay are considered as worse as trains with a relatively small delay (larger than the margin)
- Delays smaller than 3 or 5 minutes are not measured, it are often these delays that cause passengers to miss connections at the transfer station.

Because of the last reason a 3 or 5 minute margin alone, are not sufficient to describe punctuality adequately. In order to gain a full understanding of the punctuality of a rail network it is necessary to measure the full distribution of arrival delays including calculations on the mean and dispersion (Juan, 2008). Delay can be measured relative to both planned arrival times and departure times. Arrival delays can be negative and positive. Negative delays indicate that a train is early, positive delays indicate that a train is late. The departure delays are nearly always positive. Apart for smaller stations trains have to await the planned departure time.

Regarding the cause of delays, two types of delays can be distinguished: Primary and secondary delays. A secondary delay is a delay that is passed on by another train because of a conflict. Delays that are not the result of a conflict are primary delays (Weeda, Wiggenraad, & Hofstra, 2006). Primary delays can be modeled by distribution functions which are preferably fitted to empirical data (Juan, 2008). In this research primary delays are modeled by distributions for dwell time and initial delay. Initially primary delays only affect the train concerned. Since a primary delay causes a deviation from the planned timetable, the delay can be transferred to the following train. Primary delay is transferred to the following train when the blocking windows overlap A blocking window is a section of infrastructure that is held occupied by a train for a certain length of time. A delay can cause the blocking windows of the train concerned to move into and over the blocking window of the second train, this is illustrated in Figure 23. The result is a conflict. In a conflict a braking action is enforced to the following train. The leading train is unaffected, but the second train does receive (part of) the delay of the first train. This is illustrated in Figure 24. The timetable allows for some deviation from the plan without hindering the following train, this is known as buffer time. Buffer time is the time distance between the blocking windows (Weeda, Wiggenraad, & Hofstra, 2006), e.g. the white spaces between displayed in Figure 23 and. Figure 24. The impact of delay propagation largely depend on this buffer time. In networks that are used close to capacity little buffer times are found, which means that slight deviations from the planned timetable will result in a conflict. On less intensively used parts of the network, the buffer times can be large, which allow for relatively large deviations from the plan before a conflict and secondary delay occur. At small buffer times a delay can propagate deeply into the network, because the secondary delay sustained by the following train is again relatively easy transferred to the next train etc. etc.

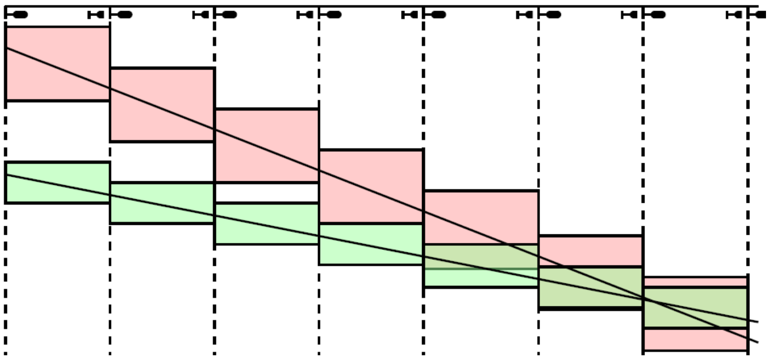


Figure 23 - Overlapping blocking windows (Ummels, 2015)

The result of overlapping blocking windows is that the signaling system enforces the train driver of the following train to stop (Ummels, 2015). This also means that once the conflict has cleared the following train has to accelerate again. This does increase energy consumption. The acceleration regime requires the most input of energy per unit of time.

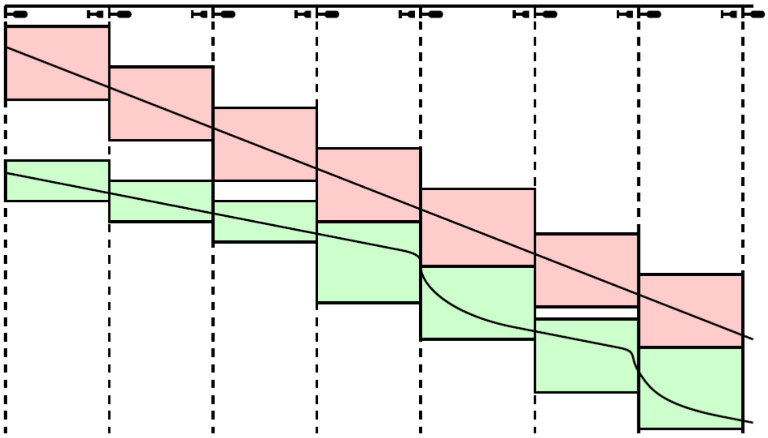


Figure 24 - Signaling system enforces a braking action (Ummels, 2015)

Secondary delays often occur at the nodes in the network, because these are the locations where train flows from different directions meet. Conflicts occur in the same direction of movement, but also in crossing movements. This is illustrated in Figure 25

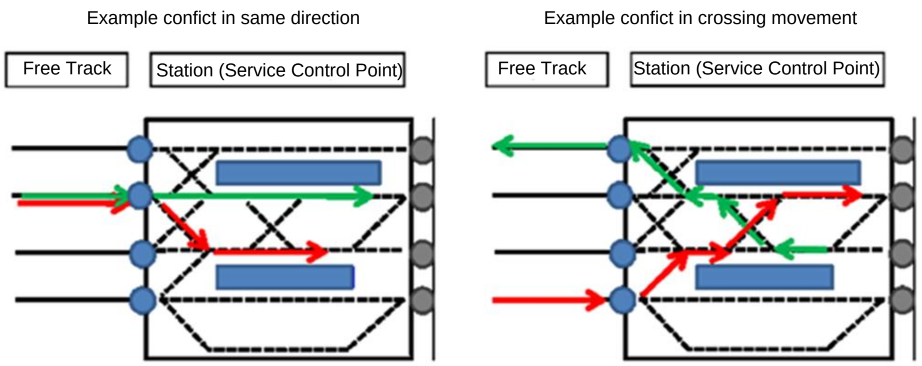


Figure 25 - Conflicts (Prorail, 2014) - Edited

Also without direct interaction between trains, primary delays can lead to secondary delays, for instance when a connection between trains is planned in the timetable (Juan, 2008).

In the Netherlands roughly three signal aspects can be distinguished that require different braking actions:

- A green signal aspect: This indicates that at least the two following blocks are clear, no braking action is required.
- A yellow signal aspect: Indicating that the block 2 blocks ahead can be occupied by another train. The train driver must apply brakes when passing the signal and be prepared to stop at the next signal, which can be red.
- A red signal aspect. Stop before the signal, the next block may be occupied by another train. At a red signal encounter the all kinetic energy is lost to braking (if no recuperation is done), because it requires a full stop.

Red signal encounters do not only cost a substantial amount of energy, they also impose a safety risk. Most accidents between trains are caused by one of the train drivers missing a red signal. Missing a red signal can bring a train into a block that is occupied by another train, with a possible collision as a consequence.

3. Conceptual model and research set-up

In this chapter the research set-up and conceptual model are discussed.

3.1. Research Strategy

The research strategy in this study is an simulation experiment based on a large case study. In an experiment one or more treatment groups are compared to a control group (Verschuren & Doorewaard, 2007). A control group acts as the reference situation (e.g. a null-scenario). For both the control and the treatment groups the magnitudes on a number of dependent variables are calculated. Comparison of the treatment group and the control group gives the effectiveness and efficiency of an the interventions can be measured (Verschuren & Doorewaard, 2007). The experiment conducted is an experiment by simulation. Real world performance of energy efficient train control is very difficult to measure, because the effects of one measure cannot be isolated from other effects influencing the running time of trains. In these cases, simulation is a valuable tool, since it enables the user to examine the effects of one measure by developing scenario's in which only one parameter is changed, in this case the driving control strategy, while all other factors remain constant.

The simulation tool used for the experiments is OpenTrack. OpenTrack is a micro-simulation tool in which both network and trains are programmed to the smallest detail in order to accurately simulate train movements and interaction within a network. OpenTrack is a tool that is capable of synchronous simulation, which means that multiple trains can be loaded to the network at once in order to simulate an actual timetable. Synchronous simulation is an important condition to simulate interaction within a network.

3.2. Scenarios

In this research four scenarios are developed to examine the effects of application of energy efficient train control on the network-level.

In scenario 1 traditional train control simulated by assigning the traditional control strategy to all passenger trains in the network. Traditional train control is regarded as the 'regular' control strategy. The traditional train control follows the following series of regimes: Acceleration, cruising and braking. It does not contain a coasting regime. The regimes are carried out at a certain performance setting. This performance setting is more elaborated on in chapter 4.

In the second scenario all passenger trains within the network are assigned the energy efficient train control. In energy efficient train control follow the strategy that is described in the optimal train control theory: Acceleration at the maximum possible rate, cruising at the maximum permissible line speed, coasting, braking at the maximum possible (comfort) braking rate. To simulate energy efficient train control the coasting points are defined for all passenger trains. The goal is to consume all slack, e.g. arrive at the next station with 0 seconds of delay. Results on energy consumption, punctuality and conflicts are compared to the results for traditional train control (scenario 1). Scenario 1 acts as the control group, scenario 2 as the treatment group. The difference between the scenarios describe the effects of energy efficient train control. With the results, sub-research questions 1,2 and 3 are answered.

In scenario 4 it is examined whether having different control strategies on the network simultaneously affects the energy consumption of either energy efficient train control or traditional train control. Trains on the network are randomly assigned the traditional train control or energy efficient train control strategy to a certain train, 50-50. Both strategies in this scenario are individual treatment groups. The traditional train control trips are compared to scenario 1, the energy efficient train control trips are evaluated relative to scenario 2.

During streamlining of the model in this research it was found that problems in the network often were traced back to freights having to stop at the critical points in the network because of a conflict with another train. Freight trains have two characteristics that can potentially affect the delays in the network: Because of their length they can block multiple corridors when having to stop for a red signal and because of their weight, freight trains gain speed very slowly. Both factors combined, means that freight trains need a fair share of the capacity of the network. In order to find if freight trains limit the energy saving potential of energy efficient train control, a fourth scenario is created in which the freight trains are left out the equation. This scenario is equal to scenario 2, except for that the freight trains are taken out of the timetable. The results are measured relative to scenario 2. This is not a realistic scenario, because freight trains are part of the system, but a difference can be used to emphasize the importance of adequate planning of freight trains in the timetable.

The scenarios are summarized in Figure 26.

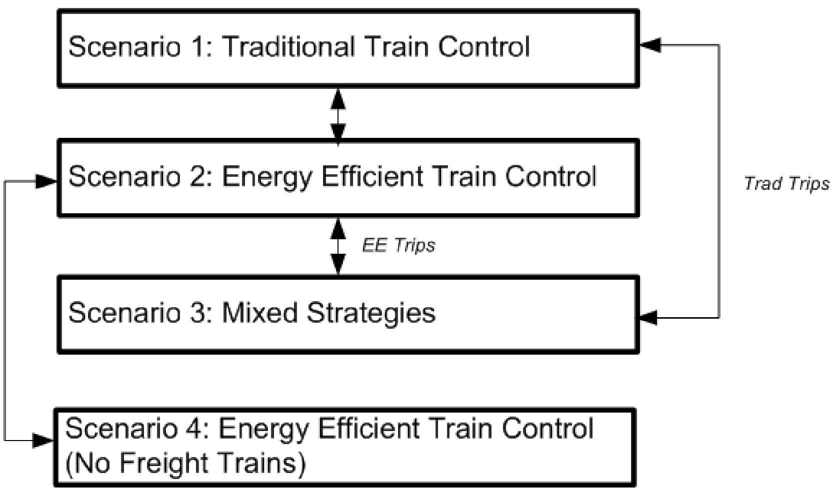


Figure 26 - Scenarios

3.3. Conceptual model

A conceptual model is a descriptive model of a system and its elements and the relations between them. Also it describes the system boundaries (Verschuren & Doorewaard, 2007). The assumptions on relations between the elements are derived from the theory in literature.

In Figure 27 the conceptual model of this research is given. This is further explained in the remainder of this paragraph. The sequence of events in the conceptual model are described from left to right, but the model is essentially constructed from right to left, starting at the goal of the research. The goal in this research is to describe the effects of energy efficient train control in the Netherlands on the network level with respect to the energy consumption, punctuality and conflicts. Although the conceptual-model is constructed from right to left it is discussed from left to right.

In energy efficient train control, the slack times are incorporated in the timetable, are used to coast. The maximum savings are achieved when the slack time is fully consumed. The saving potential, largely depends on the magnitude and distribution of the slack time. The magnitude is found by comparing the technical minimum running time to the running time that is derived from the departure and arrival times in the timetable. The technical minimum running time is the shortest possible running time between two stations. The technical minimum running time is determined by network and train characteristics, it is found at the maximum of the trains performance given the infrastructure. The magnitude of the slack time is in essence found by measuring the size of the negative arrival delay at the station at the maximum performance level.

From the resulting slack time a speed profile for energy efficient train control can be constructed. By defining the coasting point. The coasting point should be situated at the location at which the train will arrive exactly on the planned arrival time on the next station to consume the full slack time available. The result is an energy efficient train control profile. Both the slack time calculation and creation of profiles is done in a deterministic simulation environment (software OpenTrack). By constructing the profiles for the entire set of trains in the network, energy efficient train control is modeled. The traditional train control strategy does not contain a coasting regime, but are defined to run at a certain level of performance.

Trains are part of a dynamic environment, the network. Within a network other trains are running with certain delays. Within the network trains interact because of the deviations from the timetable. At the start of a journey, at the departure station a train can sustain an initial delay. Initial delay is an example of a primary delay and can have numerous causes (for example the train driver arriving late). The initial delay is a delay relative to the planned departure time. The delay can be positive, but in general not negative, because trains have to await the departure time. This means that the maximum slack time available on a section of the track is fixed. The size of the departure delay initially determines whether or not any slack time is available for coasting in the energy efficient train control strategy.

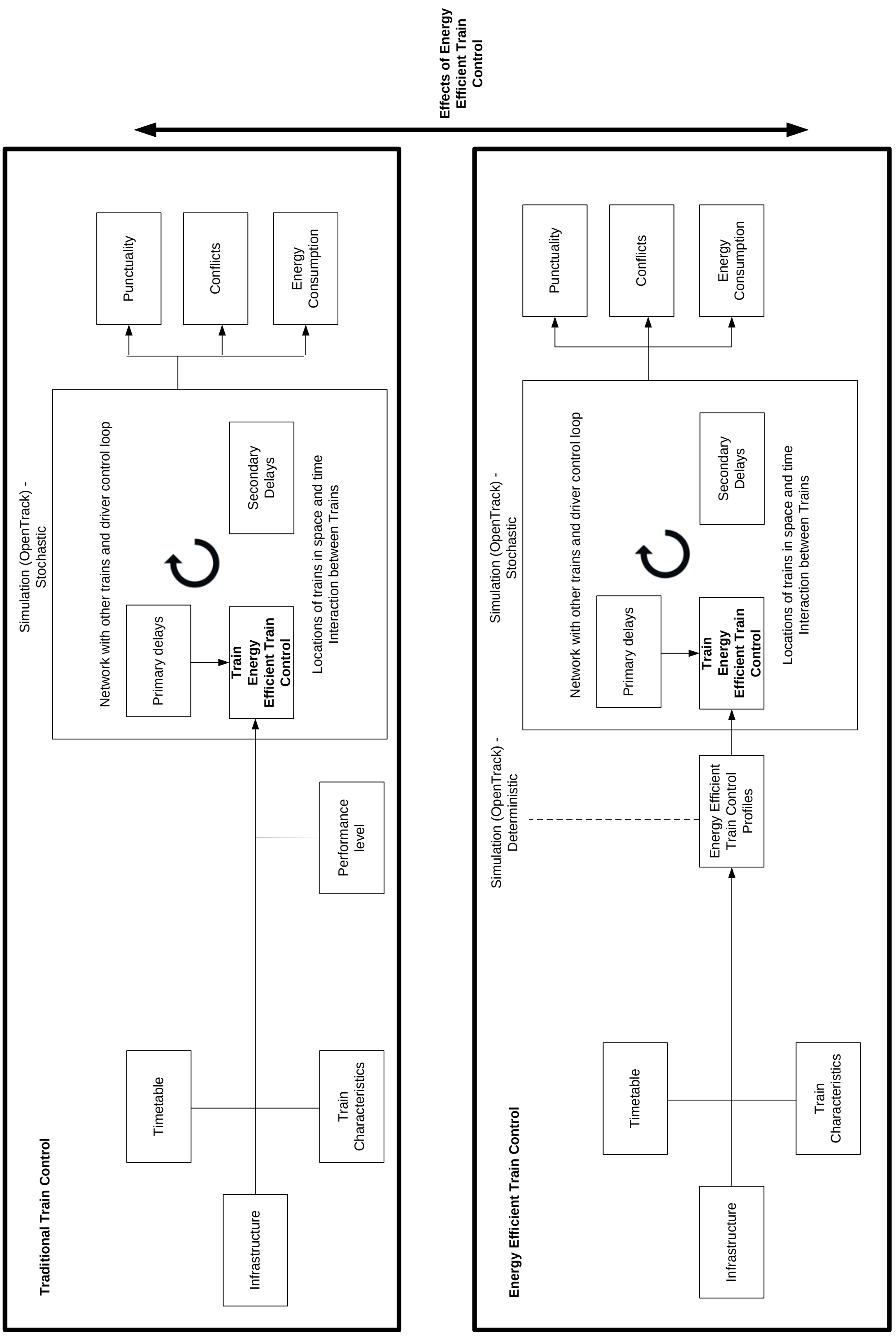


Figure 27 - Conceptual model

Now the train enters the network and becomes part of the dynamic environment. In this environment the train driver will adapt the strategy to the situation (traction, coasting, braking) . This is described in the driver control loop.

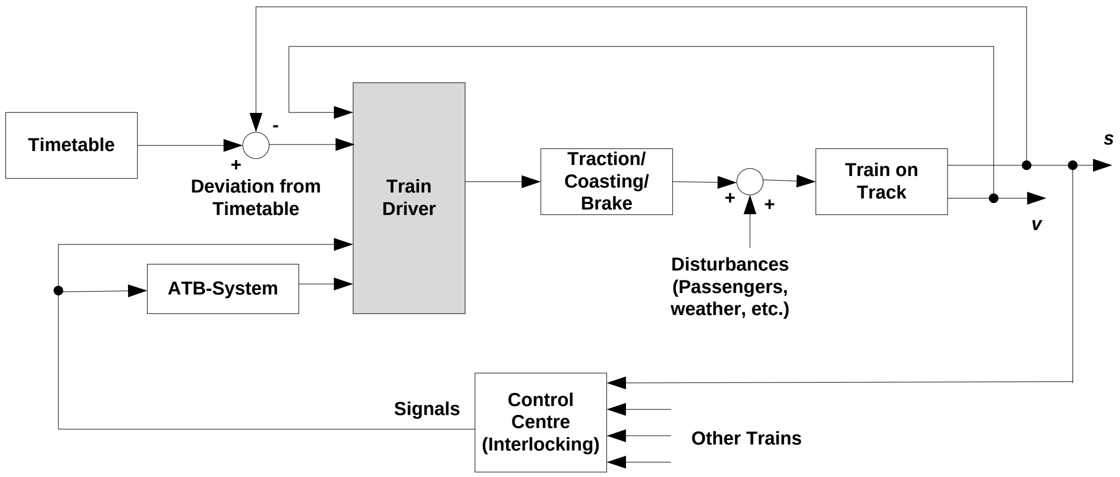


Figure 28 - Driver control loop revisited

Within the network the train can sustain more delay because of conflicts. In general coasting can be applied as long as the sums of delay (primary delay + secondary delay) does not exceed the amount of slack time. When a train-based DAS system is used, this system will calculate the coasting point for which the arrival at the next station will be exactly on time. It should be noted that it optimizes the strategy for the own train only. When the delay is too large to ensure on time arrival the train driver will drive at the maximum performance to minimize the delay. Coasting is not applied in this situation. Compared to traditional train control, in which no coasting is applied, applying energy efficient train control will cause trains to arrive later at the next station because of coasting. In traditional train control trains will arrive early when no delay is sustained during the trip from the previous station.

In the timetabling process slack time is often used as a tool for resolving conflicts in the planning. The conflicts often occur at the nodes in the network, because trains from different directions meet at the nodes. The nodes are often found close to the large stations in a network. The conflict is resolved by adding slack time to the running time of one of the trains in the conflict. This train is then planned to pass the conflict area behind the other train. In the energy efficient train control strategy this slack time is consumed for coasting. Because the coasting point is situated well before the node, the slack time is (largely) consumed when a coasting train reaches the critical node. If the second train in the conflict has sustained a delay, the conflict can still occur. Because the time-buffer has been consumed, the coasting train will arrive late at the next station. The energy efficient train control strategy therefore can potentially effect punctuality negatively. Because the optimization of the strategy is train-based, conflicts cannot be foreseen. In traditional train control the train will arrive early at the node in general, because the slack time is not consumed.

When traditional train control is applied, in general more trains will arrive early at the node. The probability of a conflict is large, because it arises when the other train in the conflict is on time. In practice this often means that the platform is still occupied by the preceding train. It is expected that these situations will occur more often than trains under energy efficient train control coasting into a conflict. The number of conflicts is therefore expected to be reduced by energy efficient train control.

3.4. Research area

A condition for testing the hypotheses in the conceptual the research area should contain large nodes, because these are the main locations where interaction takes place. Also the slack time is concentrated near the large nodes in the network (Van Weert, 2014). The research area chosen to be modeled is a large section of the rail network situated in the Randstad area of the Netherlands.

Figure 30 - Research area

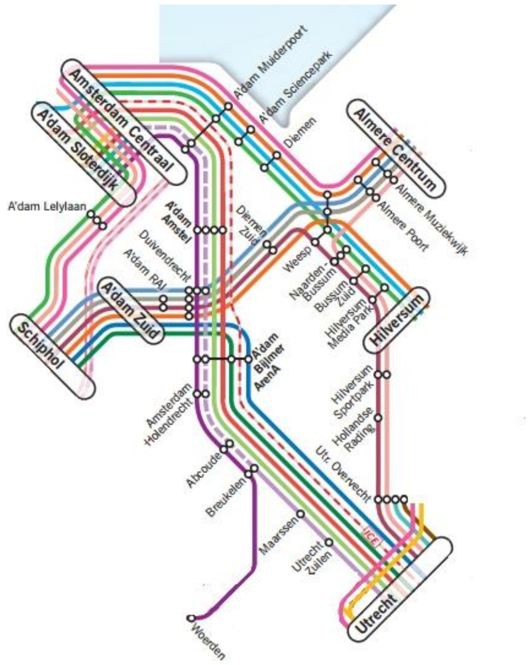


Figure 29 - Research Area with passenger services

Within this network the occupations are high, meaning that the buffer times (e.g. the time between two following trains are low). Therefore a slight deviations from the planned timetable gives high probabilities of conflicts. This makes this network especially suitable for examining effects on punctuality and interaction (conflicts) that are the result of the strategy energy efficient train control.

The calculations are carried out on the basis of the 2014 timetable, because for this timetable distributions from empirical data are available that define the primary delays in the system. Since the method for timetable design has not changed in many years it is assumed that the results found are largely representative for future timetables also, as long as the method for assigning slack time is not changed.

The simulated period is an entire Wednesday, the measured objects are all passenger trains running in this time period. Wednesday is chosen in consultation with OpenTrack expert and engineer David Koopman of RHDHV, because it represents an evenly distributed flow of freight trains to and from the hinterland. Passenger services do not tend to differ much over weekdays. More or less the same trains run every day.

A detailed schematization of the research network can be found in Appendix C. All train services running in the model are described in Appendix B

3.5. Dependent variables and measurement

In this paragraph it is described what the dependent variables are and how they are measured. For all variables applies that they are determined bottom-up which means that they are initially measured for single trains, or for punctuality on individual stations. These data are aggregated to describe the entire system, The hierarchy of trains is illustrated in Figure 31. The hierarchy is described shortly below.

Every train has its own unique train number for instance the 3516. The first two digits represent the train series, in this case the 3500. A train series is a unique service. The example given is an intercity service from Heerlen to Schiphol and vice versa. Whether the last two digits of the train number are even or odd determine the direction of travel. A rule of thumb is that the even direction is the direction towards Amsterdam. All train series taken together represents the train traffic.

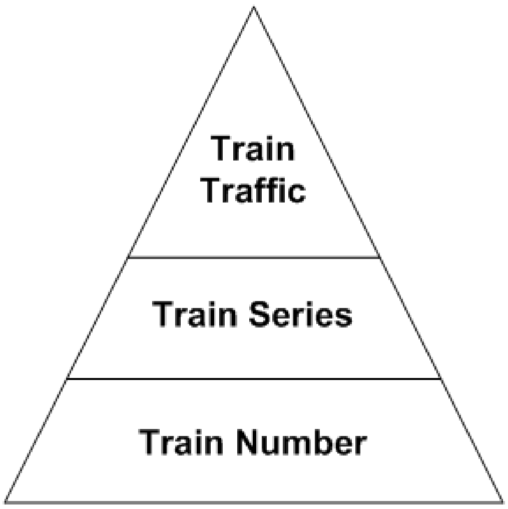


Figure 31 - Train system hierarchy

Energy Consumption

Energy consumption is measured at the wheel in kWh. OpenTrack does measure the energy consumption directly for every time step in the simulation for every unique train number. The data is stored in a physics file, which further contains information travel distance, acceleration and speed.

Punctuality

As concluded from the literature, measurement of punctuality as the number of trains arriving within a certain delay margin is not sufficient. A solid analysis includes the full distribution, mean and dispersion of the arrival delay (Juan, 2008). On time arrival is especially important at transfers, because small deviation from the plan can already result in missing a connection. At transfer the travel time can significantly increase, because the waiting time on the next service ads to the total travel time of passengers. Whereas on the destination only the magnitude of the delay determines the extra travel time. Dispersion in arrival times are important, because they are a measure for the reliability of the mean arrival time. A smaller dispersion means that trains arrive in a narrower time window. This is beneficial to the capacity of the network.

With respect to the locations where punctuality is measured, especially stations that fulfill a major transfer function are important. For the network in this network, these stations are displayed in Table 6

Station	Abbrev.	Passengers origin/destination (2014) (Treinreiziger.nl, 2015)	Transferring passengers (NS, 2014)
Utrecht Centraal	Ut	176292	Very High
Amsterdam Centraal	Asd	162103	Very High
Schiphol	Shl	68689	Very High
Amsterdam Sloterdijk	Ass	47804	High
Hilversum	Hvs	23490	High
Duivendrecht	Dvd	14231	High
Weesp	Wp	9222	High
Almere Centrum	Alm	24071	Medium

Table 6 - Important stations in research network with respect to punctuality

In this research the 3-minute punctuality is measured, as well as the full distributions on the arrival delay for the stations mentioned in the table above and the research network in its entirety.

In OpenTrack the punctuality can be derived from a timetable statistics file which contains the original times depicted in the timetable as well as the simulated times and differences between the planned and realized timetable. The latter is used to measure the punctuality.

Conflicts

Conflicts are a measure of the safety of train operation. Red signal encounters are considered less safe, because if the train driver fails to stop at the signal it can bring the train into a block section that can be occupied by another train. Conflicts require a braking action from the train driver and therefore also influence the energy consumption. After a conflict has cleared, the train has to accelerate again. Acceleration needs the largest input of energy per unit of time. The influence of energy efficient train control on conflicts is measured by calculating the occurrences of certain signal aspects for every train, for both traditional and energy efficient train control. Because conflicts are calculated as the number of occurrences the contribution of conflicts to the energy consumption are not considered (e.g. the energy consumption of the conflicts themselves). This would require an extensive calculation on the speed profiles (e.g. dissipated braking energy), that is hard to achieve within the time span of this research. It can only be concluded whether the differences in occurrences of conflicts have contributed either positively or negatively to the energy savings found.

Conflicts also have an influence in the punctuality calculated, because a delay is sustained in a conflict, though not every delay has an impact on the punctuality. If it has an impact depends on whether or not slack time is left that can act as a time-buffer.

To safety occurrences of red signal aspects are most relevant. Regarding energy consumption all signal aspects that require a braking action are relevant. These are red and yellow signal aspects.

It should be explained that if a train finds a yellow or red signal aspect on its route, it is not always caused by a conflict. Especially at large stations the exit signal (signal at the end of the platform) is deliberately kept on red. If it were on green, the 2 blocks ahead have to be reserved, which means no other trains crossing or following this path can leave the station during the stop of the first train. This would limit the capacity of the network. For smaller stations stop connections can exist. This is a special circuit connected to an adjoining level crossing. The exit signal of the station is kept on red to allow the level crossing directly after the station to stay open during the approach of the train to the station. When the train arrives at the station a timer is triggered after which the level crossing is closed and the exit signal turns to green. The situations described affect both the traditional and energy efficient train control equally. The differences between the strategies therefore concern differences in conflicts.

In OpenTrack, it is registered on the train level when a braking action at a certain signal aspect occurs. These types are described in Table 7. For red signal aspects two types are registered. Approaches of red signal aspects and full stops at red signal aspects. The signal aspects are related: red signal aspect (full stop) is always preceded by a red signal aspect (approach) which is always preceded by yellow signal aspect. Because the aspects can improve during the braking action, red signal aspect (full stop) occur least.

Type of signal aspect	Action
Red signal aspect (full stop)	Stop for a red signal aspect
Red signal aspect (approach)	Approaching a red signal aspect
Yellow signal aspect	Braking at a yellow signal aspect

Table 7 - Conflict types measured

4. Model set-up

In this paragraph the construction of the simulation model is described. The construction of the model has proven to be the most time consuming part of this research. The tool that is used is the micro-simulation software OpenTrack. Being a micro simulation utilized on a macro scale, many effort has to be put in before the model works correctly.

The model construction can be divided into three parts:

- Initialization
- Deterministic simulations
- Stochastic simulations

In the initialization the timetable and distributions are imported in the simulation software. Deterministic simulation is used to build the energy efficient train control profiles. De output of the model is generated through stochastic simulations. The full process of the model construction is displayed in Figure 32. The steps in this process are discussed in the following paragraph.

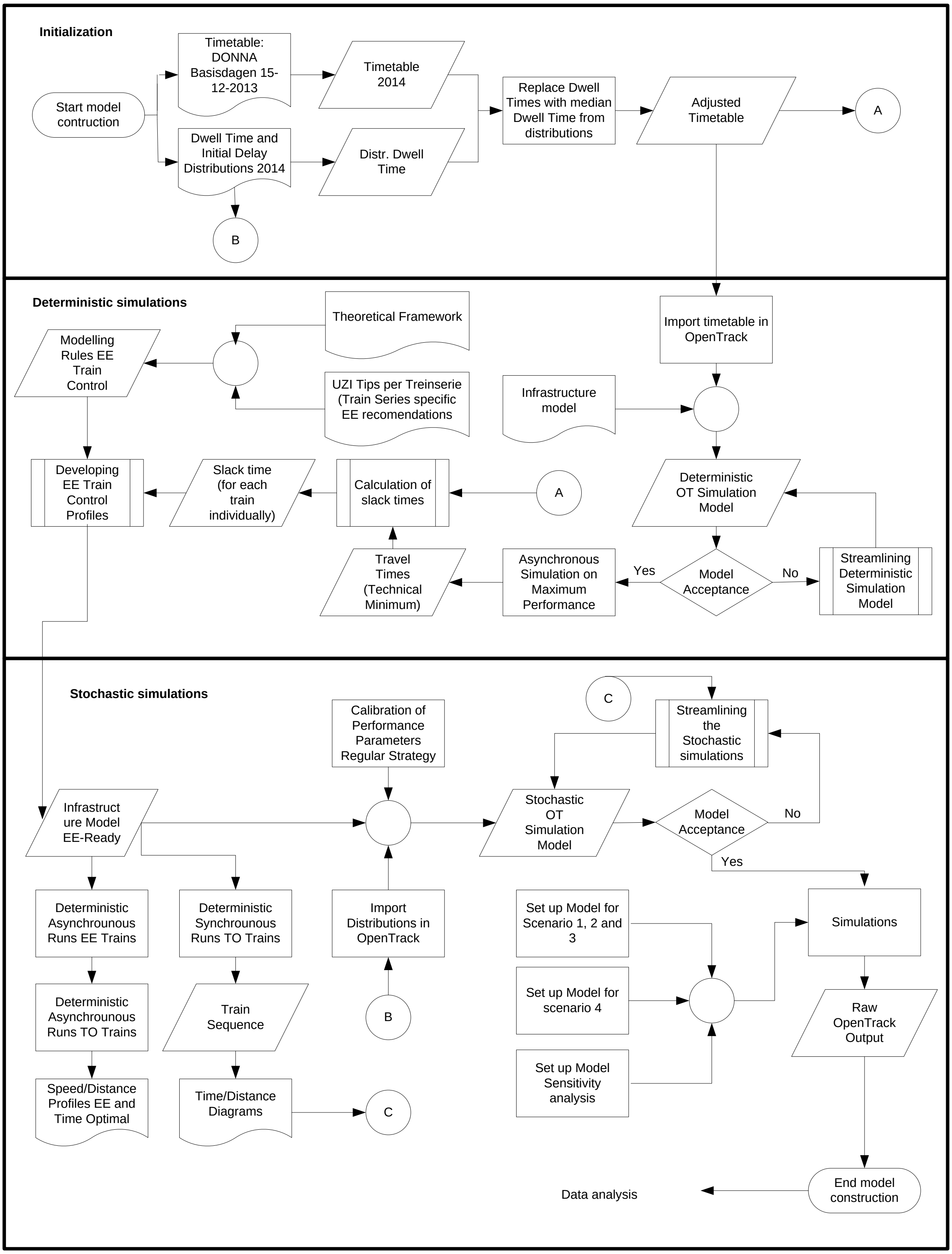


Figure 32 - Flowchart model construction

4.1. Initialization of the model

Timetable

The first step that taken initialization of the timetable in the simulation software. The timetable that is used is a 'Dagplan' of January 2014, which is provided by infrastructure operator ProRail. The timetable contains all planned activities on the entire rail network in the Netherlands for a full week including freight trains.

In Table 8 an example of the timetable format is displayed

Train #	Station/scp	Track	Activity	Planned time	Valid days	Dwell time	Cat.	Train type
3516	Ut	7A	V	06:43	JJJJJNN	0	IC	IRM8
3516	Utma	AE4	D	06:45	JJJJJNN	0	IC	IRM8
3516	Mas	801	D	06:48	JJJJJNN	0	IC	IRM8
3516	Bkla	701	D	06:50	JJJJJNN	0	IC	IRM8
3516	Bkl	AC8	D	06:51	JJJJJNN	0	IC	IRM8
3516	Aco	671	D	06:55	JJJJJNN	0	IC	IRM8
3516	Ac	AB3	D	06:56	JJJJJNN	0	IC	IRM8
3516	Ashd	AB2	D	06:57	JJJJJNN	0	IC	IRM8
3516	Asb	2	A	06:58	JJJJJNN	60	IC	IRM8
3516	Asb	2	V	06:59	JJJJJNN	0	IC	IRM8
3516	Dvaw	DD	D	07:02	JJJJJNN	0	IC	IRM8
3516	Rai	2	D	07:03	JJJJJNN	0	IC	IRM8
3516	Asdz	4	A	07:05	JJJJJNN	60	IC	IRM8
3516	Asdz	4	V	07:06	JJJJJNN	0	IC	IRM8
3516	Skbr	RS	D	07:07	JJJJJNN	0	IC	IRM8
3516	Asra	R3	D	07:08	JJJJJNN	0	IC	IRM8
3516	Shl	4	A	07:12	JJJJJNN	60	IC	IRM8

Table 8 - Example DONNA Dagplan timetable for Train 3516

The timetable contains information about the full trajectory and the planned times of all activities that take place. Activities can be 'V' for Departure, 'D' for pass through and 'K' for short stop (not in the example table) The first column displays for which train the table is valid. The second column the location at which the activity in the fourth column takes place at the planned time in the fifth column. The second to last column mentions the train category in which roughly four categories can be distinguished: IC for intercity services, SPR for regional services, INT for international services and GO for freight trains. The seventh column contains the planned dwell times. In order to model delays, the dwell times are taken from dwell time distributions. The dwell times in the Dagplan are therefore not used. This is elaborated on later. The sixth column describes the days for which the timetable is valid. For the train in the example the timetable is valid on Mondays to Fridays. In consultation with OpenTrack expert David Koopman, engineer at Royal HaskoningDHV Wednesday is chosen as the modeled day. Wednesday's generally have evenly distributed flow of freight trains to and from the hinterland. For passenger trains all days, except for the weekends, contain roughly the same trains. Passenger services are roughly equal on the weekdays, but different in the weekends. The Dagplan is filtered for all stations in the research area and Wednesday's to find a complete list of all trains in the research area. The model contains about 2000 unique train numbers.

Distributions

To simulate the delays in the model, distributions for the dwell time and initial delay are imported into OpenTrack. These distributions are based on empirical data from 2014, as is the timetable. The dwell time is in essence not a delay as long as the dwell time that is drawn from the distribution is shorter than the dwell time planned in the timetable. It does become a delay if the drawn dwell time is larger. In Figure 33 an example for the dwell time distribution is given. OpenTrack fits a piecewise linear distribution through the bins in the distribution.

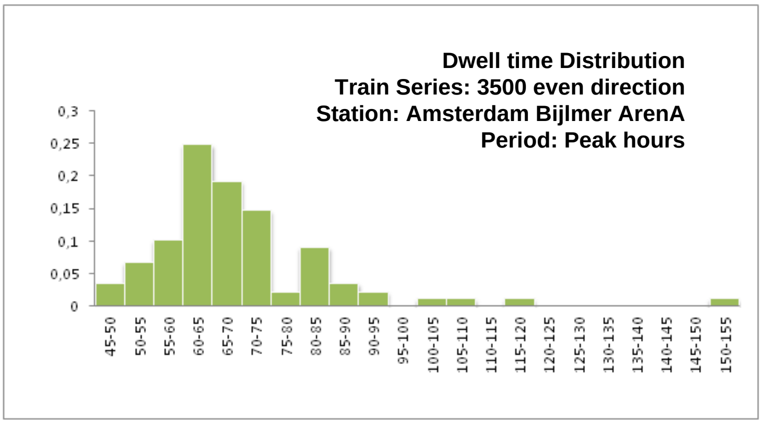


Figure 33 - Example dwell time distribution

The initial delay distribution is a delay relative to the planned departure time for only the first departure of a trip. This type of distribution is not used until the stochastic simulations are carried out. An example of an initial delay distribution is presented in Figure 34.

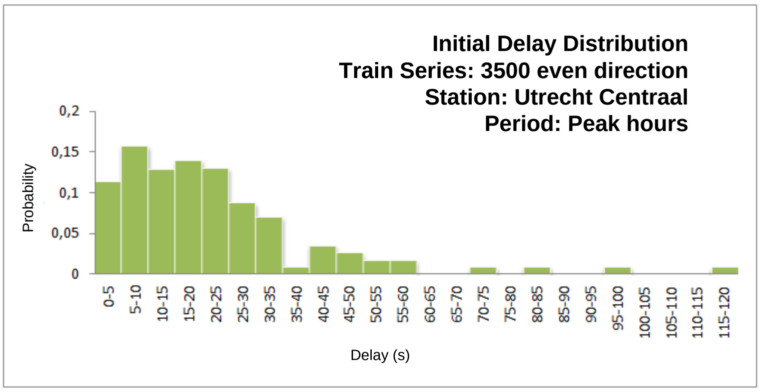


Figure 34 - Example initial delay distribution

The dwell time distributions are used to adjust the dwell times in the Dagplan. For every dwell distribution the median is calculated which replaces the planned dwell time in the Dagplan. Since the dwell times will eventually been drawn from the distribution, the mean dwell time gives an average representation of the dwell time that will be drawn than the dwell time in the original timetable.

In the process of replacing the original dwell times with the medians from the distributions it is found that the median is often larger than the dwell time in the Dagplan for short stops. Since these distributions come from empirical data, the planned dwell times are too short on average. This has also been found in (Scheepmaker, 2013).

Converting the Dagplan in a course and timetable file.

After adjusting the timetable it is converted and split up into two files by means of a conversion sheet in order to be able to import the Dagplan information in OpenTrack. A course file and a timetable file are created. The course file contains information about the train: A course ID (or train number) train type, train category and information about the route within the model. The timetable contains information about the planned times for all the activities in the DONNA Dagplan. In OpenTrack both files are linked by the train number.

A cutout of the course file is displayed in Figure 35. The course file needs some editing for the entry speed. The edges of the model are chosen at stations. Passenger trains therefore will start in the model at a speed of zero. Freight trains however don't stop at the stations but are planned to drive through. For these trains the entry speed is set at the permissible line speed at the specific location.

After this process is completed the files can be imported into OpenTrack

courseID	Descrip tion	kind	train	speedType	entrySpeed	name	prio
3516	IC Ut7A-Shl4	IC	03500 even IRM8	Normaal	0	03500 Ut7A-Shl4	1
48519	GO Asdta84-Ut15	GO	CLA66(591m3550t)1	Goederen	40	GO Asdta84-Ut15	1

Figure 35 - Coursefile example

4.2. Deterministic simulations

In this phase the deterministic simulations are carried out. With deterministic simulations the slack times in the timetable are calculated and used as the basis for the creation of the energy efficient train control profiles.

Streamlining the deterministic model

After importing the course file and the timetable file both files are must be coupled to the infrastructure file. RHDHV has developed the Nederland model in which the entire main rail network is modeled to detail.

The route a course runs through the infrastructure model has to be manually defined in a so called itinerary. An itinerary consists of a series of paths, which in its turn consists of a number of routes. Routes are defined from signal to signal and contain information about the signal aspects for this specific route. The signal aspect relations are provided by ProRail. Paths typically run from one station to the next. Most routes and paths were already in the model except for freight trains.

The relations between itineraries, paths and routes are illustrated in Figure 36.

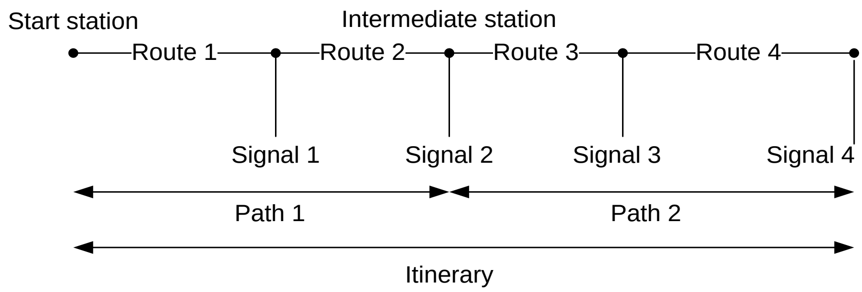


Figure 36 - Relations itinerary, paths and routes

After defining all itineraries a basic deterministic simulation model is ready. The model now has to be streamlined because it still contains a number of errors. Initially large errors are found, resulting in deadlocks in the simulation. A deadlock is a situation in which a train is locked in place somewhere in the model. An example is given in Figure 37. In this example both of the trains cannot move forwards along the planned route, because they are in each other's way. These situations can exists because the Dagplan timetable does not contain information about the routes within a station, but only about the corridor it is coming from, the planned platform the train is planned to stop and the corridor it the train will go to after the stop. The deadlock in the example is solved by creating new routes around the other train, for the train that is planned to depart first. In creating a diversion one must beware not to plan the deviation route in the path of another train. The 'puzzle' of deadlocks is particularly hard to solve for Amsterdam Centraal.

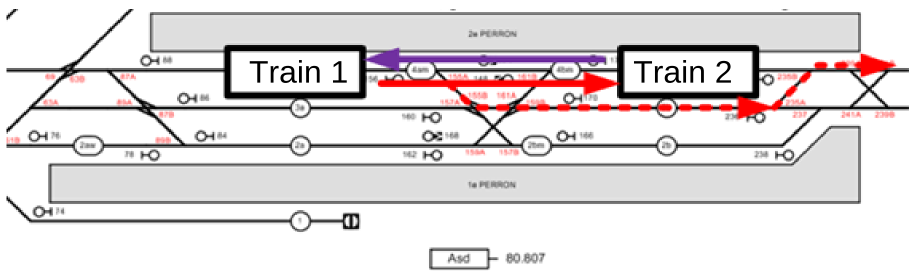


Figure 37 - Deadlock example

After solving the deadlocks the model does complete the runs for the entire day, but still contain large delays that are the result of errors in the model. OpenTrack contains an output file in which the delays are sorted. One by one the largest delays are investigated and resolved. The experience is that the lower the delays get, the harder they are to solve. At one point one has to accept the model. In consultation with OpenTrack expert David Koopman it is determined the largest delay must be lower than 120 seconds. The largest delays were mainly caused by trains leaving a large station in the wrong order. The order is determined by the timetable but generally can be described as: Intercity, Sprinter, Freight train. The train order can be enforced by building connections in the timetable. Connections have two functions:

- Ensuring that the returning train cannot depart until the incoming train has arrived. At the end stations train turn around and generally run the same service back in the other direction.
- Enforcing a certain sequence of trains to prevent the wrong train from departing first.

The condition in a connection that is made in the timetable-file looks like: Train x waits at the exit signal of Asd for the departure of train Y in Asd. After it is established that the maximum delay is sufficiently low, the model is ready to determine the slack times incorporated in the timetable.

Determining slack times

The total slack time for a station to station section of track is the difference between the running time described by the timetable (this is the running time that contains all reserves) and the technical minimum running time

$$Total\ slack\ time = Running\ time\ timetable - Technical\ minimum\ running\ time$$

The slack time is calculated by running asynchronous simulations at the maximum performance level. Running the trains at the maximum performance level implies that the technical minimum running time is found. Asynchronous simulations are runs in which the trains are run one by one to make sure no interactions can occur. If interaction occurs one of the trains is forced to brake, which means that one is no longer dealing with the minimum running time. To save time the runs are made for half a train series at the time (one direction each time). Generally train series has a frequency of 2 trains/hour (e.g. half an hour apart). It can safely be assumed that these trains won't interact, because they at least are separated by half an hour. In Table 9 an example of the OpenTrack output is given for the minimum running time for a single train. The running time found is time optimal.

Train number	Station, Sc point	Act.	Arrival plan.	Dep plan.	Arrival sim.	Departure sim.	ΔArr (s)
3516	Ut	Dep.	06:42:00	06:43:00	HH:MM:SS	06:43:00	0
3516	Utma	Pass	HH:MM:SS	06:45:00	HH:MM:SS	06:44:35	0
3516	Mas	Pass	HH:MM:SS	06:48:00	HH:MM:SS	06:47:42	0
3516	Bkla	Pass	HH:MM:SS	06:50:00	HH:MM:SS	06:49:42	0
3516	Bkl	Pass	HH:MM:SS	06:51:00	HH:MM:SS	06:49:53	0
3516	Aco	Pass	HH:MM:SS	06:55:00	HH:MM:SS	06:54:45	0
3516	Ac	Pass	HH:MM:SS	06:56:00	HH:MM:SS	06:55:17	0
3516	Ashd	Pass	HH:MM:SS	06:57:00	HH:MM:SS	06:56:19	0
3516	Asb	Stop	06:58:00	06:59:00	06:57:45	06:59:00	-15
3516	Dvaw	Pass	HH:MM:SS	07:02:00	HH:MM:SS	07:00:56	0
3516	Rai	Pass	HH:MM:SS	07:03:00	HH:MM:SS	07:02:00	0
3516	Asdz	Stop	07:05:00	07:06:00	07:03:38	07:06:00	-82
3516	Asra	Pass	HH:MM:SS	07:08:00	HH:MM:SS	07:08:43	0
3516	Shl	Stop	07:12:00	07:13:00	07:12:30	HH:MM:SS	30

Table 9 - Example slack time in output

Marked in the last column of the table are the slack times. As can be seen this specific train has a 15 second slack time between Utrecht Centraal and Amsterdam Bijlmer ArenA. This is a typical example of a track section where the planners removed running time (e.g. it should have at least 5 percent of slack time if no running time would have been removed). Based on a running time of 15 minutes this would equal 45 seconds. The difference is probably added to the next section of track: The running time of Amsterdam Bijlmer ArenA to the next stop is just 6 minutes and the slack time is 82 seconds. The reason for concentrating the slack time at this location is probably because Dvaw is a critical point. The lines Hilversum-Schiphol and Utrecht-Schiphol meet. For the last section the slack time is negative, which means that no energy efficient train control can be applied.

The slack time calculations are collected per half train series from which it is determined how many unique slack profiles exist within the series. The majority of trains within a series have equally distributed slack times, though on the beginning and end of the day irregularities to the pattern exist.

Because of limited time not all unique profiles could be build into the model. Building a profile in the model is just as time consuming for a profile that fits a large share of a train series as it is to create a profile for a single train that does not fit the pattern of the rest of the series. The number of profiles had to be limited. Generally speaking, a profile is build if it contains two or more trains. For single unique trains, the train is placed under the profile of other trains in the series as long as the single slack time is of larger magnitude than the profile it is fitted to. This ensures that the sub-optimal solution does not cause the single train to arrive late because of coasting. When it has less slack time than any of the other profiles for that specific train series, the profile is build nonetheless

Construction of energy efficient train control speed profiles.

In this paragraph it is described how the energy efficient train control speed profiles have been determined and build into the model.

When it is determined how many energy efficient profiles had to build by calculation of unique slack distributions per half a train series, these profiles have to be build in OpenTrack. Coasting can be simulated in OpenTrack by placing coasting signs along the track. At the height of the sign a train will start to coast if the conditions described in the coasting sign are met.

In the coasting sign it is described:

- For which trains the coasting sign applies. This property is of great importance, because this allows for creating different profiles for each unique slack time distribution.
- The lower limit of the speed to which is coasted. These are set at 80km/h in consultation with OpenTrack expert and engineer at RHDHV David Koopman. Coasting below a certain speed is assumed to be potentially perceived negatively by passengers, because of large differences in speed that are perceived at traditional train control and energy efficient train control. When a train hits the lower limit it will maintain this speed until further braking action is required. This setting can have a large effect on the saving potential of energy efficient train control. Within the network numerous sections of track have a permissible line speed that is 40 km/h or less. Especially around the Amsterdam Centraal station a large low

speed zone (≤80 km/h) is in place. The effects are elaborated on in chapter 5. In Appendix C a detailed visualization of the research area is displayed in which the areas where a permissible line speed of 80 km/h and lower are described. In these zones coasting cannot be performed.

- A delay condition. This makes the sign valid when the simulated delay is not larger than a certain value. By specifying this it is assured that trains will ignore the sign when the delay exceeds a certain threshold in order to assure that coasting is not applied when the train is delayed (as the theory on energy efficient train control describes). When a train is delayed it should try to make up for it by performing on the maximum possible performance of the train. Punctuality is after all ranked higher in the priority hierarchy.

The coasting signs are placed according to a number of modeling rules. These are derived from the theory on optimal energy efficient train control. Because of limited time some constraints apply that give a close approximation of the optimal profile, but are somewhat suboptimal, because the coasting points are accepted at a certain level of error.

The coasting signs are placed following the next rules

- All slack time is consumed at the location it is available (slack time situated between two station stops of which an example is given in Table 9). It is not allowed to transfer slack time over a stop to consume it somewhere else. The slack time is fully consumed if the train arrives at exactly the planned arrival time on the next station.
- The location of placing the sign is in essence a trial and error process by placing a sign, do a test run to check the deviation from the planned arrival time at the next station is, re-locating the sign etc. The location is accepted if the deviation from the planned arrival time is at maximum 5 seconds (positive or negative).
- The lower coasting limit is 80 km/h
- The optimal energy efficient train control in literature describes a maximum acceleration, drive the maximum permissible line speed, coasting and braking sequence. This is the first strategy that is applied. In case too much slack time is available at a certain line section which allows for driving the entire section of track at the lower speed limit, this strategy is applied. This is the second best optimal control strategy.
- If not all slack time can be consumed by driving the slowest possible strategy (driving 80km/h all the way), trains will still arrive early at the next station. The sign is in this case directly placed at the platform of the departure station. The magnitude of the remaining slack after execution of the slowest possible profile is the delay trains are allowed to have to meet the delay condition in the coasting sign.
- Delayed trains can still coast as long as the departure delay is smaller than the slack time that is available. For these situations coasting signs are placed at intervals of 15 seconds of slack. This means that numerous signs are placed for a single train of which the location is further down the line as the delay increases. For

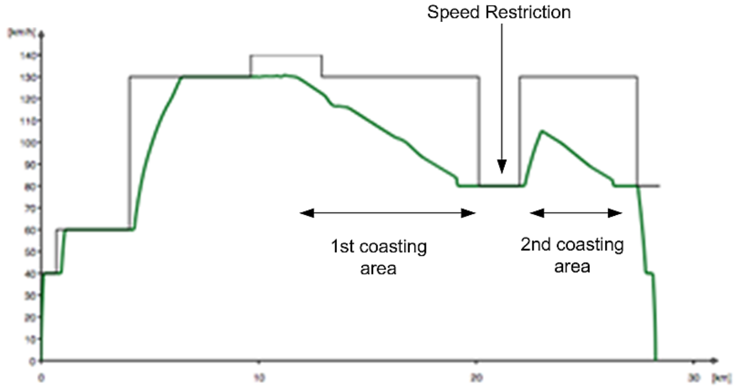


Figure 38 - Two coasting areas in one station to station sequence

instance when the slack time is 30 seconds, profiles are build by placing a sign that consumes 30 seconds of slack time and a sign that consumes 15 seconds of slack time.

- In some situations more than one coasting area can apply. This is the case when a permissible line speed reduction is in place between two stations stops, which is later increased. An example of this is illustrated in Figure 38. In these cases the coasting areas are derived from the 'UZI tips per treinserie' (Train series specific tips for coasting) in (Franke, 2012).

Example of coasting sign placement

In this paragraph an example of placement of coasting sign is described, based on train 3516 of which the slack times are displayed in Table 9 for the trajectory Utrecht-Amsterdam Bijlmer ArenA. As can be seen from the table 15 seconds of slack time are available. This means that for this train one coasting sign is placed which consumes 15 seconds of slack. The location that is found by the process of placing-testing-replacing until the 5 second margin on the arrival time is satisfied is found to be at the Abcoude station, see, Figure 39. From the train it is determined what the delay to the timetable is. This happens to be 15 seconds. This is measured at the previous service control point, which in this case is service control point Abcoude Overloopwissels (Aco). The delay is visible on the train that is visualized on screen, see figure. The upper and lower speed limit are set at the lowest allowed coasting speed of 80 km/h. The upper limit is equal to the lower limit, to ensure the train does not accelerate after the lower limit has been reached. For this specific example the train will never reach the lower limit, because of the low amount of slack and high permissible line speed for this section, but the lower limit can be reached at large quantities of slack or low permissible line speed. In the category window (see figure) the train for which the sign applies is selected.

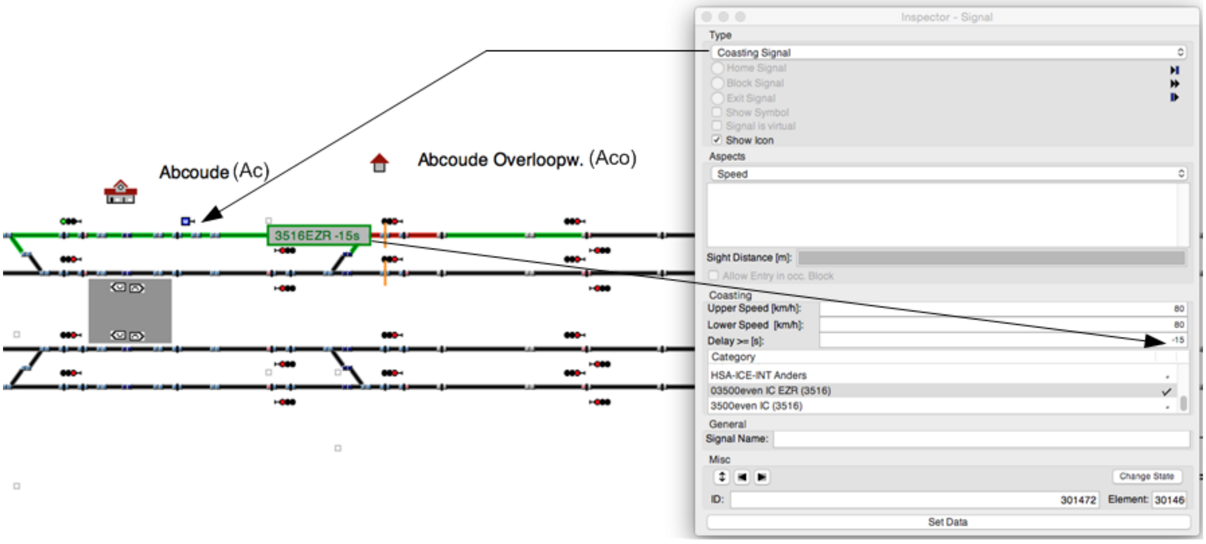


Figure 39 - Interface coasting sign setting

At the stop a coasting at Amsterdam Bijlmer ArenA, a coasting sign is placed that resets the strategy by defining a larger than permissible line speed in the upper and lower speed window. After which the process described is repeated for the section Amsterdam Bijlmer ArenA-Amsterdam Zuid. This section contains a large quantity of slack, see Table 9. Which means that more signs are placed to allow for coasting under a slight delay. A delay is simulated by deliberately let the piece of infrastructure malfunction, directly after the departure station. By doing so, the train will be held for the duration of the malfunction. After adding malfunctions (in portions of 15 seconds) the locations of signs for delays are determined.

The process described is repeated for all unique slack profiles that have been calculated. Making the model suitable for energy efficient train control is a very time-consuming task, because of the great number of slack time distribution profiles . It is advised to investigate on a more dynamic way of building the profiles into OpenTrack in the future.

4.3. Stochastic simulations

Determination of the energy efficiency of energy efficient train control profiles and creation of time-distance diagrams

All energy efficient train control profiles that are build are given in Appendix E, except for the profiles at delays. In the appendix, also the energy consumption of both the time optimal (e.g. the technical minimum running time) and energy efficient are given to give an idea about the saving potential of individual profiles. As can be seen from the large number of energy efficient train control profiles even within train series, in order to achieve the savings that will be calculated from them, train based, real time DAS (like the Uitrolapp) is a necessity.

The model is now run at the maximum performance level to make time-distance diagrams of all corridors in the model. The time-distance diagrams clearly visualize the planned timetable, which is easier than determining the sequence from the original tabular timetable. Train sequence is an important factor in setting up the stochastic simulations from which ultimately the results are extracted.

In Figure 40 an example of a time-distance diagram for the corridor Utrecht-Amsterdam Sloterdijk for a time window of two hours is given. In the figure described, trains run on maximum performance. On the y axis the distance is specified, on the x-axis the time. Displayed in green are intercity services, in blue sprinter services (regional trains) in purple international services (such as ICE-trains) and in red freight trains. The dotted lines represent the planned timetable which is a straight line in between to service control points. It is straight because only planned times at service control points are described in the timetable. The uninterrupted lines represent the simulated time-distance. The difference between the planned and realized time slack time. Also visible in the figure are braking actions that are enforced by signaling (circles). These can represent conflicts. As mentioned before not all braking actions enforced by the signaling are conflicts, because for certain stations the exit signal is deliberately kept on red.

The network contains a high train intensity as can be seen. The slightest deviations from the planned timetable can already lead to conflicts, as of which a few examples can be found in the diagram.

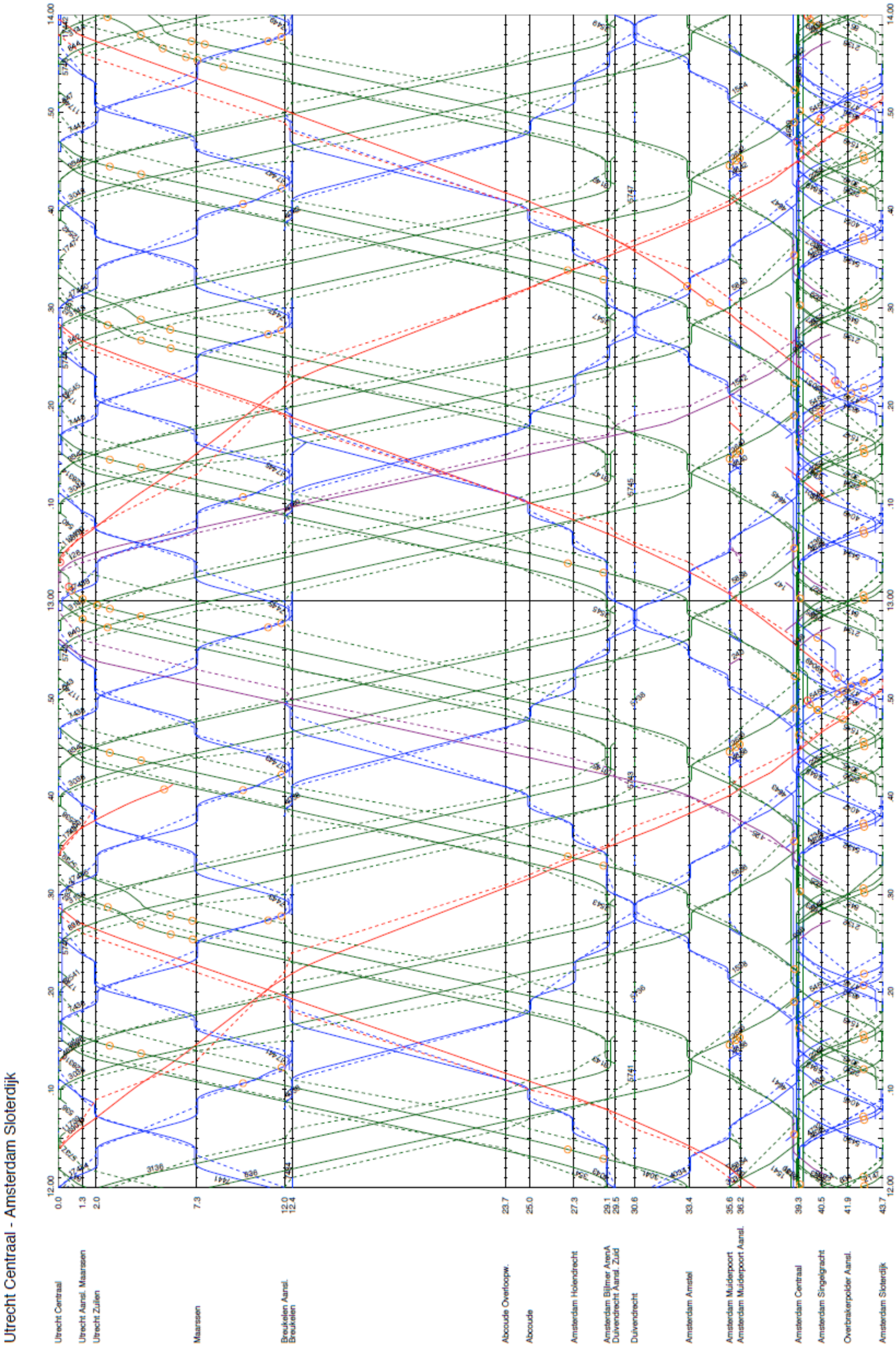


Figure 40 - Example time-distance diagram

Setting of the performance parameter

Now that the model is ready for energy efficient train control operation, the performance parameter has to be set for the traditional train control trains in the model.

Regular train control is not the equivalent of time-optimal train control. Which means that train drivers do not run on maximum performance. By setting the performance lower than 100% the speed profile becomes sub-time optimal.

The performance parameter is a percentage of the maximum performance. acceleration, cruising speed and braking force applied are executed at the rate of the specified percentage.

The settings of the performance parameter are taken from an earlier research, from which also the empirical data on initial delay and dwell time are used in this research.

For energy efficient train control the performance is determined by the performance setting in combination with the coasting sign, which realizes lower performance. The performance parameter is set to 100%, because the strategy is described by maximum acceleration, driving the maximum permissible line speed and maximum (comfortable) braking

Summarized the performance for traditional and energy efficient train control are set as:

Traditional train control:
Performance delayed: 97%
Performance on-time 94%

Energy efficient train control
Performance delayed: 100%
Performance on-time: 100%

The performance parameter is of large influence on the running time calculations and energy consumption calculations (Agricola, 2009). For this reason a sensitivity analysis is conducted to examine its effects on the results in this research. This is done by equalizing the performance for both strategies by setting the traditional train control parameters both to 100%.

Setting the distributions

The timetable in OpenTrack contains the connections that have been set to streamline the deterministic model as described earlier. This timetable is exported, after which the dwell times are replaced by the name of the distribution the dwell time is drawn from in the stochastic simulations. For the first departure the departure delay distribution is set in the timetable. The timetable is imported back in OpenTrack and the distributions (which are in a separate file) are imported. Now the basic model for Stochastic modeling is ready.

Streamlining the stochastic model

Just as in the deterministic model from which the energy efficient train control profiles have been determined, the stochastic model will deadlock initially. Contrary to the deterministic model these are not caused by trains locking each other in because of the planned tracks (these issues are after all resolved in the streamlining of the deterministic model), but only by deadlocks because of a wrong train sequence. This is illustrated in Figure 41.

Train 1 has a connection at the station, it waits for train 2 to pass. Train 3 is scheduled to wait until train 1 has left the station. Somewhere along the network train 3 came in front of train 2 which deadlocks the system

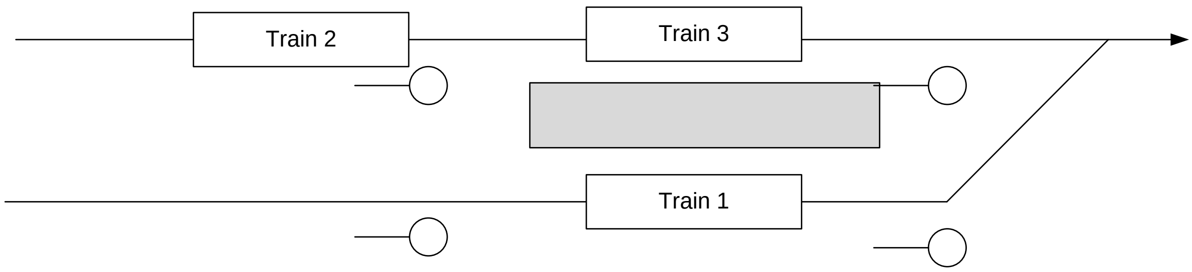


Figure 41 - Deadlock related to train sequence

Because of the delays that are introduced by the distributions, the trains make shifts to the right in the time-distance diagram. Since these are drawn from distributions the shifts differ between trains. This increases the chances of trains running in the wrong order, which deadlocks the simulations.

To resolve these deadlocks even more connections than in the deterministic scenarios had to be set. This essentially fixes the train sequence at these locations. Since train traffic control only changes the sequence for delays larger than 15 minutes, fixing the train sequence for certain locations is assumed to be allowed. The model is therefore accepted if the maximum delays are near 900 seconds. This is sampled by running tests for different delay scenarios (a delay scenario is a sheet of random variables from which OpenTrack draws the distributions).

The process of streamlining the stochastic simulations is a time consuming task, because different delay scenarios create other deadlocks. After resolving the deadlocks for many different delay scenarios and verifying the largest delays, the model is accepted.

Now the model is ready to run the different scenarios

Set-up and running of scenarios in the model

During the streamlining of the stochastic model it became apparent that some of the larger delays could not be resolved, because they are the result of freight trains having to stop in large stations to wait for a delayed train to leave. A freight train stopping in a station often causes many other tracks to be blocked, because of the length of the train (it simply does not always fit in the station). This is illustrated in Figure 42. The train with the red number is the freight train that is running to the right. Behind it (red track sections) are the track sections it keeps occupied because of its length. Preventing other trains from entering/leaving from the crossing corridors. This causes delays, because the stop of the freight train is unplanned.

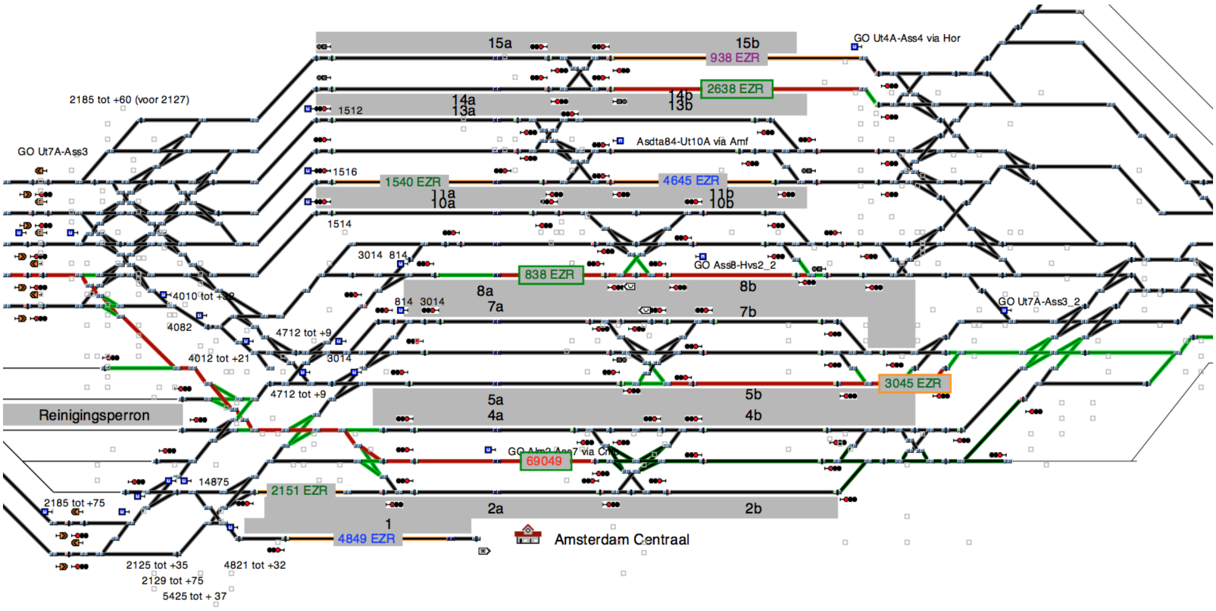


Figure 42 - Example freight train blocking corridors

If the conflict is cleared and the freight train can leave it will take a long distance for it to gain a reasonable speed, which can influence the trains behind. These delays can cost a reasonable portion of saving potential. To examine its effects a scenario in which no freight trains are modeled is compared with the scenario for energy efficient train control (in which freight trains are present). Though freight trains cannot be simply removed from a network in reality it can emphasize the importance of adequate planning of freight trains.

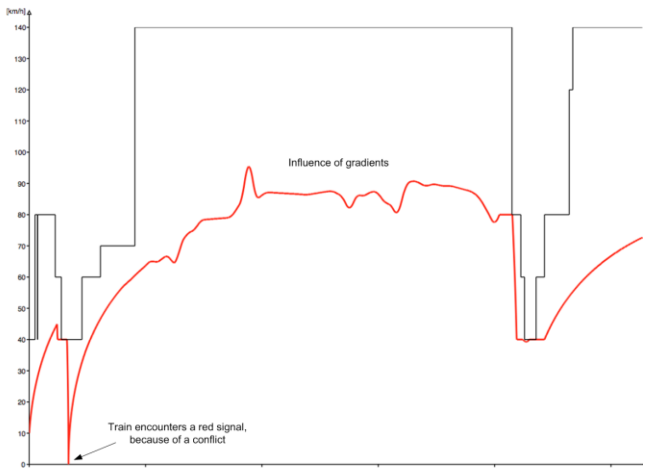
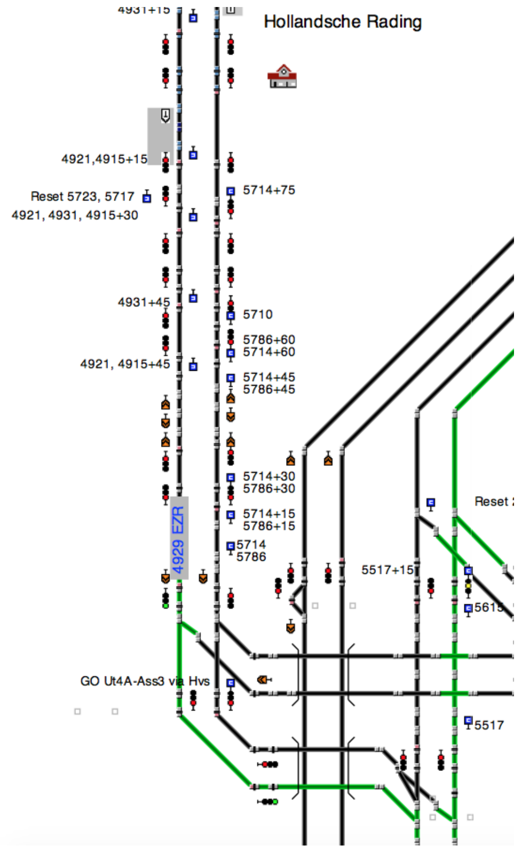


Figure 43 - Example freight train speed-distance diagram

For every passenger service after al the construction of profiles, a traditional train control and an energy efficient train control exists. Only freight trains only have a traditional variant with a performance of 100% regardless of the delay.

In consultation with expert David Koopman it is determined that 50 simulation runs have to be done. The goal of rerunning the simulations is to obtain multiple samples in order to find a sufficiently accurate estimate of the real means of the dependent variables. The number of runs are evaluated on the accuracy they provide in the next paragraph.

For the mixed strategies scenario both traditional train controlled trains as well as energy efficient train controlled train will be simultaneously simulated. For every train number the strategy is randomly determined with chances being 50-50. This scenario is therefore run 100 times.



Summarized the scenarios are set up as:

- Scenario 1 (50 runs): Traditional train control 100%. Performance:97% delayed, 94% on time
  Scenario 2 (50 runs): Energy efficient train control 100%. Performance: 100% delayed, 100% on time
- Scenario 3(100 runs): Traditional train control (~50%) Performance:97% delayed, 94% on time, Energy efficient train control (~50%), Performance: 100% delayed, 100% on time
- Scenario 4 (50 runs): Energy efficient train control 100%. Performance: 100% delayed, 100% on time, no freight trains

Sensitivity analysis 2 sets of simulations:

- Control group (50 runs): Traditional train control 100%. Performance:100% delayed, 100% on time
- Treatment group (50 runs): efficient train control 100%. Performance: 100% delayed, 100% on time. For these the simulations of scenario 2 are used.

After the simulations the raw output of OpenTrack is assembled in the program MatLab (Matrix Laboratory) to extract the desired results. The results of this research are analyzed in the next chapter.

4.4. Number of runs - Accuracy of dependent variables

In this paragraph it is determined to what degree the number of simulation runs give a sufficiently accurate estimate of the mean performance of the dependent variables. The variables are arrival delay (for punctuality), energy consumption and number of occurrences of braking actions at signals (for conflicts).

In this research the stochastic simulations are replicated 50 times. A replication is a run of a simulation that uses specific streams of random numbers. In a replication the random numbers are taken from another stream of random numbers and the simulation is re-run. The aim is to produce multiple samples to obtain a better estimate of mean performance (Robinson, 2004). The stochastic elements in this research are dwell time and initial delay. These are drawn from distributions (based on empirical data) by OpenTrack. To draw from distributions OpenTrack uses streams of random variables that are referenced in delay scenarios. For every re-run another delay scenario is selected, which results in 50 different samples.

Two methods are used to determine whether the output is sufficiently accurate, a graphical method and a calculation of the deviation of the upper and lower confidence levels relative to the mean.

In the graphical method, the mean and confidence intervals are plotted for the number of replications. As more replications are done, the graphs of the mean and confidence intervals should become flat lines. This means that they should show minimal variability (up and down movement) and should not show an upward or downward trend. The number of replications necessary is the number of runs for which the lines become flat. Performing more replications will only give marginal improvements of the estimate of the mean. If a line does not become flat within the number of replications done, the number of replications are not sufficient.

The deviation of the confidence interval method is used together with the graphical method in order to determine how accurate the estimated means of the independent variables are. A confidence interval is a means for showing how accurately the mean is estimated. The narrower the interval the more accurate the mean is deemed to be. In general the more replications are executed, the narrower the interval becomes. The confidence is calculated by the following formula (Robinson, 2004):

$$CI = \bar{X} \pm t_{n-1,\alpha/2} \frac{S}{\sqrt{n}}$$

where:

$\bar{X} = mean\ of\ the\ output\ data\ from\ the\ replications$

$S = standard\ deviation\ of\ the\ output\ data\ from\ the\ replications$

$n = number\ of\ replications\ (runs)$

$$t_{n-1,\alpha/2} = value\ from\ the\ Student's\ t - distribution\ with\ n - 1\ degrees\ of\ freedom\ and\ significane\ level\ of\ \alpha/2$$

The standard deviation is calculated by

$$S = \sqrt{\sum_{i=1}^{n} \frac{(X_i - \bar{X})^2}{n-1}}$$

where:

$$X_i = the\ result\ from\ replication\ i$$

In this research 50 runs are done per scenario. Given the time it costs to perform a simulation run in combination with the number of scenarios this number of runs is close to the maximum that could be executed given the capacity of OpenTrack licenses at RHDHV. Because this evaluation on the number of runs can only be executed after the dataset is fully assembled generates the desired format of output, e.g. in a late stage of this research. Therefore no extra runs will be done if the number of replications is not sufficient. Inaccurate data is excluded from the calculations if found. The significance level used in this research is α 0,05. This gives a 95% probability that the value of the real mean, the mean that is found if an infinite number of replications were done) lies within the confidence interval. The confidence levels are at α=0,05 are called the 95% confidence intervals.

It is found that on every dependent variable, the energy efficient train control is the determinant strategy regarding the required number of runs. In this strategy the means take more runs to stabilize than in the traditional train control strategy. The results on the individual dependent variables are discussed below.

Energy consumption

In Figure 44 the graphical representation of the cumulative mean and 95% confidence intervals for the energy consumption at the wheel is displayed. In this figure it can be seen that the mean energy consumption stabilizes around 20 runs of the model. A slight hiccup in the mean is found around run 43. In Table 10 the deviation of the confidence intervals relative to the cumulative mean is displayed. The cumulative measurements represent the number of trains for which the energy

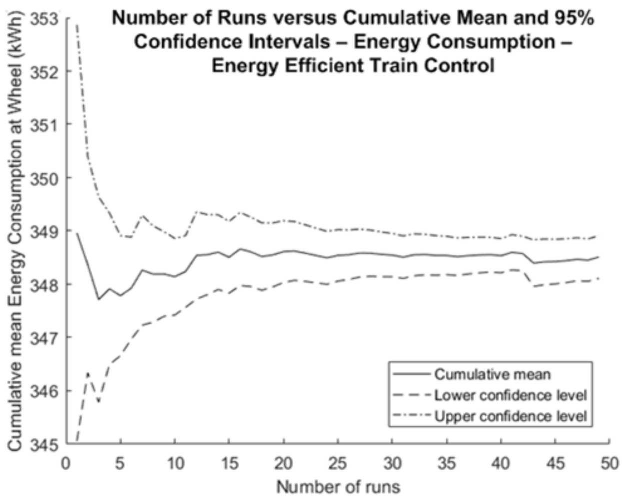


Figure 44 - Number of runs versus cum. mean and 95% CI - Energy consumption EE

consumption is calculated (all passenger trains) multiplied by the number of runs.

it is seen that this hiccup is responsible for a reduction in the cumulative mean of only .1 kWh. Since this is a very minor deviation when the total energy consumption is considered (cumulative mean*number of measurements), it is concluded that 20 runs of the model is sufficient to accurately estimate the mean energy consumption. In the last column of the table it is seen that the confidence intervals show a very small deviation from the mean, meaning that the mean energy consumption shows little variation between runs.

Runs	Cum. # of measurements .	Mean (kWh)	Cumulative mean (kWh)	Standard Deviation (kWh)	Lower Confidence Level (kWh)	Upper Confidence Level (kWh)	**Deviation Cumulative mean (%)**
1	1689	348,3	348,3	n/a	n/a	n/a	n/a
2	3378	349,6	349,0	0,9	345,1	352,9	1,1
3	5067	347,2	348,4	1,2	346,3	350,4	0,6
4	6756	345,7	347,7	1,6	345,8	349,6	0,6
5	8445	348,7	347,9	1,5	346,5	349,3	0,4
6	10134	347,1	347,8	1,4	346,7	348,9	0,3
7	11823	348,8	347,9	1,3	347,0	348,9	0,3
8	13512	350,6	348,3	1,5	347,2	349,3	0,3
9	15201	347,6	348,2	1,5	347,3	349,1	0,3
10	16890	348,2	348,2	1,4	347,4	349,0	0,2
20	33780	349,1	348,5	1,6	347,9	349,1	0,2
30	50670	348,0	348,6	1,4	348,1	349,0	0,1
40	67560	348,8	348,6	1,2	348,2	348,9	0,1
50	84450	351,4	348,5	1,7	348,1	348,9	0,1

Table 10 - Number of runs versus deviation cum. mean - Energy consumption EE

Arrival Delay (punctuality)

In Figure 45 the graphical representation of the cumulative mean and 95% confidence intervals for the energy consumption at the wheel is displayed. It is seen that the mean becomes flat around 12 runs. However in Table 11 it can be seen that the deviation of the confidence interval is narrowing reasonably up to run 30. Therefore it is concluded that for punctuality at least 30 runs are necessary to give an accurate approximation of the mean arrival delay. Furthermore it that the mean

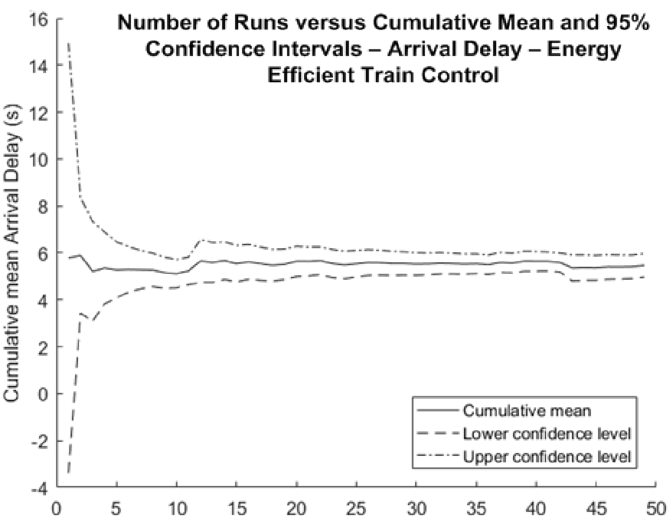


Figure 45 - Number of runs versus cum. mean and 95% CI- Arrival delay EE

arrival delay shows the same hiccup around run 43 as in the figure for energy consumption. De influence of this is again small. The deviation of the confidence intervals relative to the mean is larger than the deviation found for energy consumption, meaning that arrival delay shows a larger variation between runs. The number of measurements in Table 11 represents the number of arrivals for all stations combined.

Runs	Cum. # of measurements .	Mean (s)	Cumulative mean (s)	Standard Deviation (s)	Lower Confidence Level (s)	Upper Confidence Level (s)	**Deviation Cumulative mean (%)**
1	3287	4,3	4,3	n/a	n/a	n/a	**n/a**
2	6574	7,2	5,8	2,1	-3,4	14,9	**158,4**
3	9861	6,1	5,9	1,5	3,4	8,4	**41,9**
4	13148	3,2	5,2	1,8	3,1	7,3	**40,9**
5	16435	5,9	5,4	1,6	3,8	6,9	**28,5**
6	19722	4,9	5,3	1,4	4,1	6,5	**22,6**
7	23009	5,4	5,3	1,3	4,3	6,3	**18,3**
8	26296	5,2	5,3	1,2	4,5	6,1	**15,5**
9	29583	5,2	5,3	1,1	4,6	6,0	**13,5**
10	32870	4,1	5,2	1,1	4,5	5,8	**12,9**
20	65740	6,3	5,5	1,7	4,9	6,2	**11,7**
30	98610	5,5	5,5	1,6	5,1	6,0	**9,0**
40	131480	8,6	5,6	1,6	5,2	6,1	**7,6**
50	164350	8,3	5,5	2,1	5,0	6,0	**9,1**

Table 11 - Number of runs versus deviation cum. mean - Arrival delay EE

Number of occurrences of braking actions at signals (conflicts)

For conflicts, measured as the nu by the number of occurrences of braking actions related to certain signal aspect, only the calculations for red signal aspect (full stop) are presented. It is calculated that this is the determinant type of braking action regarding the number of runs needed.

In Figure 46 it can be seen that the cumulative mean of this variable becomes flat around 15 runs of the model, whereas the confidence interval reasonably narrows up till around 20 runs, which is seen in Table 12. It is therefore concluded that 20 runs would have been sufficient to accurately estimate the occurrences of braking actions at certain signal aspects.

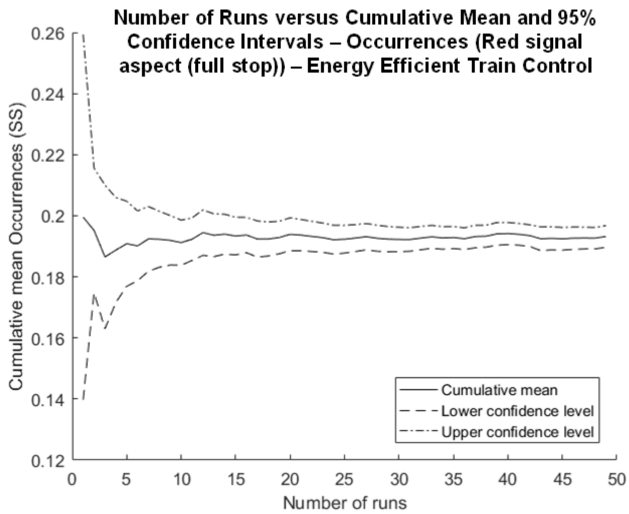


Figure 46 - Number of runs versus cum. mean and 95% CI - Occurrences (Red signal aspect (full stop)) EE

The number of measurements in this table are the number of trains. So the cumulative mean represents the average number of times a train encounters a red signal and has to come to a full stop.

Runs	Cum. # of measurements.	Mean (#)	Cumulative mean (#)	Standard Deviation (#)	Lower Confidence Level (#)	Upper Confidence Level (#)	**Deviation Cumulative mean (%)**
1	1689	0,19	0,19	n/a	n/a	n/a	**n/a**
2	3378	0,21	0,20	0,01	0,14	0,26	**29,98**
3	5067	0,19	0,20	0,01	0,17	0,22	**10,45**
4	6756	0,16	0,19	0,02	0,16	0,21	**12,61**
5	8445	0,20	0,19	0,02	0,17	0,21	**9,10**
6	10134	0,20	0,19	0,02	0,18	0,20	**7,29**
7	11823	0,19	0,19	0,02	0,18	0,20	**6,01**
8	13512	0,21	0,19	0,02	0,18	0,20	**5,49**
9	15201	0,19	0,19	0,01	0,18	0,20	**4,76**
10	16890	0,19	0,19	0,01	0,18	0,20	**4,22**
20	33780	0,20	0,19	0,01	0,19	0,20	**2,76**
30	50670	0,18	0,19	0,01	0,19	0,20	**2,15**
40	67560	0,22	0,19	0,01	0,19	0,20	**1,91**
50	84450	0,22	0,19	0,01	0,19	0,20	**1,84**

Table 12 - Number of runs versus deviation cum. mean - Occurrences (Red signal aspect (full stop)) EE

From the calculations it is concluded that arrival delay is the determinant variable in this research, since it needs the most runs in order to accurately estimate the mean. The results described above are calculated on network scale (e.g. the totals for the entire network). In this research also includes results at smaller levels of aggregation: The arrival delay at the most important stations in the network and energy consumption for individual train series. Since the number of measurements is lower at lower aggregation levels, at these levels often a larger number of runs are required.

Data that is insufficiently accurate at 50 runs are taken out of the results of the concerning aggregation level, but will be part of the calculation on the network level, since the accuracy is proven to be sufficiently accurate for 30 runs of more.

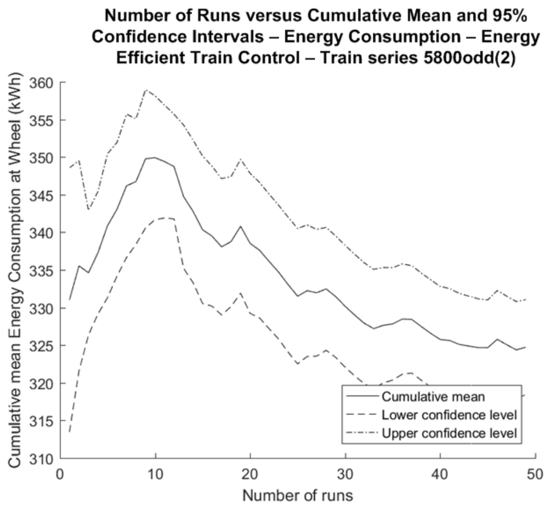


Figure 47 - Number of runs versus cum. mean and 95% CI - Energy consumption 5800odd(2) EE

Energy consumption of individual train series

It is calculated that the deviation of the confidence levels relative to the mean energy consumption for all train series individually is relatively low in all occasions. However for a number of train series the mean energy consumption does not become flat. An example is given in Figure 47. For this train series the mean still shows a downward trend after 50 runs, e.g. the mean does not settle within 50 runs. Since the mean is still changing, the estimation of the mean energy consumption is inaccurate. It is found that a number of train series also fail to stabilize within 50 runs, these train series are displayed in Table 13. The train series concerned are not evaluated in calculations on the train series level. It is seen that the number of measurements (the number of trains). The train series concerned do not contain many trains (1-3 trains per series) and are all part of a larger series, e.g. some of the train series have been split up into more clusters, because some trains within a series show different behavior relative to other trains in the series, for instance making an extra stop. Because this, the behavior of these trains is not representative for the majority of the series and these series are therefore split up into one or more clusters. The clusters are described in Appendix F.

Train series (cluster)	Cum. # of measurements
1500even(3)	50
1500odd(3)	50
2600even(2)	100
3000even(2)	100
3000even(3)	50
4000even(2)	150
4000odd(2)	100
4600even(2)	50
5800odd(2)	50
5800odd(3)	50

Table 13 - Train series with insufficient accuracy on mean energy consumption

Arrival delay of individual stations

For the individual train stations similar calculations are performed. For all stations except for Hilversum the mean is stable within 50 runs. The graphical representation of the cumulative mean and 95% confidence intervals for arrival delay at station Hilversum is displayed in Figure 48. This station will not be part of the assessment of effects on punctuality on the station level.

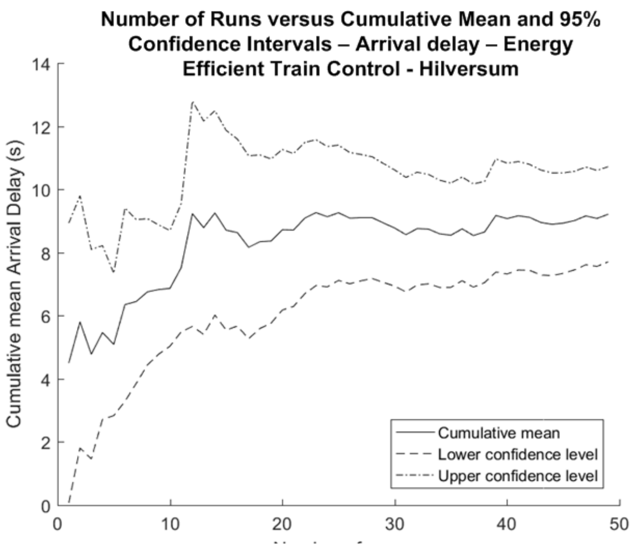


Figure 48 - Number of runs versus cum. mean and 95% confidence intervals - Arrival delay Hilversum EE

It is concluded that for calculations on the network level 30 runs of the model would be sufficient to accurately predict the mean values on all dependent variables. However at the lower aggregation levels 50 runs are not sufficient to accurately predict the means for certain train series and stations. The unreliable results are therefore not described in the results on these levels of aggregation.

5. Results

In this chapter the results of this research are discussed. In the first paragraph

5.1. Traditional Train Control versus Energy Efficient Train Control

Energy consumption

The effects energy efficient train control within the research network are described by means of a scatter plot. This scatter plot is displayed in Figure 49. Every sample point represents a train for which the energy consumption of traditional train control is directly compared to the energy consumption under energy efficient train control. OpenTrack uses streams of random variables that are referenced in delay scenarios to draw from the distributions on initial delay and dwell time. For

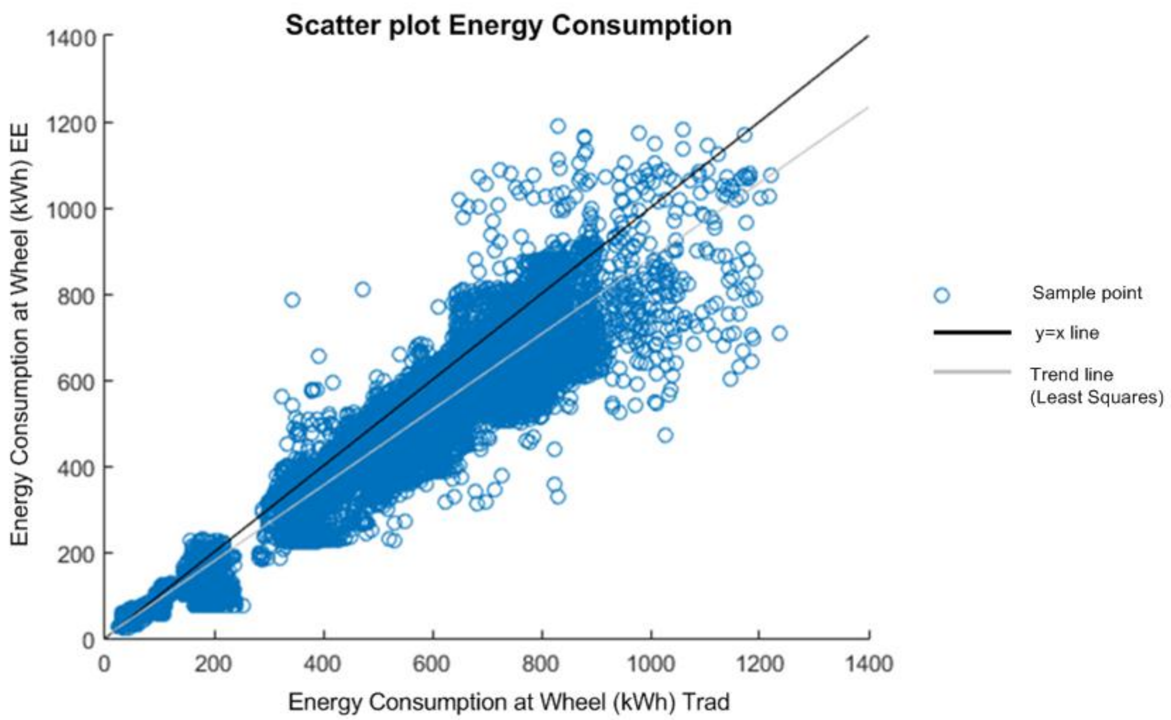


Figure 49 - Scatter plot Energy Consumption - Traditional train control versus regular train control

both strategies the same sequence of delay scenarios are used, which means that the strategies can be compared directly. Also plotted in the figure are the y=x-line and the trend line based on a least-squares fit. Energy efficient train control is plotted to the y-axis, traditional train control is plotted to the x-axis. If no differences between the control strategies would exist, the sample points would be plotted on the y=x-line. It is clear that energy efficient train control has led to both increases and decreased in energy consumption. On average the energy consumption has decreased, e.g. the trend line deviates downwards from the y=x-line. So when energy efficient train control is applied by all trains in the network, this will in general lead to an energy saving. However many sample points are above the y=x-line meaning that the energy consumption has increased. Scatter plots on individual train series show similar behavior; increases are found in the majority of series, meaning that they occur throughout the network.

A network is a highly dynamic environment in which interaction takes place. The applied control strategies have influence on the position in space and time of all trains in the within a network. Together with different distributions of delay, e.g. delay scenario's, this will lead to different patterns of interaction between trains, affecting running times and energy consumption. It is outside the scope of this research to provide a full understanding of interaction related to energy efficient train control, therefore the behavior on a network is to complex. Interaction is only described by effects of energy efficient train control in terms of number conflicts and effects on punctuality. The complexity of network dynamics are illustrated by a specific case below.

Figure 50 represents a deterministic simulation of the planned timetable as provided by ProRail. Deterministic simulation implies that no stochastic elements are present, meaning that a replication of the simulation would lead to the same outcome in a replication. Although the planned timetable is almost free of conflicts, a conflict has been found and is displayed in the figure.The freight train in red and the international train in purple are planned to use the same section of track on the same time, because the planned trajectories (dotted lines) meet. As this is impossible it results in a conflict. Braking actions are enforced by the signaling system to the international train (circles in the time distance diagram). This is not an error within the model: Although four parallel tracks are present at the specific location (two for each direction), both trains are planned on the same track. The slow track, regional trains are fixed to the slow inside track as the platforms of the regional stations are only situated at this track. Because the freight train overtakes a regional train (the blue line), it means that the freight train is planned on the fast outside track, the same track that is used by the following international train. The provided track planning in the timetable provided confirms that indeed the trains in the conflict are planned on the same track. This error in the planning does provide a useful opportunity for describing network dynamics: As this conflict is planned to take place, having no delays in the system would mean that the conflict takes place in every run of the model. In Table 14 the energy consumption of the international train (train 123) are given for every run of the stochastic model. The results represent stochastic simulation, which means that delays are present in the entire network.

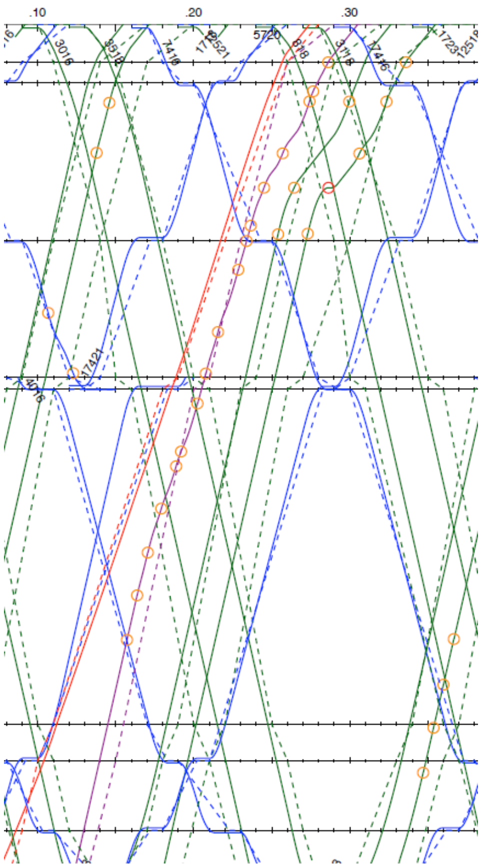


Figure 50 - Cut out time distance diagram of conflict in the timetable

Run number	Energy Consumption Trad. (kWh)	Energy Consumption EE (kWh)	Run number	Energy Consumption Trad. (kWh)	Energy Consumtion EE (kWh)
1	643,2	601,5	26	773,8	457,2
2	**640,1**	**327,8**	27	720,9	614,0
3	608,3	444,7	28	480,8	425,7
4	812,3	616,7	29	697,4	315,4
5	482,9	429,3	30	390,7	654,1
6	625,2	315,4	31	742,4	865,5
7	553,6	422,9	32	688,5	438,6
8	809,1	821,0	33	324,1	561,4
9	668,9	492,5	34	763,3	501,5
10	324,1	334,1	35	552,7	342,7
11	650,5	478,9	36	815,1	555,5
12	778,5	453,2	37	591,0	388,0
13	727,0	377,7	38	574,7	425,5
14	503,0	507,8	39	498,1	309,5
15	**471,8**	**808,8**	40	490,2	540,1
16	823,9	438,6	41	476,9	323,3
17	449,0	501,5	42	810,5	837,0
18	521,4	412,6	43	344,3	785,6
19	683,3	311,9	44	830,3	330,5
20	367,2	356,5	45	822,7	815,9
21	712,9	346,6	46	324,1	379,7
22	683,2	450,5	47	693,9	564,8
23	518,9	301,8	48	491,1	330,0
24	589,4	356,7	49	641,3	409,5
25	689,1	646,1	50	506,2	404,1

Table 14 - Energy consumption train 123 Trad. versus EE for 50 runs.

The output for each stochastic simulation represents the outcome for a certain delay-scenario. From the outcome of the asynchronous discrete simulations it is found that the energy consumption for the train described is around 320 kWh when it can travel A to B free of other trains. As can be seen from the table, the conflict as incorporated in the timetable does and does not occur alternately with various degrees of impact. Alternation is found in both the energy efficient train control strategy and traditional train control strategy. In some delay scenarios the conflict happens in the traditional train control strategy where it doesn't in energy efficient train control (for instance run 2) and in other delay scenarios the opposite happens (for instance run 15).

The example has shown that different delay-scenarios can lead to very different patterns of interaction within the network. It shows that a strategy choice for the own train, whether this is traditional train control or energy efficient train control does not guarantee a certain outcome regarding the energy consumption. The outcome of a certain strategy is highly dependent on the delays in the network. Applying energy efficient train control does therefore not guarantee an energy saving is achieved, although on average it will lead to less energy consumption.

In Table 15 the calculated energy consumption of both traditional train control and energy efficient train control are displayed. The energy consumption calculated is the energy consumption per train, measured over all trains in the network based on 50 runs of the simulation.

It can be seen that by application of energy efficient train control, 11.3% of energy is saved relative to traditional train control.

	Traditional Train Control	Energy Efficient Train Control	Difference in %
n	84450	84450	
Min (kWh)	24,8	24,0	-3,2
25th prct (kWh)	108,3	99,6	-8,0
Median (kWh)	421,9	367,5	-12,9
75th prct (kWh)	613,1	557,9	-9,0
Max (kWh)	1238,7	1189,3	-4,0
Mean (kWh)	392,7	348,5	-11,3
Dispersion (std) (kWh)	265,9	239,2	-10,0
Reject H0 (α=0,05) **2-sample K-S Test**	Yes		

Table 15 - Results energy consumption

To determine whether or not the decrease of energy consumption is significant a statistical test is conducted. This ensures that the difference is not found bases on chance, but is in fact structural. The datasets are statistically compared by use of the 2-sample Kolmogorov-Smirnov test. The 2-sample Kolgomorov Smirnov test is a nonparamtetric test for equality between the empirical cumulative distibution functions of two samples. The test statistic of the Kolmogorov Smirnov is the maximum vertical distance between the empirical cumulative distribution functions. The null-hypothesis of the K-S test states that both datasets come from the same distribution. Rejection of the null-hypothesis means that the data comes from different distributions (e.g. both datasets are significantly different). The empirical distribution functions are displayed in Figure 51 It has been smoothed for esthetic reasons by Kernel smoothing.

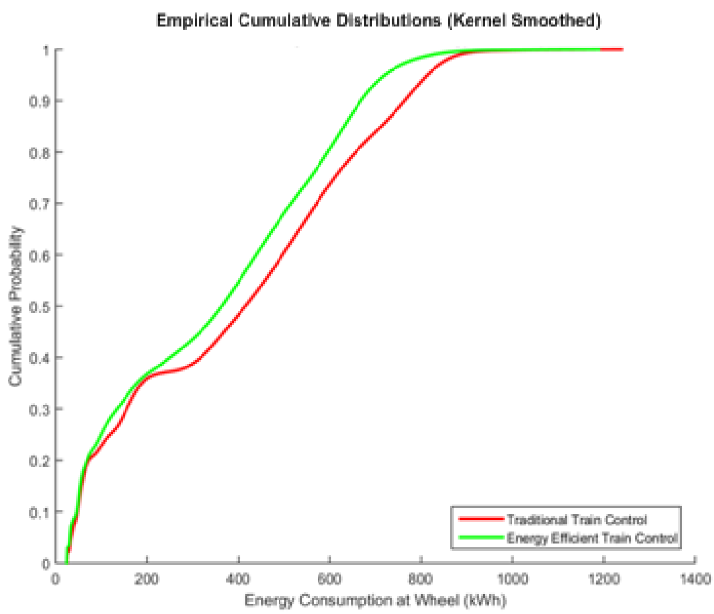


Figure 51 - Empirical cum. density energy consumption - Trad vs. EE

The Kolmogorov-Smirnov tests rejects je null-hypothesis at significance level α=0,05, meaning that the difference between energy efficient train control and traditional train control is significantly different. This proves that appying the energy efficient train control strategy will lead to an decrease in energy consumption.

To assist the drivers in energy efficien train control, NS is currently experimenting with a train based dynamic-DAS system. Train based dynamic DAS-systems advice train drivers on the strategy to follow in order to maximize the energy efficiency of the trip, based on the current location of the train in space and time relative to the timetable. Because it is based on the current position relative to the timetable it gives a taylor-made advice incorporating the delay of the train in the calculation. This approach is very similar to the modeling of energy efficients strategy in this research: Based on the timetable of a train, the characteristics of the train and the infrastructure, the coasting points are determined for delays that allow for coasting (e.g. ranging from no delay to a delay that is equal to the slack time available). At perfect execution of the advice from the DAS the savings of 11.3% can be achieved. As train based DAS only optimizes the speed profile of the own train only following the strategy will just as in this research not always lead to an optimal solution for the train concerned. Connected-DAS (or c-DAS) has the potential to increase the saving potential within a network. In c-DAS the positions of all trains are communicated with traffic control through a GSM-R network. A traffic management system calculates an optimal solution for the combined network and communicates the best individual strategies back to the trains. This potentially can reduce increases in energy consumption and with that increase the energy saving potential of energy efficient train control. Currently only an experiment with train based dynamic DAS is conducted. It is adviced to implement this system. Finding the optimal coasting points has resulted in a great variety of energy efficient train control profiles, because the distributions of slack time greatly vary amongst train series and even within train series. These profiles can be found in Appendix E. In order to achieve the savings calculated a dynamic DAS system is an essential tool.

In Figure 52 the spatial distribution of energy savings over the network are displayed. For all track sections between service control points it is calculated how much energy is consumed by the trains utilizing the specific sections for both the traditional train control strategy and the energy efficient train control strategy. The figure displays the savings of energy efficient train control relative to traditional train control. Decreases in energy consumption are displayed in blue/green shades. Increases in energy consumption in yellow/red shades.

From the figure it is seen that not every track section is suitable for coasting. These show slight increases in energy consumption.

Under certain conditions coasting is not applied at a track section:

- Trains on the section of track do not have slack time available for coasting, either because it is not incorporated in the timetable or not available due to delays.
- The track section is not a coasting area and trains are in another regime at this section (acceleration, cruising or braking)
- The permissible line speed is lower than the lower coasting limit. A lower coasting limit is set at 80 km/h (e.g. coasting is never applied below this speed).

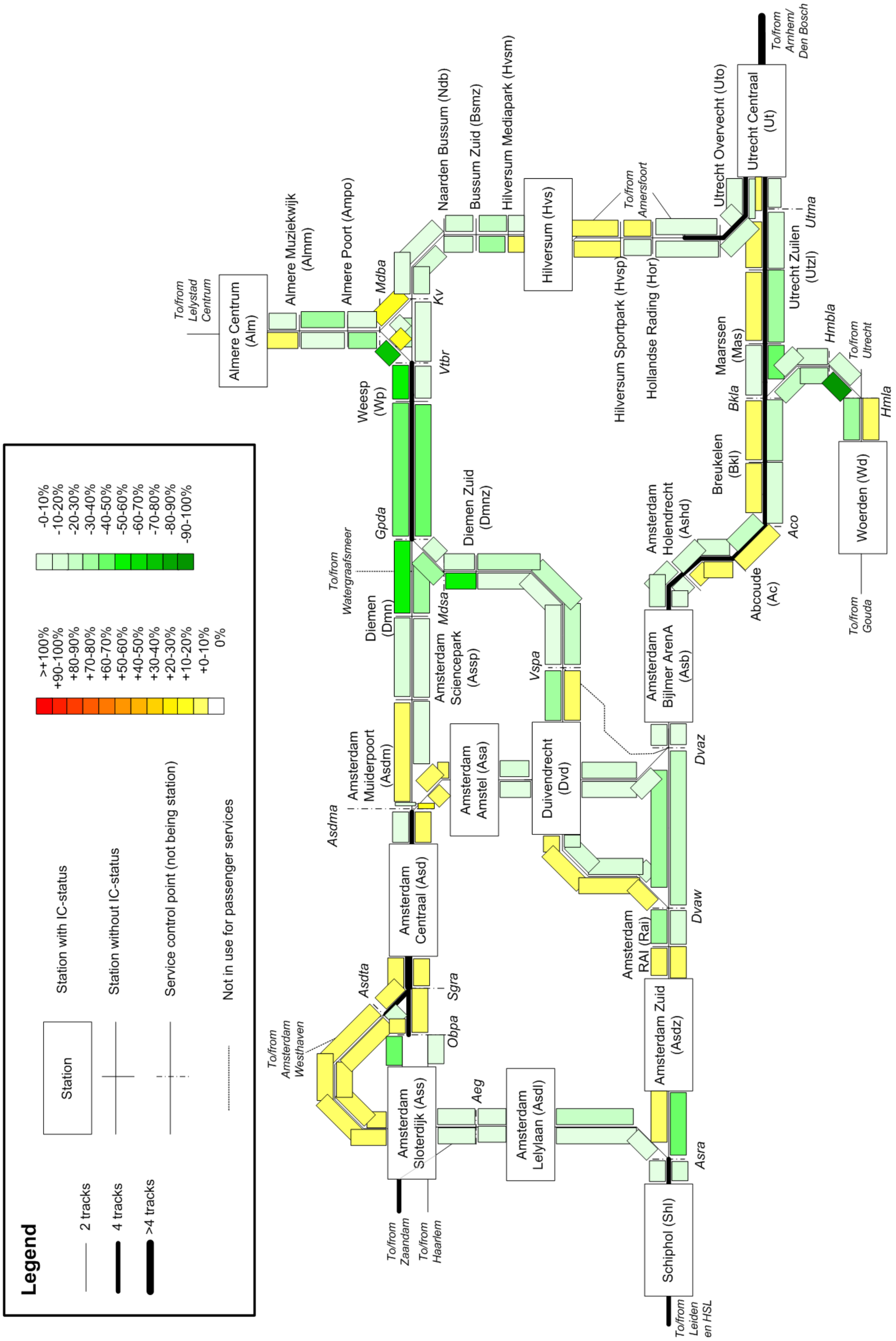


Figure 52 - Energy savings spatial distribution

When coasting is not applied the traditional train control strategy and traditional strategy are nearly equal (e.g. both strategies only contain acceleration, cruising and braking regimes). A setting in one of the parameters (the performance parameter in OpenTrack) causes the trains carrying out the energy efficient train control to run slightly faster than trains carrying out the traditional train control strategy. As could be seen in the previous chapter the performance setting for traditional train control is 97% when a train is delayed and 94% when a train is early. The percentage describes at what rate the regimes are carried out. Performance of 97% means that acceleration is done at 97% of the maximum rate, the train cruises at 97% of the maximum permissible line speed and brakes at 97% of the maximum rate. Trains carrying out the energy efficient train control are modeled to always run at 100% of the maximum performance to ensure that the slack time that is available for coasting is maximized, as it is described in the theory on optimal train control. By running slightly faster the energy consumption of energy efficient train control is higher when no coasting is applied (e.g. the regimes are equal). A sensitivity analysis on the performance parameter is conducted later in this research to determine the effects of the performance parameter setting.

Figure 52 shows that on the majority of the network energy savings are measured, but especially in the Amsterdam Centraal region increases in energy consumption are found. Those mainly relate to the setting of the lower coasting limit of 80km/h. The areas where a speed limit of 80km/h are in place are described in Appendix C. The lower coasting limit can have a substantial influence when a permissible line speed of 80km/h is in place in between station stops. This is the case for the area roughly reaching from Amsterdam Sloterdijk up to Amsterdam Amstel/Amsterdam Muiderpoort. Slack time in between stops at these stations will not be consumed, because coasting is not applied due to the setting. The slack time in essence becomes unusable for energy efficient train control. To estimate the effect of the low speed zone around the Amsterdam Centraal Station, a calculation on energy consumption for the trains not running through Amsterdam Centraal is made. Although this strictly does not tell anything about the magnitude of unused potential of the lower coasting limit (this would require new simulations with a different speed setting) it gives an impression of lost potential. In Table 16 the train series not running through Amsterdam Centraal are displayed as well as the energy savings of these series. The energy savings of individual train series are found in Appendix G.

As can be seen the savings are reasonably higher for trains not calling at Amsterdam 12.1% to 11.3%.

Train series not running through Amsterdam Centraal				
11600even	17400even	3500even	4900even	5700odd(2)
11600odd	17400odd	3500odd	4900odd	700even
12700even	3100even	4300even(1)	5700even(1)	700odd
12700odd	3100odd	4300even(2)	5700even(2)	7400even(1)
1600even	3300even	4300even(3)	5700even(3)	7400even(2)
1600odd	3300odd	4300odd	5700odd(1)	
Energy Consumption over 50 runs of Train series not running through Amsterdam Centraal				
Traditional Train control	1,66E+07 kWh			
Energy Efficient Train Control	1,46E+07 kWh			
Energy savings	-12,1%			

Table 16 - Energy consumption without train series calling at Amsterdam Centraal

It is assumed that coasting at low speeds can be perceived negatively by passengers. This is why the lower coasting limit is set. It should be investigated whether this assumption is justified, because saving potential in the timetable is not effectuated..

In general it is seen that a reasonable energy saving can be achieved by applying the energy efficient train control strategy throughout the network. It has not yet been described that delays also influence the saving potential directly. As long as a delay is not larger than the slack time that is available coasting can be applied. The magnitude of the delay determines the off slack time that is available for coasting. The amount of slack time largely determines the energy savings achieved. This means that the saving potential can be increased by reducing delays in the network, both reduction of primary delays (for instance a delay at dwelling) as secondary delays would benefit the saving potential within a network.

Regarding the energy consumption it is concluded that application of energy efficient train control in general leads to a reduction of the energy consumption of a train, although applying the strategy does not guarantee that an energy saving is made. Due to the network dynamics in combination with different patterns of delay the strategy will in some situations lead to an increase in energy consumption. The saving potential of energy efficient train control can be increased by tackling issues that lead to delays and/or implementing a connected-DAS. Since connected-DAS is not foreseen in the near future (Luijt R. , 2016) it is advised to implement the train based dynamic DAS system that is experimented with in the Netherlands. This system would help the train driver to optimize the energy efficient train control strategy and helps to effectuate the saving potential within the timetable. The analysis has shown that a substantial saving of 11.3 percent can be achieved within this network, even though this network can be considered heavily utilized and that the network contains a large low speed zone in which no coasting is applied. This shows that energy efficient train control is an effective means of reducing energy consumption.

Punctuality

In this section the results on punctuality are discussed. Punctuality is a performance indicator of on-time arrival within a network. It is measured by calculating the deviations of the actual arrival times in relation to the planned arrival times. This gives the arrival delay. In Figure 54 the distributions of the arrival delay are displayed for both the traditional and energy efficient train control strategy. This figure is based on the arrival delays of all stations in the network combined. It should be mentioned that not all station stops are part of the punctuality calculations. For short stops no arrival times are specified in the Dagplan timetable. Short stops are stops that are planned with a dwell time shorter than one minute. For these stops only a departure time is defined in the timetable. All times in the timetable are rounded, meaning that if a stop is planned to take less than one minute no arrival time can be defined. Not rounding the arrival times would solve this issue, and the punctuality calculated would be more 'fair,' because the calculations would contain all trains.

As it can be seen from the figure, the distributions generally follow the same shape except for the peak that is seen around zero seconds. This indicates that in the energy efficient train control strategy a larger number of trains arrive close to the planned arrival time. In the right tail of the distribution the positive delays are found (e.g. trains that arrive late). It is seen that energy efficient train control does not cause more trains to arrive late relative to traditional train control.

It is also seen that although energy efficient train control is applied, still a lot of trains do arrive early in this strategy. As seen in the previous section on energy consumption a large low speed zone is in place around Amsterdam Centraal station. In combination with the setting of the lower coasting limit, this prevents trains from coasting in the vicinity of Amsterdam. The slack time situated in this zones is therefore not consumed, which means that trains will arrive early when no conflicts are experienced. Since Amsterdam Centraal is one of the largest stations in the network in times of number of arrivals, this station is responsible for a large share in the overall results of the network.

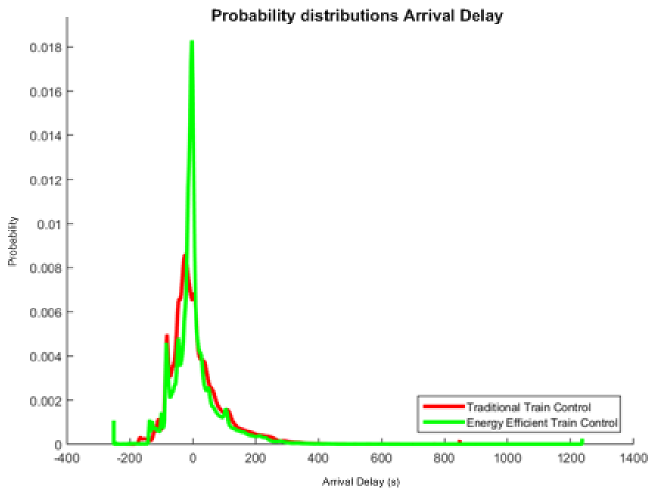


Figure 53 - Arrival Delay probability distributions

To provide better understanding of the effects of energy efficient train control the results on punctuality of Weesp are discussed. Weesp is a station that is situated in a part of the network where the highest savings are calculated as can be seen in Figure 52. The distributions of traditional and energy efficient train control for Weesp station are displayed in Figure 54.

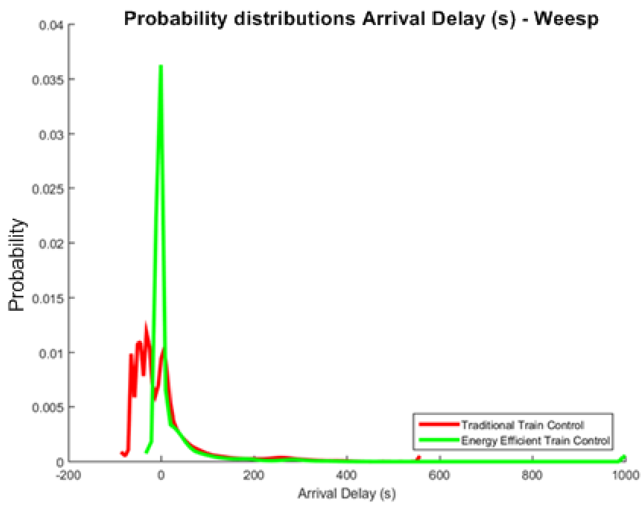


Figure 54 - Arrival delay distributions station Weesp

From the figure it is seen that in a region where the energy efficient train control is very efficient the arrivals tend to be exactly on time for the energy efficient train control strategy, whereas in the traditional train control strategy more trains arrive early. The tails of the distributions again overlap indicating that by application of the energy efficient train control does not lead to trains arriving late more often. Instead most trains arrive around the planned arrival time. Arriving at the arrival time, rather than early should not affect passengers negatively as long as the transfer times to connecting trains services are adequately determined. This is important, because by missing a connection the travel time of passengers significantly increases, because the waiting time for the next train ads to the total travel time. The delay distributions are determined for all stations in the network that fulfill an important transfer function. These distributions can be found in Appendix H.

In order to determine whether the distributions of the arrival delay are statistically different for both control strategies, again the 2-sample Kolmogorov-Smirnov test is conducted for the individual stations within the network as well as for the arrival delay for all stations combined.The two-sample Kolmogorov-Smirnov tests accepts the null-hypothesis for the cumulative density functions of the results of all stations combined, Amsterdam Centraal, Amsterdam Sloterdijk and Duivendrecht and rejects the null hypothesis for the stations Almere Centrum, Schiphol Utrecht and Weesp. This means that only for the latter 4 stations significant differences between the two strategies are proven. The stations for which the null-hypothesis is accepted (e.g. no significant difference between the strategies is proven) have in common that little energy is adjoining track sections or that trains on the adjoining sections have more slack time than can be consumed. The latter applies to Duivendrecht. Because Duivendrecht is near some important nodes, much slack time is concentrated here. Because the distance to the surrounding stations is fairly short trains will often arrive in Duivendrecht with slack time left. For Amsterdam Centraal and Amsterdam Sloterdijk applies that these stations are situated in the low speed zone.

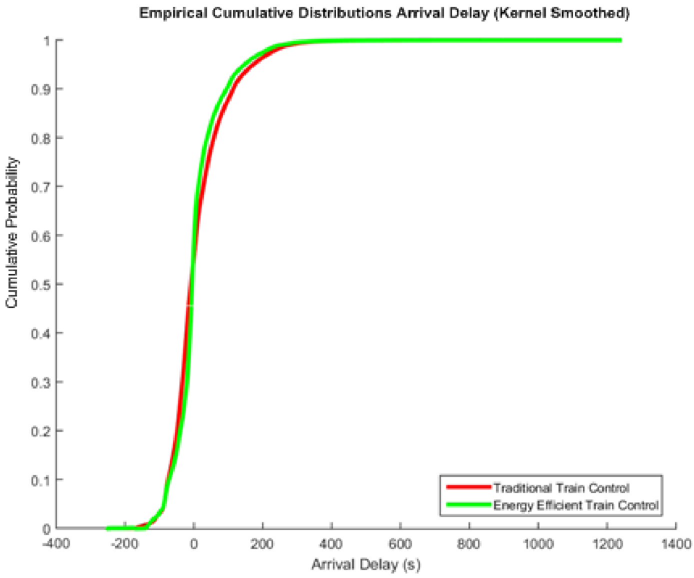


Figure 55 - Empirical cumulative density arrival delay - Trad vs. EE

	Traditional Train Control	Energy Efficient Train Control	Difference in %
Punctuality 3-minutes (%)	95,4	96,7	1,4
n	164350	164350	0,0
Min (s)	-251	-251	0,0
25th prct (s)	-42	-27	-35,7
Median (s)	-8	-4	-50,0
75th prct (s)	40	24	-40,0
Max (s)	848	1237	45,9
Mean (s)	8,7	5,5	-37,5
Dispersion	81,5	72,0	-11,6
Reject H0 (α=0,05) 2-sample K-S test	No		

Table 17 - Results punctuality

For the stations for which the 2 sample K-S tests rejects the null-hypothesis it applies that the energy savings on the adjoining sections of track are relatively large and that the slack time can largely be fully consumed. As is seen in the example for station Weesp, the majority of trains arrive close to the planned arrival time when the energy efficient train control strategy is applied, whereas in traditional train control more trains arrive early. It is also seen that the dispersion in the arrival times is reduced by energy efficient train control. This means that the mean arrival times found are a more reliable prediction of the real mean arrival time. Because of smaller dispersion, the time windows for trains passing through certain section of track are narrowed when all trains would apply the energy efficient train control strategy. This enhances the capacity of the network.

NS uses the 3-minute punctuality norm to define the on-time performance of stations. The 3-minute norm describes the percentage of trains that arrive within three minutes of delay at a certain station. The 3-minute norm for this network with respect to both strategies are displayed in Table 15. As can be seen the punctuality actually shows an increase for application of the energy efficient train control. The increase is actually caused by the setting of the performance parameter, which has been discussed before. Due to this setting, in delayed condition trains using the energy efficient train control run slightly faster. It does not seem plausible that in reality train drivers that prefer to use traditional train control do drive slower in delayed condition than train drivers that prefer to apply the energy efficient train control strategy. In the sensitivity analysis that is described later, both strategies are re-run with equal settings of the performance parameter.

As can be seen from Table 5 the 3-minute punctuality is initially high, over 95 percent. The 95 percent punctuality is the punctuality that is achieved given the distribution functions. In reality this number is often lower around (90-91% (NS, 2015). One reason for the large difference between the real and modeled punctuality is the lack of large disruptions in the model, which are present in the real world. This research does not aim to find the real punctuality. The goal is to determine whether and how punctuality is affected by energy efficient train control.

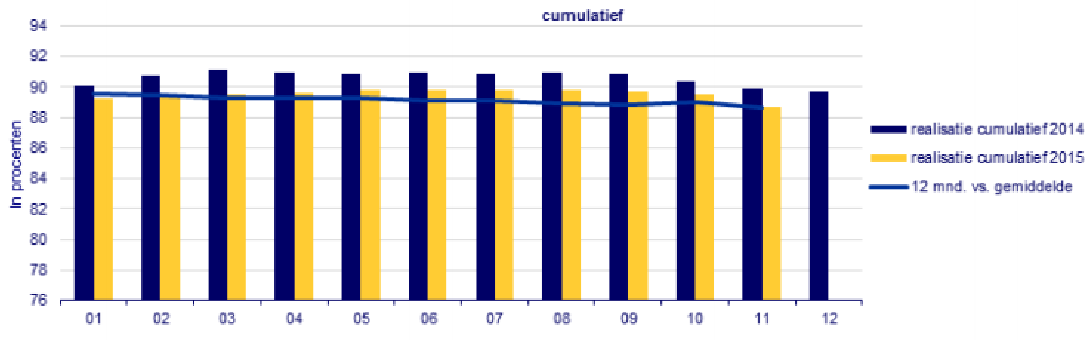


Figure 56 - Realized Punctuality 2014 3-minute margin (NS, 2015)

When reviewing the results on energy consumption, although it is found that some trains will not benefit from application of the energy efficient train control strategy (e.g. higher energy consumption) this had not led to negative consequences on punctuality. The theory that coasting can lead to more delay at the nodes in the network from the conceptual model is not supported by the results.

It is concluded that regarding the punctuality, energy efficient train control does not lead to negative effects. In general it is seen that for stations where energy efficient train control is applied effectively on the adjoining sections of track, trains will arrive close to the planned arrival time that is described in the timetable. Trains for which the traditional train control is applied generally arrive more early. Arriving close to the planned arrival time, rather than early does not affect passengers negatively as long as the transfer times to connected services are determined accurately. The dispersion in the distribution of arrival time for energy efficient train control is smaller than the dispersion found for the arrival delay distribution of traditional train control. A lower dispersion means that the time-windows for passing through a section of the network become smaller. This means that energy efficient train control enhances the capacity of the network.

Conflicts

In this paragraph the changes in conflicts between traditional train control and energy efficient train control are described.

Conflicts are a measure for the interaction between the trains in the network. A conflicts are explained by the differences with respect to the occurrences of certain signal aspects between traditional train control and energy efficient train control. Conflicts have an influence on safety, energy consumption and indirectly on the punctuality (e.g. delay from a conflict does not necessarily lead to late arrival, because slack time can act as a time-buffer). In Table 18 the results on occurrences of braking actions for certain signal aspects are given, the differences between traditional train control and energy efficient train control in the last column represent difference in conflicts. The values displayed represent the number of occurrences per train trip (e.g. a value of .22 on the mean for red signal aspect (full stop) means every train in the model has to stop.22 times for a red signal in a single trip (or approximately once every 5 trips)). The difference in conflicts between the control strategies are explained by the difference in occurrences of the signal aspects. For red signal (full stop) this means that application of the energy efficient train control strategy leads to .22 -0.19=.03 less conflicts for every trip, or once in approximately 33 trips a full stop conflict is averted. This is a reduction of 10.7 percent.

Braking actions at signals	Traditional Train Control	Energy Efficient Train Control	Difference in %
n	84450	84450	
Red signal aspect (full stop)			
Min (#occurrences/train trip)	0	0	
25th prct (#occurrences/train trip)	0	0	
Median (#occurrences/train trip)	0	0	
75th prct (#occurrences/train trip)	0	0	
Max (#occurrences/train trip)	4	5	25
Mean (#occurrences/train trip)	0,22	0,19	-10,7
Disp. (std) (#occurrences/train trip)	0,49	0,46	-5,3

Red signal aspect (approach)			
Min(#occurrences/train trip)	0	0	
25th prct (#occurrences/train trip)	0	0	
Median (#occurrences/train trip)	0	0	
75th prct (#occurrences/train trip)	1	1	0
Max (#occurrences/train trip)	14	17	21,4
Mean (#occurrences/train trip)	0,57	0,52	-10,0
Disp. (std) (#occurrences/train trip)	1,08	1,06	-2,0
Yellow signal aspect			
Min (#occurrences/train trip)	0	0	
25th prct (#occurrences/train trip)	1	1	0
Median (#occurrences/train trip)	2	2	0
75th prct (#occurrences/train trip)	5	4	-20
Max (#occurrences/train trip)	26	26	0
Mean(#occurrences/train trip)	3,12	2,68	-14,3
Disp. (std) (#occurrences/train trip)	2,82	2,46	-12,5

Table 18 - Results conflicts

As can be seen all conflicts are reduced with application of the energy efficient train control strategy in ranges from 10-15 percent. Because the number of red signal occurrences (Red signal aspect (full stop) and red signal aspect (approach)) have reduced, energy efficient train control is beneficial to safety.

All types of braking actions enforced by the signaling will have contributed to the energy savings found. Differences in yellow signal occurrences have probably contributed most, because usually these require the largest speed reduction, from permissible line speed to 40 km/h. For red signal aspects the speed reduction is 40km/h to 0km/h.

The most likely explanation for the differences between the control strategies is in conflicts is that trains using the traditional train control arrive early at the node, increasing the chance that the next block has not yet been cleared by the preceding train. In practice this often implies that the planned arrival platform is not yet cleared by the preceding train, resulting in the train having to wait for a red signal aspect.

To determine whether the changes found are statistically significant, the 2 sample t-test is conducted. The 2-sample Kolmogorov-Smirnov tests can only be used on continuous distributions, since the number of occurrences is a discrete variable (it can only take integer values), the 2-sample K-S test cannot be used. The two-sample t-test tests for differences between the means of two datasets. This test are conducted over the mean of the individual runs (e.g. n=50 for both scenario's) at a significance level α of 0,05. The null-hypothesis states that the means come from the same population (e.g. no statistically significant differences). The two-sample t-test rejects the null hypothesis for all signal aspects, which means that energy application of energy efficient train control leads to significantly less conflicts.

The test statistics of the test are displayed in The differences between traditional train control and energy efficient train control are visualized in the normal density plots in Figure 57.

	Red signal aspect (full stop)	Red signal aspect (approach)	Yellow signal aspect
Reject H0 (2-sample unpaired t-test)	**Yes**	**Yes**	**Yes**
p	5,54E-08	1,44E-14	6,94E-74
Upper confidence level	0,0173	0,0469	0,4317
Lower confidence level	0,0289	0,0678	0,4621
Test statistic	78,408	108,896	58,2997
Degrees of freedom	98	98	98
Standard deviation	0,0147	0,0263	0,0383

Table 19 - 2-sample t-test - conflicts

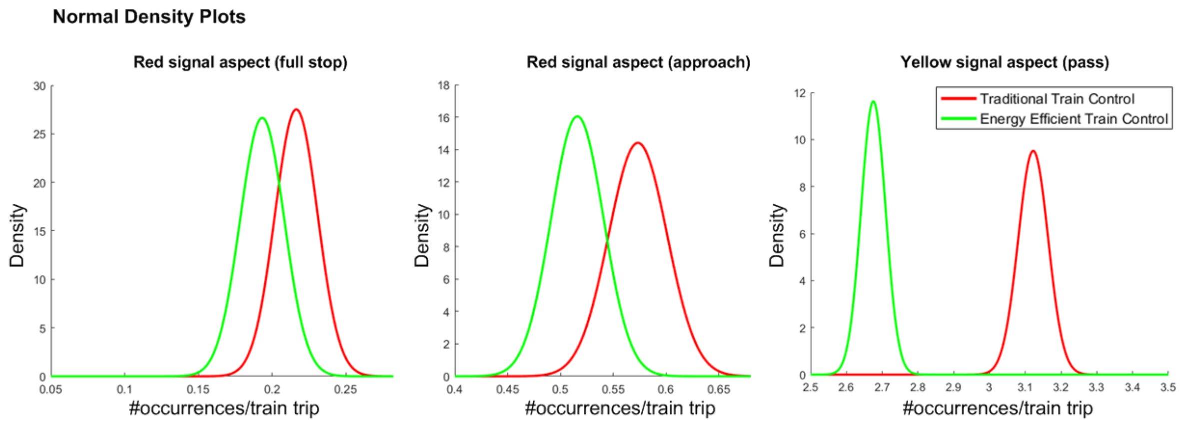


Figure 57 - Normal density plots occurrences of braking actions at different signal aspects - Trad vs. EE

It is concluded that energy efficient train control reduces the conflicts within a network. Reductions of 10-14 percent have been found. Red signal encounters have been reduced by around 10 percent. This benefits the safety within the network. The reductions in conflicts has contributed to the energy savings found. Reduction of conflicts at application of energy efficient train control are most likely explained by trains arriving around the planned arrival time, rather than early in the traditional train control strategy. Arriving early increases the probability that a conflict occurs, because the block section ahead has not yet been cleared by the preceding train because of the planned timetable.

5.2. Mixed control strategies on the same network

To investigate whether the energy efficient train control can influence the energy consumption of traditional train control and vice versa, in scenario 3, simulations are run in which the two strategies are both present on the network simultaneously. By comparing the energy efficient train control trips in this scenario with the energy efficient train control trips in scenario 2, in which 100% of the trains run under energy efficient and doing the same for the traditional train control trips (compare with traditional train control in scenario 1), it can be found whether or not the energy consumption is influenced by having mixed strategies on the same network simultaneously.

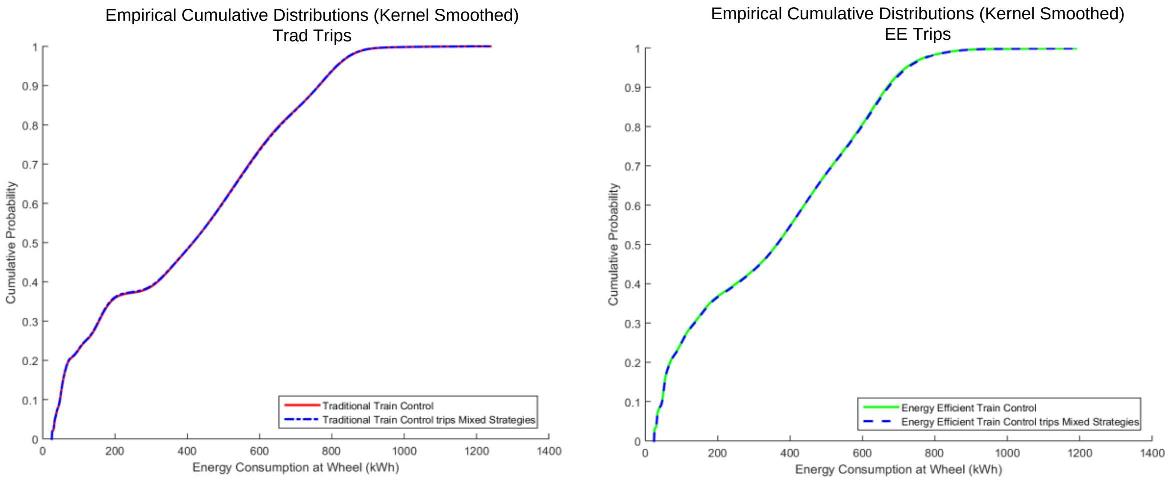


Figure 58 - Empirical Cumulative Density Functions, influence of mixed strategies.

Both strategies seem unaffected by having different train control strategies on the same network. looking at the Empirical Cumulative Density functions, because the distributions overlap. In Table 2, the differences are displayed. As can be seen for traditional train control the energy consumption seems to decrease (e.g. having less energy efficient train control trips benefits traditional train control trips, e.g. the traditional train control trips experience an increase in energy consumption due to energy efficient train control trips), whereas for energy efficient train control trips it seems to increase (e.g. having more traditional train control on the network increases the energy consumption of energy efficient train control).

The Kolmogorov-Smirnov test accepts the 0 hypotheses for both the energy efficient control and traditional train control trips. Though small differences are found. It cannot be proven they are statistically different and therefore these differences can be explained by chance. It can be concluded that there is no proof that having different train control strategies on the same network affects energy consumption. The energy savings are therefore assumed to be proportional to the degree in which energy efficient train control is applied.

Table 20 - Results mixed strategies on energy consumption

	Trad. trips Sc1	Trad. trips Mix Strat	Diff in %
n	84450	84364	-0,1
Min (kWh)	24,8	24,8	0,3
25th prct (kWh)	108,3	106,9	-1,3
Median (kWh)	421,9	421,7	0,0
75th prct (kWh)	613,1	615,4	0,4
Max (kWh)	1238,7	1233,0	-0,5
Mean (kWh)	392,7	392,5	-0,1
Disp (std) (kWh)	265,9	266,3	0,1
Reject H0 (α=0,05) 2-sample K-S test	No		

	EE trips Sc1	EE trips Mix Strat	Diff in %
n	84450	84536	
Min (kWh)	24,0	24,0	0,0
25th prct (kWh)	99,6	101,3	1,8
Median (kWh)	367,5	368,7	0,3
75th prct (kWh)	557,9	559,9	0,3
Max (kWh)	1189,3	1203,2	1,2
Mean (kWh)	348,5	349,7	0,3
Disp (std) (kWh)	239,2	239,7	0,2
Reject H0 (α=0,05) 2-sample K-S test	No		

5.3. Influence of freight trains on energy savings

In this paragraph the influence of freight trains on the energy saving potential of energy efficient train control is described. During the streamlining of the model, it became apparent that in situations with large delays often a freight train was present in the near vicinity. Freight trains have two properties that could potentially affect the delays in the system and therefore can influence the energy consumption, since only when a train is not (very) delayed it is able to coast. Freight trains have the potential to affect the delays in the system: Because of their weight acceleration is slow and because of their length freight trains can block sections of track when having to stop for a red signal aspect Although freight trains cannot just be taken from a network, differences between energy efficient train control with freight trains and energy efficient train control without freight trains, can emphasize the importance of adequate planning of freight trains . In this chapter the differences between the two are described.

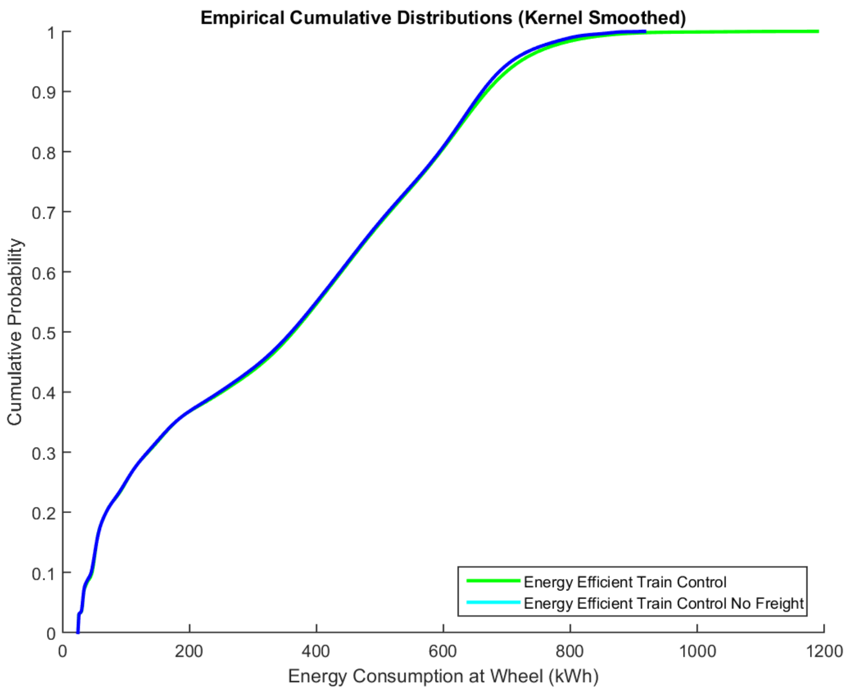


Figure 59 - Empirical Cumulative Density - Energy Efficient Train control with an without freight trains

The Empirical Cumulative Density functions of the energy efficient train control scenario and energy efficient train control without freight trains on the network show a large overlap. Only in the tail both distributions deviate.

In Table 21 the results with respect to the quartiles mean and standard deviation are given.

	EE with Freight Trains	EE without Freight trains	Diff in %
n	84450	84450	0
Min (kWh)	24,0	24,0	0,0
25th prct (kWh)	99,6	99,6	0,0
Median (kWh)	367,5	364,9	-0,7
75th prct (kWh)	557,9	557,4	-0,1
Max (kWh)	1189,3	917,1	-22,9
Mean (kWh)	348,5	345,5	-0,9
Disp (std) (kWh)	239,2	236,3	-1,2
Reject H0 (α=0,05)	Yes		
2-sample K-S test			

Table 21 - Results EE with Freight Trains vs. EE without Freight Trains

The 2-sample Kolmogorov Smirnov test rejects the null hypothesis, which confirms both scenarios are different. From Table 21 it can be seen that the difference is particularly explained in the right tail of the distributions. The difference in the mean states that the average train is slightly limited in energy efficient train control, since the energy consumption has decreased by 0,7%.

Since freight trains do not seem to affect the energy consumption largely, except for the tail, it is investigated how the large difference is explained. In Figure 60 the QQ-plot for the datasets with and without freight trains are plotted. It confirms that the change in the tail is significant, because in the region of these high energy consumptions the density of sample points is low, the problem is only related to a few trains in the model.

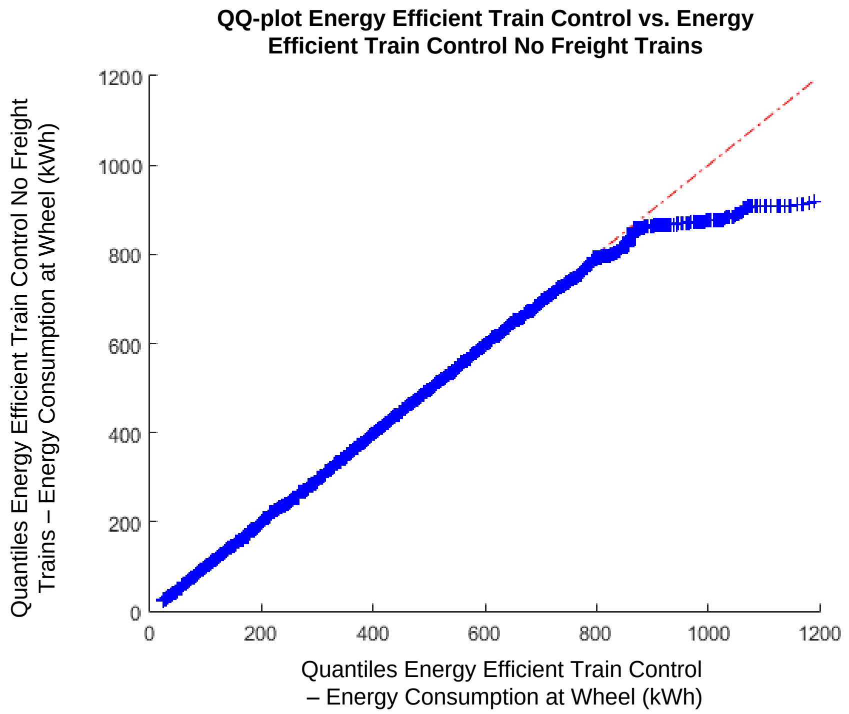


Figure 60 - QQ-plot EE with Freight trains vs. EE without freight trains

It is found that the difference is related to the conflict in the planning that has been described earlier. The large energy consumption values found are related to the trains following the freight train. following the freight train (train 123 from the series 100odd, train 3137 from the series 3100odd and train 837 from the train series 800 odd).

Since the energy consumptions found overlap largely in both the QQ-plot and the cumulative empirical density distribution, except for in the tails it is assumed that having freight trains will under normal circumstances not have an influence on the energy saving potential of energy efficient train control. The issue found is related to a planning error, (e.g. the train movements are planned on the same track and the same time, this causes a conflict.)

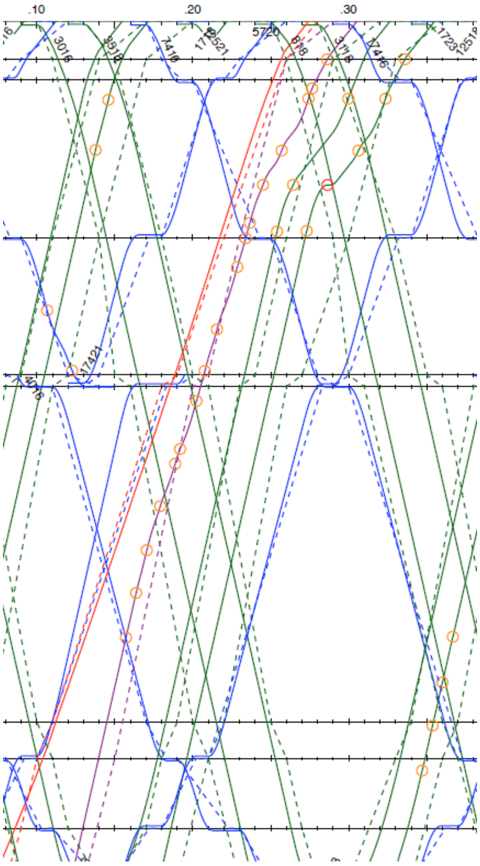


Figure 61 - Scatter plot energy consumption 100 odd direction

5.4. Sensitivity analysis performance parameter

In this paragraph the sensitivity of the setting of the performance parameter is evaluated on the output for energy consumption, punctuality and conflicts.

The performance parameter is defined a percentage of the maximum performance for the acceleration, cruising speed as the percentage of the maximum permissible line speed, and the braking rate.

The settings of the performance parameter are taken from an earlier research, from which also the empirical data on initial delay and dwell time are used in this research. The performance parameter for traditional train control is set as 97% when a train is delayed and 94% when a train is on time. Whether a train is delayed or on time is measured at the previous service control point the train passed, by comparing the actual simulated time with the time depicted in the timetable. For energy efficient train control the performance is 100% until the train reaches a coasting sign in the model. The performance is 100% because the theory describes the optimal train control strategy with respect to energy saving as: Accelerate at the maximum rate, drive the maximum permissible line speed, coast and brake at the maximum comfortable rate. This setting implies that in all regimes the performance of traditional and energy efficient train control are different.

By setting the performance levels for both delayed and on-time condition to 100% the performance this inequality is taken out of the equation. The only difference between the strategies is the coasting regime that is in the energy efficient train control strategy. For this sensitivity analysis 50 extra runs of the model had to be made, re-running only the traditional train control strategy at 100%. The sensitivity to the new setting to energy consumption, punctuality and conflicts are described in the remainder of this paragraph. The sensitivity is described as the difference between the results of the main model that are discussed in the previous paragraph with the results of the simulations for equal performance setting.

Energy Consumption

	Traditional Train Control	Traditional Train Control Equal Performance	Energy Efficient Train Control
n	84450	84450	84450
Min (kWh)	24,8	24,3	24,0
25th prct (kWh)	108,3	108,9	99,6
Median (kWh)	421,9	433,1	367,5
75th prct (kWh)	613,1	638,2	557,9
Max (kWh)	1238,7	1218,6	1189,3
Mean (kWh)	392,7	408,9	348,5
Disp (std) (kWh)	265,9	278,4	239,2

Table 22 - Results energy consumption main model versus equal performance

In Table 22 the results for both the model and the runs at 100% performance are displayed. The differences between these are described in Table 23.

	Results Trad vs. EE in % Main model	Results Trad vs. EE in % Equal Performance	Difference Main Model and Model Equal Performance in percent point	Difference Main Model and Model Equal Performance in %
Min	-3,2	-1,3	1,8	
25th prct	-8,0	-8,5	0,5	
Median	-12,9	-15,2	2,3	
75th prct	-9,0	-12,6	3,6	
Max	-4,0	-2,4	1,6	
Mean	-11,3	-14,8	3,5	31,0
Disp (std)	-10,0	-14,1	4,1	

Table 23 - Energy savings between main model and model at equal performance

From both tables it can be concluded that the energy consumption of traditional train control is increased by running scenario at 100% performance. Because the traditional train control trips are now run faster, this increases the energy consumption for this strategy. This means that the calculated energy savings are larger (11.3% to 14.8%). The found savings would be 3.5 percent higher were this research done with a performance setting of 100% for traditional train control. The sensitivity for the increase in performance is 31%. The performance parameter therefore has a considerable influence on the energy saving found.

Punctuality

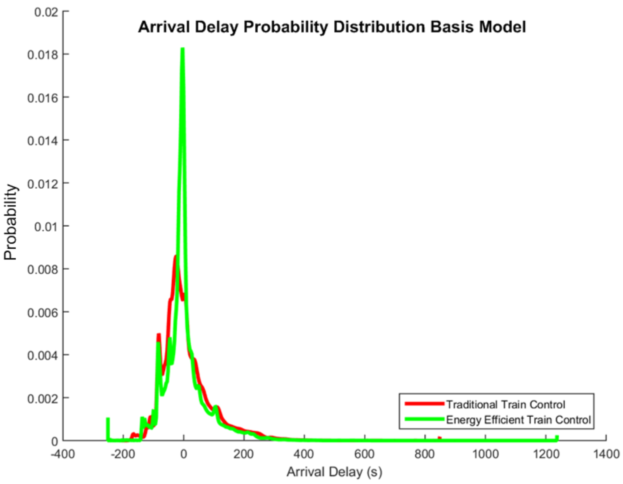


Figure 63 - Probability distribution arrival delay main model

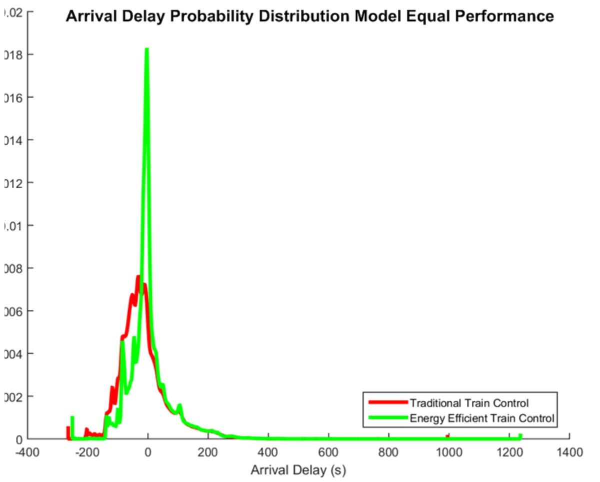


Figure 62 - Probability distribution arrival delay model equal performance

In Figure 62 and Figure 63 and the probability distributions of both the main model as the model with 100 percent performance are given. Because essentially the traditional train controlled trains are faster now, these trips shift slightly to the left in terms of arrival delay (traditional train control trips will arrive even more early). In the tail of the distribution both strategies now overlap, resulting in equal 3-minute punctuality. The difference is explained by the behavior under delayed condition. In the main model delayed trains drive at 100% when they have the label energy efficient train control and 97% when they have the label traditional train control. The 100% in the energy efficient train control is based on theory about energy efficient train control. Energy efficient train control trips are therefore better capable of reducing the sustained delay. It is doubted that train drivers will behave differently whether they are categorized as traditional or energy efficient train drivers. It is therefore advised to investigate what can be considered the real maximum performance, because it has an influence in the tail of the distribution and therefore on the punctuality (3-minute margin). The results on punctuality are displayed in Table 24. The differences between the models are displayed in Table 25.

	Traditional Train Control	Traditional Train Control Equal Performance	Energy Efficient Train Control
Punctuality (3 Minutes)	0,95	0,97	0,97
n	164350	164350	164350
Min (s)	-251	-265	-251
25th prct (s)	-42	-62	-27
Median (s)	-8	-26	-4
75th prct (s)	40	18	24
Max (s)	848	995	1237
Mean (s)	8,7	-13,0	5,5
Disp (std) (s)	81,5	80,1	72,0

Table 24 - Results punctuality main model versus equal performance

	Results Trad vs. EE in % Main model	Results Trad vs. EE in % Equal Performance	Difference Main Model and Model Equal Performance in percent point	Difference Main Model and Model Equal Performance in %
Punctuality (3 Minutes)	1,4	-0,2	1,6	
Min	0,0	-5,3	5,3	
25th prct	-35,7	-56,5	20,7	
Median	-50,0	-84,6	34,6	
75th prct	-40,0	33,3	73,3	
Max	45,9	24,3	21,6	
Mean	-37,5	-142,0	104,5	278,7
Disp (std)	-11,6	-10,0	1,6	

Table 25 - Arrival delay differences between main model and model at equal performance

In Table 24 it can be seen that when the performance parameter is brought out of the equation, the 3-minute punctuality norm is equal for both the traditional and energy efficient train control strategy. It is assumed that in delayed condition, performance won't differ much between train drivers in reality. It is therefore unlikely that the 3-minute punctuality improves when energy efficient train control is applied. With respect to the mean arrival delay, the difference between traditional train control and energy efficient train control grow further apart (trains assigned the traditional train control strategy arrive even more early). With respect to punctuality it is therefore concluded that energy efficient train control has no negative effects on punctuality. There is no proof of higher delays since the tails in the delay distributions overlap.

The sensitivity for the performance parameter on the mean arrival delay is very large. The results between the main model and the model with equal performance differ almost by a factor 3. The setting of the performance parameter is therefore especially important for calculations on punctuality.

Conflicts

In Table 26 the results for both the main model and the model with equal performance is displayed with respect to the number of occurrences of braking actions enforced by the signaling system. What can be seen is that yellow signal aspects occurrences are slightly lower for trains driving under traditional train control. It is assumed that this is caused by distributed performance in this control strategy that is present in the main model (97% delayed, 94% on time). This causes longitudinal movements, whereas in the strategy under equal performance is the control strategy is uniform.

Red signal aspect (full stop)	Traditional Train Control	Traditional Train Control Equal Performance	Energy Efficient Train Control
Min (#occurences/train trip)	0	0	0
25th prct (#occurrences/train trip)	0	0	0
Median (#occurrences/train trip)	0	0	0
75th prct (#occurrences/train trip)	0	0	0
Max (#occurrences/train trip)	4	6	5
Mean (#occurrences/train trip)	0,2	0,2	0,2
Disp (std) (#occurrences/train trip)	0,5	0,5	0,5

Red signal aspect (approach)	Traditional Train Control	Traditional Train Control Equal Performance	Energy Efficient Train Control
Min (#occurrences/train trip)	0	0	0
25th prct (#occurrences/train trip)	0	0	0
Median(#occurrences/train trip)	0	0	0
75th prct(#occurrences/train trip)	1	1	1
Max (#occurrences/train trip)	14	15	17
Mean (#occurrences/train trip)	0,6	0,7	0,5
Disp (std) (#occurrences/train trip)	1,1	1,3	1,1

Yellow signal aspect	Traditional Train Control	Traditional Train Control Equal Performance	Energy Efficient Train Control
Min (#occurrences/train trip)	0	0	0
25th prct (#occurrences/train trip)	1	1	1
Median (#occurrences/train trip)	2	2	2
75th prct (#occurrences/train trip)	5	4	4
Max (#occurrences/train trip)	26	28	26
Mean (#occurrences/train trip)	3,1	2,8	2,7
Disp (std) (#occurrences/train trip)	2,8	2,5	2,5

Table 26 - Results braking actions enforced by signaling main model versus model equal performance

The increased occurrences of Red signal aspect approaches can be explained by the improvement of the overall performance (94% to 100% and 97% to 100%). This causes all traditional train control trains to run faster. Because the reach the station earlier, the chances that the platform is still occupied by another train increase, causing a red signal approach. The mean for red signal stops stays about equal for all strategies under all performance levels. In Table 27 the differences between the results of the main model and the model under equal performance are given. Since the occurrences are rare in general, the results show very fluctuating percentages, but all show a decrease.

Red signal aspect (full stop)	Results Trad vs. EE in % Main model	Results Trad vs. EE in % Equal Performance	Difference Main Model and Model Equal Performance in percent point	Difference Main Model and Model Equal Performance in %
Min				
25th prct				
Median				
75th prct				
Max	25,0	-16,7	41,7	
Mean	-10,7	-4,6	6,1	-57,0
Disp (std)	-5,3	-1,5	3,8	
Red signal aspect (approach)	Results Trad vs. EE in % Main model	Results Trad vs. EE in % Equal Performance	**Difference Main Model and Model Equal Performance in percent point**	Difference Main Model and Model Equal Performance in %
Min				
25th prct				
Median				
75th prct	0			
Max	21,4	13,3	8,1	
Mean	-10,0	-23,9	13,9	139,0
Disp (std)	-2,0	-20,3	18,3	
Yellow signal aspect	Results Trad vs. EE in %	Results Trad vs. EE in %	**Difference Main Model and Model Equal**	Difference Main Model and Model

	Main model	Equal Performance	Performance in percent point	Equal Performance in %
Min				
25th prct				
Median				
75th prct	-20	0	20	
Max	0,0	-7,1	7,1	
Mean	-14,3	-2,8	11,5	-80,4
Disp (std)	-12,5	0,0	12,5	

Table 27 - Differences braking actions enforced by signaling main model and model at equal performance

Between the different signal aspects, red signal approaches are the most sensitive to the performance parameter as can be seen from Table 27.

It is seen that the performance parameter has a significant influence on the results of this research. From the dependent variables the arrival delay (punctuality) is the most sensitive for the performance parameter. Although the performance parameter has a significant influence on the outcomes. It is seen that when the performance is increased the findings in the results still apply: Traditional train control trips arrive even earlier, increasing the red signal approaches and the energy savings found are larger. If the real performance would be lower than the defined performance, the strategies move towards each other, reducing the effects of energy efficient train control.

5.5. Validation and evaluation of the model

Validation is an important aspect in simulation studies. A model is a simplified representation of the real world, in which assumptions are made. Ideally validation of OpenTrack is done by means of validation to empirical data (Huerlimann & Nash, 2010). This is a time consuming task, because models apply to certain conditions for which exact matches from the real world have to be found, which cannot be executed in the time-span of this research, it is a topic for a thesis by itself. This cannot be executed in the time span reserved for this research, it is a topic for a thesis itself. In (Agricola, 2009) a research is described that specifically concerns the validation of OpenTrack. This concluded that a generic validation of OpenTrack is not yet possible. If validation to the real world is cannot be done, comparison of outputs can be compared to other models, but these also have their own strengths and weaknesses.

For validating this research, there is relied on the experts' knowledge used to set the important parameters, and a sensitivity analysis for the most important parameter, performance (Agricola, 2009). A sensitivity analysis is generally seen as a powerful system validation technique (Smith, Szidarovszky, Karnavas, & Bahill, 2008).

The most challenging task in simulations is to incorporate human behavior in the simulation. In this thesis only two types of train drivers exists and within the category of train drivers all 'drivers' behave equally. In reality behavior amongst train drivers show variation. They will execute control a similar control strategy differently. Regarding energy efficient train control, the coasting point is nearly optimal for delay a train can take in the simulations. In reality the train driver will not always find the right coasting point. When coasting is applied to late, this will affect the energy saving (lower) and the train will arrive earlier at a, which gives higher probability of a conflict. When the coasting is applied to early, the train will arrive late at the next station. So although it is found that the strategy itself does not influence the punctuality negatively, sub-optimal behavior can lead to different outcomes. In other words, it cannot be guaranteed that the conclusions of this research will always apply.

Another important aspect in this research is that a lower coasting limit applies which means that not all slack time can always be consumed. If in the real world coasting is applied below this speed more slack time is consumed than calculated in this research, this means that higher energy savings will are likely to be achieved, but it cannot be guaranteed that the punctuality remains unaffected, because no calculations are carried out for a lower coasting limit (e.g. calculations in which the slack time in the low speed zones is consumed

In this sensitivity analysis it is seen that the outcomes with respect to energy consumption, punctuality and conflicts can vary greatly if the performance parameter is set differently. This does however not lead to very different conclusions when the performance is increased to 100% in general the effects found are larger (in traditional train control trains arrive earlier, sustain more conflicts and the energy saving found is larger. It is not calculated what the effects would be if the real performance of traditional train control would be lower than the performance level that is set. When the performance of traditional train control is calibrated to optimistic (e.g. too fast), the differences between the strategies would potentially decrease. The behavior of both strategies relative to each other decreases, because traditional train control also consumes slack time with a lower than maximum performance setting. The strategies in essence become more equal.

Summarized it can be said that sub-optimal behavior of train drivers can lead to different outcomes than found in this research. The effects of coasting below a 80 km/h are not examined. It can therefore not be guaranteed that the outcomes of this research will still apply when coasting is performed below this speed. The performance setting has a large influence on the outcomes, when increased, but the conclusions are not affected, because the effects are in the same direction. If the performance setting of traditional train control is set to optimistic the effects of energy efficient train control measured decrease relative to the calculated effects.

6. Conclusions and recommendations

6.1. Conclusions

Energy efficient train control has proven to be an effective strategy to reduce traction energy consumption when applied on a network scale. The mean energy savings calculated are 11.3 percent, compared to traditional train control. Although application of energy efficient train control leads to an energy saving in general, it does not guarantee that an energy saving is made on every trip. Occasions are found when application of the energy efficient train control leads to an increase in energy consumption when applied network-wide. The outcome of the strategy is highly dependent on the delay distribution within the network. Different patterns of delay lead to different interaction patterns at different strategies. It is not possible to tell beforehand whether a certain trip will be energy efficient or not. The energy efficient train control profiles are optimized on the train-level. This optimization approach is similar to the optimization method of a dynamic train-based DAS. Optimizing on the train level implies that interaction with other trains is not accounted. The coasting point is based on the deviation from the timetable of the own train. When interaction takes place, this can lead to sub-optimal outcomes e.g. increases in energy consumption. A connected-DAS system can potentially decrease the occurrences of increases in energy consumption, because optimization is done on the network-level. Since a connected-DAS system is not foreseen in the near future and train based-dynamic DAS is not yet fully implemented in the Netherlands it is advised to first fully implement the train-based DAS system. This system is a necessity to cash in the saving potential the timetable offers, because the optimal strategies greatly vary between and even within train series, due to the way in which the slack time is allocated during the timetabling process. The energy savings found are likely to be achievable in other parts of the network, since the research area of this study is one of the most heavily used parts of the Dutch rail network. Coasting is modeled with a lower coasting limit. Below this limit coasting is not applied. It is important to understand that when such a rule is in place in order to prevent coasting at low speeds, this can influence the saving potential within a network. If such an area is in place between station stops, the slack time between these stations cannot be used for coasting. For the network in this research it is estimated that this has reduced the energy saving potential by 1 percent.

Although it is found that the energy consumption is not guaranteed to decrease when the energy efficient train control is applied and therefore is not beneficial to all trains, no evidence was found that the punctuality is negatively affected by energy efficient train control. Energy efficient train control does not cause more trains to arrive late when compared to traditional train control. In the energy efficient train control strategy it is found that within the network most trains arrive close to the planned arrival time. In traditional train control trains arrive early in general. Arriving close to the planned arrival time does not affect passengers negatively as long as the transfer times to connecting train services are adequately determined. For energy efficient train control it is seen that the dispersion of the arrival time is decreased. This means that the trains arrive within a smaller time-window. This enhances the capacity of the network.

With respect to conflicts it is found that energy efficient train control reduces the conflicts within a network. In traditional train control it is found that trains will arrive early. Early arrival increases the probability of a conflict, because the preceding train has not yet cleared the block ahead. In practice this often means that the track along platform at the station is not yet clear, which means that the trains using the traditional train control strategy will encounter a red signal and wait for the conflict to clear. In energy efficient train control the trains generally arrive at the planned arrival time. Because the activity happens as it is planned (e.g. on time arrival), the conflict will in general not occur, because the timetable is designed almost free of conflicts.

It is not proven that having mixed strategies within the same network affects the energy consumption of either the energy efficient trains control strategy or the traditional train control strategy, e.g. traditional train control trips do not affect the energy consumption of energy efficient train control and vice versa.

Energy saving potential is also not influenced by freight trains. During the model construction it was seen that freight trains have the potential to affect other trains when delayed. Because of their length they don't always fit in a single block section (between signals) when a red signal is encountered. If this happens in a large station, this can cause a blockage of the corridors behind the train. Secondly, it will take a freight train a relatively long time to gain speed because of their mass. Although freight trains have the potential to hinder other trains, no evidence is found that they have an influence on the energy consumption of energy efficient train control.

It is concluded that even in a network that is heavily utilized, energy efficient train control is an effective strategy to reduce the energy consumption. Apllication of the strategy will in general lead to an energy saving, although application of the strategy does not guarantee a saving beforehand. No evidence is found that energy efficient train control affects the punctuality negatively. The strategy leads to arrivals close to the planned arrival time, rather than early arrivals. Although this implies that the arrivals happen later on average, passengers are not affected as long as the transfer times to connecting train services are adequately determined. Trains applying the energy efficient train control strategy arrive within a smaller time window, this enhances the capacity of the network. The number of conflicts are reduced by energy efficient train control. This is beneficial to the safety within the network and contributes to the energy savings.

6.2. Recommendations

Define arrival times for short stops in the planning.

Currently only planned departure times are defined for short stops. These are dwells shorter than one minute, because the timetable is rounded to full minutes. This means that for dwell times shorter than one minute no arrival time is specified in the timetable. Because punctuality is calculated on basis of arrival delays. Trains with short stops are not part of the punctuality calculations in this research and in reality. Short stops are mainly planned on smaller stations along the free track, but also for larger stations that fulfill an important transfer function such as Amsterdam Sloterdijk. It is important to measure punctuality on stations with an important transfer function, because at low punctuality passengers will miss their connecting service, which increases travel time. For stations with mixed short stops and stops based on an a planned arrival and departure time punctuality calculations do not represent the full set of trains calling at the station. By defining an unrounded planned arrival time, at least in the planning, punctuality calculations of all train traffic would be possible.

Measure punctuality for at least all stations with a transfer function.

The stations where punctuality is currently measured do not contain all stations with an important transfer function. Examples of these are the mentioned Amsterdam Sloterdijk, but also Schiphol. As mentioned punctuality is especially important at transfer stations. A delay can cause passengers to miss their connecting service which increases their travel time. A delay at a transfer often has a larger effect at on travel time at a transfer than at the destination, because at the destination only the delay of the train determines the extra travel time whereas at the transfer also the waiting time for the next train is added to the travel time, the latter depends on the frequency of trains. Synchronize the stations where punctuality is measured with at least the stations that fulfill an important transfer function.

Implement DAS 'Uitrolapp' as soon as possible.

Since the slack times are not distributed over the network uniformly, advise based on general rules for energy efficient train control are obsolete and might cause delays; they assume the slack time to be evenly distributed, e.g. slack time is allocated everywhere in equal portions, when in reality there might not be slack time at all. This can cause delays because of energy efficient train control. The coasting tips per train series (UTT) are better in this respect, since they are specific to a specific service (e.g. the magnitude and distribution of the slack time are incorporated in the advice). The UTT is however still static advice and assumes and does not account for delays. This might again lead to delays, when implemented on a delayed service. A dynamic advice which incorporates the actual position of the train to an optimal energy efficient profile counts in (slight) delays gives the train driver more accurate guidance. The Uitrolapp which is in an experimental state and is currently used by 75 train drivers is a good example of the Driver Advisory System (DAS) that could fulfill this guidance. It is suggested to provide this application to all train drivers as soon as possible en and assure that the train drivers are trained in how to use it properly.

Create a broader basis of support for energy efficient train control among train drivers.

As is concluded in this research energy efficient train control leads to a substantial energy saving while maintaining overall punctuality. It is also beneficial to safety, because it reduces the number of conflicts. For the passengers energy efficient train control ensures a more comfortable and punctual trip. Energy efficient train control has many benefits, raise more awareness about this among the train drivers. Currently it is estimated that about 50 percent of the train drivers implies some sort of energy efficient train control (Luijt R. , 2016). The Uitrolapp might help to persuade train drivers to apply energy efficient train control, because it is easy to understand and the gaming element (battle against the successful profile) even makes energy efficient train control an entertaining experience. Possibly a reward system can be added to the application to motivate train drivers to apply energy efficient train control. For instance reward points for successful energy efficient trips that can be traded in, for instance on vouchers of large retailers. Reward on the basis of energy saving in combination with punctuality. Rewarding on energy saving alone could lead to undesirable behavior, e.g. Coasting more than there is slack time for. This could cause delays.

For higher energy saving potential make energy efficient train control part of the planning process

Slack times are currently added to the timetable for punctuality and safety purposes and not with energy efficient train control in mind. For this reason, most of the slack time is situated near the critical locations in the network (at the node stations), because of the high potential for conflicts. This leads to an uneven distribution of slack time over the network. Higher energy savings can be made at a more uniform distribution (Scheepmaker, 2013).

Integrate a more dynamic way to define energy efficient profiles in OpenTrack.

Currently the method to integrate energy efficient train control in OpenTrack is to manually place signs in the network that determine the starting location of the coasting zone. Finding the location at which the simulated arrival time equals the planned arrival time is a time consuming and not particularly challenging task, especially when this procedure has to be repeated for all trains in a large network and for different magnitudes of delay. To decrease the modeling time the signs have to be placed to certain tolerances, e.g. deviations from the exact optimal coasting points. It is advised to develop some kind of tooling that given a magnitude of slack time and train specification and the infrastructure in OpenTrack, calculates the coasting point. Ideally the placing of the sign should also be done automatically to minimize the building time. OpenTrack is not (yet) able to handle network optimal energy efficient train control, since the ability of OpenTrack to 'look ahead' is limited. A first step in modeling energy efficiency towards a fully dynamic system would be to integrate the train based optimal coasting points calculation- method in the software.

Compare calculated running times in of all planning tools for validation

It is known that the planning tools of infrastructure operator ProRail and OpenTrack produce different running time calculations, the exact differences are however not known, because the modeling conditions are different. For instance, in DONNA gradients are not modeled whereas in OpenTrack they are. It is advised to compare the models under equal conditions to gain insight in the differences they produce. Ultimately different running time calculations result in different running time reserve calculations, which will lead to different energy calculations.

Evaluate the influence of large disruptions with respect to energy efficient train control

In this research only minor deviations from the timetable are modeled; initial delays at departure and distribution off dwell times can cause delays. This might have contributed to the high initial punctuality in the model, compared to the punctuality in reality. The model is stable under these minor delays, causing no effects on punctuality. This is not certain for large disruptions, because these are not investigated. Large disruptions often cause an oil slick effect, causing delays that propagate deep in the network. This could significantly reduce the saving potential.

Dwell times must be adequate

Especially for short stops it has been found that the mean dwell times in the distributions used are higher than the planned dwell time in multiple occasions. Differences between realized and planned dwell times were also pointed out by Scheepmaker, 2013. A longer than planned dwell time implies that the train will leave the station with a slight delay. This delay can often be made up for because of the slack time. In the mean time this reduces the saving potential, because the slack cannot be utilized for energy efficient train control, because making up for the delay has priority. Currently the dwell times are based on the train type (e.g. the number of doors is an important factor) and the type of stop (short stop or stop with planned arrival and departure time). It is advised to also take the location and time (peak hours and off-peak hours) into calculation. These can be derived from empirical data.

Ensure that transfer times are adequate.

In energy efficient train control generally arrive around the planned arrival time. In traditional train control train generally arrive early. This makes an adequate calculation of necessary transfer times for connections more important. On average the time available for a transfer is lower in energy efficient train control because of the later arrival.

Define the real maximum performance

In optimal energy efficient train control theory, the optimal driving technique is described as: Acceleration at the maximum possible rate, driving the maximum permissible line speed, coast and brake at the maximum rate. This implicates a performance of 100%. For traditional train control the maximum performance is not considered to be 100%. This discrepancy has effects on the results. It is advised to further investigate what real maximum performance of train control is, so the discrepancies are taken out of the factor.

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List of figures

List of Tables

Appendix A - Driver Advisory Systems

Driver advisory system 'UZI Basis'

Planned travel time in minutes	Traction to idle at (speed)
2	80 km/h
3	90 km/h
4	100 km/h
5	110 km/h
6	120 km/h
7	130 km/h*
8	140 km/h*
* Not applicable to SGMm trains (top speed not sufficient)	

Permissible line speed	Traction to idle at (time)
140 km/h*	8 minutes before planned arrival time
130 km/h*	7 minutes before planned arrival time
120 km/h	6 minutes before planned arrival time
110 km/h	5 minutes before planned arrival time
100 km/h	4 minutes before planned arrival time
* Not applicable to SGMm trains (top speed not sufficient)	

Driver advisory system - 'UZI Pro'

Indicator/Advice	Description
+	Station with stop
-	Pass station or service control point
TSB	Temporary speed limitation
VSB	Permanent speed limitation
BVS	Permissible line speed
HH	Maintain speed
1x (speed) (for instance 1x140	Accelerate to speed indicated and switch of traction
40	Maintain speed indicated
7 (8)	Planned travel time (7 minutes) versus technical minimum travel time. A higher technical minimum indicates a planned timetable that is too tight. This means that no slack time is available on this line and Energy Efficient Train Control should not be conducted.
5(4)	Technical minimum travel time is less than the planned travel time in the timetable. The difference is the slack time available for Energy Efficient Train Control.
Time Check	Check deviation from timetable

From	To	Travel time	UZI advice in km/h	Speed references	Comments
Asd	-Ass	5	80	80	
-Ass	-Asra	5	1x100	80 130 80	
-Asra	+Shl	3	1x110	80 130 80	
+Shl	-Rvbr	14	1x120	80 130 140	Time Check
-Rvbr	-Ledn	5	Coast (UZI Basis)	140	
-Ledn	+Gv	9	1x120	140 130 100 90 80	Time Check Gvm
+Gv	-Dta	6	1x50	80 130 140	1900 has right of way
-Dta	-Dt	3	1x100	140 130 100	1900 stops at Dt
-Dt	-Sdm	7	1x120	100 140 130 90	
-Sdm	+Rtd	3	1x90	90	

Appendix B - Train series in Research Area

The train series in the table below describe the series that are modeled an part of the calculations.

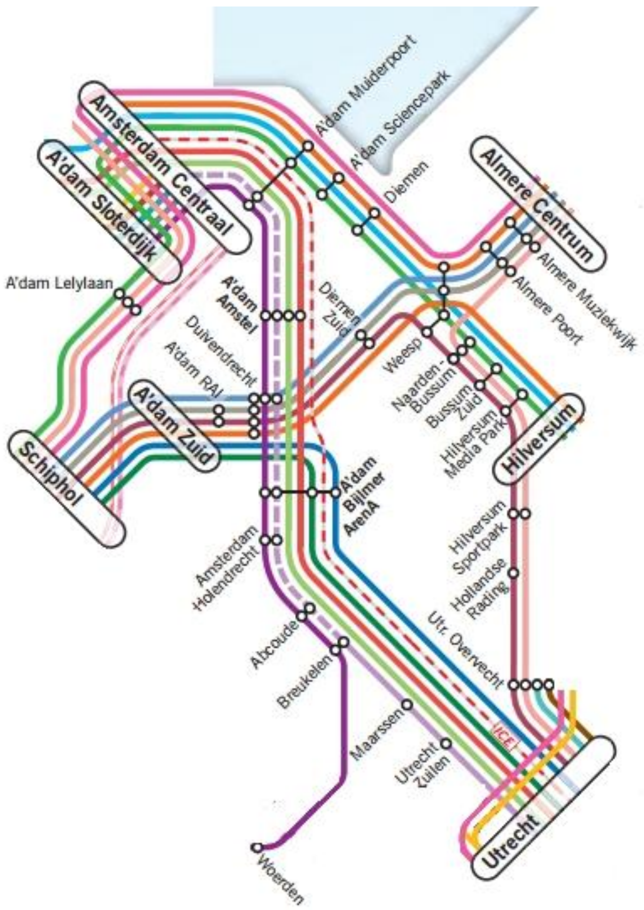
Train Series	Train Cat.	Route (even direction)	Freq.
100/120/200	ICE	(Basel SBB-)-Frankfurt (M) HBF-Amsterdam Centraal	8/day
140/240	INT	Berlin Ostbahnhof-Amsterdam Centraal	1/2 hours
400	INT	Dld.-Amsterdam Centraal	2/day
700	IC	Groningen-Den Haag Centraal	1/hour
800	IC	Maastricht-Alkmaar(-Schagen)	2/hour
900	HSN	Amsterdam Centraal-Breda	2/hour
1000	HSN	Amsterdam Centraal-Rotterdam Centraal	2/day
1500	IC	(Deventer-)Amersfoort-Enkhuizen	2/hour
1600	IC	Enschede-Schiphol	1/hour
2100	IC	Den Haag Centraal-Amsterdam Centraal	2/hour
2200	IC	Dordrecht-Amsterdam Centraal	2/hour
2600	IC	Lelystad Centrum-Vlissingen	2/hour
3000	IC	Nijmegen-Den Helder	2/hour
3100	IC	Nijmegen-Schiphol	2/hour
3300	SPR	Hoofddorp-Hoorn Kersenboogerd	2/hour
3500	IC	Heerlen-Schiphol	2/hour
4000	SPR	Rotterdam Centraal-Uitgeest	2/hour
4300	SPR	Almere Oostvaarders-Hoofddorp(-Leiden Centraal)	2/hour
4600	SPR	Zwolle-Amsterdam Centraal	2/hour
4700	SPR	Amsterdam Centraal-Uitgeest (over Zaandam)	2/hour
4800	SPR	Uitgeest-Amsterdam (over Haarlem)	2/hour
4900	SPR	Utrecht Centraal-Almere Oostvaarders	2/hour
5400	SPR	Zandvoort aan Zee-Amsterdam Centraal	2/hour
5700	SPR	Utrecht Centraal-Den Haag Centraal (over Weesp)	2/hour
5800	SPR	Amersfoort Vathorst-Hoofddorp	2/hour
7400	SPR	Rhenen-Breukelen(-Amsterdam Centraal)	2/hour
9300	THA	Amsterdam Centraal-Paris Nord	1/hour
9900	THA	Amsterdam Centraal-Lille Europe	2/day
11600	IC	Amersfoort Schothorst-Schiphol	1/hour
12600	IC	Groningen/Leeuwarden-Vlissingen	4/day
12700	IC	Leeuwarden-Den Haag Centraal	1/hour
14500	IC	Enkhuizen-Amsterdam Centraal	4-5/day
14800	SPR	Hoorn-Amsterdam Centraal	10/day
15800	SPR	Hoofddorp-Amsterdam Centraal (only odd direction exists)	1/day
17400	SPR	(Veenendaal Centrum-)Utrecht Centraal-Breukelen	2/hour

The train series described in the table below are modeled but not measured These are series that flank the model and are within the model for a very short amount of time.

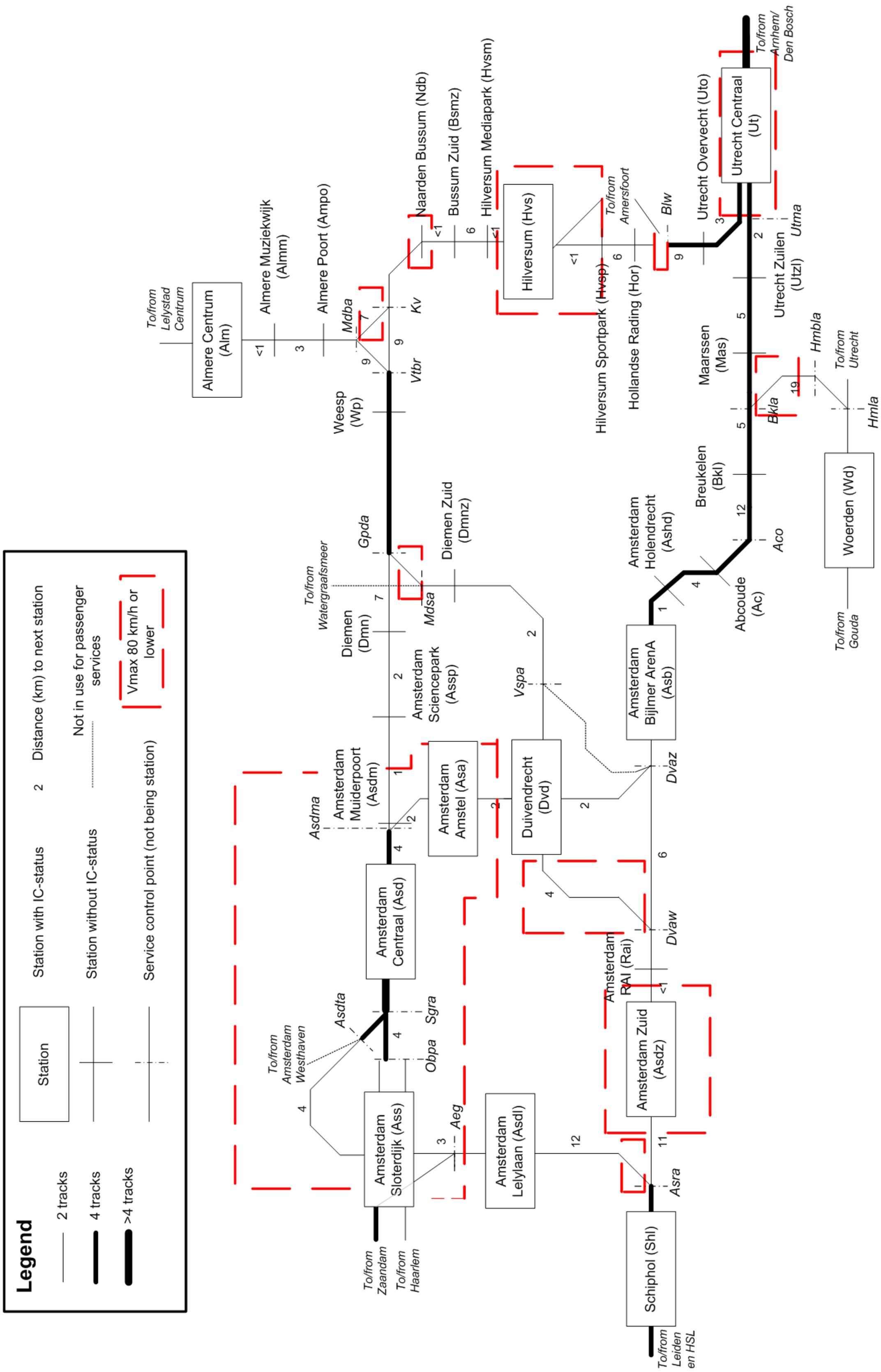
Train Series	Train Cat.	Route (even direction)	Freq.
500	IC	Groningen-Rotterdam Centraal	1/hour
1700	IC	Enschede-Den Haag Centraal	1/hour
5500	SPR	Baarn-Utrecht Centraal	2/hour
5600	SPR	Zwolle-Utrecht Centraal	2/hour
11700	IC	Amersfoort Schothorst-Den Haag Centraal	1/hour
12500	IC	Leeuwarden-Den Haag Centraal	1/hour
28300	SPR	Utrecht Maliebaan-Utrecht Centraal	1/hour

In the table below the series 1400 is described. This is a train series in the research area, but it is neither modeled or measured. It is a night service that displays very irregular behavior in reality, for instance running on the left track, zigzag though point complexes to clear oxidation etc. This irregular behavior cannot be accurately simulated.

Train Series	Train Cat.	Route (direction even)	Freq.
1400	IC	Rotterdam Centraal-Utrecht Centraal (over Shl and Asd)	1/hour



Appendix C - Detailed Research Area

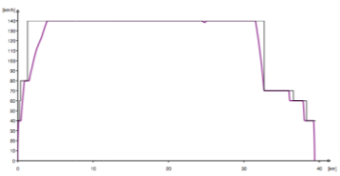
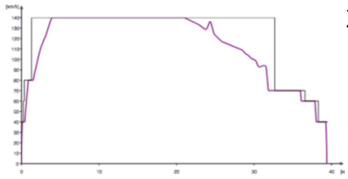
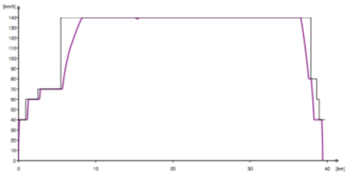
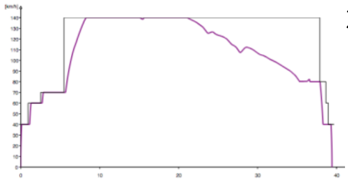
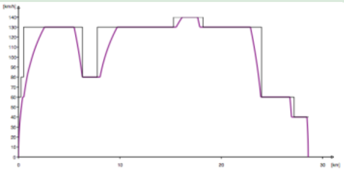
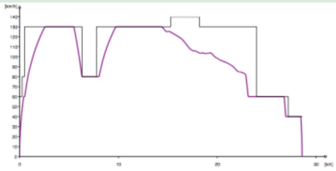
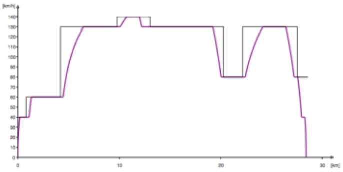
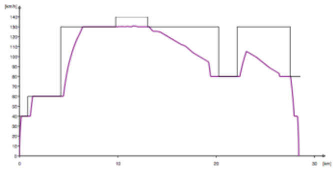
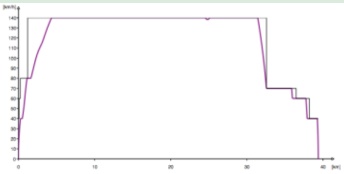
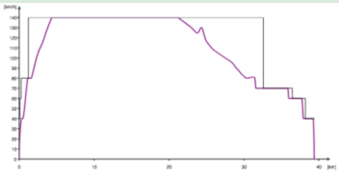
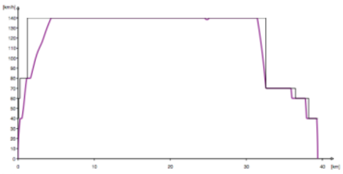
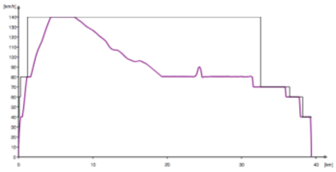
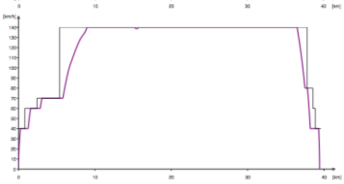
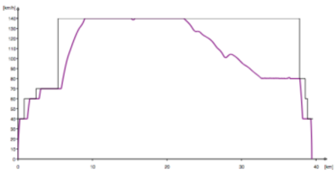
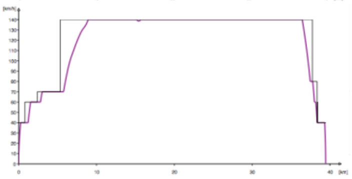
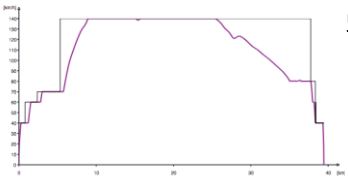


Appendix D - Station Abbreviations

Abbreviation	Name service control point
Ac	Abcoude
Aco	Abcoude overloopwissels
Aeg	Amsterdam Erasmusgracht aansluiting
Alm	Almere Centrum
Almm	Almere Muziekwijk
Ampo	Almere Poort
Asa	Amsterdam Amstel
Asb	Amsterdam Bijlmer ArenA
Asd	Amsterdam Centraal
Asdl	Amsterdam Lelylaan
Asdm	Amsterdam Muiderpoort
Asdma	Amsterdam Muiderpoort aansluiting
Asdta	Amsterdam Transformatorweg aansluiting
Asdz	Amsterdam Zuid
Ashd	Amsterdam Holendrecht
Asra	Amsterdam Riekerpolder aansluiting
Ass	Amsterdam Sloterdijk
Assp	Amsterdam Sciencepark
Bkl	Breukelen
Bkla	Breukelen aansluiting
Blw	Blauwkapel-West
Bsmz	Bussum Zuid
Dmn	Diemen
Dmnz	Diemen Zuid
Dvaw	Duivendrecht aansluiting west
Dvaz	Duivendrecht aansluiting zuid
Dvd	Duivendrecht
Gpda	Gaasperdammerweg aansluiting
Hmla	Harmelen aansluiting
Hmlba	Harmelen-Breukelen aansluiting
Hor	Hollandse Rading
Hvs	Hilversum
Hvsm	Hilversum Mediapark
Hvsn	Hilversum Noord
Hvsp	Hilversum Sportpark
Kv	Keverdijk
Mas	Maarssen
Mbga	Muiderberg aansluiting
Mdsa	Muiderstraatweg aansluiting
Ndb	Naarden-Bussum
Obpa	Overbrakerpolder aansluiting
Rai	Amsterdam RAI

Sgra	Singelgracht aansluiting
Shl	Schiphol
Ut	Utrecht
Utma	Utrecht Maarssen aansluiting
Uto	Utrecht Overvecht
Utzl	Utrecht Zuilen
Vspa	Venserpolder aansluiting
Vtbr	Vechtbrug bij Weesp
Wp	Weesp

Appendix E - Speed/Distance profiles Energy Efficient Train Control

Profile ID	Profile Time-Optimal Train Control (TO)	Energy Cons. TO (kWh)	Profile Energy-Efficient Train Control (EE)	Energy Cons. EE (kWh)	Δ (%)
Train series 100					
100(1)		316,7		234,4	-26,0
100(2)		336,9		234,0	-30,5
Train series 140					
140(1)		386,6		299,5	-22,5
140(2)		357,7		245,8	-31,3
Train series 400					
400(1)		679,8		517,9	-23,8
400(2)		679,8		432,8	-36,3
400(3)		711,3		527,8	-25,8
400(4)		711,3		549,2	-22,8

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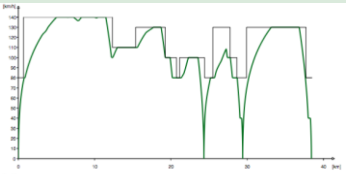
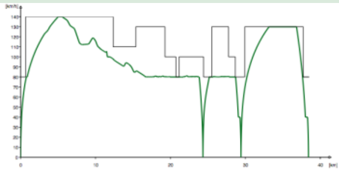
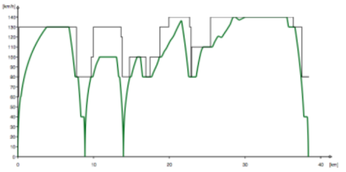
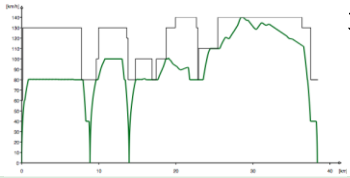
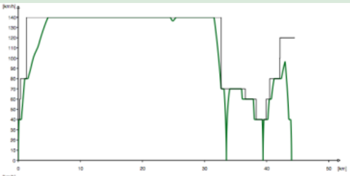
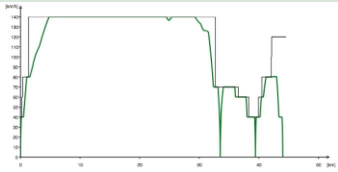
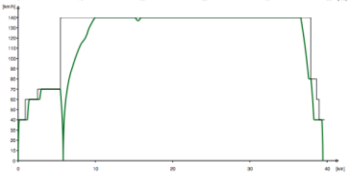
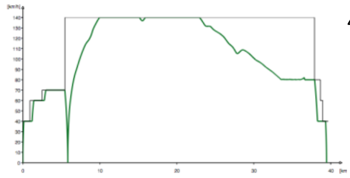
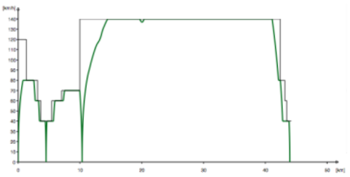
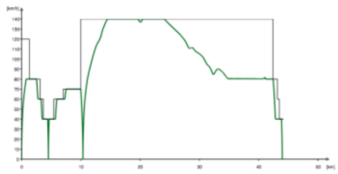
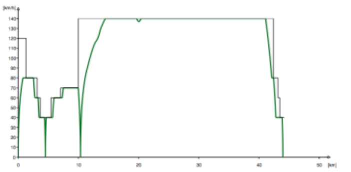
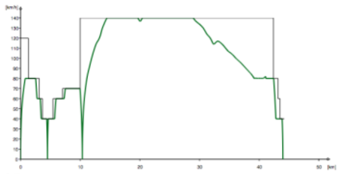
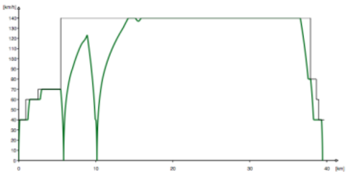
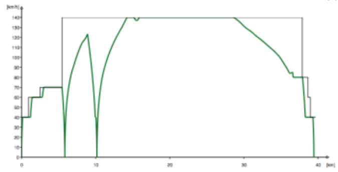
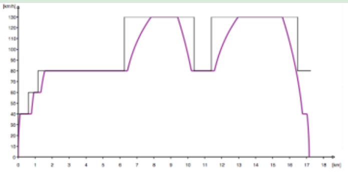
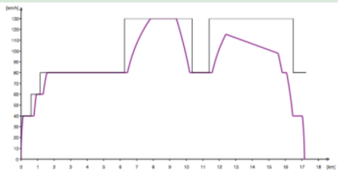
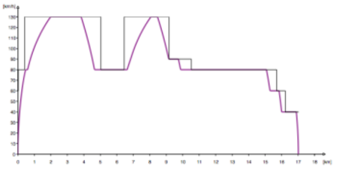
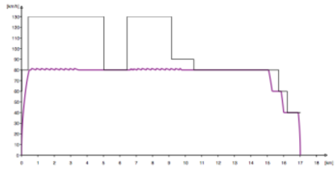
700(1)		607,9		410,6	-32,5
700(2)		588,1		376,4	-36,0
Train series 800					
800(1)		674,4		622,2	-7,7
800(2)		607,7		454,0	-25,3
800(3)		674,5		497,9	-26,2
800(4)		674,5		530,4	-21,4
800(5)		696,4		583,1	-16,3
Train series 900					
900(1)		184,6		152,1	-17,6
900(2)		179,8		89,4	-50,3

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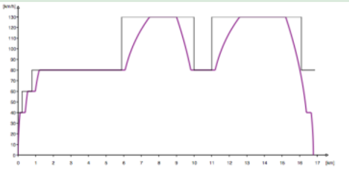
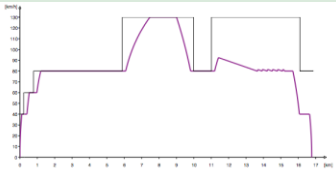
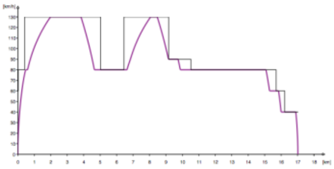
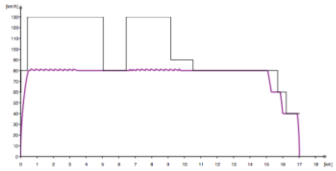
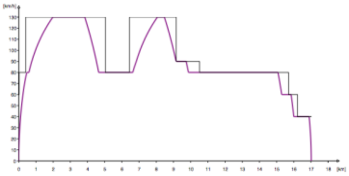
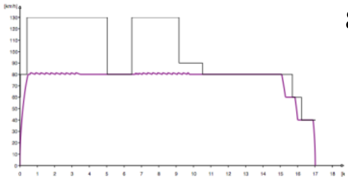
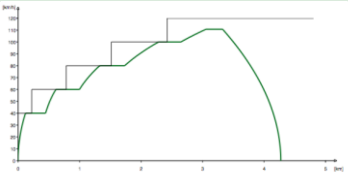
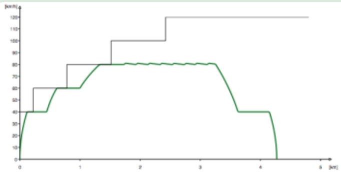
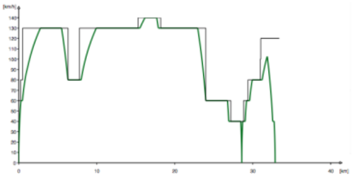
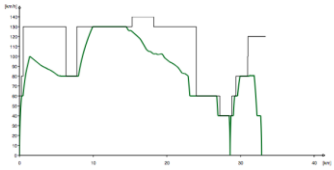
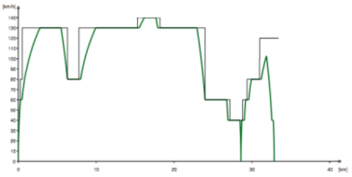
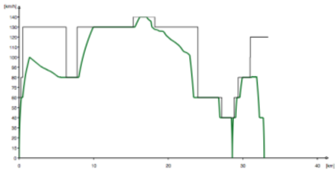
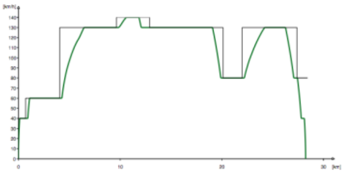
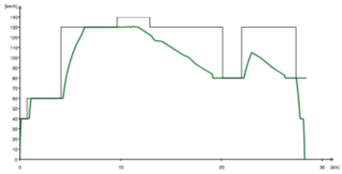
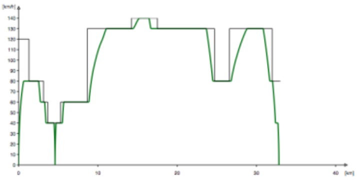
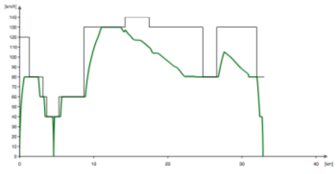
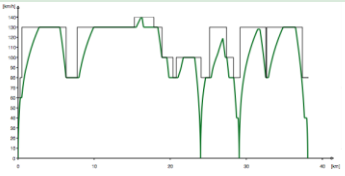
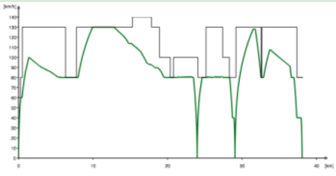
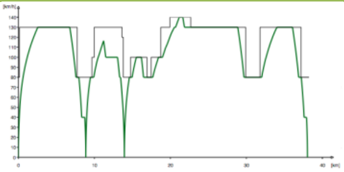
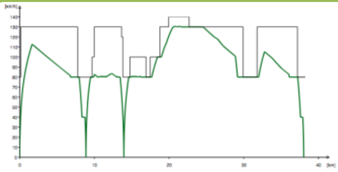
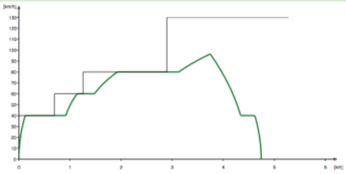
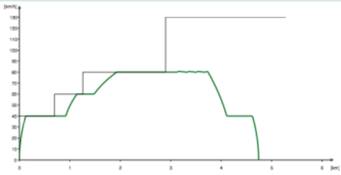
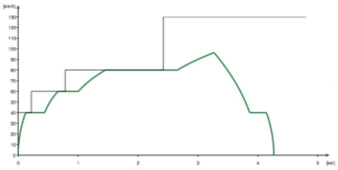
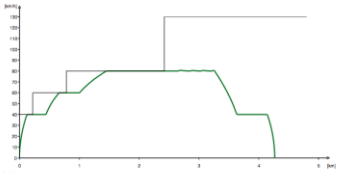
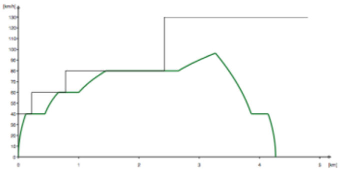
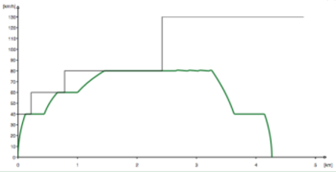
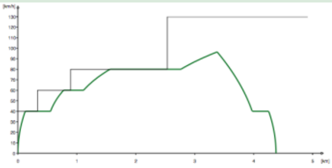
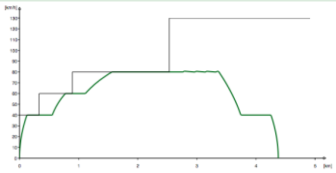
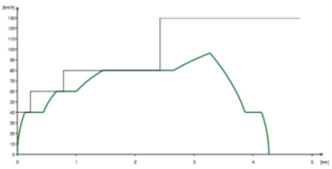
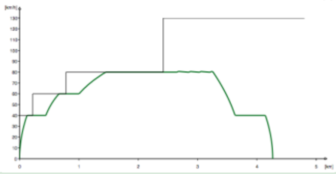
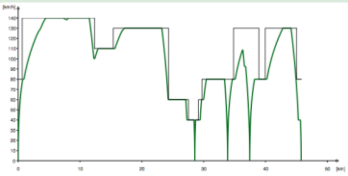
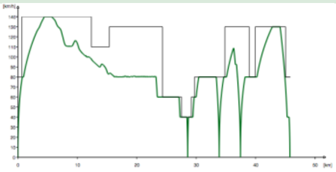
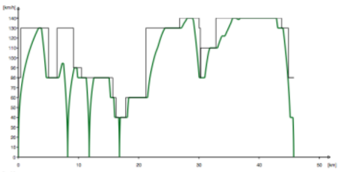
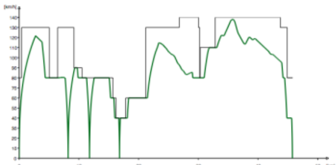
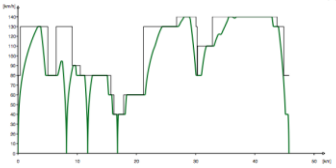
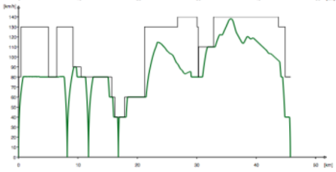
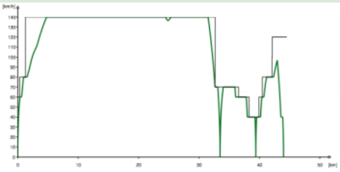
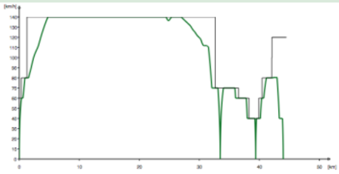
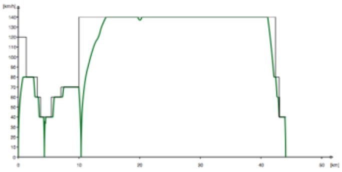
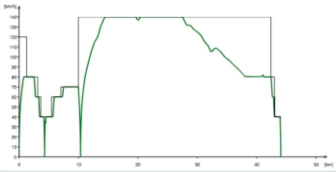
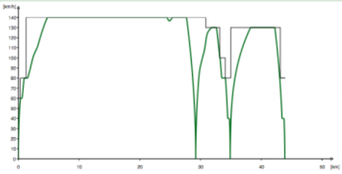
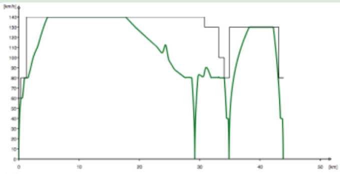
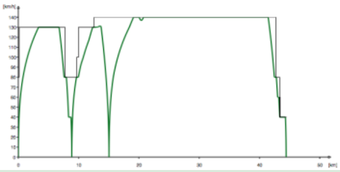
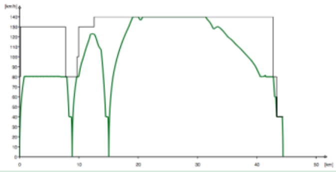
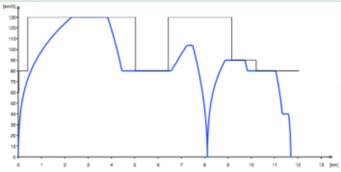
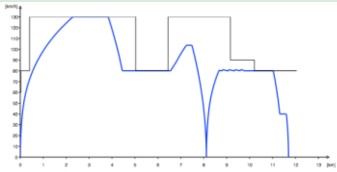
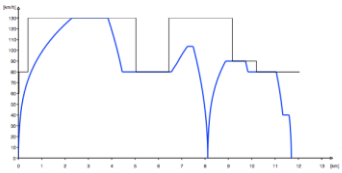
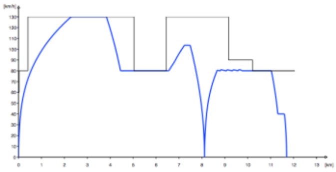
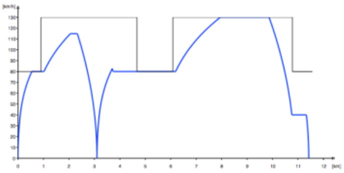
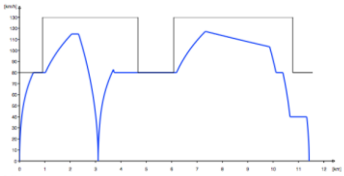
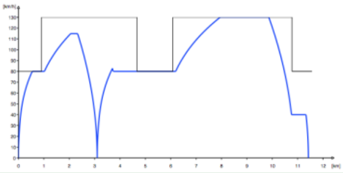
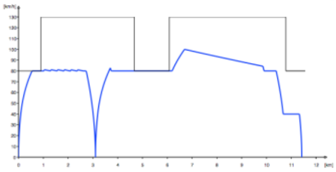
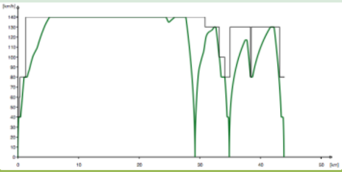
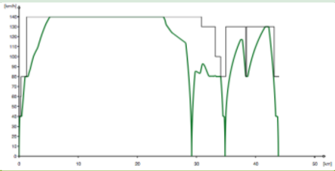
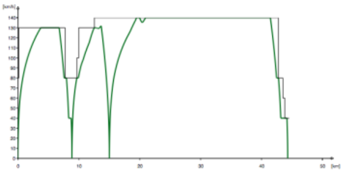
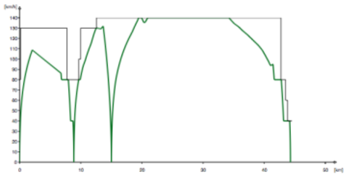
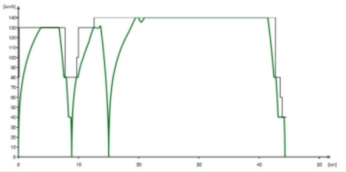
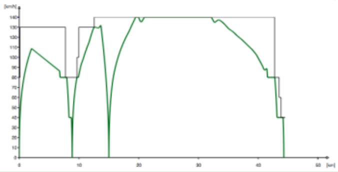
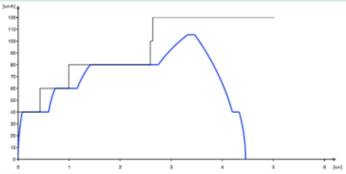
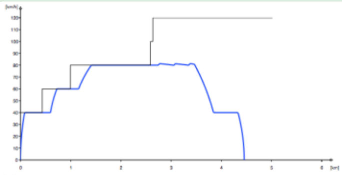
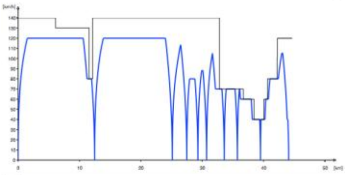
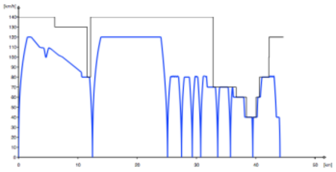
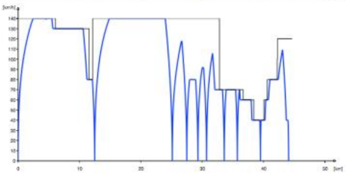
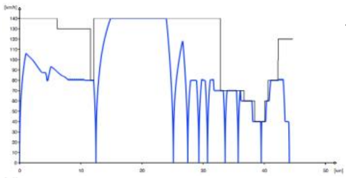
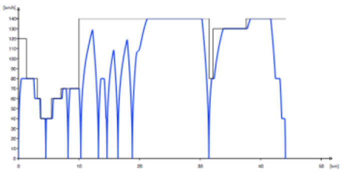
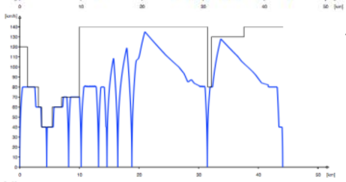
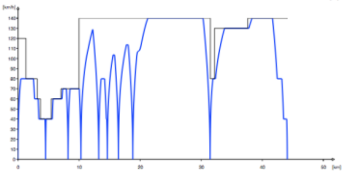
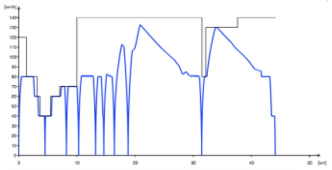
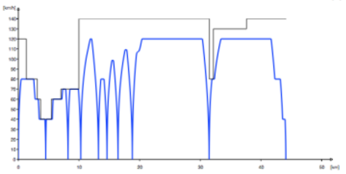
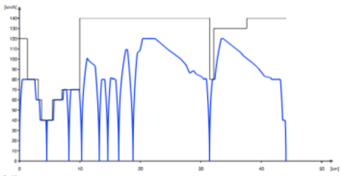
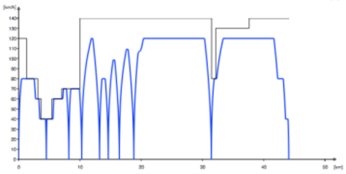
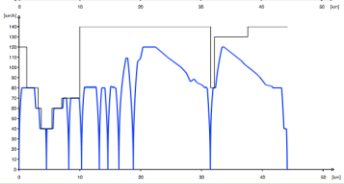
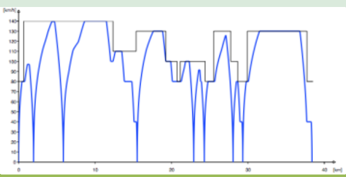
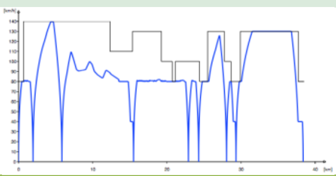
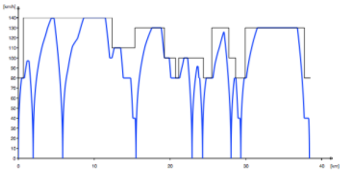
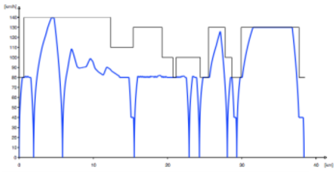
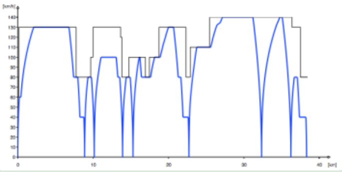
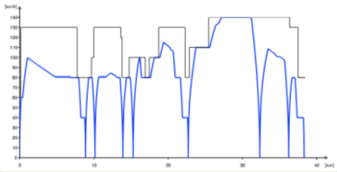
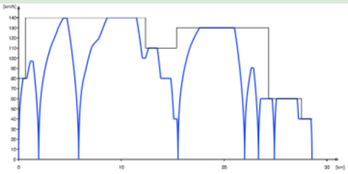
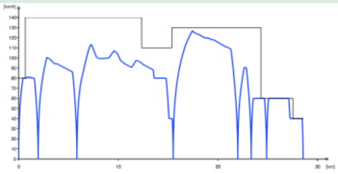
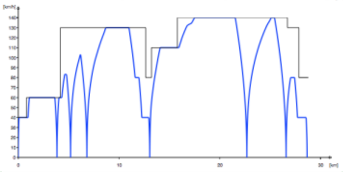
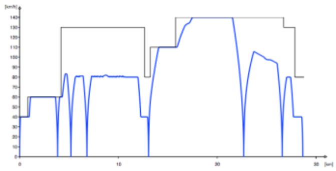
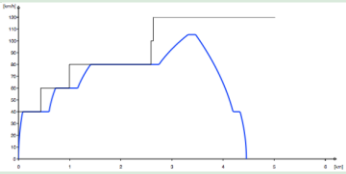
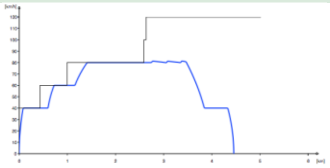
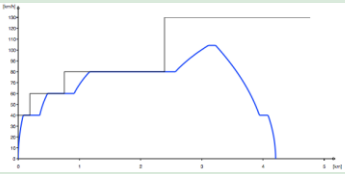
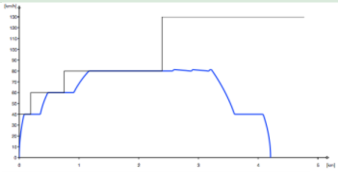
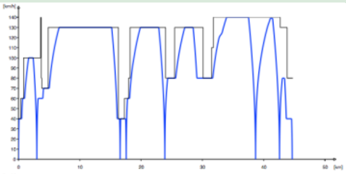
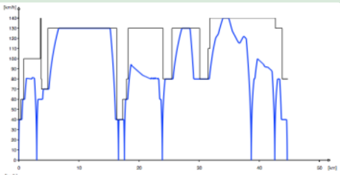
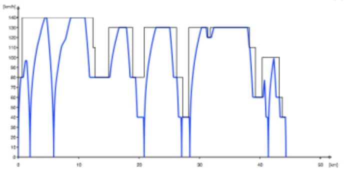
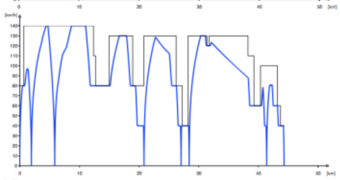
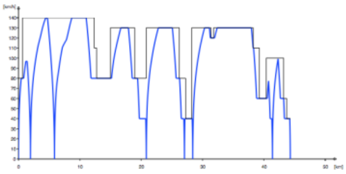
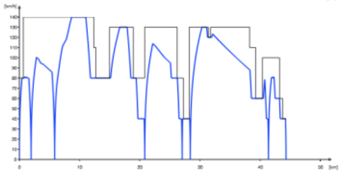
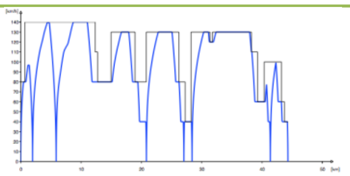
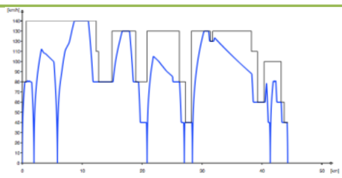
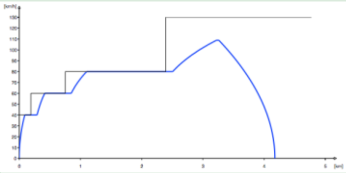
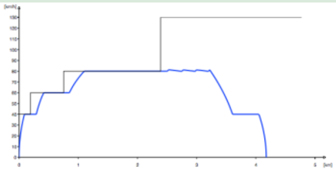
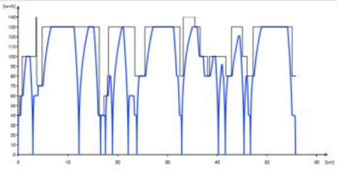
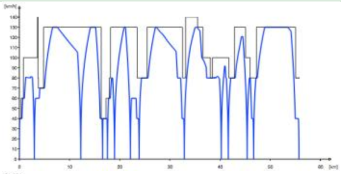
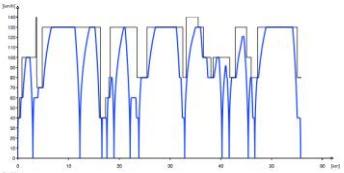
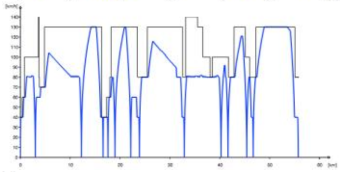
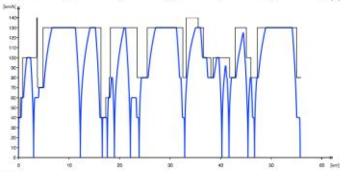
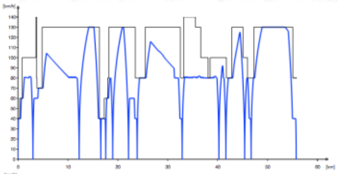
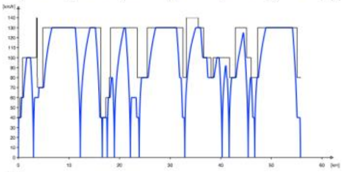
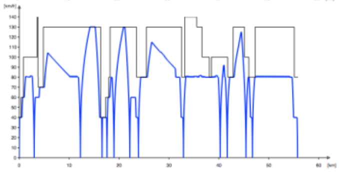
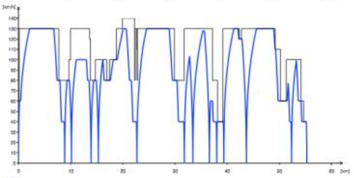
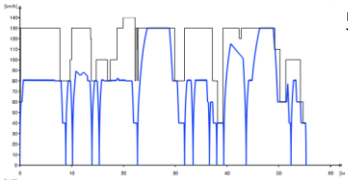
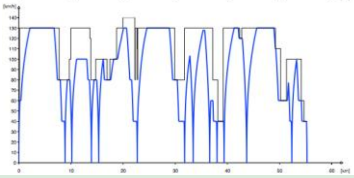
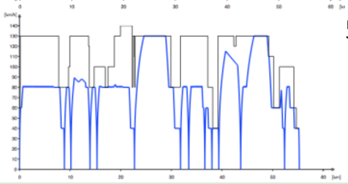
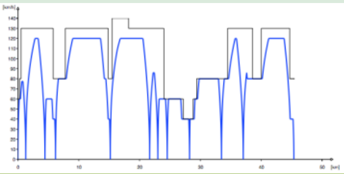
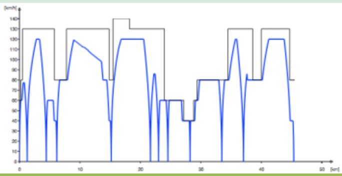
1000(1)		183,4		135,2	-26,3
1000(2)		179,8		89,4	-50,3
1000(3)		179,8		89,4	-50,3
Train series 1500					
1500(1)		68,2		41,2	-39,6
1500(2)		373,2		224,1	-40,0
1500(3)		373,2		262,0	-23,7
1500(4)		304,3		184,9	-39,2
1500(5)		348,8		217,3	-37,7
Train series 1600					
1600(1)		563,6		344,7	-38,8

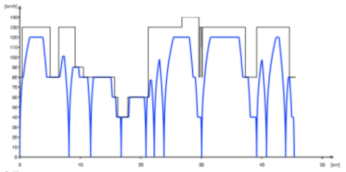
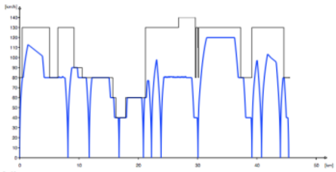
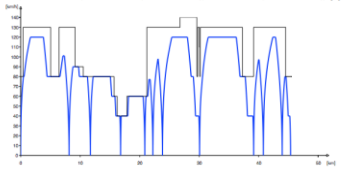
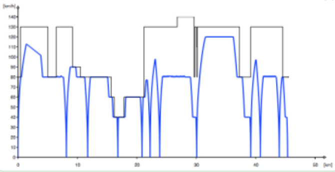
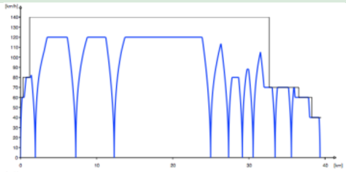
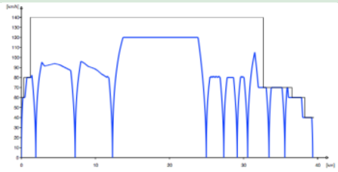
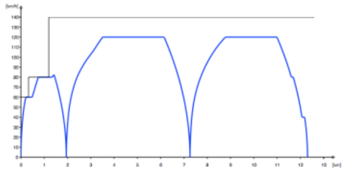
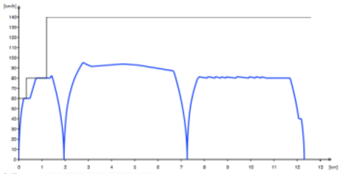
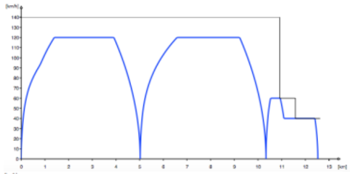
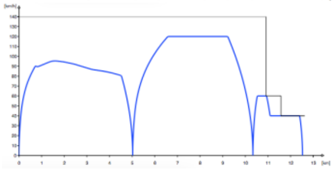
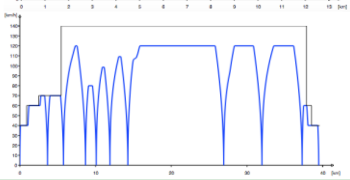
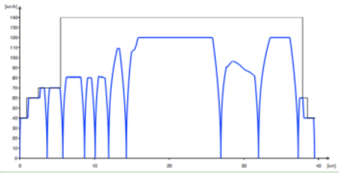
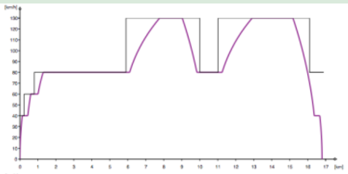
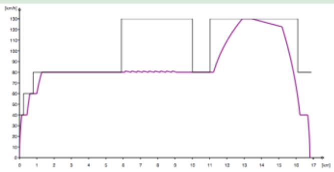
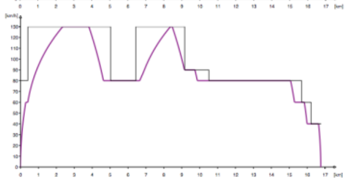
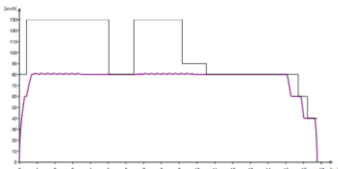
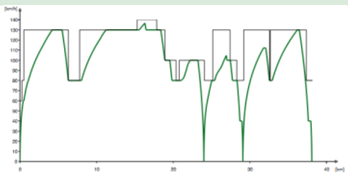
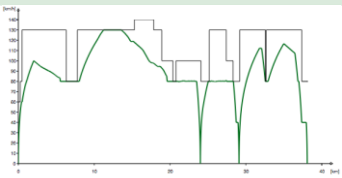
1600(2)		506,0		303,6	-40,0
Train series 2100					
2100(1)		69,1		52,7	-23,7
2100(2)		67,7		51,3	-24,2
2100(3)		67,7		51,3	-24,2
Train series 2200					
2200(1)		68,0		51,6	-24,1
2200(2)		67,7		51,3	-24,2
Train series 2600					
2600(1)		834,8		627,1	-24,9
2600(2)		832,5		576,7	-30,7
2600(3)		832,5		520,5	-37,5

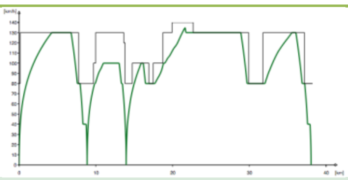
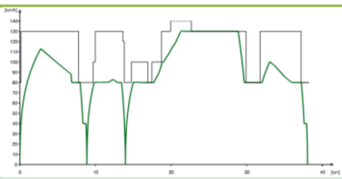
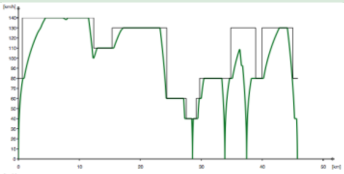
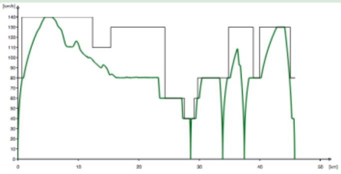
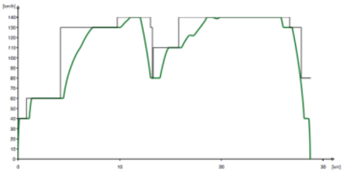
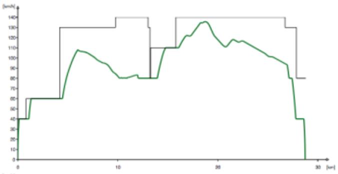
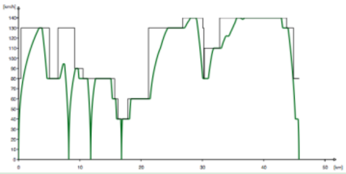
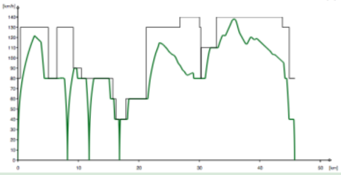
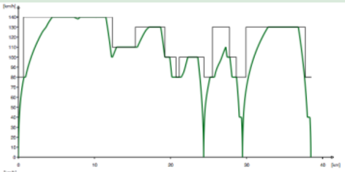
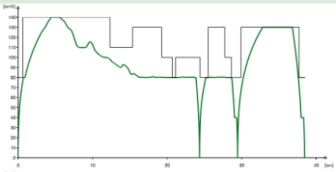
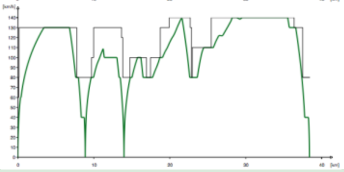
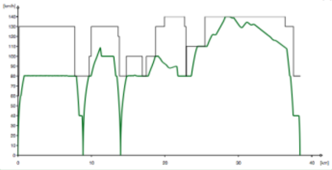
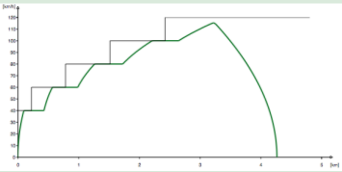
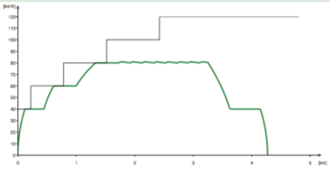
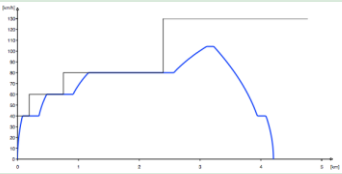
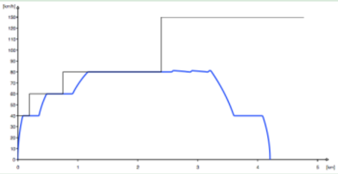
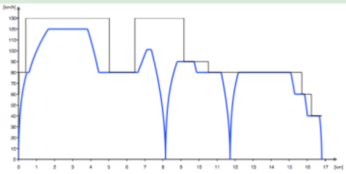
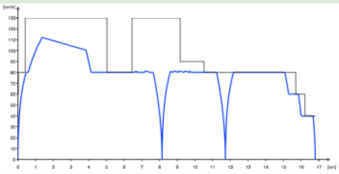
Train series 3000					
3000(1)		677,2		596,2	-12,0
3000(2)		675,0		521,9	-22,7
Train series 3100					
3100(1)		801,0		583,2	-27,2
3100(2)		863,9		593,8	-31,3
Train series 3300					
3300(1)		101,5		97,6	-3,8
3300(2)		101,5		97,6	-3,8
3300(3)		105,2		87,6	-16,7
3300(4)		105,2		57,8	-45,1
Train series 3500					
3500(1)		625,4		520,3	-16,8

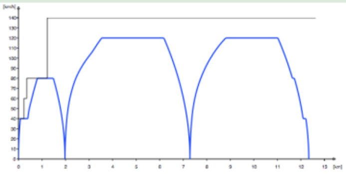
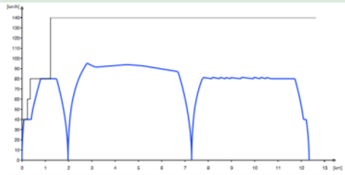
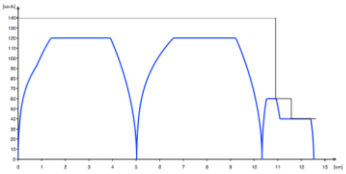
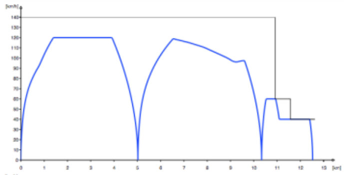
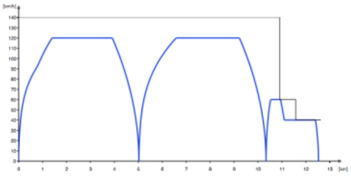
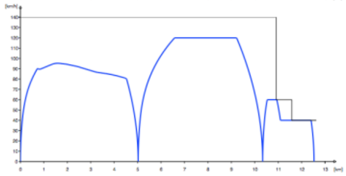
3500(1)		646,1		510,4	-21,0
3500(2)		646,1		496,2	-23,2
Train series 4000					
4000(1)		48,1		31,9	-33,7
4000(2)		437,1		340,6	-22,1
4000(3)		563,0		431,7	-23,3
4000(4)		580,3		403,7	-30,4
4000(5)		571,7		374,2	-34,5
4000(6)		437,7		342,5	-21,8
4000(7)		437,7		334,8	-23,5
Train series 4300					
4300(1)		525,0		390,6	-25,6

4300(2)		525,0		389,7	-25,8
4300(3)		473,2		361,7	-23,6
Train series 4600					
4600(1)		362,0		234,2	-35,3
4600(2)		362,0		270,4	-25,3
Train series 4700					
4700(1)		48,1		31,8	-33,9
Train series 4800					
4800(1)		46,8		31,5	-32,7
Train series 4900					
4900(1)		588,2		449,4	-23,6
4900(2)		603,7		531,0	-12,0
4900(3)		603,6		454,5	-24,7

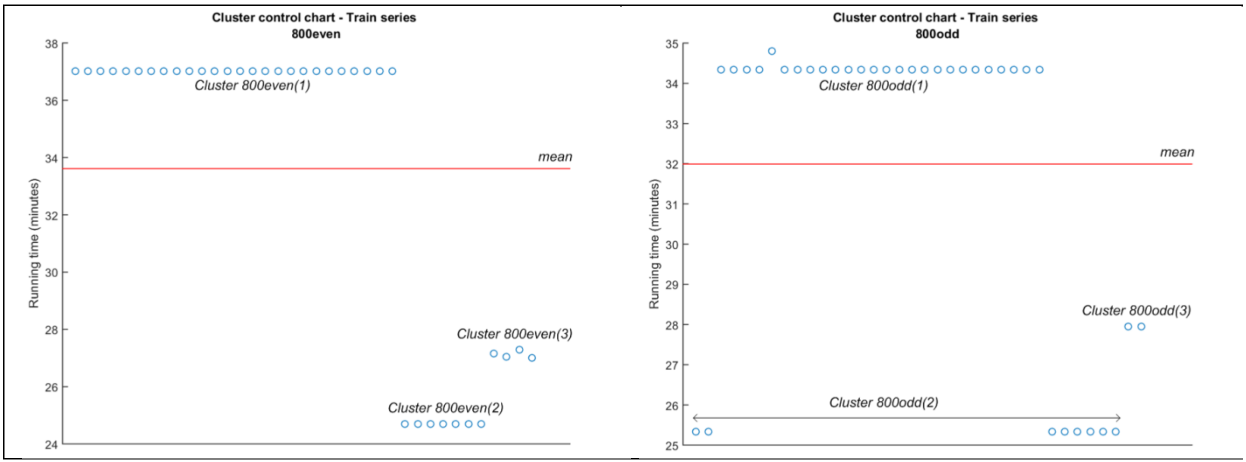
4900(4)		603,6		456,6	-24,4
Train series 5400					
4900(5)		39,3		25,3	-35,6
Train series 5700					
5700(1)		813,5		723,6	-11,1
5700(2)		817,4		641,7	-21,5
5700(3)		817,4		641,7	-21,5
5700(4)		817,4		586,7	-28,2
5700(5)		792,7		566,9	-28,5
5700(6)		792,7		573,2	-27,7
Train series 5800					
5800(1)		492,7		457,2	-7,2

5800(2)		517,9		428,4	-17,3
5800(3)		517,9		429,4	-17,1
Train series 7400					
7400(1)		449,2		365,5	-18,6
7400(2)		159,9		102,6	-35,8
7400(3)		156,1		127,3	-18,5
7400(4)		465,1		397,2	-14,6
Train series 9300					
9300(1)		180,7		120,3	-33,4
9300(2)		177,4		76,2	-57,0
Train series 11600					
11600 (1)		568,6		380,8	-33,0

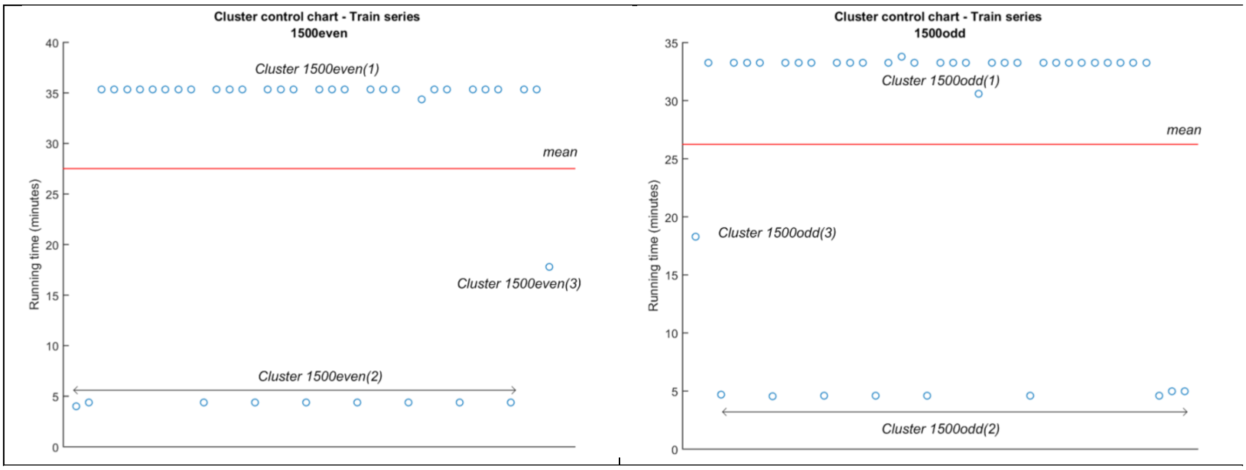
11600 (2)		521,4		369,3	-29,2
Train series 12600					
12600 (1)		834,8		627,1	-24,9
12600 (2)		488,7		263,7	-46,0
12600 (3)		832,6		576,1	-30,8
Train series 12700					
12700 (1)		800,0		536,7	-32,9
12700 (2)		787,8		503,1	-36,1
Train series 14500					
14500 (1)		91,2		91,2	0*
Train series 14800					
14800 (1)		46,5		46,5	0*
Train series 15800					
15800 (1)		162,1		128,1	-21,0

Train series 17400					
17400 (1)		158,5		101,4	-36,0
17400 (2)		156,1		136,4	-12,6
17400 (3)		156,1		127,3	-18,4

Appendix F - Clustering Train Series

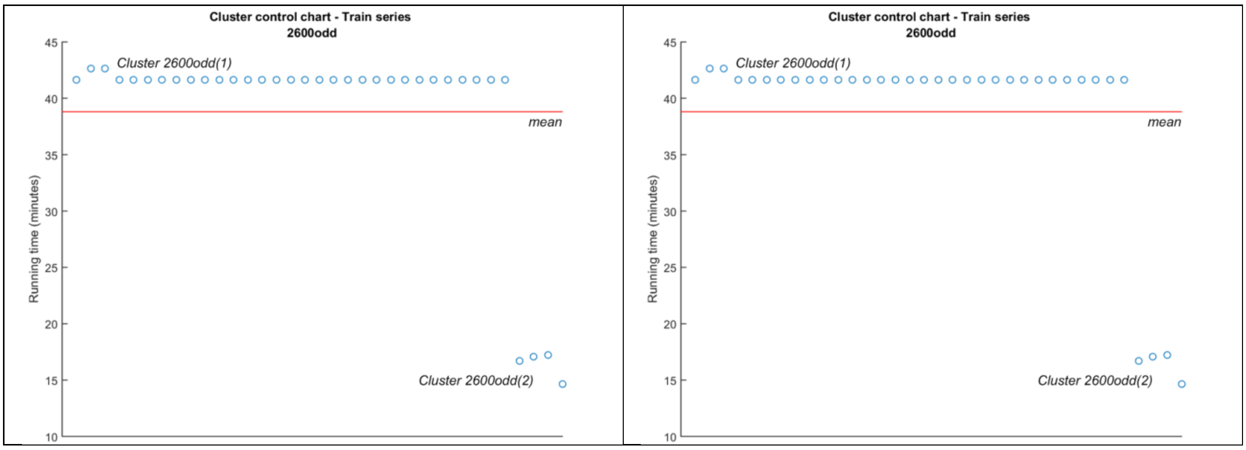


Cluster	Cluster members	Route in model	Remarks
800even(1)	814-864	Ut-Ass	
800even(2)	866-878	Ut-Asd	
800even(3)	880-886	Ut-Asd	Extra stop Asb
800odd(1)	823-873	Ass-Ut	
800odd(2)	819-821/875-885	Asd-Ut	
800odd(3)	887-889	Asd-Ut	Extra stop Asb

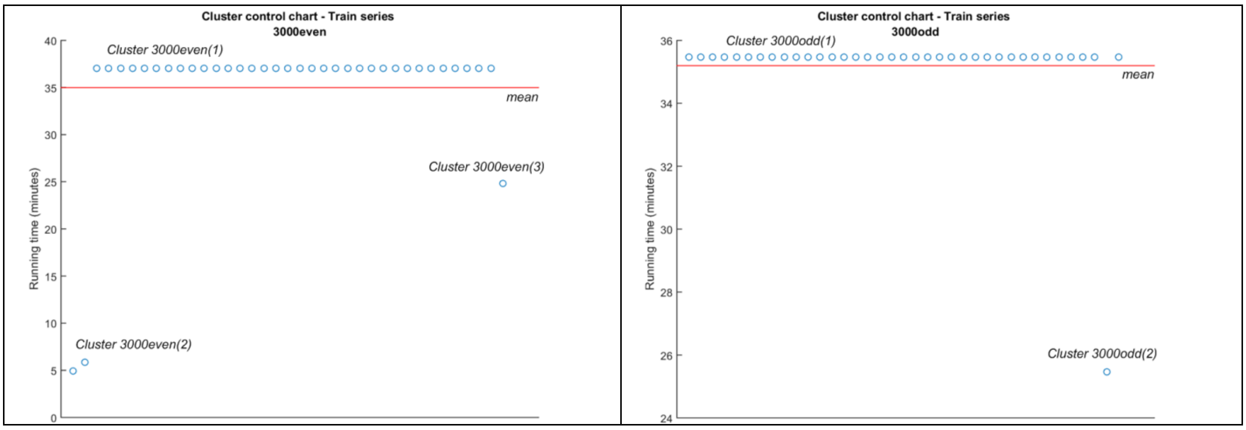


Cluster	Cluster members	Route in model	Remarks
1500even(1)	1516-1530/1534-1538/1542-1546/1550-1554/1558-1562/1566-1570/1574-1578/1582-1584	Hvs-Ass	
1500even(2)	1512-1514 /1532/1540/1548/1556 /1564/1572/1580	Asd-Ass	Does not run section Hvs-Asd when series 140even is running
1500even(3)	1586	Hvs-Asd	
1500odd(1)	1519/1523-1527/1531-1535/1539-1543/1547-1551/1555-1567/1571-	Ass-Hvs	1561: Shorter dwell time at Asd

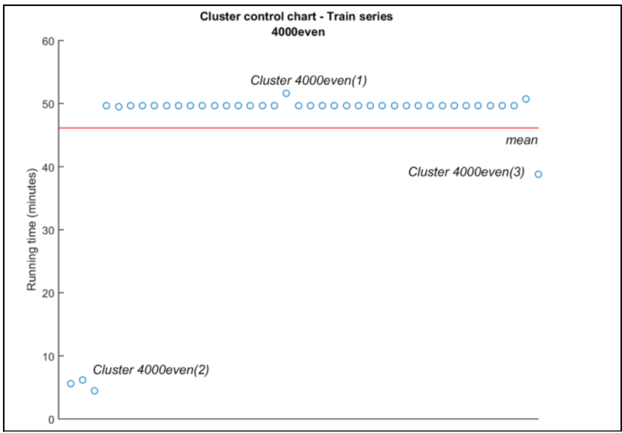
	1587		
1500odd(2)	1521/1529/1537/1545 1553/1569/1589-1593	Ass-Asd	Does not run section Asd-Hvs when series 140odd is running
1500odd(3)	1517	Asd-Hvs	

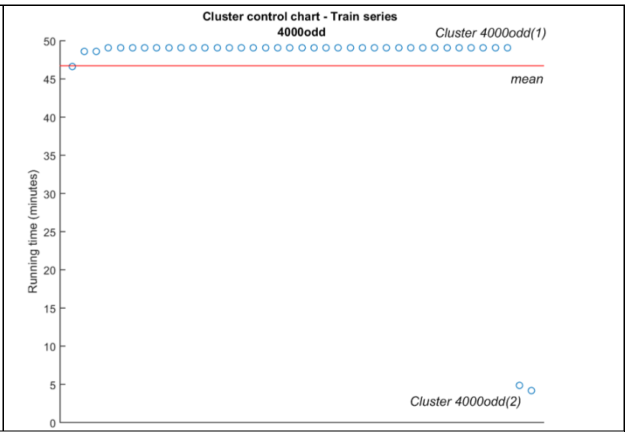


Cluster	Cluster members	Route in model	Remarks
2600even(1)	2612-2676	Alm-Shl	
2600even(2)	2608-2610	Asd-Shl	
2600odd(1)	2621-2681	Shl-Alm	
2600odd(2)	2689-2695	Shl-Asd	Non-existing trains: 2683-2687

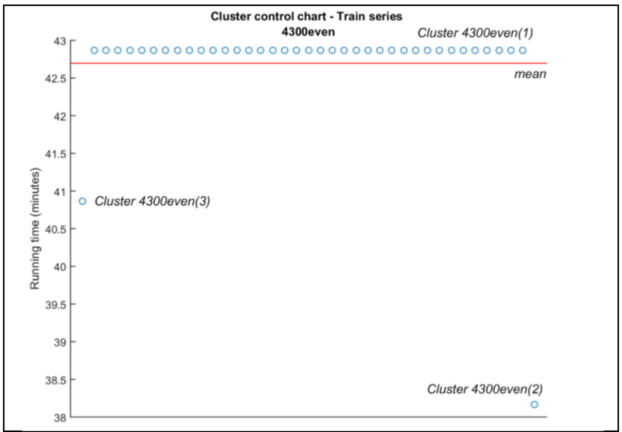


Cluster	Cluster members	Route in model	Remarks
3000even(1)	3014-3080	Ut-Ass	
3000even(2)	3010-3012	Asd-Ass	
3000even(3)	3082	Ut-Asd	
3000odd(1)	3019-3087/3091	Ass-Ut	
3000odd(2)	3089	Asd-Ut	

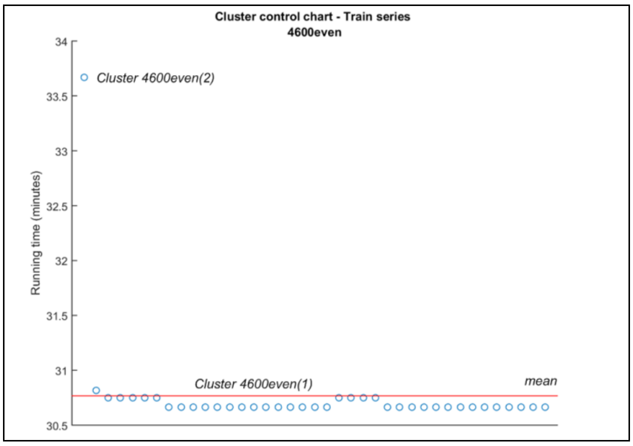




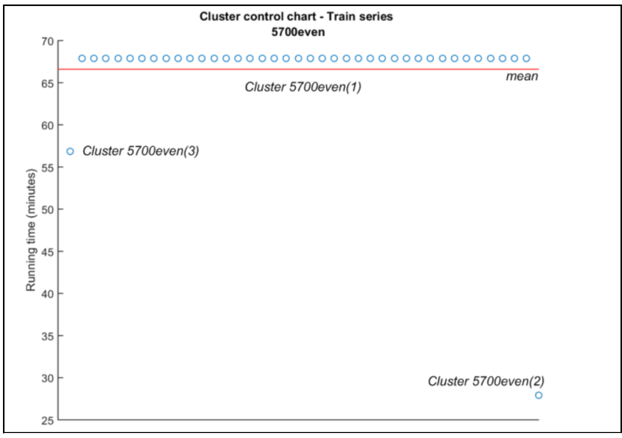
Cluster	Cluster members	Route in model	Remarks
4000even(1)	4012-4082	Wd-Ass	
4000even(2)	4006-4010	Asd-Ass	
4000even(3)	4084	Wd-Asd	
4000odd(1)	4019-4091	Ass-Wd	
4000odd(2)	4093-4095	Ass-Asd	

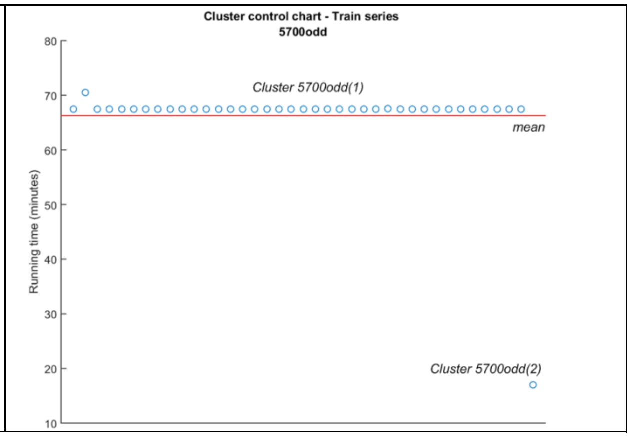


Cluster	Cluster members	Route in model	Remarks
4300even(1)	4310-4384	Alm-Shl	
4300even(2)	4386	Alm-Shl	Shorter dwell/waiting time at Wp, Dmnz and Dvd
4300even(3)	4308	Alm-Shl	Shorter dwell/waiting time at Wp

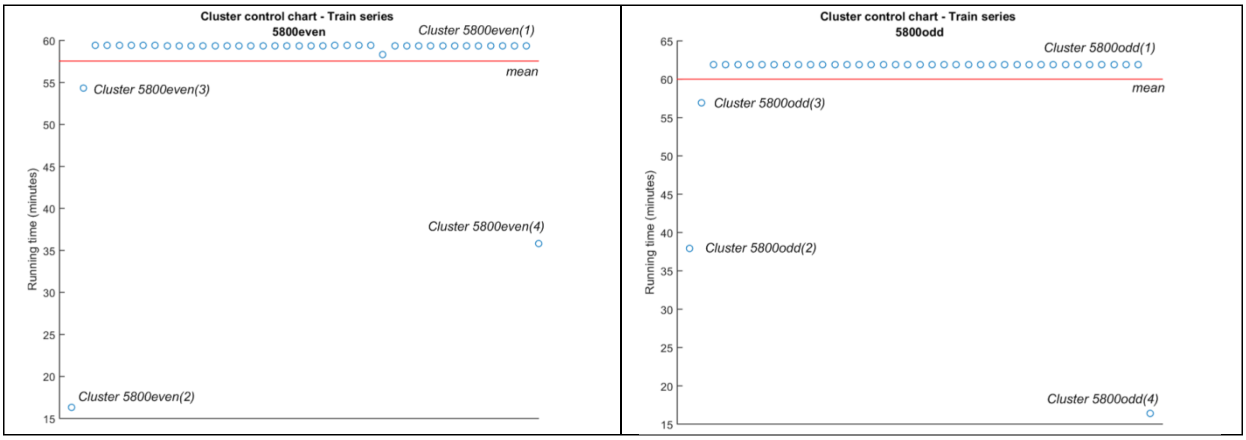


Cluster	Cluster members	Route in model	Remarks
4600even(1)	4612-4686	Alm-Asd	
4600even(2)	4610	Alm-Asd	Longer dwell/waiting time at Wp

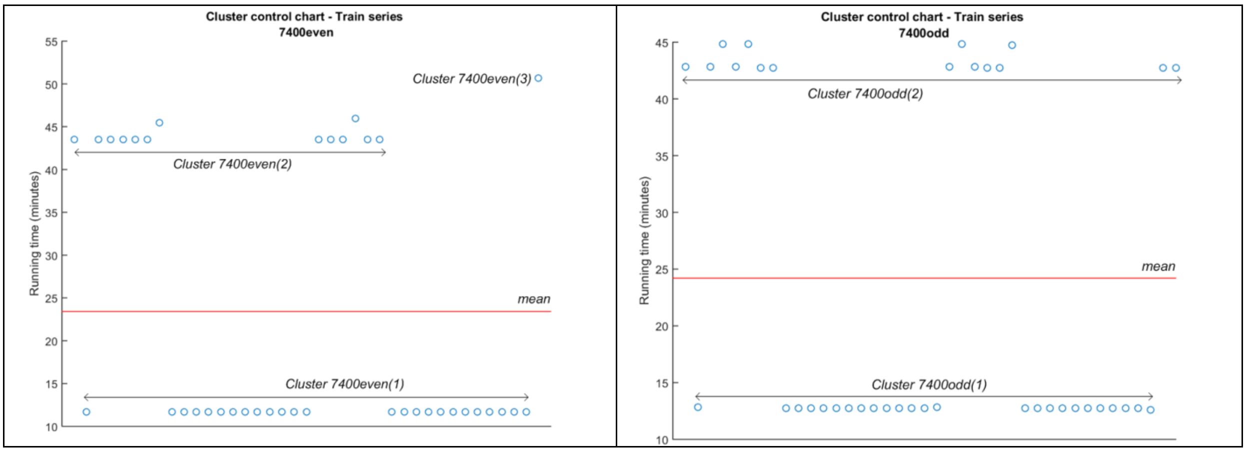




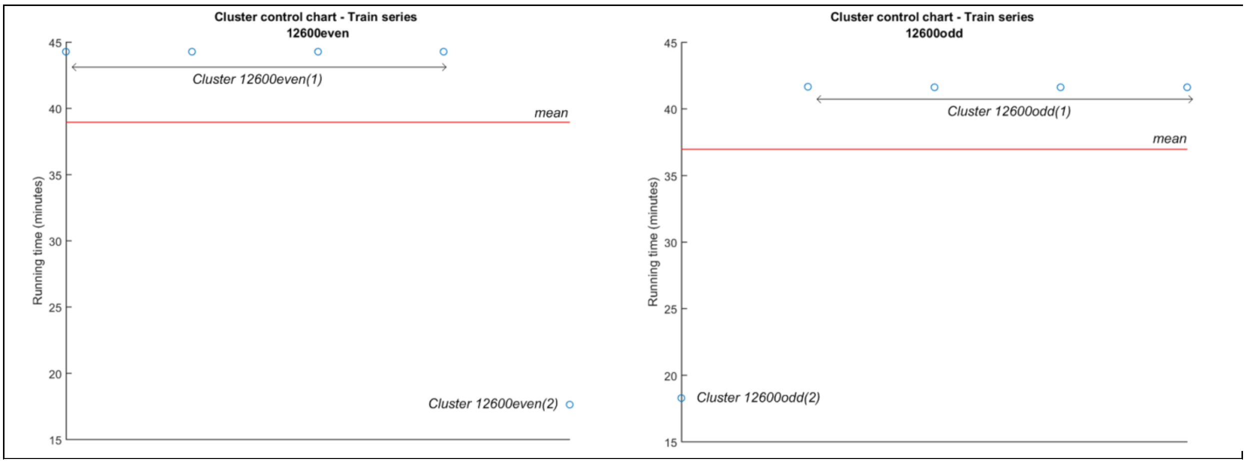
Cluster	Cluster members	Route in model	Remarks
5700even(1)	5712-5786	Ut-Hvs-Shl	
5700even(2)	5788	Ut-Ndb	
5700even(3)	5710	Ut-Hvs-Shl	Significantly shorter dwell/waiting time at Wp (2 min. compared to 9 min. (1) and (2)
5700odd(1)	5715-5789	Shl-Hvs-Ut	
5700odd(2)	5791	Shl-Dmnz	



Cluster	Cluster members	Route in model	Remarks
5800even(1)	5810-5882	Hvs-Shl	
5800even(2)	5806	Asd-Shl	
5800even(3)	5808	Hvs-Shl	Shorter dwell/waiting time at Wp and Asd
5800even(4)	5886	Hvs-Shl	Non-existing trains: 5884
5800odd(1)	5821-5891	Shl-Hvs	
5800odd(2)	5817	Asd-Hvs	
5800odd(3)	5819	Shl-Hvs	Shorter dwell/waiting time at Asd
5800odd(4)	5893	Shl-Asd	



Cluster	Cluster members	Route in model	Remarks
7400even(1)	7410/7424-7446/7460-7482	Ut-Bkl	
7400even(2)	7408/7412-7422/7448-7458	Ut-Asd	
7400even(3)	7484	Ut-Ass	
7400odd(1)	7419/7433-7457/7471-7491	Bkl-Ut	
7400odd(2)	7417/7421-7431/7459-7469/7493-7495	Asd-Ut	



Cluster	Cluster members	Route in model	Remarks
12600even(1)	12678-12684	Alm-Shl	
12600even(2)	12686	Alm-Asd	
12600odd(1)	12619/12683-12687	Shl-Alm	Non-existing trains: 12621-12681
12600odd(2)	12617	Asd-Alm	

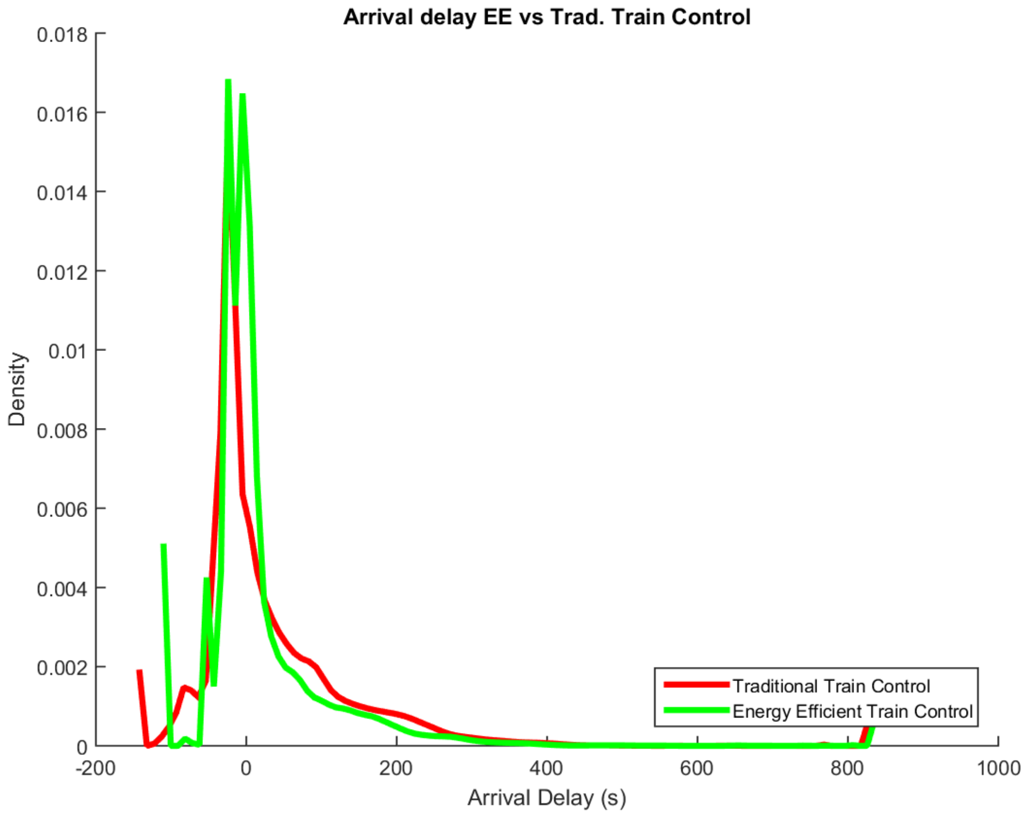
Appendix G: Energy savings per train series

Train series	n	Traditional Train Control (kWh)	Energy Efficient Train Control (kWh)	Difference in %
9300odd	650	170,7	89,3	-47,7
1000odd	150	175,8	110,8	-37,0
900odd	1600	182,1	119,2	-34,6
12600odd(2)	50	461,7	325,0	-29,6
1500odd(1)	1450	346,4	261,2	-24,6
1600even	900	540,7	410,8	-24,0
700even	800	596,4	455,7	-23,6
1500even(1)	1400	359,3	278,6	-22,4
12700even	800	779,9	607,8	-22,1
1600odd	950	502,5	394,2	-21,6
7400even(3)	50	607,4	482,8	-20,5
5400odd	1850	37,5	30,1	-19,6
17400even	1400	154,5	125,5	-18,7
2600odd(1)	1550	785,4	640,6	-18,4
4000odd(1)	1850	432,8	353,5	-18,3
11600even	950	543,6	444,1	-18,3
4600even(1)	1900	342,5	284,2	-17,0
800odd(2)	400	589,0	489,9	-16,8
12700odd	750	752,7	626,8	-16,7
2600even(1)	1650	822,6	686,3	-16,6
100odd	350	389,6	325,3	-16,5
2100odd	1950	65,1	54,9	-15,6
12600odd(1)	200	794,2	670,9	-15,5
4300even(1)	1850	510,3	432,4	-15,3
3100odd	1450	866,8	737,8	-14,9
4300even(3)	50	505,4	433,0	-14,3
5700odd(1)	1900	769,9	662,8	-13,9
700odd	800	569,6	491,6	-13,7
7400even(1)	1250	150,2	129,8	-13,6
400even	100	654,6	567,9	-13,2
4800odd	1350	47,7	41,4	-13,2
4600odd	1900	346,0	300,4	-13,2
5700odd(2)	50	194,4	169,9	-12,6
800odd(1)	1300	702,7	615,5	-12,4
5700even(1)	1900	773,4	679,6	-12,1
4300even(2)	50	519,6	457,2	-12,0
3300odd	1900	103,5	91,6	-11,5
140odd	350	366,4	324,4	-11,5
400odd	100	688,5	611,3	-11,2
4300odd	1900	454,2	403,4	-11,2
3000odd(2)	50	654,4	582,5	-11,0

11600odd	900	519,4	469,5	-9,6
4000even(1)	1800	428,8	390,2	-9,0
3000odd(1)	1800	717,9	659,0	-8,2
4900even	1600	551,4	510,4	-7,4
3500odd	1800	618,3	576,3	-6,8
4900odd	1650	575,9	536,8	-6,8
3100even	1500	754,1	704,3	-6,6
4700even	1300	48,6	45,5	-6,5
800odd(3)	100	673,5	631,9	-6,2
5700even(2)	50	330,0	311,3	-5,7
12600even(2)	50	462,4	436,8	-5,5
7400even(2)	650	426,8	403,5	-5,5
5800odd(1)	1800	507,8	480,7	-5,3
4000even(3)	50	392,6	375,2	-4,4
3500even	1750	602,7	578,7	-4,0
140even	350	376,0	364,7	-3,0
12600even(1)	200	810,7	790,3	-2,5
15800odd	50	157,2	153,6	-2,3
7400odd(2)	750	450,3	440,7	-2,1
800even(1)	1300	646,5	634,7	-1,8
5800odd(4)	50	170,7	167,8	-1,7
7400odd(1)	1250	149,0	147,0	-1,3
1500odd(2)	450	44,4	43,9	-1,2
4700odd	1350	38,4	38,0	-0,8
2100even	1900	52,9	52,5	-0,8
2200even	1650	52,2	51,9	-0,5
5700even(3)	50	773,6	770,1	-0,5
5800even(4)	50	304,5	303,4	-0,4
4800even	1500	31,9	31,9	-0,1
5400even	1800	25,2	25,2	0,0
3000even(1)	1700	650,6	651,2	0,1
5800even(3)	50	472,8	477,1	0,9
5800even(1)	1850	473,6	479,6	1,3
1500even(2)	450	58,9	59,7	1,3
800even(2)	350	561,8	569,7	1,4
3300even	1800	98,5	99,9	1,4
5800even(2)	50	169,2	172,1	1,7
900even	1600	176,4	179,8	1,9
1000even	100	178,4	181,9	1,9
9300even	600	181,2	184,8	2,0
2200odd	1650	64,8	66,5	2,5
800even(3)	200	625,1	641,4	2,6
100even	350	315,7	324,5	2,8
17400odd	1400	148,5	153,1	3,1
2600odd(2)	200	329,7	340,5	3,3

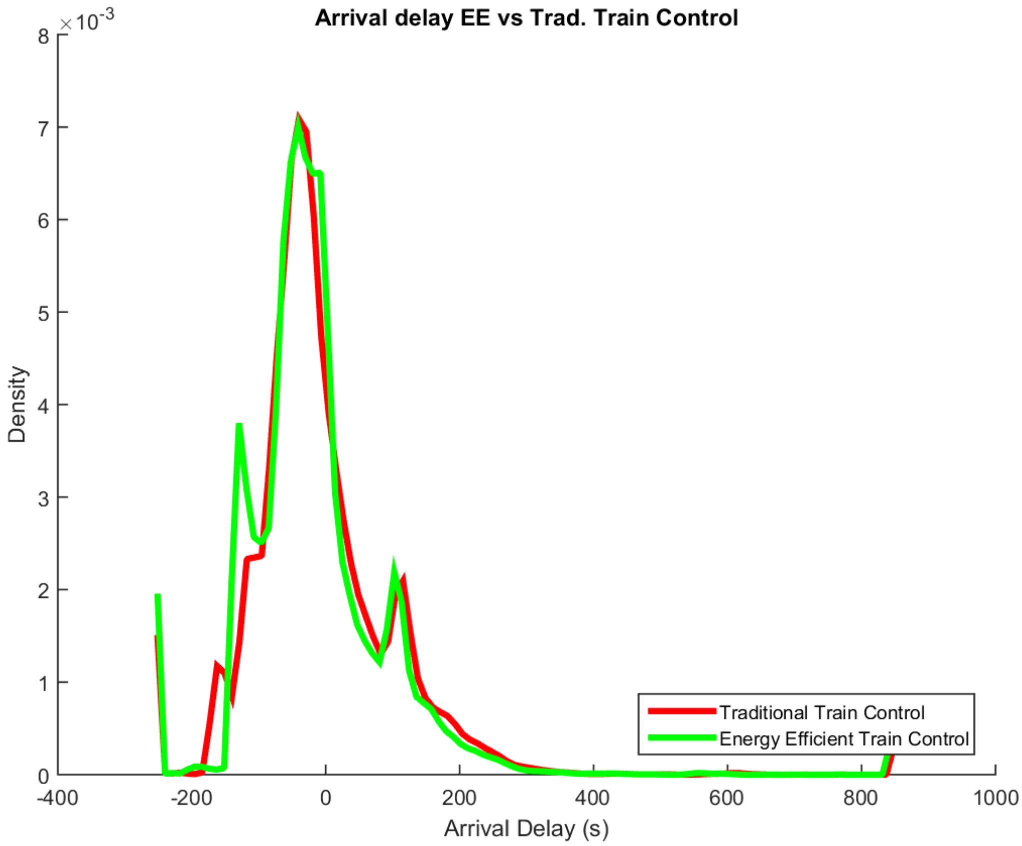
Appendix H - Punctuality per station

Utrecht Centraal



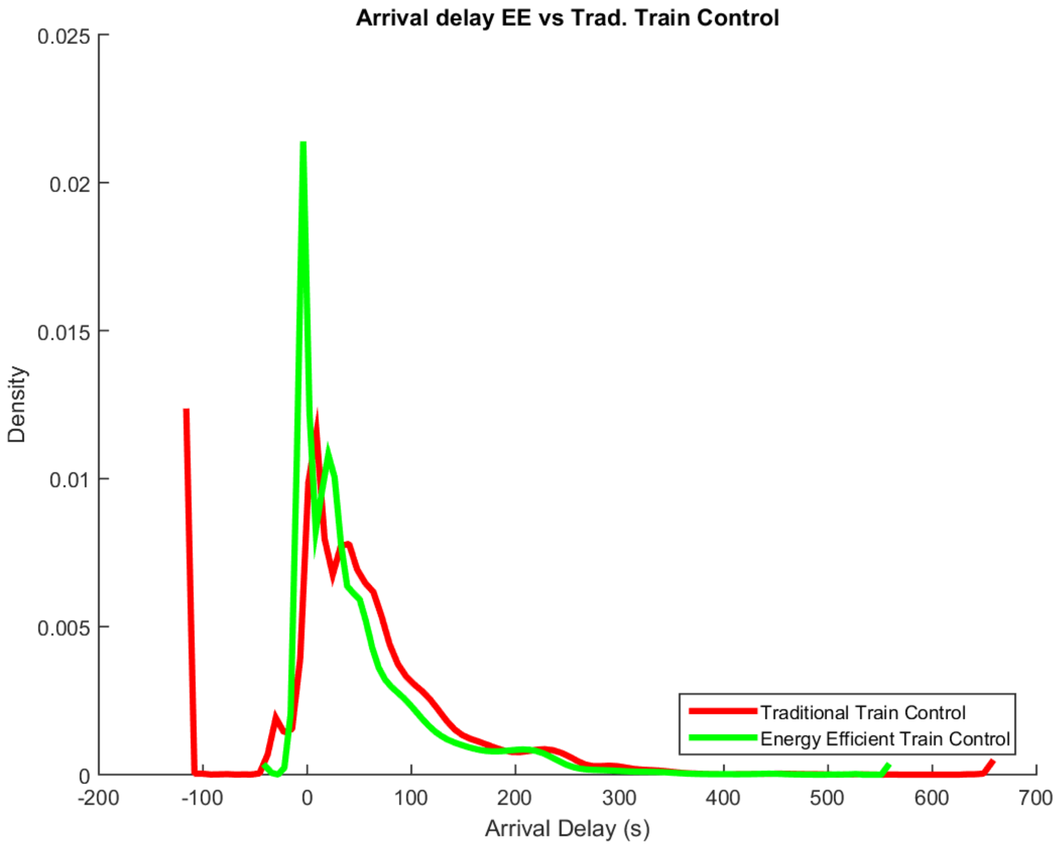
	Ut Traditional Train Control	Ut Energy Efficient Train Control	Difference in %
Punctuality (3-minutes)	0,92	0,95	3,42
n	14300	14300	0
Min (s)	-142	-110	-23
25th prct (s)	-22	-22	0
Median (s)	-4	-2	-50
75th prct (s)	62	28	-55
Max (s)	827	835	1
Mean (s)	28,4	21,5	-24,5
Disp (std) (s)	88,5	73,2	-17,3
Reject H0 (α=0,05)	**Yes**		

Amsterdam Centraal



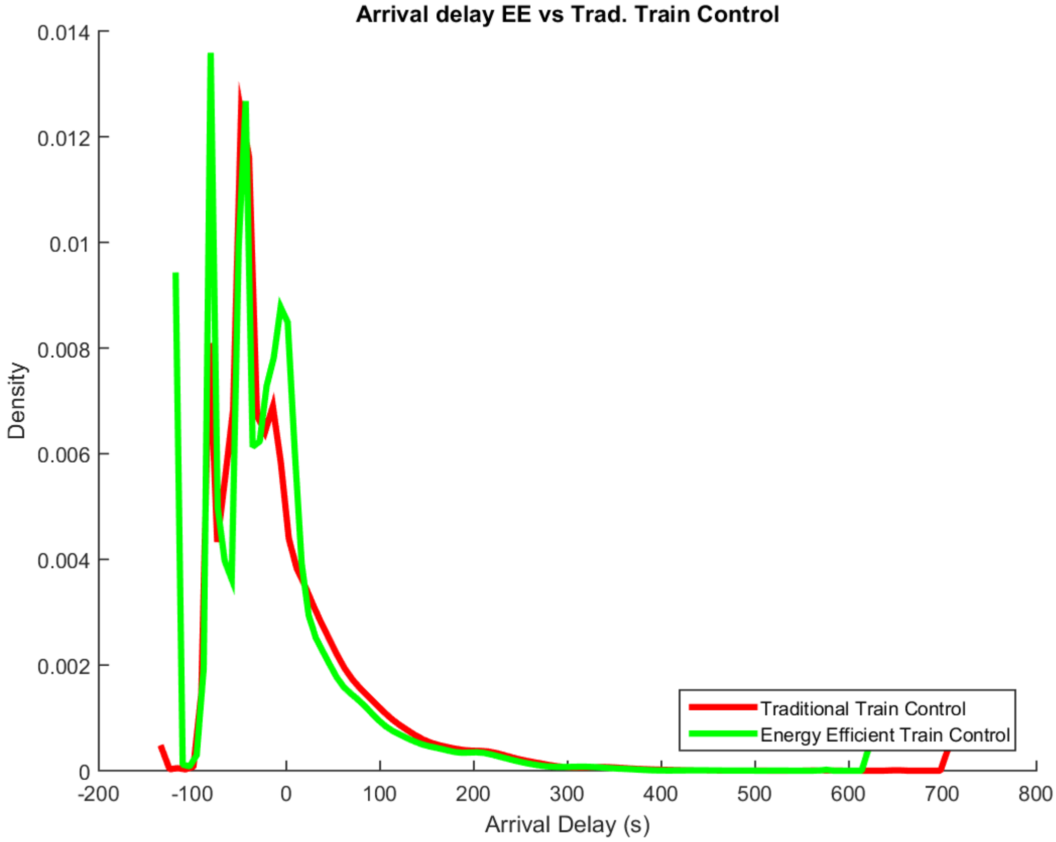
	Asd Traditional Train Control	Asd Energy Efficient Train Control	Difference in %
Punctuality (3-minutes)	0,96	0,97	1,11
n	35650	35650	0
Min (s)	-251	-251	0
25th prct (s)	-63	-65	3
Median (s)	-25	-28	12
75th prct (s)	33	18	-45
Max (s)	848	842	-1
Mean (s)	-6,9	-13,7	98,6
Disp (std) (s)	91,1	86,2	-5,4
Reject H0 (α=0,05)	No		

Schiphol



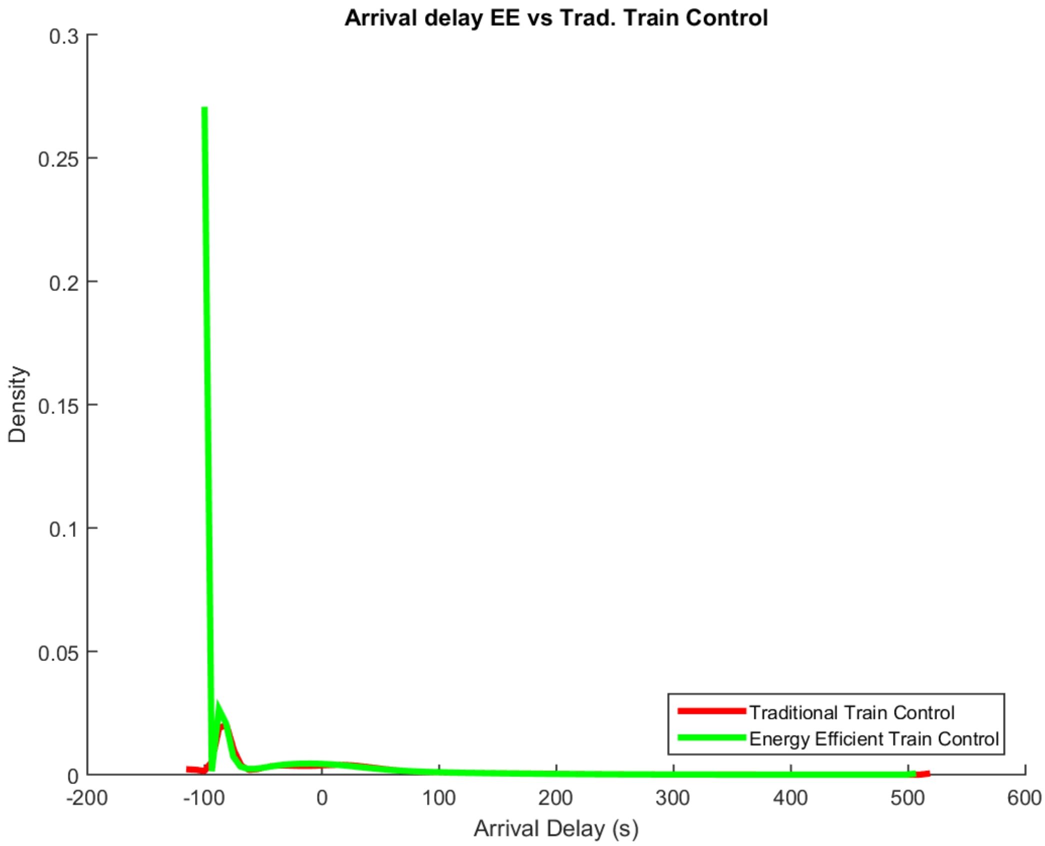
	Shl Traditional Train Control	Shl Energy Efficient Train Control	Difference in %
Punctuality (3-minutes)	0,91	0,93	2,13
n	18700	18700	0
Min (s)	-116	-40	-66
25th prct (s)	9	0	-100
Median (s)	46	26	-43
75th prct (s)	94	70	-26
Max (s)	657	557	-15
Mean (s)	66,2	50,0	-24,4
Disp (std) (s)	74,2	66,9	-9,9
Reject H0 (α=0,05)	**Yes**		

Amsterdam Sloterdijk



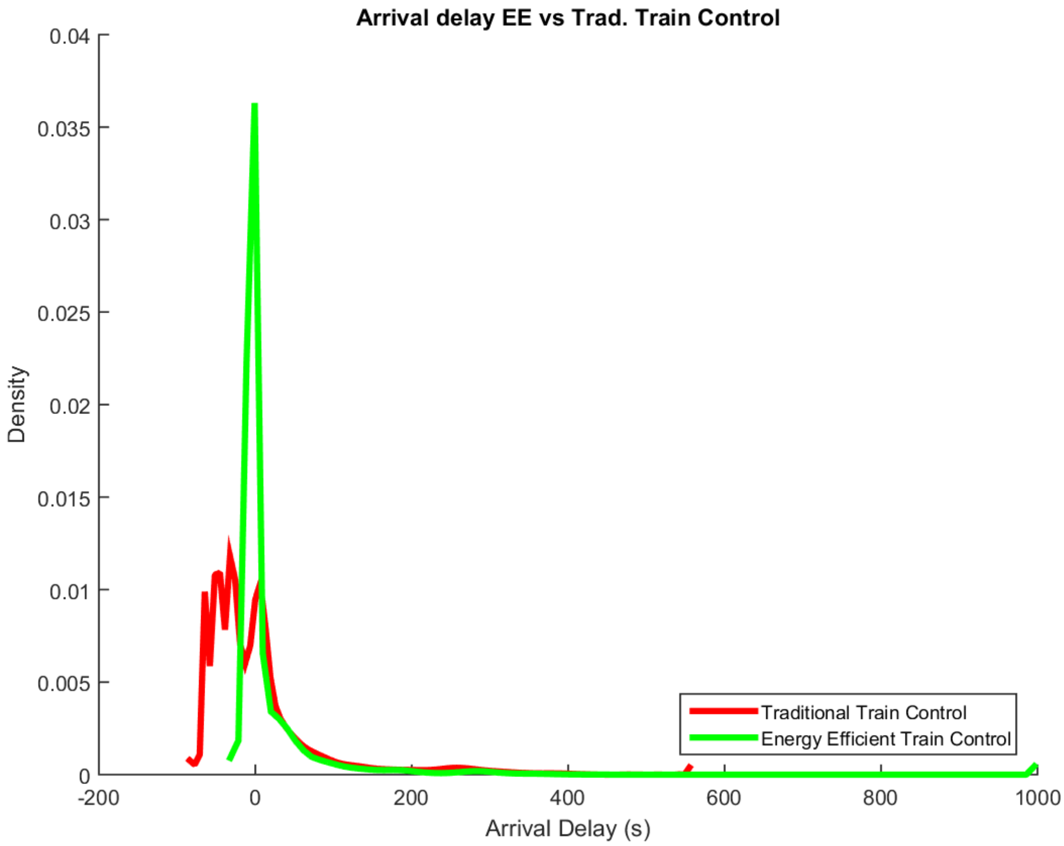
	Ass Traditional Train Control	Ass Energy Efficient Train Control	Difference in %
Punctuality (3-minutes)	0,96	0,97	0,63
n	16850	16850	0
Min (s)	-133	-118	-11
25th prct (s)	-48	-46	-4
Median (s)	-25	-20	-20
75th prct (s)	24	10	-58
Max (s)	706	621	-12
Mean (s)	-3,5	-6,9	96,2
Disp (std) (s)	75,1	69,7	-7,2
Reject H0 (α=0,05)	No		

Duivendrecht



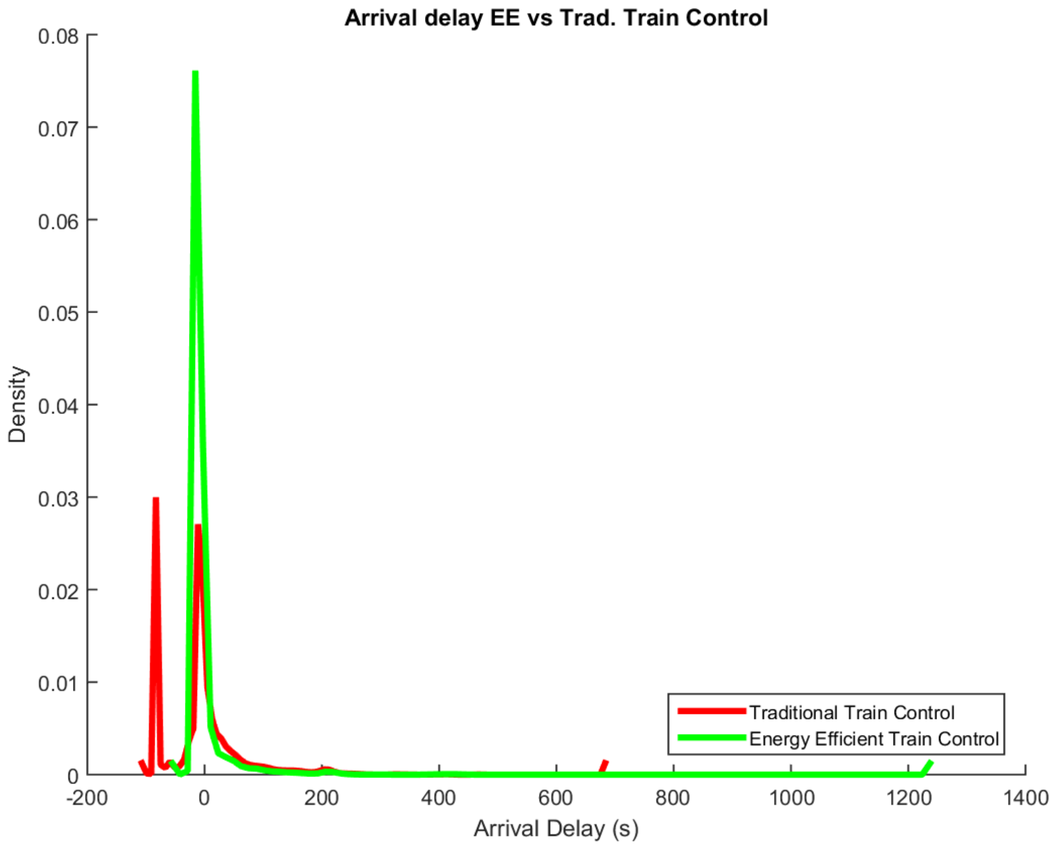
	Dvd Traditional Train Control	Dvd Energy Efficient Train Control	Difference in %
Punctuality (3-minutes)	0,97	0,98	0,55
n	11050	11050	0
Min (s)	-113	-100	-12
25th prct (s)	-84	-84	0
Median (s)	-42	-36	-14
75th prct (s)	22	14	-36
Max (s)	516	504	-2
Mean (s)	-24,3	-24,5	0,8
Disp (std) (s)	78,8	73,7	-6,5
Reject H0 (α=0,05)	No		

Weesp



	Wp Traditional Train Control	Wp Energy Efficient Train Control	Difference in %
Punctuality (3-minutes)	0,95	0,97	2,17
n	15400	15400	0
Min (s)	-84	-32	-62
25th prct (s)	-41	-11	-73
Median (s)	-13	-1	-92
75th prct (s)	14	6	-57
Max (s)	555	996	79
Mean (s)	4,8	12,0	150,9
Disp (std) (s)	74,3	52,7	-29,1
Reject H0 (α=0,05)	Yes		

Almere Centrum



	Alm Traditional Train Control	Alm Energy Efficient Train Control	Difference in %
Punctuality (3-minutes)	0,97	0,98	1,07
n	8750	8750	0
Min (s)	-107	-55	-49
25th prct (s)	-13	-16	23
Median (s)	-8	-7	-13
75th prct (s)	15	1	-93
Max (s)	683	1237	81
Mean (s)	2,9	5,1	78,1
Disp (std) (s)	63,3	48,2	-23,8
Reject H0 (α=0,05)	Yes		