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ERIK MAGNI VINBERG Energy Use in the Operational Cycle of Passenger Rail Vehicles

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Energy Use in the Operational Cycle of Passenger Rail Vehicles

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Energy use in the operational cycle of passenger rail vehicles

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MSc thesis in Vehicle Engineering

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Abstract

This master thesis investigates and analyzes the energy use for traction and auxiliary equipment in passenger rail vehicles. It covers both the train service with passengers and when the trains are going through other stages in the everyday operation. The *operational cycle* and associated *operational situations* are introduced as a way of describing the varying use of a train over time. The descriptions focus on the most common activities and situations, such as stabling and parking, regular cleaning, inspections and maintenance. Also how these situations affect energy use by their need for different auxiliary systems to be active.

An energy model is developed based on the operational cycle as a primary input, together with relevant vehicle parameters and climate conditions. The latter proving to be a major influence on the energy used by the auxiliary equipment. The model is applied in two case studies, on SJ's X55 and Västtrafik's X61 trains. Both are modern electric multiple units equipped with energy meters. Model input is gathered from available technical documentation, previous studies and by measurements and parameter estimations. Operational cycle input is collected through different planning systems and rolling stock rosters. Climate input is finally compiled from open meteorological data banks.

The results of the case studies show that the method and models are useful for studying the energy used by the trains in their operational cycles. With the possibility to distinguish the energy used by the auxiliary equipment, both during and outside the time the trains are in service with passengers. With this it's also possible to further investigate and study potential energy saving measures for the auxiliary equipment. Simulations of new ventilation control functions and improved use of existing operating modes on the trains show that considerable energy savings could be achieved with potentially very small investments or changes to the trains.

The results generally show the importance of a continued investigation of the auxiliary equipment's energy use, as well as how the different operational situations other than the train service affect the total energy use.

Keywords:
energy use, passenger train operation, auxiliary power, auxiliary systems, energy modelling, case studies, stabling, parking, service, climate, HVAC.

Sammanfattning

Detta examensarbete utreder och analyserar energianvändningen för passagerarjärnvägsfordons traktion- och hjälpkraftssystem, både under tågdriften med passagerare och andra delmoment som tågen genomgår under den normala dagliga driften. För detta introduceras *driftcykeln* och tillhörande *driftsituationer* som ett sätt att beskriva användningen av ett tåg över tiden. Syftet är att beskriva de vanligast förekommande aktiviteterna och situationerna, såsom uppställning och parkering, regelbundna inspektioner, klargörningar och underhåll. Även hur dessa situationer påverkar energianvändningen genom ett varierande behov av hjälpkraft och aktiva funktioner i tågen.

En energimodell baserad på driftcykeln som huvudsaklig indata, tillsammans med tågets egenskaper samt det omgivande klimatet, tas fram. Klimatet visar sig vara en avgörande faktor i hjälpkraftens energianvändning. Modellen utvärderas i typstudier på SJs X55 och Västtrafiks X61. Båda är elektriska motorvagnståg utrustade med energimätare. Indata till modellen samlas in genom tillgänglig teknisk dokumentation, tidigare studier och genom mätningar samt parameterestimering. Driftcyklerna för tågtyperna sammanställs med hjälp av olika planeringssystem och omloppsplaner. Väder- och klimatdata samlas slutligen in från öppna databaser för metrologiska data.

Resultaten från typstudierna visar att metoden och modellerna är användbara verktyg för att kunna beskriva tågens energianvändning i deras driftcykler. Med möjligheten att särskilja hjälpkraftssystemens energianvändning vid tågdriften med passagerare men även i de övriga situationerna. Med detta blir det också möjligt att undersöka potentiella energibesparingsåtgärder för hjälpkraftssystemen. Simulering av förbättrade styrfunktioner för ventilationen och förbättrat utnyttjade av redan inbygga energibesparande driftlägen på tågen visar att betydande energibesparingar kan fås med relativt små medel och få förändringar på fordonen.

De sammantagna resultaten av arbetet visar på vikten av att forsätta undersöka och utreda hjälpkraftens energianvändning samt hur driftsituationerna utanför tågdriften med passagerare påverkar den totala energianvändningen.

Nyckelord:
Energianvändning, passagerartåg, hjälpkraft, hjälpsystem, energimodell, typstudier, uppställning, parkering, drift, klimat, HVAC.

Preface

Before I began my studies at KTH I worked as a depot crew member on the rail yard in Hagalund, Solna. I started out in 2008, cleaning windows on the locomotives and refilling water in the coaches. I later went on to become a shunting locomotive driver on SJ AB, shunting the trains, carrying out inspections and light maintenance, all while preparing the trains for their service. In late 2013 I went on leave to study, then for my Bachelor in mechanical engineering. Later to start my studies for a Master's degree in rail vehicle engineering.

Back on SJ during a summer's job in 2017, I was tasked with investigating the energy use for the trains' auxiliary systems while outside of service. My experience from the time I spent working on the rail yard in Hagalund was an important factor in getting me this assignment. The outcome of that investigation was also what would lead up to the present work, and as a result the subject of this master thesis was chosen on request from SJ. The work that followed has also largely been conducted as an activity within SJ. Thus the working perspective of this master thesis naturally became that of a train operator. With a strong focus on the use of current trains and technology, and how energy efficiency could be increased within those boundaries. Looking back, the work has been fun, interesting and hard. I really think the subject is one worthy of the attention, and I hope this master thesis will help shed some light on the issues surrounding it.

I would also like to express my gratitude to all those who helped me on my way to a finished master thesis. Special thanks go to my supervisor Justus Stern at SJ, for all his encouragements, valuable feedback and all the off-topic discussions we have had. And thanks to Hans Ekblom at *KEN Indoors environments*, Mats Bohm at *Bombardier* and Björn Ållebrand at *Trafikverket* for their helpful input and support. I would also like to thank the rest of the folks at SJ's *Division Fordon* in general, for the encouragements they've given me. And finally I would also like to thank the professors, PhDs and students at the Rail Vehicle Engineering programme at KTH for the two years of master stuides. It's been a wonderful journey!

Stockholm, June 2018
Erik Magni Vinberg

Contents

1. Introduction

Energy use in the operation of passenger trains is a broad subject. If only considering the trains themselves it's important to understand that the main factor determining energy use is how the trains are used. First and foremost, the type and intensity of the train service, in terms of speed, distances and passenger loads. This is also where the useful work of transporting passengers is carried out. But the energy use extends well outside of this service, as the trains are not simply turned off with the last passenger disembarking. The operation instead continues on stations and in depots, where regular activities and tasks are carried out in preparation for coming service assignments.

Energy use throughout all these different situations is based on the train's many auxiliary systems, with parts of which to some extent are always on in order to protect the trains from damage and to allow for different works to be carried out in and around the trains. So to grasp the subject of energy for passenger trains, and how it's affected by the many aspects of the operation, the perspective must include all these factors. For this purpose the aim of this master thesis is to introduce and describe the *energy use in the operational cycle of passenger rail vehicles*.

1.1 Background

To provide (much needed) background to this work it's important to know that trains, in terms of their transport capacity, are inherently energy efficient. Trains have always had the benefits of low rolling resistance and air resistance, brought about by the use of steel wheels and rails and by connecting multiple vehicles into trains. The way the railway infrastructure works has also allowed railways to effectively utilize electric propulsion for many years. But despite this, large possibilities for improvement still exist.

Railways are now facing real competition in the area of energy efficiency from other passenger transport industries, such as automotive and aviation, as great progress has been made in those industries towards improving energy efficiency and sustainability.

Because of these reasons, the railway industry is currently pursuing improvements. The ongoing European research programme *Shift2Rail* is an example of such an effort, which aims at developing and promoting rail transport for both passengers and freight. Part of the *Shift2Rail* is the project *FINE1*, which aims at lowering costs and increasing energy efficiency of rail transport solutions [1]. New trains and technology are a large part of this, but equally important is the work dedicated to improving energy efficiency of current trains and operations. As trains are usually designed and built with long life-spans in mind, many older vehicles will remain in service even when modern and more energy efficient alternatives are introduced. Measures that aim at improving the energy efficiency of the older vehicles is thus a common and important focus, for example through Eco-driving methods or point actions where selected sub-systems are rebuilt to increase energy efficiency. These kind of measures often turn out to be the most useful in the wait for newer trains replacing old fleets of rolling stock.

While an existing passenger train's energy efficiency can be improved, e.g. through Eco-driving, the measures are most often aimed at reducing the traction energy use. For the train's auxiliary systems, there is a surprising lack of common methods and grasp of the subject. Parallel to the development of new and more efficient traction systems during the twentieth century the size of the auxiliary systems, in terms of installed power, has grown [2]. On the early electric railways, the auxiliary systems in the trains were often limited to some simple pneumatic control equipment, interior lights and heating. The evolution of the auxiliary systems into to what they currently are, with full HVAC (Heating Ventilation and Air Conditioning), multiple control systems, catering equipment, lavatories and water, emergency power, etc. has greatly increased the energy use. Today it's not uncommon that up to 20% or more of a passenger train's total energy use can be attributed to the auxiliary systems. [3]

Passenger trains in general spend most of their time outdoors, whether they're in service, parked or stabled, in all climates and weathers. Figure 1.1 shows common conditions in Sweden's largest rail yard and depot for passenger trains. As the trains need to be protected from freezing, or the build up of humidity, heating and other functions are always active to protect the trains from damage. When regular work such as cleaning, inspections and lighter maintenance is to be done, there's also requirements for auxiliary power functions. If the train is to be shunted between tracks in a depot, or to be prepared for traffic, most of the auxiliary systems need to be active. The energy use of the auxiliary systems thus extends into many situations where the trains are actually standing still, outside of service. The hypothesis following these findings is that many possible improvements of energy efficiency could be found in the improved design and use of the auxiliary systems throughout the operation.

Figure 1.1: Hagalund's depot, Stockholm. Common conditions for passenger trains not in service. *Photo: Hannah Vinberg*

1.2 Purpose and goals

The purpose of this master thesis work is to investigate and analyze how energy used by passenger trains is affected by their daily operation and surrounding factors, with extra attention on the auxiliary systems' energy use and the time spent outside of train service.

The work has been carried out in the interest of Swedish train operator SJ AB, and is part of SJ's current efforts towards improved energy efficiency and energy surveys. New EU regulations concerning energy audits [4], have lead to an interest in being able to account for how energy is used in the operation. An important task has thus also been describing these factors in a detailed and comprehensive manner. The *operational cycle* is introduced for this purpose. Ultimately, an energy model based on the operational cycle as an input is designed in order to further describe, analyze and quantify the energy use. Then with the potential of identifying ways of improving the overall energy efficiency. The goals of this work also tangent the aims of current railway industry initiatives such as *Shift2Rail*, in which KTH takes part, and thus also the *FINE1* project. [1] The intent is that the method and results of the present work thus may be of use in a wider perspective.

To summarize, the goals set for this work have been as follows:

- Investigate and describe the connections between the operational cycle and energy use.
- Develop a model for energy use using the operational cycle as an input, among others.
- Evaluate the method and model in case studies on the X55 and X61 train types.

An important aim is also that the method developed in this work should be valid for any type of passenger train and service, and that the concept of the operational cycle and the later defined *operational situations* also should be general enough to be useful in further studies on the subject. While the primary goal of this work is to describe and model the energy use, the work has also allowed for some study of potential for energy savings in the case studies.

It should also be noted that the energy use that is analyzed in this work is limited to the energy in the rail vehicles themselves. Thus, for an electric train, the boundaries for the study is the pantograph connection in one end and the wheels in the other. Losses in the catenary system, the energy transmission before that or the energy production are not considered in this work. The work also only addresses the energy use by *passenger trains*, as it's passenger trains that carry the most (high powered) auxiliary systems.

For terms, definitions and abbreviations used in this report please refer to Appendix 1.

2. Literature review

In this chapter, previous works relevant to the subject of energy use in passenger rail vehicles are discussed. As the perspective of this work is that of a train operator, with a focus on what can be done to improve energy efficiency in the operation of current fleets of rolling stock, the literature is also studied in this light. Initially, a wider grasp of the field of energy for passenger rail operations is taken, on how to improve energy efficiency, describe and model energy use. Then narrowing down on the subject of energy use in the vehicles and their auxiliary systems during out-of-service times. The purpose of the literature review was to find and evaluate potential methods and viewpoints suitable for the scope of this work.

The academic literature search have been conducted with the help of the KTH Library's search functions as well as *Google Scholar*. Previous energy studies conducted internally on SJ AB as well as relevant standards have also been available and consulted. It's worth mentioning that rail vehicle's energy use is a quite common subject of both research papers, industry studies and general investigations into sustainable transport solutions. There are also several books, papers and articles on the subject. Because of this, the papers and works reviewed here can be seen as only a small selection, and not as an exhaustive literature study on the subject of energy use in passenger rail vehicles.

2.1 Improving energy efficiency of existing passenger trains

In academic works the subject of improved energy efficiency in passenger rail vehicles is the focus in works ranging from vehicle specific solutions and technology, to LCC (Life Cycle Cost) analysis and studies of entire rail transport systems. The trains energy use is often in focus, and where the energy efficiency of existing vehicles is concerned, the most common approaches on energy optimization are:

- Eco-driving methods
- Timetable and traffic control optimization
- Introduction of new technology, physical changes to the vehicles and point actions

The reason why the trains' energy use gets the majority of the focus in many works is because it makes up the largest part of the energy use for many rail transport operations. Even when including the energy use in the transport system as a whole, with the surrounding infrastructure. An example is the Beijing urban rail system, where 40-50% of the system's total energy use is related to the trains themselves [5, 6]. The rest is divided on stations, depots and substations of the urban rail infrastructure. Feng et al. [7] in their review of traction energy for urban rail also point out that a single station on the Hong Kong Metro can have a daily energy use of 230 MWh. Yet the trains still make up the single largest part of the energy use in the system as a whole.

To improve the energy efficiency of trains already in operation, Eco-driving is among the most common methods, and a subject often discussed in the literature. While the implementation of new trains and technology may be slow and costly, Eco-driving bases itself on a change in the use of the current technology and rolling stock, by optimizing driving style of the trains, and can thus both be cheap and easy to implement. It's therefore a preferred energy optimization measure for many passenger rail operators. Eco-driving principles usually involve lowering speeds where possible and utilizing coasting before stopping at stations. This of course risks having the drawback of longer run times, and may require necessary system capacity in order to be implemented. The largest possible savings thus often come in combination with optimized timetabling and traffic control, providing the necessary margins, making it possible to take full effect of the Eco-driving principles. In these systems the energy saving potential is often in the range of 10-35% for the trains' energy use [5, 6, 7, 3, 8]. Many examples and studies of Eco-driving and optimized timetabling exists, Yang et al. in their review paper [5] provide a good survey of this field.

In places where optimized timetables and traffic control can't be implemented, the full benefits of Eco-driving may be hard to reach. An example is given in a study by Khanbaghi and Malhame [9], where simulated energy savings from optimal Eco-driving only reached 6% when not increasing the travel time of the trains. Another study, with a very detailed simulation model and optimization process for the operation of New Jersey metro trains, by Liu and Golovitcher [10], also states that without any additional run-time necessary for Eco-driving principles, optimized control of the trains operation could only save 3% of their energy use. Thus Eco-driving may be ineffective in rail systems where there's little capacity for extra timetable slack or longer run-times. It may even risk to be in conflict with the customer requirements for short travel times. For example, Haramina et al. [8] in their study on optimized commuter train operation, suggest a travel time increase on inter-station distances by 5-12% in order to get the projected energy savings of ca. 20% of the traction energy use. On longer commuter lines, this risks severely extending the travel times for the passengers on outer stations, with risk of decreased ridership. Also, as a common measure of energy efficiency of a passenger transport system is the *kWh/passenger-km*, a decrease in ridership following longer travel times may be damaging to the energy efficiency of the transport system as a whole, even if the energy use in kWh/km of the trains are lowered. Finally, a possible issue is also the situations where the train operators don't have full authority over the timetabling process or traffic control, i.e. in situations where the operators run their trains on an infrastructure owned by another company or authority. For example in the case of SJ AB operating its trains on Trafikverket's infrastructure.

To end the discussion on Eco-driving, there are also some works examining its future possibilities in combination with new technology.

For example Liu and Golovitcher [10] and González-Gil et al. [3] imply going to driver-less trains and fully automatic traffic control, as this would allow for the full possible benefits of Eco-driving. But this is currently not a viable option for most train operators. Driver-less technology in the mainline operation of trains would require huge investments in new technology on both the vehicles and infrastructure, as well as changes in the rules and regulations regarding mainline train operation. More likely is the continued introduction of driver assisting systems in the trains, helping the drivers with Eco-driving where possible. Such systems already exist, both in the vehicles, and in the form of mobile and tablet *apps* for the drivers.[1]

New technology does of course not only concern Eco-driving, as some technological changes to existing trains can be viable in some cases in order to improve energy efficiency. For example aerodynamic improvements, like adding fairings over externally mounted equipment or improving the aerodynamics of the the pantographs. Also changing to more efficient power electronics, i.e. new transformers and inverters can help reduce losses and often makes the trains lighter. And this weight reduction also helps improve the energy efficiency. Feng et al. [7] point to traction energy savings of 7-8% with a weight reduction of only 10% in the vehicles of the Hong Kong metro. But just as with other technological changes, the investments necessary to rebuild or upgrade older vehicles may be limiting. More commonly, new technology is introduced when new vehicles enter service or during major refurbishments of vehicle fleets in their mid-life.

As discussed in the background to this work, most trains continue to use energy outside of the train service with passengers. But on this subject there are far less literature, nor common approaches and methods on how to optimize this energy use on current trains. Also as the auxiliary systems are largely unaffected by measures like Eco-driving, which aims at lowering traction energy use, other methods need to be applied in order to improve energy efficiency. The studies that exist often put their focus on the impact of the HVAC equipment, as the HVAC usually makes up the largest part of the auxiliary systems' energy use, both during train service and stabling. A paper often cited in literature is an empirical case study conducted by Powell et al. [11]

[1] SJ for example utilizes a smart-phone application called *TrAppen* which gives the drivers advice on when and where it's possible to lower speed and save energy.

on the Newcastle T&W metro, where the energy use of a two-vehicle EMU (Electric Multiple Unit) was followed over the course of one year. The results showed that the energy use while outside of service where non-negligible compared to the rest of the operation (11% of the total energy used by the EMU where from the stabling periods). It should be possible to improve on it by changing how the trains where handled outside of the service. The authors also regret the lack of an academic grasp on the subject and calls for further work. Another similar case study by Vetterli et al. [12] was conducted on the SBB EWII passenger coaches. This study also points out large potential energy savings for the HVAC in stabled vehicles as well as during train service. For example, the use of different set temperature during stabling and service, as well as improved ventilation control for the HVAC. Apart from these two studies, very few papers investigate or suggest improvements of auxiliary energy use and for the time spent outside of service.

2.2 Methods for describing and modelling energy use

Works on the subject of modelling energy use by passenger trains also range from system level down to very detailed case studies and models of single vehicles and trains. Approaches also vary between academic and industry studies, depending on the factors deemed the most important in the case. Starting to appear are also dedicated models aiming at describing HVAC energy use. Some of the common model approaches studied here can be summarized as:

- Traction energy models of single vehicle or trains in service, with simplified expressions for auxiliary energy use
- Train energy models on system scale, using empirical expressions, but thus including the energy use outside of train service and for auxiliaries
- HVAC energy models, for the energy use of the HVAC components, mostly during train service

As expected, most modelling works concern the traction energy use, focused on the time in train service with passengers as this makes up the single largest part of the energy used by the trains. While the traction energy models can be quite sophisticated, the auxiliary systems' energy use is often just included as a constant power or as part of the losses in the energy efficiency ratio [13]. An example is the work of Haramina et al. [8] where a detailed traction energy model is developed for the evaluation of Eco-driving methods. In it, the auxiliary power is simply assumed as a constant in the calculations, 250 kW for the simulated train in question. Some energy models are also constructed on the transport system level, then often including auxiliary energy use and out-of-service time, but instead through very simple empirically derived relationships. In a case study by de Andrade and de Almeida D'Agosto [14] on the projected new line of the Rio de Janeiro metro, the trains' energy model is simplified to a fix energy use per kilometre. This value is based on the actual energy use by trains on the existing lines in relation to their generated train-kilometres. Then including an average energy use for auxiliary equipment and the time outside of train service. These kind of empirical models can thus be very useful as long as the simulated case uses the same kind of vehicles and has a similar operation as the one used for reference.

While the traction energy is the most common focus in both vehicle or system energy models, there are also a number of works focused on modelling the energy use for HVAC equipment. The impact of more advanced HVAC systems on energy use has led to the initiation of several studies, both academic and industrial. In a paper by Dullinger et al. [15] a detailed and thorough energy model of a passenger vehicle HVAC is shown and discussed, together with a case study on the Vienna Light rail system. The HVAC model they propose is based on a thermodynamic model of the vehicle. Hofstädter et al. [16] have also published a quite extensive work on how to construct and determine the necessary input for such an thermodynamic HVAC model. Other works utilizing models of the HVAC are the case studies of Vetterli et al. [12] on SBB passenger coaches, and Beusen et al. [17] on trams in Ghent, Belgium. These different works show the possibility of HVAC models to find improvements in energy efficiency. Some even as large as 55% of the HVAC's energy use, through simple measures such as regulating fresh air intake and using lower set temperature during winter time. An issue however, turns out to be defining representative operating conditions, also necessary as input for an HVAC energy model. In the work of Hofstädter et al. [16], it's shown that a large part of the work on their Vienna light rail case study was defining the variations in sun radiation and ambient temperature for the model to provide useful and realistic results. The subject of finding these operating conditions has also led to dedicated works on the matter, such as a paper by Luger et al. [18], where representative operating conditions for main line passenger trains HVAC are sought for. There are however currently no widely established methods on how these HVAC models and their inputs should be designed. Nor are there any combined models of traction, auxiliary and HVAC energy for more global studies of passenger trains' totals energy use.

2.3 Energy use outside of service and for auxiliary equipment

While some of the works concerning energy use while stabling [11, 12] and for auxiliary equipment such as HVAC [15, 17] have already been discussed in the literature review so far, a more narrow focus on the auxiliary energy use, as well as energy use while outside of service is taken in this section. Specific works on the energy use of auxiliary equipment are far less common than those that include them together with the traction energy. Thus some of the already mentioned and discussed works will be visited again.

As mentioned in the background to this work, auxiliary equipment on passenger rail vehicles have undergone a rapid growth of installed power in recent years. About thirty years ago, the impact of the auxiliary power might have been negligible, when compared to the traction power and energy use of the older locomotives. But with more efficient traction systems and more auxiliary power functions, this ratio is changing. Bolton in his review paper [2] gives a good summary on the evolution of auxiliary systems in rail vehicles. He points out the introduction of electrically powered HVAC systems as a main reason for the increase in auxiliary power use. Being that this step in the evolution is quite recent, this could be an explanation on why auxiliary energy use have been an unexplored academic subject up until recently. Another result of the quick increase in the auxiliary system's complexity is that they are lacking the same level of standards as those available for e.g. traction systems, which is something that is pointed out in a paper by Laska et al. [19]. This issue makes it harder to construct generalized models and descriptions of the auxiliary energy use between different vehicles. As the vehicles may have very different auxiliary systems and functions, sometimes controlling and using them differently in seemingly similar operating modes.

Arguably, the work by Powell et al. [11] is also one of the better studies conducted on the subject of auxiliary energy use and the time outside of service. Their approach is experimental, utilizing one year of data for a two-vehicle EMU train. The experiment's results and empirically established relation between ambient temperature and auxiliary power use provide many interesting points, see Figure 2.1.

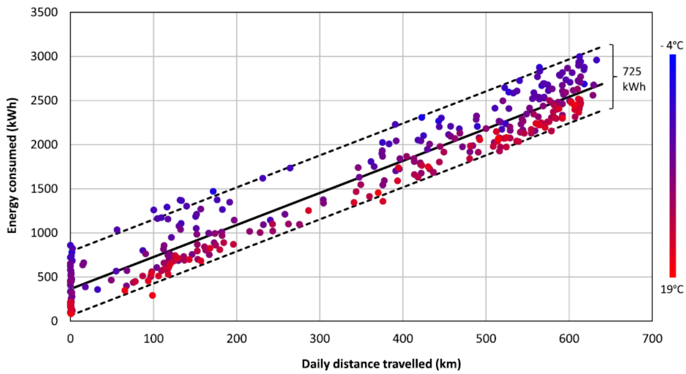

Figure 2.1: Energy use plotted against the daily travel distance and ambient temperature in the case of the T&W Metro [11].

The compiled data in the figure shows that while there's an obvious relationship between energy use and the daily running distance a difference of 725 kWh is shown to correlate with the ambient temperature. This shows that ambient temperature has a big impact on energy use, due to the varying use of the heating and ventilation systems in the trains. Worth mentioning here is that the vehicles in the study lack cooling functions, i.e. they have no air conditioning capabilities. Thus the energy use goes up only for the colder weather. The conclusion of the work states that the energy used by auxiliary equipment outside of train service is a total of 11% of the vehicles' energy use.

As auxiliary energy use is starting to appear as a subject in some energy studies, the amount of energy found to be used by the auxiliary systems can sometimes be quite substantial. In the study by González-Gil et al. [3] on urban rail energy usage, it's stated that roughly 20% of the energy use can be credited to the auxiliary systems. And in the case study Powell et al. [11], 11% of the total energy use could be attributed to only the stabling part of the day. Even though the power need is much lower outside of train service, the significant amount time which the vehicle spend stabled with the auxiliary equipment active gives rise to a continuous power being drawn. Over the course of days, months and years this results in substantial amounts of energy being used by these systems. A major factor in this matter is thus the amount of time spent under certain stabling and parking conditions. Unfortunately, the distribution and effects of the different conditions and activities carried out outside of train service have got little attention in the papers referenced here. The common division is usually only between the train service and the time outside of it.

Nevertheless, there's an emerging interest in analyzing auxiliary energy use, and this can also be seen in another work by González-Gil et al. [20]. With research programmes like *Shift2Rail* [21] there has been an interest in determining ways of energy-labeling different transport solutions for easier comparison. The work by González-Gil et al. suggests so called Key Performance Indicators (KPI) for this purpose. While the focus of these KPIs is mainly on a transport system level, the authors suggest dedicated KPIs for the different parts of the system. For example KPIs for the vehicle traction, HVAC and stabling energy use are suggested. This is because they consider the use of only using a single KPI for the vehicles misleading, as a vehicle with highly efficient traction may suffer from a non-optimized HVAC and vice versa. It's likely that this trend will continue, and that both HVAC and other auxiliary systems may become subject to these kind of energy labels in the future.

2.4 Previous energy studies at SJ AB

Worth mentioning in the literature review are also the previous works and studies conducted by the passenger train operator SJ on the subject of train energy use, specifically those concerning energy use for auxiliary systems. As with the introduction of the new requirement for energy audits [4], more wide-grasping studies on the energy use have been carried out in SJ's organization. While these studies are part of SJ's internal documentation and thus not available for the general public, they have been important references for this work. Also a lot of significant and useful information has been gathered from them.

SJ has recently conducted surveys on the energy use for both their traction energy, as well as a dedicated study on the auxiliary energy use stabling, as a direct result of the new requirement for energy audits [4]. Both these studies have been summarized in internal reports [22, 23].[2] The results from the gathered material points to the possibilities of energy saving measures for mainly the auxiliary energy use, as SJ have already introduced Eco-driving principles where possible, with the help of training of its drivers and with a driver support system in the form of a smart-phone/tablet application also in place. The hypothesis is that the next energy saving measure in line should be aiming at the auxiliary energy use, as this is an area where the measures could be simple to implement but still save relatively large amounts of energy.[23]

Before the major energy surveys, some case studies on energy had also been carried out, such as dedicated survey of the X55 and X40 EMU fleets. The X55 [24] energy study was one of the first studies of energy use by SJ to take into account ambient temperature and weather in the analysis of the total energy use of the vehicles. The results showed a correlation between fleet energy use and the different seasons, where higher energy use was recorded for cold winters as well as warmer summer months. As the study was conducted on a macro-level, concerning the whole vehicle fleet over several months in the years 2014-2015, the causes of fluctuations in energy use was not detailed further. Similarly, a study conducted on the X40 vehicle fleet [25], aiming at determining temperature and humidity levels in the vehicles while stabling, showed quite high energy use for the HVAC even while stabling. The hypothesis being that this was due to the high set temperatures and fresh air intakes, which confirmed the notion of energy saving potential during stabling.

[2] The second study [23], aiming at auxiliary energy use can be seen as part of the background for this master thesis.

An even earlier study has also been carried out on the energy use for heating in SJ's B7 passenger coaches, in 2006 [26], investigating possible energy saving measures such as utilizing heat recovery for the ventilation air. The work was never fully finalized, as the proposed exhaust air heat exchangers would have posed a too large change in the vehicles, in terms of added weight as well as space restrictions due to the need of extra air ducts. The measurement data from thermography and measurements on the auxiliary energy use in the vehicle still showed the potential for energy savings.

2.5 Standards concerning auxiliary energy use

Another important matter worthy of mention in the literature review is some standards that affect energy use and performance of auxiliary systems in trains. While general standards for auxiliary system architecture have been lacking [19], the subject of HVAC and auxiliary energy use is starting to receive some focus. There is currently a draft for a new EN standard concerning specifications and verification of energy use for rolling stock, prEN 50591 [27], that is to replace the older CLC/TS 50591:2013. A major difference in the new draft is the inclusion of a more detailed section regarding auxiliary equipment's energy use, with extra focus on the HVAC systems and some suggestions for the energy use during the time outside of the commercial service. This development is very positive, as this may lead to further standards for auxiliary equipment and system architecture down the line. But unfortunately, the draft lacks some detail in its descriptions of how trains and their auxiliary systems are used outside of service.

Regarding current standards there are also a number of standards aiming specifically at the HVAC systems and their performance, that can be shown to have an impact on the energy use of the vehicles [23]. The main HVAC standards for passenger rail vehicles is the EN 13129:2016 [28], as well as UIC 553 [29]. Both these standards pose limits and suggest control functions on the interior set temperatures, humidity levels and fresh air intakes for different climatic zones and types of operation. Vehicle manufactures employ these standards or similar ones when designing and constructing the vehicles' HVAC systems

[30]. What this seems to cause, as the standards for example regulates the fresh air intake as per passenger, is that in many vehicles the fresh air intake dimensions after the number of seats or the passenger load capacity. This means that trains not operating at a 100% occupancy rate will have an excessive intake of fresh air, that may then need to be heated, cooled and/or dehumidified, thus resulting in energy waste.

While following these standards there is also some conflict when trains are being rebuilt to sometimes feature CO_2-level control of the amount of fresh air being taken in. As neither the EN 13129 nor the UIC 553 propose limits for the CO_2 levels, systems that use this kind of control cannot fully adhere to the standards. Other standards worthy of a short mention are those concerning rail vehicle driver cab's HVAC, such as EN 14813-1:2006+A1:2010 and UIC 651. While also concerning HVAC parameters and limit functions they ultimately pose less of an issue on the energy use, as the driver cab's HVAC usually is either part of or a relativity small sub-system compared to the passenger HVAC.

3. Methodology

This chapter describes and summarizes the general methodology and work flow of this master thesis. As the main objective has been to analyze the energy use during the everyday operation of passenger trains, the relevant factors of the trains' service and operation must be investigated and described in a comprehensive way. The energy use, as a function of the operational cycle, is also finally modelled so that the energy can be quantified and the model validated against recorded figures.

3.1 Information gathering

The work started with the literature review, summarized in the previous chapter (2). The search for relevant literature was conducted with the goal of gathering information on the energy use in the operation of passenger rail transport from different perspectives, specifically those taking into account the auxiliary systems energy use and time spent outside of train service. The literature was evaluated in the light of what specific actions a train operator such as SJ can take to improve the energy efficiency of existing fleets of rolling stock. Unfortunately, the works found on this subject were either not that wide-grasping or very general in their approach. Often all the aspects of everyday passenger operation and auxiliary energy use were not considered. Or the studies focused only in specific case studies conducted on a single vehicle type and operation.

3.2 Describing and modelling the energy use

The main goal of this work has been to describe the energy use of passenger rail vehicles as a function of their use in the everyday operation in a generalized manner. Thus the definitions regarding energy use in passenger rail vehicles need to be clarified. This is done in Chapter 4. What follows is then the definitions of how the operation, i.e. the utilization of the trains, connects to the energy use. And finally how an energy model can be developed to suit this description.

3.2.1 The connection between utilization and energy use

By studying the utilization of SJ's fleet of rolling stock over time, the goal has been to develop a generalized way of describing the everyday operation of passenger trains. For this purpose, the concept of the operational cycle is introduced in Chapter 5. This also serves as a way of describing the varying energy need throughout the operation. This is done by dividing the operational cycle into a set of operational situations. The purpose being that these operational situations may work as general descriptions of the different stages in everyday operation. These situations have different needs in terms of active auxiliary systems and functions, thus affecting the energy use.

3.2.2 Compiling a suitable energy model

With the operational cycle defined, a model for the energy use is developed with the operational cycle as an input. As mentioned in the background and literature review to this work, energy use for the traction of rail vehicles is something that has been thoroughly investigated and modelled before. Since softwares that are capable of calculating the energy use for a train's traction system exist in many forms, the focus of this work was instead put on developing an energy model for the auxiliary systems, described in Chapter 6. For the traction energy simulations an already existing simulation software was used;

KTH's software *STEC* (Simulation of Train Energy Consumption) [31]. Using the operational situations as a starting point, an auxiliary energy model that takes into account vehicle specific operating modes, surrounding climate and temperature, the number of passengers on board, etc. has been developed. Simulations of energy use can thus be carried out for any part of the operational cycle, including stabling periods, preparatory activities before service, *deadheading* and normal train service.

KTH's STEC software is then only used to calculate the energy and other relevant data for the traction during train service or deadheading, based on the service profiles of the studied operation. As the work of this master thesis is focused on the auxiliary energy model the goal has been that the developed software EAUX (Energy for auxiliary equipment) should be possible to use together with traction energy simulation output from STEC or any other similar software. This makes it possible to calculate the total energy use during the operational cycle.

3.3 Case studies

In order to evaluate the usefulness of the developed method and model the present work has also involved two cases studies, described in detail in Chapter 7. Both of these case studies have been conducted in parallel to the model development, and as such the level of detail in the models has mostly been decided by the available information and validation possibilities. The aim has been to balance the level of detail in order to get a useful model, without having to make to many assumptions when preparing the input.

3.3.1 The trains in the case studies

The vehicle types chosen for the case studies are SJ's X55 and Västrafik's X61. Both trains are modern EMUs. The X55 is a 4-unit train in *Bombardier's Regina* family of trains, used mainly for intercity traffic, with catering in the first class compartment, a bistro car, and double lavatories in each unit. The X61 is also a 4-unit train, in *Alstom's Coradia*

Nordic family, with a Jacob's-bogie arrangement, effectively making it about 30 metres shorter than the X55. The X61 is operated in commuter train service around Göteborg, lack any sort of catering and only carries one lavatory per train. As of today, SJ employ 20 X55 trains and Västtrafik 22 X61 trains.[3]

The trains where chosen based on their use of energy meters, using Trafikverket's *EREX*-system [32], which allows for the collection of recorded energy use as well as measurements and validation work during the case studies. Figures 3.1 and 3.2 show the two vehicle types.

Figure 3.1: SJ's Bombardier X55. *Picture source: www.jarnvag.net*

Figure 3.2: Västtrafik's Alstom X61. *Picture source: www.jarnvag.net*

[3] Here the choice was made to only include Västtrafik's own vehicles in the study, as Västtrafik currently also has a number of X61 trains on lease from Skånetrafiken.

3.3.2 Gathering necessary model input

The case studies required a large amount of data gathering in order to compile all the necessary model input. Most data have been gathered through SJ's internal systems and available technical documentation for the two train types. Some measurements followed by parameters estimations were also carried out, primarily to get hold of input for the thermodynamic model used for calculating the HVAC system energy use. Based on a model from the literature [15], the parameterization of the coefficients necessary for the model were then done according to a method suggested in other literature [16]. By grey-box representations of the vehicles' thermal system in MATLAB [33], and by using a built in function for PEM (prediction error method) parameter estimation to find the unknown parameters.

3.4 Evaluating the results

Results and validation of the complete models for the two case studies are summarized in Chapter 8. The validations have in part been done by comparing the simulated power need for the vehicle's auxiliary systems during different ambient climate conditions, to that of recorded energy use data from the EREX-system, paired with climate data from open data bases[4] as well as through comparisons between total simulated and recorded energy use for the operation, on both a monthly and annual basis, for the two train types. Where possible, the models were calibrated by fine adjustments on some of the uncertain parameters. Finally, with validated models it was also possible to identify and evaluate some potential measures for energy savings, both in terms of introducing new technology in the vehicles and improving the use of already existing operating modes.

Discussion about the results of the case studies and general conclusions if the thesis work is given in Chapter 9.1, together with a number of suggestions for further works.

[4]Mainly SMHI's (Swedish: *Statens Metrologiska och Hydrologiska Institut*) [34]

4. Defining energy use in passenger rail vehicles

In order to describe and model energy use in passenger trains, it's important to first define and explain that energy use. So far the concepts of *traction* and *auxiliary* energy have been discussed without any further descriptions, so in this chapter these definitions will be clarified. In order to also make a general model for the energy use of the many different auxiliary sub-systems, they need to be divided into categories where they can be described and understood. For the case of the later modelling, the concepts of *constant* and *varying* auxiliary power load components are introduced in this chapter. Figure 4.1 shows a summary of the energy flows going into a passenger rail vehicle, based on the descriptions in this chapter. The figure also shows some of the energy flows that affect the vehicle's HVAC systems, as the interior climate will be very much affected by heat flows coming from e.g. the sun radiation, ambient temperature and passengers.

So far the main split between energy users in passenger trains has been the traction and auxiliary systems. This is an intuitive way of initially separating the energy users as the traction system can simply be seen as the one responsible to deliver the energy necessary for the trains' propulsion, while the auxiliary systems is responsible for all other functions in the vehicles, such as control equipment, lights, ventilation, heating, etc.

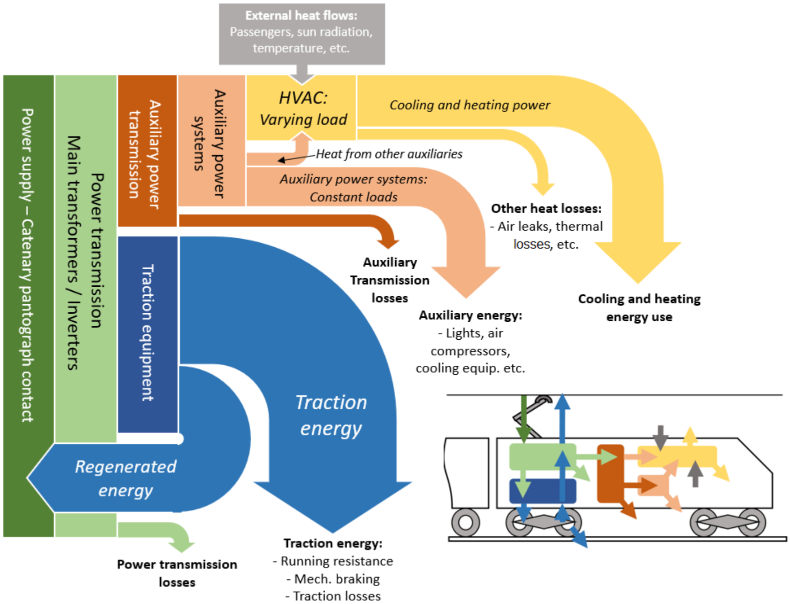

Figure 4.1: Energy flow diagram of a passenger rail vehicle, including heat flows affecting the HVAC energy use.

4.1 The traction

The power and energy necessary for the traction is mainly connected to the fundamental running mechanics of a rail vehicle. Rolling resistance, air resistance and the efficiency of the traction and power transmission are all large influencing factors on the energy use of the vehicle's traction system. The mechanical power delivered by the traction systems must be able to generate enough force to overcome the running resistance as well as the inertia when the train is to accelerate. The power and energy use thus becomes dependent on factors such as the trains weight, aerodynamics, suspension characteristics and any gradients necessary to be overcome as well as any internal losses in mechanical transmissions, power electronics and motors. Commonly, passenger rail vehicles worldwide are electric, and use a catenary or third rail power supply system. But diesel powered vehicles are still used in many places the world. Still, the fundamental relationship between power and energy use remains the same, although the energy use for the combustion engines must be considered in terms of their fuel consumption, with extra losses then often occurring in the engines.

The energy used by the trains' traction equipment can also be split in to two different parts, one *unrecoverable* part, and one that may be partially *recovered*. The unrecoverable energy use for a train's traction is made up by the energy consumed by the continuous running resistance and the losses in the power transmission. The energy dissipated if the train brakes mechanically is also a large contributor. The traction systems also suffer from losses, both in the transmission (gears) but also in the windings and electric power transmission through transformers and inverters. These losses add to the unrecoverable part of the traction energy use. Similarly a diesel powered rail vehicle, whether it has mechanical, hydraulic or electric transmission suffer similar losses in its traction system. But, some of the kinetic energy from acceleration of the train and potential energy from going up a gradient can also be recovered through regenerative braking or used more efficiently through coasting, methods commonly used in Eco-driving.

The losses in the many steps of the traction energy transmission also often require dedicated cooling systems, both in the traction motors and for the transformers and inverters. These systems also need to be controlled and monitored continuously. The traction systems thus require a suite of supporting auxiliary systems. But these supporting systems' energy use is on the other hand not considered as part of the traction's energy use in this work, but rather as a part of the auxiliary energy use.

4.2 The auxiliary systems

The separation of auxiliary systems from that of traction is not always completely intuitive, as many of the auxiliary systems are closely linked to the traction (as mentioned in the previous section). In some models of vehicle energy use the auxiliary equipment supporting the traction is sometimes even included in the efficiency ratio of the traction [13]. But in the case of this work the systems supporting the traction are considered as part of the auxiliary energy users. So the division of auxiliary systems used here is that of the *traction auxiliaries* and *comfort auxiliaries*. The traction auxiliaries are those systems necessary for the traction to function continuously and for the train to start, run and brake normally. This includes systems as control equipment, compressed air for braking, fans and pumps for cooling of the traction equipment, etc. The comfort auxiliaries are then the systems connected to the passenger compartments and comfort functions in the trains, such as the HVAC, lavatories, catering, etc.

The many different auxiliary systems and their power loads, consisting of both the traction and comfort auxiliaries, can then also be divided further into the common system groups contained within them. Such as:

- A constant base load, consisting of idling power for transformers, inverters and control equipment, etc.
- Loads necessary for supporting the traction at power, such as extra cooling for motors, inverters etc.
- Emergency power loads, such as battery chargers and redundant systems in case of failures
- The many different passenger comfort systems, such as HVAC, interior lights, catering equipment, Wifi repeaters, etc.

This sort of division into different system groups gives a more detailed overview of how a train's different auxiliary systems use energy, and can be very helpful for detailed studies for specific vehicles. But for a more general grasp of the auxiliary systems energy use, and for the case of modelling, it's necessary to take another approach.

More suitable for a general purpose method and model of auxiliary energy, is that the auxiliary power systems are instead divided into a set of *constant and varying loads*. Those auxiliary systems that can be assumed to draw constant power in a continuous operation of the vehicle are then part of the total *constant auxiliary load*, containing the constant power loads from both the comfort, base load and traction auxiliaries. The *varying load* is then the auxiliary systems which power has a strong dependency on more than just the current operating mode, instead depending on factors such as ambient temperature, the number of passengers, sun radiation, etc. This method of dividing the auxiliary system loads was also used in the SJ study [23] and proved effective for making a simple general model for the instantaneous auxiliary power.

4.2.1 Constant loads

Introducing the concept of constant loads might seem in conflict with the aim of this work, which is trying to move away from the common assumption of the auxiliary load as a constant power. But in this case the definition of the constant loads only make up a part of the total power of the auxiliary equipment.

The constant auxiliary loads of a passenger rail vehicle are defined here as those systems that are continuously active in a specific *operating mode* for the vehicle. For example:

- Control equipment and computers
- Lights
- Continuously running fans, pumps and compressors

These different loads can be assumed constant over time. Constant loads are either turned *on* or *off* when different parts of auxiliary systems are activated in different vehicle operating modes. Or when the traction equipment is used, in the form of extra cooling and control that may be necessary for the traction motors.

The assumption is that in using this categorization the sum of the constant loads take on a single constant value (in kW) for a given *operational situation*. The constant loads are of course in reality not truly constant, but it's a good simplification when the energy use of the systems is to be described and modelled. The power to lights, computers and control equipment can all basically be seen as constant loads, with little dependencies on surrounding factors such as temperature, passenger load and speed. Other, in reality non-constant loads, such as the cyclic but regular power use of cooling fans, air compressors and water pumps can also be modelled as constant when regarding the energy use over time. Dependencies on surrounding factors for some of the loads here assumed constant are of course also present. Especially for systems such as the traction's cooling equipment, which is most likely temperature dependent. But in the case of this work these dependencies are assumed to negligible. If these dependencies are to be expressed in a more detail manner, they would likely need to be modelled separately. This is discussed further in the considerations for continued work, in section 9.2.

4.2.2 Varying loads

The varying loads are those parts of the auxiliary power that does not only vary with the vehicle's operating modes, but also with external factors such as ambient temperature, number of passengers, speed etc. The bulk of these systems are those contained within the HVAC; the heating, ventilation and air-condition (cooling) systems of the vehicles. The main power need and energy use of these systems comes from the need to heat or cool the interior environment in the train, in order to maintain the comfort for both passengers and staff. The ventilation systems of most modern passenger trains often run continuously while on, and its power use can thus actually be seen as part of the constant loads. But the ratio of fresh and recirculated air is usually controlled with the help of dampers, giving rise to a varying energy flow, as the amount of fresh air being taken in also needs to be heated or cooled depending on the ambient temperature. Figure 4.2 shows an example of principal dependency of the varying load on the ambient temperature.

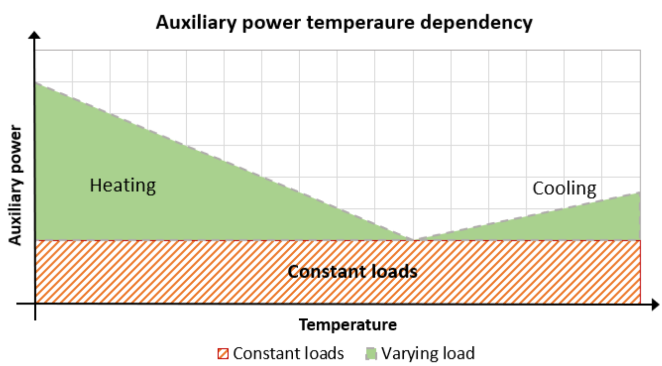

Figure 4.2: Example of total auxiliary power need with an ambient temperature dependent varying load.

The constant auxiliary loads also affect the varying loads to some extent, as losses from internally mounted auxiliary systems will help heat up the indoor environment. Typically lighting, ventilation fans, information systems and computers all supply their full power to the indoor environment in the form of heat, helping the HVAC during colder weather. But similarly, these systems' heat works against it during warmer weather, as the HVAC will then have to remove the extra heat in order to keep the interior comfortably cool. In the same way the passengers on the train will supply heat to the system through their normal metabolism, which decreases the power need when heating, but increases it when the cooling system is active.

Finally the driver cab's HVAC can also be seen as included in varying load, even though the driver's cab HVAC usually is a separate system and very small in comparison to those of the passenger compartments. It also often follows similar settings as the passenger HVAC, so in this work the driver's cab will simply be considered as part of the passenger HVAC.

4.3 Vehicle specific operating modes and settings

The total power and energy used by a passenger train's different auxiliary systems will ultimately depend on the specific vehicle types and how they are designed. The auxiliary energy use will differ with the magnitudes of the constant and varying loads, which in turn depend on which auxiliary systems that are currently active, and what settings the HVAC systems are operating after. What systems and settings that are active are often determined by the train's *operating mode*. With operating mode it's here meant the vehicle specific control and settings for its different auxiliary systems. For example all passenger vehicles have some sort of active mode, where all auxiliary systems necessary for the traction and comfort systems are active to maintain operating performance and passenger comfort. During the time outside of service, most vehicles also feature some sort of parking, stabling or energy-saving operating mode, turning off some of the auxiliary equipment in order to save energy. These modes often feature different protection measures, such as low level heating to protect the trains from freezing damage, battery charging, emergency lights etc. as well as functions necessary for the quick activation and start up of the trains in case of them going into train service.

As mentioned in the literature review, apart from standards concerning HVAC and passenger comfort [28, 29], there are no clear standards concerning auxiliary system architecture or operating modes [19]. Thus the vehicle operating modes can differ quite a lot between vehicle types and manufactures. Settings, such as set points for interior temperature and fresh air intake for the ventilation, may also differ quite a lot between vehicle types as several standards for this exist. Some trains may also have separate operating modes for HVAC and the rest of the vehicle's auxiliary systems, where the HVAC may be in an energy saving mode while the rest of the vehicle is active and vice versa. When the vehicle's energy use in relation to its auxiliary systems is to be analyzed it's therefore necessary to compare and match the available operating modes to what is commonly used in the different *operational situations*. This is further explained in Chapter 5 and the section on operational situations (5.1).

4.4 About energy efficiency and stationary power supplies

Another important factor concerning energy use in passenger trains is the energy efficiency of the vehicles' internal power transmissions. For electric trains operating in AC-systems[5], all the train's systems usually receive their power through the traction transformer(s). Then either through different windings, where the auxiliary systems have one or more dedicated windings of their own feeding auxiliary converters, or as is more common in modern EMUs that the auxiliary inverters are connected to a shared DC-link with the traction motor inverters then with shared rectifiers connected to the traction transformers feeding the DC-link. The efficiency of these systems of converters (primarily utilizing GTO thyristors and IGBT) is about 98.5–99.5%. Compared to the efficiency of traction motors, which are about 90–95%, the energy efficiency in these systems are quite high. In turn, the efficiency of the gearboxes for transmission of power between motor and wheel

[5] 15 kV and 25 kV AC are the two most common power systems for main line railways throughout Europe.

are evaluated to be around 96-98% [3] making the overall power transmission in most electric rail vehicles quite efficient.

Efficiency of traction transformers is usually also quite high, in the range of 85-95% [13]. But when considering the large power output that can be drawn from a traction transformer, the losses will generate large amounts of heat that needs to be cooled away. Part of the efficiency figure is also the idling losses, which can be around 1-5 W/kg for common traction transformers (weight of iron and windings, not including the oil used for cooling) [35]. So for a vehicle with a 3000 kg transformer the idling losses can be somewhere in range of 3-15 kW. This means that the even when a train is standing still in an energy saving operating mode, there's a part of the energy use that is caused directly by the idling losses in the transformer. These losses can sometimes be circumvented by using a stationary power supply feeding the auxiliary systems, bypassing the need for the traction transformer in the vehicle. These power supplies are often connected to larger and more efficient stationary transformers. In Sweden, the stationary power supplies deliver 1 kV 16 2/3 Hz AC, which is an older standard stemming from locomotive hauled train's auxiliary and heating systems.[6]

But for modern vehicles, this 1 kV AC usually needs to be transformed and converted into the today more commonly used 400 V 3-phase 50 Hz auxiliary power, meaning there are still losses in that conversion. The benefits of using stationary power supplies for modern trains are thus not as large as they were for older vehicles, where the 1 kV AC was the main auxiliary power. It's therefore more common, especially for modern EMUs, to be parked or stabled connected to the catenary with their pantographs as this does not influence the energy use substantially and also allows for easier start-up and activation of the trains. Yet another factor limiting the use of stationary power supplies in most stabling situations is the availability as there's often much fewer stationary power supplies than there are vehicles in larger depots, meaning the use of them often get prioritized to the older locomotive hauled passenger coaches which have no power supply of their own.

[6]Swedish: *Tågvärmepost* Translated: "Train heating post" - Comes from the original use of supplying steam from a stationary boiler for heating in coaches not connected to a locomotive during stabling.

5. The operational cycle

Established in the background to this work is the fact that the main influence on the energy use by a passenger train is its utilization throughout the everyday operation. A train that spends a day running will always use more energy than one stabled during the same time. So in order to describe and model the influence on the energy use by the different aspects of the operation, it needs to be broken down into its constituents and analyzed. In this chapter the *operational cycle* is introduced as a concept for this purpose, set out to function as a generalized description of representative operating conditions for passenger trains. This can then be used to compare, model and evaluate different trains energy use as well as the influence of type of operation they are put in.

The operational cycle is a way of describing the utilization of a passenger rail vehicle over time, similar to the concepts of *duty cycles* or *service profiles* used for situations when the traction energy is the main concern. So the purpose of the operational cycle is not to describe any specific vehicle's operation and use, but rather the different common stages of the everyday operation and what demands they pose on the train, its auxiliary systems and subsequent energy use. To get a proper level of detail, the separation between *in service* and *outside of service* time is not enough to fully describe the varied use of a train and the energy used by the vehicles in these situations. Therefore the different stages of the operational cycle are here divided into a set of *operational situations*.

5.1 Defining the operational situations

The division of the operational cycle into the different operational situations is based on the varying demand for auxiliary power and functions in the different stages of the operation. Thus the description makes no difference between the situation of idling at a station, while for example waiting for passengers to board, to that of idling in a depot while a cleaning crew is cleaning the train after service. Both situations place roughly the same demand on the vehicle systems and functions, and they can thus both be considered as the same kind of situation. What follows is a list of the different operational situations identified and defined in this work:

1. *Stabled without power supply*
2. *Stabled with stationary power supply*
3. *Parked before train preparations*
4. *Parked after train preparations*
5. *Idling*
6. *Shunting and deadheading*
7. *Train service*

The list makes up the most common situations that passenger rail vehicle may be in during a normal operational cycle. Determining the need for auxiliary power in these operational situations can then be done by matching the vehicle operating modes and settings to that which is commonly used in those situations. In the *Train service* situation, the influence of the train service profile also plays a key role in the energy use. And for the varying load of auxiliary systems, current weather and other surrounding factors also impact the energy use. These factors are further explained in Section 5.2.

It should be noted here that the operational situations listed above are based on the utilization of SJ's trains. Yet it's easy to assume that the different stages of the operational cycle look roughly the same for any train operator and that the operational situations defined here can be considered general as they have been designed to have somewhat broad definitions.

5.1.1 Example of the use of the operational situations

Just listing the identified operational situations does not provide a sufficient grasp of what they mean in terms of utilization and energy use. So what follows in this subsection is a descriptive example of how the seven different situations can fit into an ordinary day for a passenger rail vehicle. As the main focus of this description is on how the demand for auxiliary power varies, Figure 5.1 provides a showcase of how the auxiliary power demand can vary along a winter day with a lighter train service.

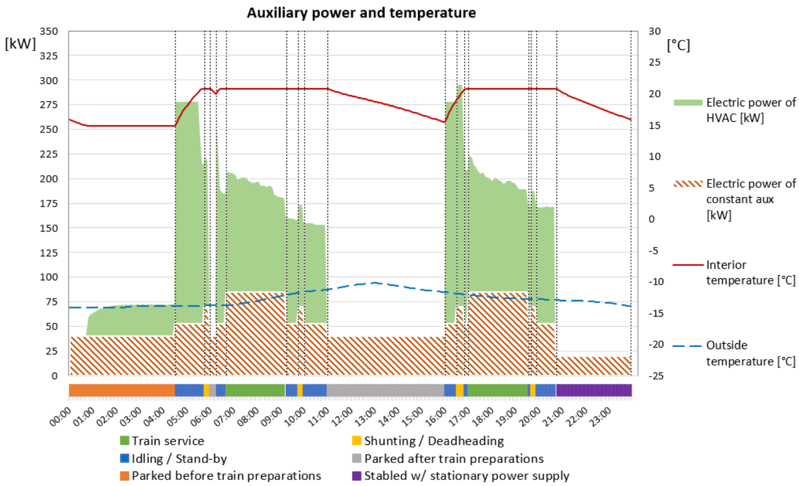

Figure 5.1: Simulated auxiliary power need for a X55 train going through a winter day. The coloured bar at the bottom illustrates the different operational situations the train is going through. The auxiliary power is made up of the two parts, the constant (striped red) and the varying (green) components. The ambient temperature as well as the vehicles interior temperature are also plotted in same figure[7]

At midnight the train may have been stabled or parked in a depot since the service the day before or earlier, commonly in situation 3. *Parked before train preparations* or occasionally also in 2. *Stabled with stationary power supply*.

[7]The figure has been generated with the simulation software *EAUX* developed in this work, see Section 6.5.

Trains that are to be taken into service during the day will have to be prepared, requiring a set of different activities in and around the trains. Regular ones, such as cleaning, refilling of water, lighter repairs etc. as well as inspections and verification of the many comfort and safety related functions of the train. For these works the trains are often in situation 5. *Idling*, as tasks such as cleaning require good lighting as well as power outlets for tools such as vacuum cleaners.[8] For the verification and testing of functions of the train, it usually also needs to be active while the driver or depot crew is performing the checks.

After the preparatory works, the train enters situation 4. *Parked after train preparations*. The reason this situation is considered different from 3. *Parked before train preparations* is that some of the auxiliary systems that were activated during the preparatory work may not be turned off again after those preparations. For example some safety related systems may have to stay active, as turning them off would require a new set of tests verifying the system's functions. Another factor is the time it may take for the train's HVAC to reach comfort levels in the vehicles and turning it off after the preparations are done, might give it too little time to return to comfort levels when the train is finally put into service.

Next, the train usually goes into the situation 6. *Shunting and deadheading*. Either in order to *shunt* the vehicles from a siding at a station onto the platform or to *deadhead* from a depot to the station where the train service is to begin. On the way, the train might also have to go through situation 5. *Idling* again, while waiting at sidings or platforms before finally opening the doors to passengers, commonly while the train crew prepares things like catering and perform the last set of preparations on the train.

Finally, the train enter situation 7. *Train service* as passengers board and the train starts to operate according to its service profile. Throughout the service day, the train may then alternate between situations 7. *Train service*, 6. *Shunting and deadheading*, 5. *Idling* and 4. *Parked after train preparations* as longer stops at stations and changes in travel direction may have vehicles shunted onto sidings, as well as having some additional cleaning done in wait for the next departure time.

[8] As trains are commonly parked outdoors in the depots, the regular cleaning is done using portable equipment.

At the end of all service assignments of the day, trains usually return to depots or are driven to sidings through situation 6. *Shunting and dead-heading*. Back in depot, regular works may again be carried out such as washing, emptying of waste water, etc. Sometimes the trains may need more extensive maintenance done and will thus have to go into workshop. While waiting for a slot time in the workshop the trains are usually stabled or parked, in situations 2. *Stabled with stationary power supply* or 3. *Parked before train preparations*. While finally in workshop the train may even be put into situation 1. *Stabled without power supply*, then usually only for shorter times, as maintenance crews work on electrical systems of the vehicles, but almost never for longer periods of time, or while the train is kept outdoors, as this poses risks for damage on the vehicles.

5.2 Factors affecting the energy use

The operational situations describe the varying need for auxiliary power and functions throughout the operational cycle. But the operational situations in themselves do not give any input or figures for the energy used by the vehicles. They only pose as indication of what auxiliary systems and functions that are needed in the different situations in order to carry them out. The energy use then depends on the vehicles, their service profile, operating modes, settings and efficiency, as well as the climatic conditions and other surrounding factors.

5.2.1 Train service profile

The main factor concerning the total energy use of a passenger rail vehicle is of course its *service profile*. With service profile it's here meant the running of the train, where most of the energy will go to the traction equipment. Following the division of the energy users in a passenger train, described in Chapter 4, the energy using systems that are affected by the service profile are the:

- Traction energy
- Varying auxiliary loads, mainly from the HVAC used for passenger comfort

Obviously, the traction energy will be mostly affected by factors linked to the train's performance, such as power, weight and length, as well as by the type of service in terms of the number of starts and stops and operating speeds. The passenger loads during train service also pose a demand on the HVAC cooling and heating functions, thus influencing the varying auxiliary load.

5.2.2 The vehicle specific operating modes

To get a measure of the energy used for auxiliary equipment at the different stages of the operational cycle, the vehicle specific operating modes must be matched to the different operational situations. As the operating modes, discussed in Section 4.3, determine which auxiliary system that are active and what settings are used, they also help determining the auxiliary power loads in the different operation situations. The operating modes thus have their biggest impact on the auxiliary power loads, mainly the:

- Constant loads, depending on which systems that are active
- Varying auxiliary loads, as the control functions for the HVAC vary with the modes of the vehicle

Sometimes the same operating mode may be used in multiple of the operational situations, as some trains may only be equipped with an *active mode* and a *parking mode*. Or, there may also be situations where there are multiple suitable operating modes for the same situation. No such cases have been found in this work, but could possibly occur if the method is brought onto more and different trains and operations. In that case the definitions and use of operational situations may perhaps need to be expanded or changed. This is further discussed in Section 9.2 on possible continued works.

5.2.3 Weather and climatic conditions

Coupled with the operating modes of the vehicle, the ambient temperature, humidity and sun radiation all play a large role in the energy use for the:

- Varying auxiliary loads, as the ambient climate cause a large impact on the HVAC energy use

The weather and climatic conditions are important to consider separately from the operational cycle and the operational situations as the same sort of operational cycle may take place during winter, spring, summer or autumn, the difference in energy use will come from how the weather affects the energy need for the train's varying loads, mainly the HVAC. Both during the train service and the time outside of service, temperature and sun radiation are two of the largest influences on the HVAC energy use [15]. Other weather effects such as wind and rain also contribute, but not on the same scale and will for this work be neglected.[9] Ambient humidity also needs to be considered due to the latent heat load this poses on the cooling equipment in the vehicle HVAC, see Section 6.3.

5.3 Time distribution between operational situations

As the operational situations determine the need for different auxiliary power systems, the time spent in the different situations throughout the operational cycle is another major influencing factor on the total energy use as the constant auxiliary loads differ between operational situations, with different systems being turned on and off, and different parts of the varying loads being in use. The energy use for the auxiliary equipment during the different parts of the operational cycle thus becomes easily estimable as the average loads multiplied by the time spent in the situations. Whereas this is mostly true for the constant loads, where temperature and other factors don't play any key role, it's an intuitive way of describing and understanding the impact of the operational situations on the energy use of the trains.

The time distribution between operational situations serves as a good overview of the everyday operation, but may of course look very different between different types of services. Metros, light rail and commuter services usually have a very effective utilization of their trains, where they can often spend up to 50% [11] of the operational cycle time in the *train service* situation. For other services, such as long-distance and intercity, the time spent in train service can (sometimes) be a bit

[9] This is also discussed further in the case studies (Chapter 7) and Section 9.2 on continued works.

lower with the trains ending up standing still for most of the operational cycle. On SJ an example of this time distribution is given in a previous study of energy use on the X55, used for fast-train and intercity traffic [24]. Figure 5.2 shows an approximate distribution between train service based on the findings in this study. What can be seen is

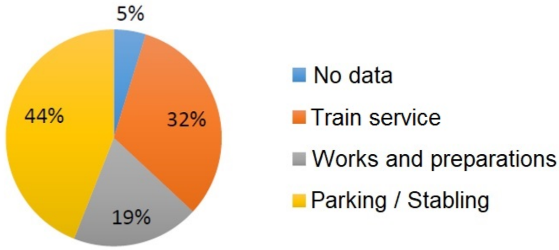

Figure 5.2: Average time distribution between train service and out-of-service situations.[24]

that the time spent in train service only makes up for 32% of the average operational cycle. The other 68% are in this case made up by the different operational situations outside of train service. But when this study was conducted, the different operational situations were not defined in the same manner as in the present work, and the separation that was made is based on differences in recorded energy use during stabling, where the *Parking / Stabling* part was for times where the energy use was at its lowest, and the *Works and preparations* were for times when the trains were standing still in depot, but where the energy use were larger than usual. This "larger than usual" energy use could represent many of the different operational situations identified above, and also shows the need for a more detailed description of the vehicle utilization outside of train service.

Another example of time distribution can also be compiled for the example given in subsection 5.1.1 and Figure 5.1, here shown in Figure 5.3.

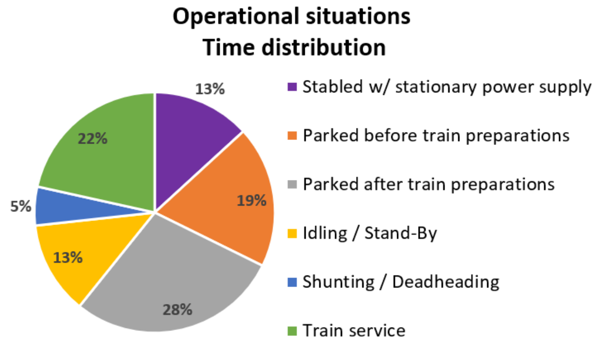

Figure 5.3: Time distribution between operational situations in example case (see Figure 5.1)

The time spent in train service is lower in this case, only 22%, as the simulated example day only includes a return trip from Göteborg to Malmö with a longer stop in Malmö. It should also be noted that this lower train service percentage is not that common, as an X55 may also spend up to 50% of some days in train service. But on average, the percentage of time in train service is closer to 30% as in the previous study [24].[10]

[10]More on this subject in the case study of the X55 is presented in Chapter 7

6. Modelling the energy use

Using the operational cycle as an input, alongside the service profiles and other surrounding factors such as climate, a model for the energy use in the operation of passenger trains is developed. The energy necessary for the traction while in train service is modelled and simulated with the help of KTH's software *STEC*. Thus the original work in this master thesis is the development of a model and simulation software to simulate the energy use of the auxiliary equipment during the train service, but also for all the other operational situations in the operational cycle. The complete model and software thus makes it possible to analyze and compare the influence on the energy use from:

- *The operational cycle*, in terms of the different operational situations and the time distribution between them
- *Climatic conditions*, in terms of temperature, sun radiation and humidity
- *Vehicle performance*, such as design parameters, operating modes, settings and auxiliary system performance

The auxiliary energy model is implemented into a VBA (Visual Basic) program in Microsoft Excel. The energy necessary for traction while in train service, as well as some other factors relevant to the auxiliary energy use is imported from STEC (which is also based on Excel and VBA). The purpose of the developed model and software is to be able to quantify and analyze the energy use of the vehicle's different systems and what the effects of the different stages in the operational cycle have on it, while at the same time laying a foundation for an energy model and simulation software open to further improvements.

6.1 Auxiliary energy

The auxiliary energy model described here is one of the main parts of the present work. The way the auxiliary systems are modelled is that of a constant and a varying load component, in accordance to the descriptions in previous chapters and Section 4.2.

The constant part of the auxiliary load is made up of the auxiliary systems that are either *on* or *off* and can be averaged as constant in an operational situation. The varying load is then made up entirely by the HVAC systems, or more specifically, its heating and cooling functions. As the HVAC gives rise to both varying and often vary large auxiliary loads, it requires the most detail to be described properly in the model. For this a dynamic model of the vehicle thermal state is used based on the works by Dullinger and Hofstädter et al. [16][15], but with some simplifications and adjustments to suit the aim of this work as well as the limitations in available information about the trains used for the case studies.

With a model for the instantaneous power need of both the constant and the varying components of the auxiliary load the energy use of the auxiliary system can be obtained by integrating the power over a studied time frame. For instance over the time spent in a certain operational situation

$$E_{Aux} = \int_0^t P_{constant} + P_{HVAC}(\mathbf{u}(t))\, dt \tag{6.1}$$

The two parts of the auxiliary power, $P_{constant}$ and P_{HVAC}, are explained in the following sections. Only P_{HVAC}, which is the varying load component, is assumed to be dependent on other surrounding factors and the time, here denoted by the input vector $\mathbf{u}(t)$.

6.2 Auxiliary power - Constant loads

The use of constant loads in the model is based on the definition and assumptions previously discussed in subsection 4.2.1, mainly that a part of the auxiliary systems can be described with a constant power as soon as their respective system is turned on. In this model, the total constant power load will be denoted with the $P_{constant}$, which is the sum of all the auxiliary systems which can be assumed constant

$$P_{constant} = P_{lights} + P_{fans} + P_{control\ eq.} + ... = \sum_{i} P_{sub-system\ i} \tag{6.2}$$

These loads are in the model considered as the gross electric powers, assumed to already contain their respective efficiency ratios $\eta_{sub-system\ i}$ as well as a general efficiency ratio for the power transmission η_{Aux}. $P_{constant}$ is thus also considered as the gross electric power load at the power input, including the factor η_{Aux}. This approach is easier to use when measured power at a train's pantograph or input (which is the basis of these powers in the case studies) is used to determine the total constant auxiliary load.

By using the total load $P_{constant}$ in the model there's some loss of detail about the impact on energy use by the different sub-system loads. But with this model it's of course also possible to consider the constant loads of each different sub-system of the auxiliary power, instead of the total $P_{constant}$. The different constant loads then have to be determined separately, either from knowledge about individual sub-system's nominal power use which can often be found in technical documentation, or by measurements on the single sub-system or on the auxiliary power as a whole. If only the useful power of an auxiliary sub-system is known, it of course has to be divided by both η_{Aux} and $\eta_{sub-system}$ to get the electric power used.

The constant loads will change with the train's operating mode. For instance, lights, control and traction cooling equipment are often turned off in energy saving parking modes. Operating modes and constant loads thus have to be matched to the different operational situations by studying which operating mode corresponds to or is commonly used in that situation. In some sense this gives rise to a time dependency for the constant load, as the constant value of $P_{constant}$ may change between the different operational situations. This is necessary in order to simulate the turning on and off of constant loads between the different stages of the operational cycle.

It should also be noted here that the power necessary for the ventilation fans that are linked to the HVAC are also included in the constant loads. So in the situations where the HVAC are on, the constant loads for the fans and continuously running equipment of the HVAC systems are added to the total load $P_{constant}$. In the HVAC model, discussed in the next section, some of the constant loads are also taken into account for their contribution of heat to the thermal state of the vehicle.

6.3 Auxiliary power - Varying loads

When active, the heating and cooling functions of the HVAC system are usually the cause of the largest auxiliary energy use in a passenger train. Just as for the different constant loads, different parts of the HVAC may be active in different operational situations with different settings and control functions. Commonly during different stabling and parking modes, the cooling functions as well as most of the ventilation in the vehicle may be turned off to save energy with only some heating to maintain a lower set temperature inside the vehicle and to protect it from damage.

As the HVAC system's instantaneous power need is very dependent on external factors it requires its own dynamic model for a good description of the energy use. The HVAC model used in this work bases itself on a second-order vehicle thermal model, as the one proposed and demonstrated by Dullinger et al. [15]. In their work, the focus is on the energy use of the HVAC only, and it's very detailed in its approach. The HVAC itself is separated and modelled with different sub-systems, such as air mixing chamber, evaporator, condenser, heating elements, etc. However, the level of detail when modelling the HVAC and its control functions in the present work will be somewhat more simplified in comparison. This is to better suit the goals of a general model and the available information and data on the trains later considered in the case studies. But the basics of the thermal system model used by Dullinger et al. remain the same, and have been found to be very useful in describing the dynamic behaviour of the vehicle thermal system and the HVAC energy use.

6.3.1 Vehicle thermal model

In the thermal model, a rail vehicle is represented with two first-order differential equations for a second-order system, consisting of two connected thermal systems. The first system consists of the vehicle's outer shell and interior environment, mainly the interior air but also some of the interior fittings in thermal equilibrium with it. The second system is a *representation* of all that's inside the vehicle shell and that have a thermal exchange with the first system. A physical interpretation of this could be metal components, walls, interior floors etc. That is, parts of the vehicle structure that due to a different heat capacity and temperature than the interior will have a heat exchange with that system. Figure 6.1 shows the system model and the heat flows that are taken into account. Where T_u, T_i and T_{veh} are the temperatures of the ambient

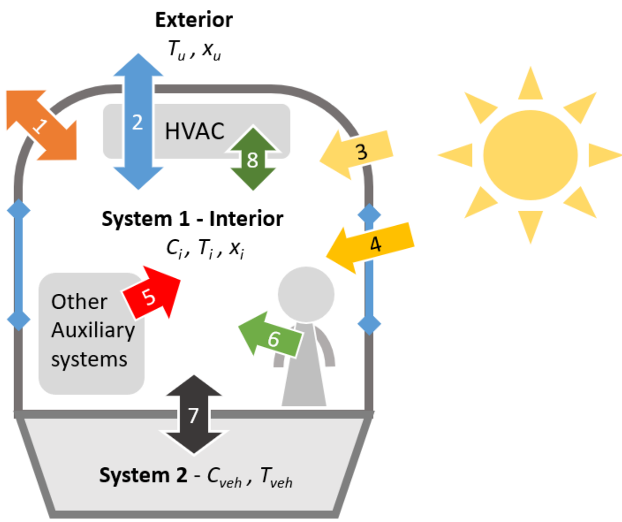

Figure 6.1: Illustrated representation of the vehicle thermal model

environment, interior and second vehicle system respectively. For the ambient environment and the interior the respective humidity ratios x_i and x_u (in *kg/kg*) are also of interest for their influence on the latent heat flows. Both systems in the vehicle model also have a heat capacity, here denoted C_i for the interiors and C_{veh} for the second vehicle system. The numbered arrows in the figure then denote the different heat flows, all here considered in *Watt* [W].

The numbers in Figure 6.1 correspond to:

1. $\dot{Q}_{She}$ - Sensible heat exchange through the outer shell
2. $\dot{Q}_V$ - Sensible and latent heat exchange due to the ventilation
3. $\dot{Q}_{Sun}$ - Sensible heat from sun radiation absorbed by the shell
4. $\dot{Q}_{Win}$ - Sensible heat from sun radiation transmitted through the windows
5. $\dot{Q}_{Aux}$ - Sensible heat from other auxiliary equipment (lights, fan motors, etc.)
6. $\dot{Q}_{Pass}$ - Sensible and latent heat from passengers in the vehicle
7. $\dot{Q}_{S2}$ - Sensible heat exchange with the "second" thermal system in the vehicle
8. $\dot{Q}_{HVAC}$ - Supplied or retracted heat from the HVAC

As can be seen in the figure, some of the heat flows are bidirectional, and will depend on the temperature and humidity differences between the systems. The *2nd* order system is also idealized in the way that all heat flows instantaneously affect the temperature and humidity in the model. Thus any transient effects of mixing and convection inside the vehicle interior of the second thermal system are neglected.

6.3.2 Governing equations

For the vehicle interior (*System 1* in Figure 6.1) the non-stationary energy balance can be described with the equation

$$C_i \frac{dT_i}{dt} = \sum \dot{Q}_{uc} + \dot{Q}_{HVAC} \tag{6.3}$$

and similarly for the second thermal system follows the equation

$$C_{veh} \frac{dT_{veh}}{dt} = \dot{Q}_{S2} \tag{6.4}$$

The sum of the *uncontrolled* heat flows in (6.3), $\sum \dot{Q}_{uc}$, can be expressed as

$$\sum \dot{Q}_{uc} = \dot{Q}_{She} + \dot{Q}_V + \dot{Q}_{Sun} + \dot{Q}_{Win} + \dot{Q}_{Aux} + \dot{Q}_{Pass} + \dot{Q}_{S2} \tag{6.5}$$

The C_i and C_{veh} are the heat capacities of respectively the first and second thermal systems[11]. The main factor that then balances or changes the temperature of the system is of course the heat flow imposed by the $\dot{Q}_{HVAC}$, which later determines the amount of necessary electric power for the HVAC's heating or cooling functions.

6.3.3 Heat flows taken into account in the model

The heat flows taken into account in the model are mostly the sensible ones, i.e. the heat flows that will change the temperature of the two systems. In the case of the ventilation and passenger supplied heat, latent heat flows are also taken into account, where latent heat is the change in enthalpy of the system in the form of an increasing or decreasing humidity level.

The first heat flow, which is purely sensible, is the shell heat exchange $\dot{Q}_{She}$. This heat flow will change direction depending on which side of the shell that momentarily has the highest temperature according to

$$\dot{Q}_{She} = k_{She} \cdot A_{She} \cdot (T_u - T_i) \tag{6.6}$$

where k_{She} and A_{She} are the average heat transfer coefficient of the vehicle's shell and its active area respectively. The k_{She} value is in this model assumed for a vehicle standing still, with negligible effects from wind conditions. For situations where the vehicle is travelling at higher speeds, the k_{She} can be assumed to increase with up to 20% to simulate the effects of forced convection.[12][36, 37]

The second heat flow, $\dot{Q}_V$, that is due to the ventilation's fresh air intake and other leakage air flows between the interior and the surroundings, can be separated into a sensible and latent part

$$\dot{Q}_V = \dot{Q}_{V,sen} + \dot{Q}_{V,lat} \tag{6.7}$$

The sensible part is only related to the temperature difference between the exterior and interior. In short, the need to heat or cool the incoming

[11]Some notations are borrowed from Dullinger and Hofstädter et al. [16][15]

[12]This is later implemented in the simulations, using simulated vehicle speeds from KTH's STEC software as input.

air before it enters the passenger compartment

$$\dot{Q}_{V,sen} = \rho_{air} \cdot c_{p,air} \cdot \dot{V} \cdot (T_u - T_i) \tag{6.8}$$

where ρ_{air} is the air density, $c_{p,air}$ the specific heat of the air, and $\dot{V}$ the air volume flow. Then the latent heat flow of the same air intake is

$$\dot{Q}_{V,lat} = \rho_{air} \cdot h_w \cdot \dot{V} \cdot (x_u - x_i) \tag{6.9}$$

where h_w is the latent heat of vaporization for water, and x_i and x_u the humidity ratios (in *kg/kg*) of the interior and exterior air respectively. Important to mention is that on most trains the ventilation works with some recirculated air, and the volume flow $\dot{V}$ used here only denotes the amount of fresh air intake. These two expressions (6.8 and 6.9) are of course also based on some assumptions, such as constant air density ρ_{air} and specific heat $c_{p,air}$. This means a minor loss of detail when density and specific heat in reality changes somewhat with ambient temperature and humidity. But the assumptions are still satisfactory for this model, and for the ambient temperature ranges that are studied.

Next is the sensible heat supplied by the sun radiation that is here taken into account in two ways, both by the sun radiation absorbed through the sunlit part of the outer shell and the radiation going into the system through the windows. For the shell, the expression used bases itself on how sun radiation is simulated or taken into account during type tests while in climatic chambers, according to the standard EN 13129 [28].

$$\dot{Q}_{Sun} = \epsilon_{She} \cdot \dot{q}_{Sun} \cdot (cos(30°) \cdot (A_{side} - A_{Win}) + sin(30°) \cdot A_{roof}) \tag{6.10}$$

The sun radiation $\dot{\boldsymbol{q}}_{Sun}$ [W/m^2] hits the side of the train with an angle of $30°$ against the horizontal line. The amount of sun radiation absorbed is dependent on the absorption factor ϵ_{She} of the shell. In this model, as the sun radiation is simplified as coming from the same angle and direction at all times, an average *shading factor* should be multiplied with the absorption factor as a vehicle is not likely to be in direct sunlight or have the sunlight coming directly from the side at all times during its operation. The same reasoning also applies for the sun radiation transmitted through the windows, with the expression

$$\dot{Q}_{Win} = \alpha_{Win} \cdot \dot{q}_{Sun} \cdot cos(30°) \cdot A_{Win} \tag{6.11}$$

where the α_{Win} denotes the transmission factor of the window, which in this model also needs to be adjusted for the fact that the sun not always shines straight from the side of the vehicle.

Next, the system will also have to include the sensible heat supplied from other auxiliary equipment inside the vehicle. This does not consist of the entire constant load $P_{constant}$, as many of these systems have dedicated cooling, forcing their heat out of the vehicle. Instead it only consist of those systems that are placed inside the vehicle's interior, such as lights, air fans, WiFi repeaters, catering equipment, etc. Thus it could be seen as only a factor $\beta < 1$ of the constant loads, or as a separate sum of those loads that are inside the vehicle

$$\dot{Q}_{Aux} = \beta \cdot P_{constant} = \sum_i P_{interior\ sub-system\ i} \tag{6.12}$$

The passengers also supply heat, both sensible and latent. Here the expressions for these heats are based on linear interpolation from figures in the standard EN 13129 [28]. The linear interpolation yields the following expression for the sensible heat

$$\dot{Q}_{pass,sen} = (98.6 - (T_i - 18) \cdot 3.56) \cdot n_{Pass} \tag{6.13}$$

where n_{Pass} is the number of passengers, and the latent heat becomes

$$\dot{Q}_{pass,lat} = (23.5 + (T_i - 18) \cdot 2.98) \cdot n_{Pass} \tag{6.14}$$

The total passenger supplied heat is thus

$$\dot{Q}_{Pass} = \dot{Q}_{pass,sen} + \dot{Q}_{pass,lat} \tag{6.15}$$

Finally the heat exchange with the second thermal system in the model (System 2 in Figure 6.1) is described with the expression

$$\dot{Q}_{S2} = K_{S2} \cdot (T_{S2} - T_i) \tag{6.16}$$

where K_{S2} denotes a heat transfer coefficient between the two systems, already including an area for which the heat exchange is taking place over. This factor, together with the two heat capacities C_i and C_{veh} in the governing equations (6.3 and 6.4) are factors that will have to be determined through measurements followed by parameter estimation, as they have no simple physical interpretation. [16]

6.3.4 Determining model parameters

Input parameters needed for the model are those of the surrounding environment, such as temperature, humidity and sun radiation as well as the current interior temperature and humidity of the train. The most important parameters however, are those linked to the thermal description of the system. The k_{She}, K_{veh}, C_i and C_{veh}, heat transfer coefficients and heat capacities of the two systems. The shell's average heat transfer coefficient k_{She} is usually a design factor for trains, set through standards and by requirements from operators. These values are often based on vehicles standing still in dry, low-wind conditions. Common values for vehicles used in Sweden are around 1-1.2 W/m^{2}K [23]. But then the heat capacities C_i and C_{veh} as well as the transfer coefficient K_{veh} are model parameters introduced by Dullinger et al. [15] in their method of modelling. Fortunately, the paper by Hofstädter et al. [16] provides some suggestions for methods of measuring and estimating these parameters.

Other vehicle specific parameters, such as the different areas (shell and windows), ventilation air flows etc. can then in most cases be determined by referencing existing documentation of the studied vehicles, such as drawings or technical descriptions for the different vehicle sub-systems as many of these factors are design parameters or regulated by standards.

6.3.5 Energy use for heating and cooling

Finally the heat flow from the HVAC, $\dot{Q}_{HVAC}$ in equation (6.3), is the term that will be controlled in a time domain simulation of the model. It will thus change in magnitude and sign in order to reach or maintain a certain set point T_s for the interior temperature T_i. From this heat flow, the gross electric power need for the heating and cooling functions of the HVAC is calculated as (with $\eta_i < 1$)

$$P_{HVAC} = \begin{cases} \dfrac{\dot{Q}_{HVAC} - \sum \dot{Q}_{lat}}{\eta_{Aux} \cdot \eta_{heating}}, & \text{when the HVAC is supplying heat} \\ \dfrac{\dot{Q}_{HVAC}}{\eta_{Aux} \cdot COP_{cooling}}, & \text{when the HVAC is cooling the interior} \end{cases} \tag{6.17}$$

Here the energy efficiency of the auxiliary power supply is taken into account with the factor η_{Aux}, as the computed necessary heat flow is the useful part of the power. For heating and cooling, two different efficiency factors also play a role. For heating, an efficiency factor of $\eta_{heating}$ is used. Normally this figure is close to 1, as most trains use convection heaters to supply the necessary heat to the interior climate. For the cooling case, the efficiency is instead determined by the COP (Coefficient of power) for the cooling equipment. Which in many cases is much larger than 1.

Another important difference between the heating and cooling is also that the sum of the latent heat flows $\sum \dot{Q}_{lat}$ is disregarded when the HVAC is heating the interior. This sum only consists of the two expressions (6.9) and (6.14) in this model. This is due to the fact that most passenger rail vehicles lack active humidity control, and that the heating function only changes the sensible heat of the interior. In the case of cooling however, the latent heat flow introduced by the passengers and ambient humidity will affect the energy used by the cooling system as the cooling system will passively condense away some of the moisture in the air. The assumption is then that most HVAC systems are designed to operate within the humidity levels of the local climate zones as well as the ones imposed by the passenger loads. The HVAC will passively maintain an interior humidity lower than the maximum allowed in the standards, e.g. $x_{i,max} = 10\,\text{g/kg}$ for EN 13129 [28][13]. This provides an arbitrary set point for the interior humidity used in this model for vehicles lacking active humidity control.

In summary, the assumptions made in this model and the expressions leading up to the necessary electric power for the heating and cooling are several. But the model is also very much based on the available information of the trains later described in the case studies. The

[13]Calculated from relative humidity at 21°C with sea level atmospheric conditions

discussion about the assumptions and precision of this model will be continued in the case study validations in Chapter 8 and in Section 9.2 on continued works.

6.4 The traction energy - STEC software

The full governing equations and model for simulating energy use for traction will not be covered in this work. The modelling and simulation of traction energy use is done using KTH's STEC (Simulation of Train Energy Consumption) software (version 2.10b). STEC simulates energy use for a train as a function of the track profile and the vehicle characteristics such as

- Running resistance, both rolling and aerodynamic
- Weight, including effect of rotating
- Available traction and braking force at different speeds
- Available adhesion at different speeds
- Efficiency of traction systems, both during traction and regenerative braking
- Track gradient, allowed speed and stops at stations

To give some information about the type of expressions used to calculate energy use in STEC, the main part is linked to the running resistance as this is the main unrecoverable part of the energy used by the trains. STEC models the running resistance for the train in the form of a common empirical expression of the running resistance

$$F = A + B \cdot v + C \cdot v^2 \tag{6.18}$$

where v is the train speed and the coefficients A, B and C contain the different parts of the running resistance. A can be seen as linked to part of the rolling resistance, which can be often be assumed constant on a tangent track. In STEC, a small averaged addition to A is used to take into account curving resistance, which can otherwise be calculated separately. The coefficients B and C are then mainly related to the air resistance of the train. Also here STEC suggests using a small averaged addition to these coefficients to take into account tunnel passages and other situations causing increased aerodynamic resistance along the track. While the expression (6.18) is an empirical one, the coefficients A, B and C are quite easily determined for a real train with the help of coasting tests, wind tunnel experiments or through simulations. The results provided by this way of modelling running resistance are usually very close to reality, even with the assumptions used. Thus this way of modelling is very useful for the level of detail aimed for in this work.

STEC is then also capable of simulating some Eco-driving through the use of coasting, as well as containing the option of setting different levels of mixed braking, thus making it possible to calculate the amount of regenerated energy. But in the case of this model and the following case studies, only the gross energy use will be considered. Also the effects of Eco-driving and coasting will neither be taken into account since the focus will be on the evaluation of the auxiliary energy model and use.

6.5 About the developed simulation software - EAUX

For the purpose of simulating the behaviour of the auxiliary energy model, a time-domain simulation program has been developed, simply called *EAUX* (Energy for Auxiliary equipment). The program has been written in Microsoft Excel, utilizing VBA script for most of the computations. The program calculates the dynamic behaviour of the vehicle thermal systems according to the two governing equations (6.3 and 6.4) using a *for-loop* stepping in time. Together with KTH's STEC software it's possible to simulate and compile the energy use for a studied operational cycle. Default in the program is a 24-hour period. Figure 6.2 displays the simulation work flow.

Energy for traction as well as necessary input for the model from the train service is imported from KTH's STEC before EAUX is run by first simulating the daily train service of the train in STEC. For example a run back and forth to another city, the energy use, run time, distance, passenger load and speed of those train services can be imported into

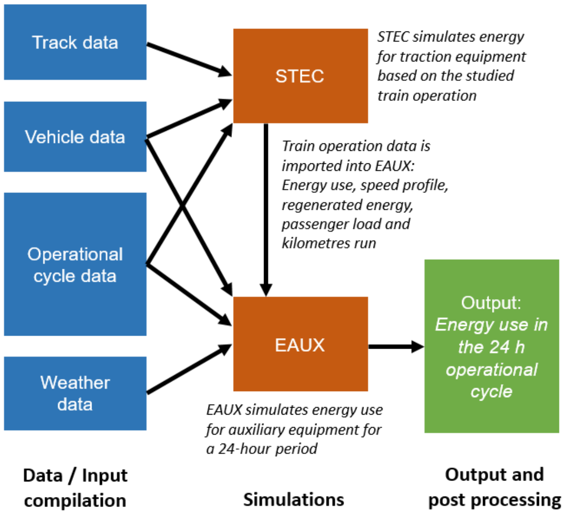

Figure 6.2: Simulation work flow

the EAUX software. The imported STEC output is automatically converted into time domain input for the simulated operational situations. As the input data may also vary in resolution, the program automatically creates an input-output size based on a set time-step, converting the different input sources automatically, using averaging or linear interpolation between data points where necessary.

In EAUX, the necessary power for heating or cooling in the current setting is calculated as the simulation program tries to maintain a steady state in the vehicle's thermal system according to the set-points in temperature and humidity. Here the time-domain simulation of the thermal system behaviour is carried out with a time increment of 1 second as default. The constant power need for the current operational situation is added afterwards and then the energy use of the auxiliary systems in each time-step is obtained with the a Riemann sum, simply multiplying the instantaneous power of the constant loads and varying loads with the time increment.

The EAUX software's user interface consists of a set of normal Excel work sheets. A main input sheet, where the vehicle parameters can be defined together with inputs for the different operational situations. Realistic (or actual) vehicle control functions, such as ventilation air volume flows, set temperatures, system switching etc. are input into the VBA script and used by the program to simulate the vehicle's behaviour. As default, a simple set of *If-functions* checks whether the interior temperature is close enough to the set temperature of the vehicle and changes between HVAC functions accordingly. Together with this a time domain input for daily weather variation can also be used in the simulation, where constantly changing temperature, humidity and solar radiation can be used. Weather data can also be set and changed, with the possibility of using a set of predefined days representative of the different season in the Swedish climate.

For more information on the EAUX software and its functions, see the info sheet, comments and code of the developed program.[14]

[14] EAUX will be available at both KTH and SJ AB after the completion of this master thesis.

7. Case studies

In this chapter the developed model for energy use in the operational cycle of passenger trains is applied to two case studies. The type of trains used for the case studies are SJ's X55 and Västtrafik's X61. Both train types are EMUs, consisting of 4 carbodies each, ehere SJ's 20 X55 trains are used for fast trains and inter-city traffic while Västtrafik's 22 X61 trains are used in commuter and occasionally some regional traffic.

These trains were chosen because of their use of energy metering, utilizing Trafikverket's *EREX* energy metering system. The X55 trains are currently the only in SJ's own fleet of rolling stock using active energy metering. But as SJ currently operates Västrafik's commuter train traffic under the affiliate company Götalandståg, it was possible to include the X61, also equipped with EREX-meters. The simulated energy use for the two train types can thus be compared with actual recorded energy, which allows for the models to be validated. The case studies thus also serve the purpose of trying out the usefulness of the model when analyzing the operational cycles and energy use for the two train types. And in by doing so, identifying potential energy savings that could be achieved by changing the use or settings of the trains.

7.1 Determining the necessary model input

The auxiliary energy model in the EAUX software requires a large number of inputs that have to be gathered, measured and estimated for the two train types. The STEC software also requires both train and track input to be able to simulate the energy use for the trains traction while in service. Most of these inputs are found in available technical documentation, previous studies or through approximations. But the main coefficients necessary for the vehicles' thermal models, as well as some of the constant load cases in the different modes of the vehicles, have also been estimated using energy and temperature-meter data recorded during field measurements.

7.1.1 Vehicle auxiliary systems and modes

For the auxiliary energy model, technical documentation for the two trains is initially used to determine the different operating modes of the trains. By matching the modes to operational situations and checking which systems are active in each mode, an idea of how the constant and varying auxiliary loads will behave is gathered.

Some of the different constant loads for the auxiliary systems can be found in the technical documentation for the two trains [30, 38]. Measurements of the total auxiliary load in different modes (carried out during the same occasions as the other measurements, see subsection 7.1.2) is also used as well as data compiled for later validation of the model (see subsection 8.1.1). A table of the different constant loads and input dependent on the operational situations can thus be compiled for the two train cases, see Table 7.1. The first operational situation, *Stabled without any power-supply* is not included in the table as all figures would be zero for this particular situation.

Technical documentation of the X55 shows that the two main operating modes of the trains are either *parked* or *active*, depending on the current operational situation. For the X61, a similar active mode is used, but rather than a power saving parking mode the trains utilize an *active-parking* mode in most situations. How these modes are used

Table 7.1: X55 and X61 model input for operational situations, constant powers, and constant heat supplied

X55	Operational situation	$P_{const.}$ [kW]	$\dot{Q}_{Aux}$ [kW]	Cooling system
	2. Stabled w/ stat. power	20	10	Off
	3. Parked before train prep.	40	10	Off*
	4. Parked after train prep.	40	10	Off*
	5. Idling	53	12	On
	6. Shunting / Deadheading	70	12	On
	7. Train service	85	12	On
X61	Operational situation	$P_{const.}$ [kW]	$\dot{Q}_{Aux}$ [kW]	Cooling system
	2. Stabled w/ stat. power	18	8	Off
	3. Parked before train prep.	20	10	On
	4. Parked after train prep.	20	10	On
	5. Idling	20	10	On
	6. Shunting / Deadheading	30	12	On
	7. Train service	40	12	On

*The X55 automatically turns on the cooling function in the parking mode if the interior temperature exceeds 27°C

in the operational cycle is determined by studying the driver manuals and work routine descriptions for the two trains. What can be seen from the table is that the X55 generally has higher constant loads, which is in part due to the X55 carrying many more comfort auxiliaries than the X61. For instance the X55 have both a "bistro" in one of the units and a kitchenette for catering in the first class compartment. And as the X55's catering supplies remain on-board between train service assignments, the coolers and freezers always remain on. The X61 also only carries one lavatory per train, while the X55 have eight.

The technical documentation for the X55 also specifies how the basic HVAC control functions behave, in terms of set-points, functions and fresh air intake for different temperatures [30]. These functions are added as control functions for the HVAC in the VBA script within the EAUX program. But for the X61, these functions have been lacking in the technical documentation available on the HVAC systems. The functions used in EAUX for the X61 have instead been based on known functions for another Alstom-made vehicle in SJ's use, the X40 (Alstom's Coradia Duplex)[39]. The assumption being that the control functions are similar enough, with the fresh air volume flow normalized after the difference in passenger load capacity. The simulated control functions for the X61 can thus serve as an example of how these functions are constructed. In those modes where the ventilation is active on the X61, the simulated fresh air intake for the train is

$$\dot{V} = \begin{cases} 3960 \text{ m}^3/\text{h for } T_u < -5°\text{C} \\ 5550 \text{ m}^3/\text{h for } -5°\text{C} \leq T_u \leq 26°\text{C} \\ 4400 \text{ m}^3/\text{h for } T_u > 26°\text{C} \end{cases} \tag{7.1}$$

Similarly the interior set temperature in those situations is a function of the exterior temperature T_u. And is for the case of the X61 simulations

$$T_{set} = \begin{cases} 20 \text{ °C for } T_u \leq 19°\text{C} \\ 20 + (T_u - 19)/4 \text{ °C for } T_u > 19°\text{C} \end{cases} \tag{7.2}$$

In situations where the ventilation is off, the average air leaks are assumed at 150 m^3/h per vehicle or unit, based on figures from the X55 [30]. For the other used control functions, see the simulation software EAUX.

7.1.2 Vehicle thermal system parameters

The vehicle thermal system parameters and those necessary for the varying auxiliary load model, are then found once again by first studying the available information and data in the form of technical documentation and previous studies. Whereas the average shell heat transfer coefficient k_{She} of the X55 at stand-still is known to be 0.98 $\text{W/m}^2\text{K}$ [37], the same figure has to be approximated for the X61. Based on what is common for trains operating in Swedish climate conditions, it's assumed this figure is about to $k_{She} = 1.1$ $\text{W/m}^2\text{K}$. With these two figures set, the remaining parameters of the thermal system, K_{S2}, C_i and C_{veh} are found through measurements and parameter estimation following the suggested method in the paper by Hofstädter et al. [16]. The measurement setups recommended are those usually used while commissioning new vehicles, or by step-response tests in climatic chambers. As these test conditions could not be met with the measurements carried out in this work, some simplifications had to be made.

The measurements for determining the parameters were carried out in the Hagalund and Sävenäs depots, on the X55 and X61 respectively. Two measurements were done on X55 trains in Hagalund, Stockholm (2018-01-30 and 2018-02-04), where the temperature inside and outside the trains were measured using Maxim's I-Button temperature loggers, here shown in Figure 7.1, while the energy use was recorded with the EREX system. One such measurement was also done on a X61

Figure 7.1: I-button temp-logger placed inside a X61 in Sävenäs

unit in Sävenäs (2018-03-10) outside Göteborg, using the same type of measurement equipment. The measurements were meant to resemble step response tests, usually carried out in controlled environments with specialized equipment. In the measurement procedure the trains were first heated up to the maximum possible interior temperate and then turned off completely, left to cool down for some time and then once again turned on with their heating set to full power. Protocols for the measurement occasions were prepared before-hand and kept together with the recorded data.

The recorded temperature and energy input into the trains were then used to approximate the trains heat capacities as well as internal heat transfer coefficients. A parameterization of the unknown coefficients was done in a grey-box representation of the trains thermal system in MATLAB. Using a built in PEM-function, the coefficients were then estimated to best fit the data from the measurements. This was done for all measurement cases, an example of the PEM parameter estimation and fitting process is here shown in Figure 7.2.

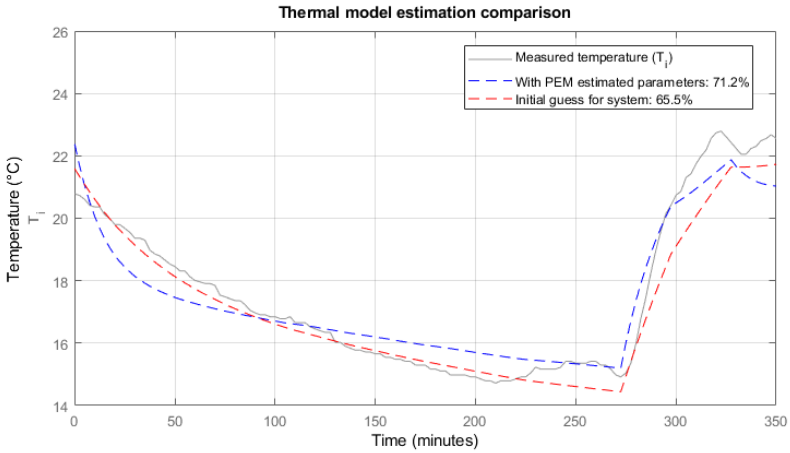

Figure 7.2: Example of PEM-estimation fit on data for one of the cool down heat up tests, performed on an X61 in Sävenäs

Where the goodness-of-fit in percent for the model on the recorded data is shown for an initial guess of parameters togheter with the PEM estimated parameters. As there were three unknown parameters for each train that was to be estimated, some of the values could be constrained while estimating the others. Multiple somewhat well-fitting combinations of K_{S2}, C_i and C_{veh} were found when running the estimator function with different constraints. The final values were thus selected on what seemed to best fit the measurement data while still being plausible compared to similar figures presented in the work by Hofstädter et al. [16].

The compiled input necessary for the thermal models of the two trains, such as the different surface areas, number of seats (used together with occupancy rate for the number of passengers), etc. is here summarized in Table 7.2. The absorption factor ϵ_{She} includes an assumed shading factor of 50% (the absorption factor for light-grey paints and metal surfaces is about 0.3 [40]). Similarly, the windows' transmission factor α_{Win} is also assumed to include some average shading. The shell and window areas have been approximated based on drawings for the two train types. Areas of side walls A_{side} and roofs A_{roof} used in equation (6.10) are then simply assumed to be 1/4 parts of the total shell area A_{She}. Finally the efficiency factor η_{Aux} is based on typical values of the

Table 7.2: Used thermal and varying load model input for X55 and X61

Paramter .... *Notation*	**X55**	**X61**	**Unit**
Shell heat transfer coef. .... k_{She}	0.98	1.1	W/m^{2}K
Second system heat tranfer coef. K_{S2}	$1.73{\cdot}10^4$	$5.17{\cdot}10^3$	W/K
Interior heat capacity .... C_i	$4.12{\cdot}10^7$	$2.88{\cdot}10^7$	J/K
Second system heat capacity ... C_{veh}	$3.24{\cdot}10^7$	$2.24{\cdot}10^7$	J/K
Outer shell area .... A_{She}	1100	710	m^2
Window area (one side) .... A_{Win}	60	36	m^2
Shell sun absorption factor ..... ϵ_{She}	0.15	0.15	
Window transmission factor .. α_{Win}	0.5	0.5	
Efficiency of auxiliary power .. η_{Aux}	0.8	0.8	
Efficiency of heating .... $\eta_{heating}$	1	1	
Avg. COP for cooling .... $COP_{cooling}$	2	2	
Number of seats	245	234*	
Installed heating capacity	183	192	kW
Installed cooling capacity	112	92	kW

*Standing passengers have not been taken into account.

efficiency in the auxiliary systems, their power supply and transmission [13, 35]. These values are assumed to be the same for both train types. Both trains also share similar efficiency factors for their cooling and heating functions. While $\eta_{heating}$ is assumed to be 1 as most of the power supplied should become heat inside the trains, the $COP_{cooling}$ factor is for both trains types based on the stated cooling capacity divided by the installed electric power of the cooling systems. Both vehicles have roughly a COP factor of 2 based on these figures. As no average values, or $COP_{cooling}$ in different operating ranges, are provided in the technical documentation for either vehicle, it's assumed that this simplification based on the performance data can be used. [36]

7.1.3 Vehicle traction parameters STEC simulations

For the traction energy simulation done in KTH's STEC software, both train, track as well as input on the service profiles are necessary. The running resistance coefficients are in the case of the X55 based on figures for similar trains in the same family, Bombardier's *Regina* X52-53. In the case of the X61, these coefficients had to be approximated, as no figures for the X61 or other trains in Alstom's *Coradia Nordic* family were available. The assumption thus is that the X61 in terms of running resistance is similar to that of the X55, and that the main differences influencing the coefficients are the length and weight of the train. As the X61 is roughly 70% the length of the X55, and 67% of the weight, the *A, B and C* coefficients are thus tuned down according to these differences. The inputs then used for the two train types are here displayed in Table 7.3. Other train data, such as top speeds,

Table 7.3: Input for traction energy simulations of the X55 and X61 trains

Running resistance coef.	**X55**	**X61**	
A	2200	1400	N
B	30	20	N/(m/s)
C	7	4.5	N/(m/s)^2
Other important input	**X55**	**X61**	
Tractive power	2750	2400	kW
Weight	228	152	tonne
Trac. adhesive Weight	179	121	tonne
Top speed	200	160	km/h

tare weights, power etc. are collected from the technical documentation [30, 38]. Traction curves for both vehicles are estimated using the power figures available. The brake curves are then based on the default vehicle in the STEC software (a *X2000* train), but with lowered brake forces to compensate for the differences in weight so that the trains do not brake uncomfortably hard in the simulations. The traction's efficiency factor η_{trac} is in the simulations set to 90% (default is 85%) for both trains. This is to reflect on the losses in the power transmission, but not on the power use of the traction auxiliaries such as control and cooling equipment, which is included in the auxiliary energy model. Other input, such as adhesion utilzation and required acceleration are kept at the default values in the STEC software.

For the track data Trafikverket's *BIS* track data system is used [41]. As STEC only uses the gradient and top speeds on the line segments for the simulation, these data are exported and converted from BIS into STEC's track input format. As both simulated trains are in what is called category "B", in terms of their allowed speed in curves, the according max speeds for the B category are imported from BIS. The lines picked from the BIS system for simulations are the ones identified for the two trains' different operational cycles, see later in subsection 7.1.5.

STEC also allows for simulation of the auxiliary energy use, by a constant auxiliary power that is multiplied with the dwelling and run-times. In these cases, the auxiliary power in STEC is simply set to zero, as the auxiliary power and energy are later computed in EAUX.

7.1.4 Climate data - Representative weather

The climate and weather is one of the main factors that is not linked to the utilization and performance of the trains, but still greatly affects the energy use. It's also the biggest influences on the varying part of the auxiliary loads in the developed model. It's therefore important to carefully chose which climatic conditions to use as input in the case studies. Weather also varies over time on several scales; annually, seasonally, monthly, daily, down to the hours. All these variations cause non-negligible effects on the energy use by the auxiliary varying load. Trying to average too many of the variations in the weather risks loosing important details, such as the more extreme cases which often are those that have the largest effect on the energy use. The most important variation is that of the seasons; winter, spring, summer and autumn as there are large differences in average temperatures, sun radiation and humidity throughout the seasons. Also important are the monthly and daily variations, as temperature can vary quite a lot between months, as well as between night and day.

For the case study simulations, average values of the four seasons are used to get the daily variations in sun radiation, temperature and humidity for the seasons. Then, monthly average temperatures are used together with these values to generate monthly variations, with three months for each season. For the monthly values, temperatures for what can be considered a *warm*, *cold* or *average* month are also gathered. This is in order to capture the variations that can happen on both annual and monthly levels, where some months and years may be colder or warmer than average. Finally, the gathered data is used to generate 36 different 24-hour weather inputs for the simulations, i.e. three representative variations of each month. Tables 7.4 and 7.5 display the basic input used for the seasons as well as the 36 monthly average temperatures. All the weather input have been gathered from

Table 7.4: Seasonal variations used as input in the simulations

Seasons	**Spring**	**Summer**	**Autumn**	**Winter**	
Average temperature	3	16	8.3	-2.7	°C
Day/night variation	15.9	17.7	16	4	Δ°C
Max sun radiation	168	489	402	154	W/m^2
Average humidity	6	8.5	5.5	4.5	g/kg

Table 7.5: Monthly average temperatures for a *warm*, *average* and *cold* years

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Warm	-1	-1	3	9	15	20	21	20	15	10	4	1	°C
Average	-3	-4	-1	3	9	15	16	16	15	7	3	-1	°C
Cold	-7	-7	-5	-1	4	9	11	11	7	3	-1	-5	°C

SMHI's open data banks and statistics summaries [34]. For the hourly values in temperature and sun radiation, days that fit the required average and variations have been manually picked from weather station records in the Stockholm region. As the time resolution in SMHI's records are in hours, the EUAX software simply interpolates values for shorter time steps. The humidity ratio x_u is assumed to stay roughly the same throughout the days and only varies with the seasons in the simulations. Figure 7.3 finally shows how the input for the simulation looks after it's been put into EAUX. Showing how the temperature and sun radiation can vary over a spring day. A major simplification used here is the fact that all the weather data is collected for static points in space, in this case from the region around Stockholm (*Svealand*). The challenge would otherwise be to try and find representative conditions as the trains are moving trough different weather conditions. Another issue is also the fact that the Swedish climate can vary considerably from north to south. The data from the Stockholm region is thus chosen as it can be seen as a centre-point for the area the two train types operate in.

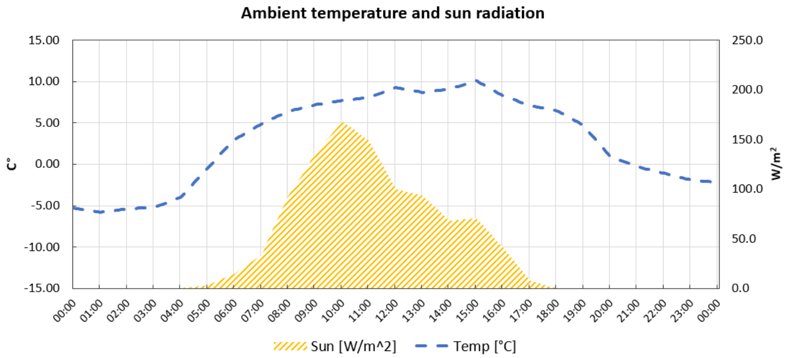

Figure 7.3: Example of simulated daily variation in temperature and sun radiation, spring day

7.1.5 Operational cycles and train service profiles

Similarly to the data gathering done for the weather input, a good representation of the operational cycles for the two train types is needed. And like the weather data, no *average* day or 24-hour cycle exists that would be useful in capturing all the possible variations in the operation. Instead, what is done is that a set of five representative 24-hour operational cycles for the two trains are manually chosen, from the different available planning systems at SJ and Götalandståg. These five *type days* are then used in combination to generate monthly and annual operational cycles that are closer to the average utilization of the trains. Here the choice was also made to focus the study of the X61 trains to the ones used for commuter train traffic around Göteborg. As mentioned previously, *Västrafik* owns 22 X61 trains which are used mostly as commuter trains on the lines closer to Göteborg. They also have 7 X61 train's on lease from *Skånetrafiken* which are more used as regional trains. But in this study, the focus is thus put on the 22 X61 trains for commuter train service profiles in order to get a more distinct difference between the service types and operational cycles of the X55 and X61.

To make sure that the five chosen type days for each train are truly representative of their operational cycles, they are compared to the average distributions of operational situations. Here SJ's and Götalandståg's different planning systems have been used to collect data and find key figures for the average utilization on an annual basis. For example, which lines they most frequently operate on, how many kilometres they run on average, how often they are set up for longer stabling or maintenance, etc. Very helpful have been the rolling stock rosters for the X55 and X61 trains, where the distribution between train service, shunting, deadheading becomes clear. The average running times, and where the trains stop along their routes are also found in the corresponding timetables. A feature built into EREX system has also been used to provide a guiding figure on the amount of time the trains spend standing still. As EREX logs GPS positions, the amount of time the vehicle has been in motion can be compared to the amount of time the vehicle has spent standing still at stations and depots. A simple VBA script is used on several sets of monthly energy reports for the X55 and X61 to compile the data. The different operational situations outside of the train service and deadheading are then distributed accordiong to work descriptions and available logs. Previous studies on SJ where similar time distributions were studied were also referenced.

For each train, the five different type days can then be combined into months and years in such as way that the annual operational cycle share the average distribution between operational situations and produced kilometres. The basic information about the five different type days used in the simulations for the two vehicle types are shown in Table 7.6 where the time distribution between situations for each day is given together with the distances the trains run each day. Once again the operational situation *1. Stabled without any power supply* is not included, as this situation is so uncommon that it's assumed to be negligible in this case. In the table, the *number of days* for each type day is then what is used in the combination of the type days into full years of 365 days.

The number of each type day used in these combinations are set manually so that the final time distribution between the operational situations as far as possible matches that compiled from the different planning systems and previous studies while also making sure that the yearly running distance in kilometres for each train does not deviate from recorded figures. The resulting compiled distributions for the X55 and X61 are shown here in Figures 7.4 and 7.5.

Table 7.6: Type days for X55 and X61 operational cycles

X55	*2. Stabled w/ stat. power*	*3. Parked before train prep.*	*4. Parked after train prep.*	*5. Idling*	*6. Shunting / Deadheading*	*7. Train service*	km	Nr. of days	Service*
Day 1	0%	42.4%	15.6%	8.0%	6.3%	27.8%	710	100	Uå-Cst
Day 2	0%	32.3%	8.3%	13.2%	3.1%	43.1%	1195	82	M-G
Day 3	0%	11.8%	44.1%	5.9%	3.5%	34.7%	1052	83	M-G-Cst
Day 4	0%	47.9%	0%	10.1%	1.7%	40.3%	1111	35	Uå-Cst-Su
Day 5	8.3%	46.5%	34.0%	6.9%	4.2%	0%	6	65	In depot
X61	*2.*	*3.*	*4.*	*5.*	*6.*	*7.*	km	Nr.	Service*
Day 1	0%	25.0%	28.1%	8.3%	3.1%	35.4%	434	80	G-Kb-G-Al
Day 2	0%	35.8%	17.7%	14.9%	3.8%	27.8%	359	55	G-Al
Day 3	0%	16.3%	14.9%	13.5%	1.7%	53.5%	604	70	G-Kb
Day 4	0%	8.7%	17.4%	8.3%	1.0%	64.6%	716	95	G-Än
Day 5	8.3%	43.4%	34.0%	11.1%	3.1%	0%	6	65	In depot

*The abbrevations are; Uå-*Umeå*, Cst-*Stockholm*, M-*Malmö*, G-*Göteborg*, Su-*Sundsvall*, Kb-*Kungsbacka*, Al-*Alingsås*, Än-*Älvängen*

The figure for the X55 time distribution agrees well with previous studies on both the X55 [24], as well as a time distribution study made on *X2000* trains [23] which is operated in a similar type of service as the X55. The X61, operating in more of a commuter train service, boasts a higher percentage of train service time.

The lines for which the trains are simulated were chosen based on which they operate on most frequently. The passenger occupancy rate is also assumed to be a constant 50% while in train service for both train types. This is based on an average for SJ's trains and is assumed to be useful also for the simulations of the X61. Even though neglected here, the variations in passenger loads on the trains could have an impact on auxiliary energy use. This is a factor that should be investigated in continued works, see the discussion in Section 9.2.

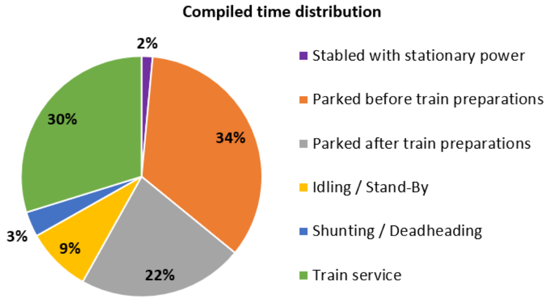

Figure 7.4: Compiled time distribution for the X55 over one year

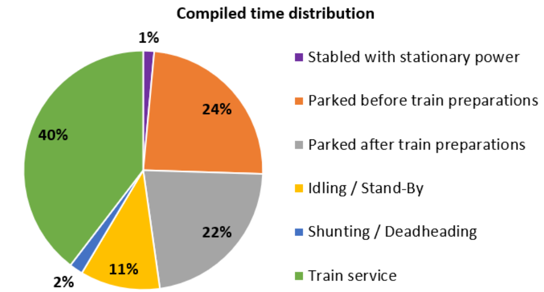

Figure 7.5: Compiled time distribution for the X61 over one year

7.2 Simulating energy in the operational cycles

This section simply contains some examples of the time-domain output from the EAUX software as well as some descriptions and discussions on the aspects of the output diagrams, together with some compiled results for the case studies later discussed in more details in Chapter 8. The simulations in the case studies are all carried out in the same manner where the five different type days for the two vehicle types are simulated with the 36 different weather input variations. Figure 7.6 displays the general workflow of the case study simulations. As KTH's STEC software also allows the simulation of regenerative braking it could have been possible to also include and analyze the *net total energy use* in this work, here meaning the energy use of the trains

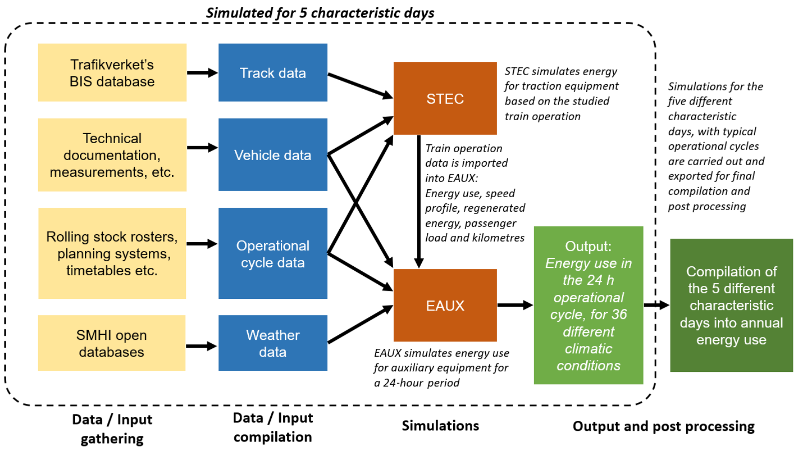

Figure 7.6: Work flow for case study simulations (based on the general simulation workflow previously shown in Figure 6.2)

after any regenerated energy has been subtracted. But as this would only have introduced another layer of assumptions and uncertainty, the energy use simulated and studied in these case studies are limited to the *gross total energy use* only.

7.2.1 Output from the 24-hour operational cycles

As default EAUX works with a 24-hour operational cycle. With the operational cycles of the five different type days and the 36 different weather conditions it's thus possible to generate a lot of output. What follows here will thus only provide some illustrative examples on what information that can be given from the time domain simulations.

One main output, used to calculate the energy use, is the instantaneous power need of the auxiliary equipment, for both the constant and varying component. The variation in power need for two different seasons is illustrated in Figures 7.7 and 7.8. Both simulations use the 24-hour operational cycle input of *type day 2* for the X55 as input, see Table 7.6.

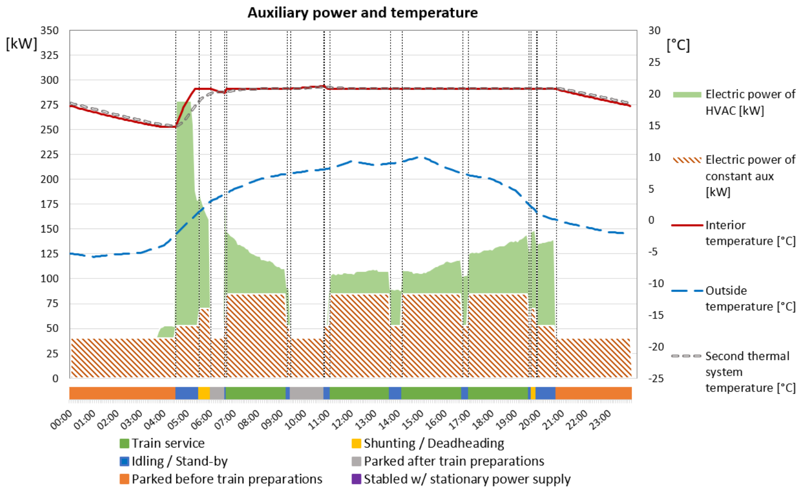

Figure 7.7: Auxiliary power use for a X55, temperature and operational situations. Simulated for type day 2, cold spring weather, with operation between Malmö and Göteborg.

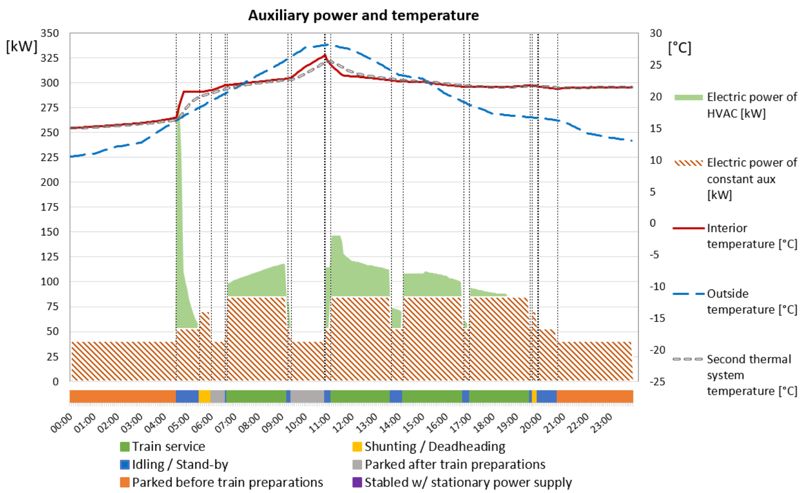

Figure 7.8: Auxiliary power use for a X55, temperature and operational situations. Simulated for type day 2, warm summer weather, with operation between Malmö and Göteborg.

The power need for the varying load behaves very differently in the two figures as the spring conditions require heating during the day while the summer case require cooling. In the figures it's also possible to follow the temperature of the second thermal system (see subsection 6.3.2) in the vehicle thermal model. It can be seen that the heating up and cooling down of this second system causes some lag in the power for heating and cooling.

For the total energy use of the train, the output from the STEC simulations can also be included in the same time domain output. Figure 7.9 displays the total energy use per five-minute time step for a X55 train in the same kind of operational cycle.

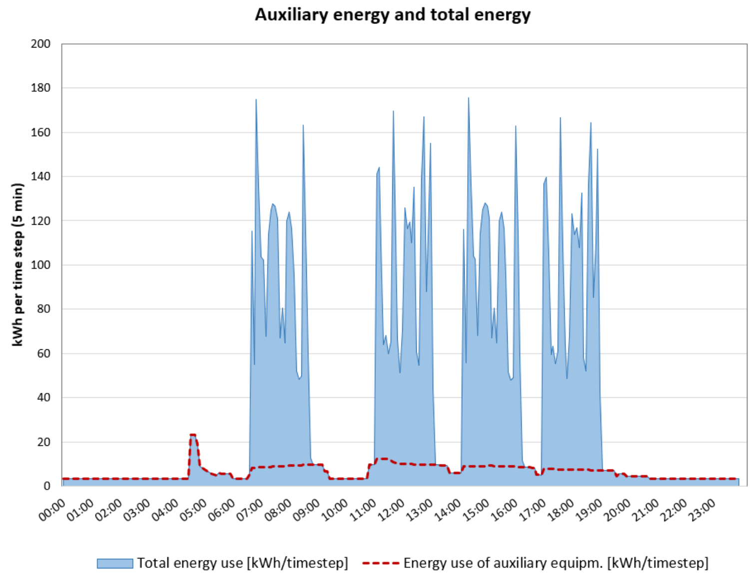

Figure 7.9: Energy use for a X55, auxiliary and total. Simulated for type-day 2, warm summer weather, with operation between Malmö and Göteborg.

The figure makes it possible to see the difference in magnitude of the two energy users, traction and auxiliaries. While the traction equipment makes up the largest energy usage, the auxiliary equipment still gives rise to a continuous energy use both in and outside of train service.

With the EAUX software it's also possible to follow and analyze the different factors influencing the auxiliary energy use over time. For the vehicle thermal model, it's for instance possible to follow all the different heat flows inside the vehicle thermal system. This can be interesting when studying ways for lowering HVAC energy use. Examples of the different heat flows over the 24-hour simulations are here displayed in Figures 7.10 and 7.11.

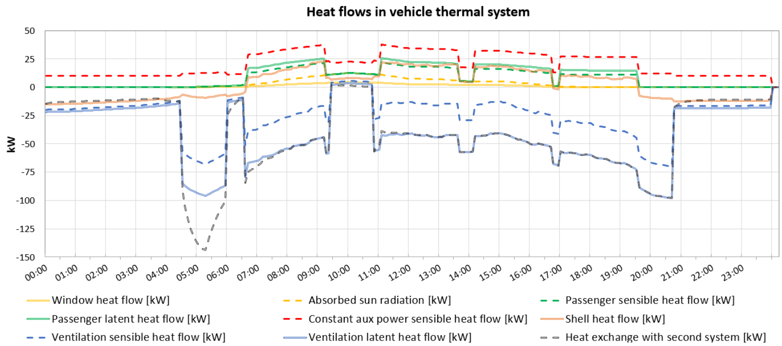

Figure 7.10: Stacked line plot of heat flows in vehicle thermal system. For X55 simulated for type day 2, cold spring weather.

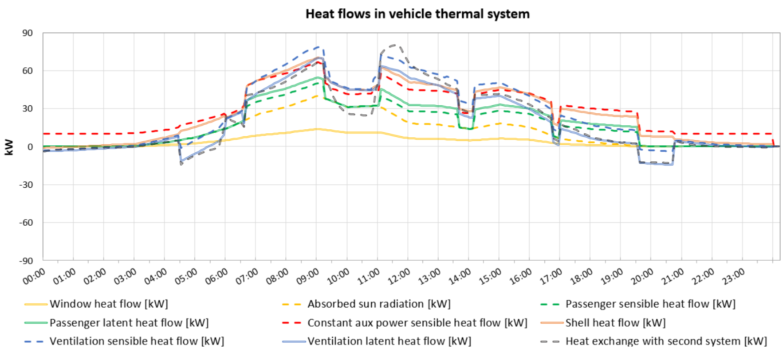

Figure 7.11: Stacked line plot of heat flows in vehicle thermal system. For X55 simulated for type day 2, warm summer weather.

These sort of diagrams can of course be hard to follow and grasp when one investigates the impact of single heat flows on the energy use, but they give some illustration of the variations in heat flow direction.

Some heat flows also may go from contributing to counteracting the HVAC's energy use. It's also possible to plot the heat flows' influence on the HVAC energy use over time. An example of which is here displayed in Figure 7.12. The figure shows the influence of the different

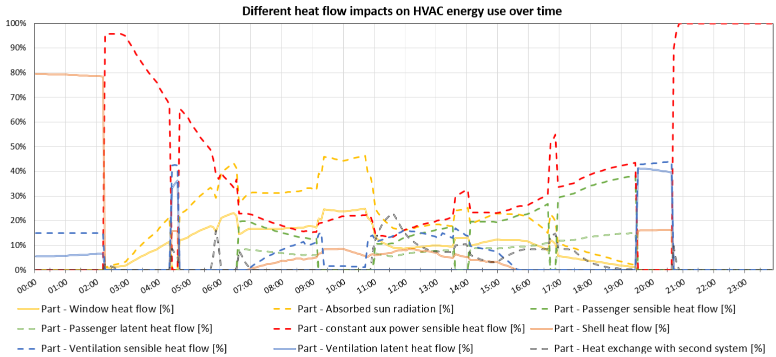

Figure 7.12: The different heat flows influence in percent on the varying auxiliary load over time on a X55. Simulated for type day 2, warm summer weather.

heat flows on the energy use for the HVAC. Once again, this kind of diagram can be a bit hard to follow but these time domain data have the benefit of also being possible to compile into key figures. Giving the average influence of the different heat flows on the energy use over a cycle.

7.2.2 Simulating monthly and annual climate variations

The 36 different weather conditions used as input for the simulations can be seen as the monthly variations of three different years. One *average* year, one that is *warmer* than average and one that is *colder*. The output from the simulations of these monthly and yearly variations can be combined to show how they affect the monthly auxiliary energy use. These results can then also be compiled for the five different type days for each vehicle type by combining the different type days into months and full years of 365 days so that the sum of the combined days energy use shows the monthly and yearly energy use in an *average operational cycle* for each simulated train type. The resulting monthly variations in auxiliary energy use for the two train types are here displayed in Figures 7.13 and 7.14.

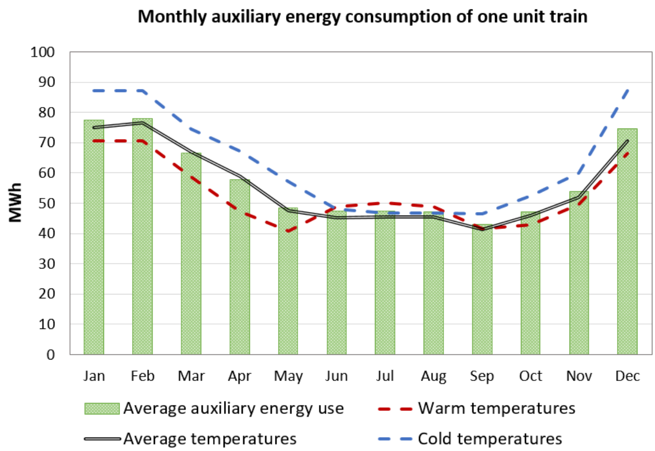

Figure 7.13: Monthly variations in auxiliary energy use for a X55 train. Simulated for a year with the *average operational cycle*

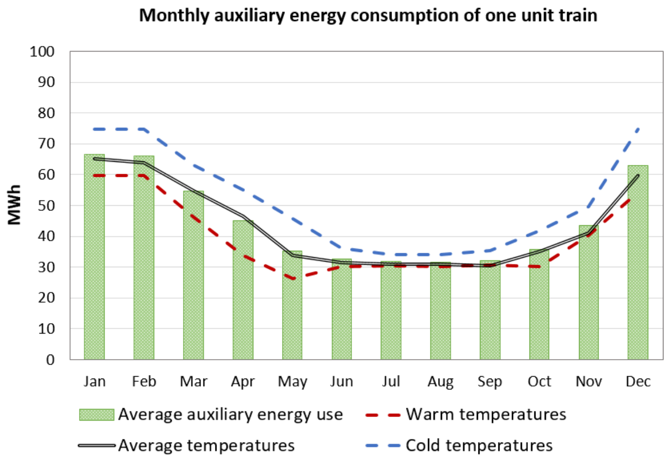

Figure 7.14: Monthly variations in auxiliary energy use for a X61 train. Simulated for a year with the *average operational cycle*

The monthly energy use displayed in the figures also contain the three types of yearly temperature variations. The differences between a cold and warm year are also quite substantial, and it can be noted that a warmer winter and an average or colder summer will have the lowest energy use for the X55. As a warm winter require less heating, and a cooler summer require less cooling. The green bar plots then also shows the average energy use of the three different variations. What can be seen is that the average temperature case not always gives rise to an average energy use. It's also this average energy use, based on the *average*, *warm* and *cold* temperature variations, that is later used in the analysis of energy use.

8. Results of case studies

After gathering all the material necessary for simulations in the case studies on X55 and X61, some analysis of the results are made. Evaluation, validation, as well as some calibration of the energy model is done by comparing the simulation output to gathered measurement data and records from the EREX system and other sources.

With a validated model it's then also possible to evaluate its usefulness, in this case by analyzing and showing some possible energy saving measures for the auxiliary systems in the two case studies, for example through different utilization of vehicle operating modes, changes in settings or possible technological improvements like CO_2-controlled ventilation functions. The potential energy savings can then be quantified, which is very useful as they could be very hard to distinguish during real measurements after they've been applied as the weather variations in themselves may cause larger differences in energy use than the energy saving measures.

8.1 Model evaluation

To evaluate the usefulness of the compiled models for the X55 and X61, they first need to be validated. Validation, as well as some calibration of the model, is thus done through comparison to measurement data and records from the series of measurements and tests carried out in case studies, but also with the help of historical data and records available in the EREX system and SMHI's databases.

As there is no practical way of following single trains in EREX while also monitoring all the relevant input in terms of ambient temperature and sun radiation, the validation of the auxiliary energy model is instead done through comparisons to parked and stabled trains' energy use together with local weather data from SHMI. In this way the influence of traction energy use can be kept outside the validation of the auxiliary energy model. When combined with the traction energy from the STEC software, the results can instead be validated against the recorded monthly and annual energy use of the real trains making it possible to evaluate the usefulness of the complete model.

8.1.1 Validation of the auxiliary energy model

The validation of the present auxiliary energy model has been done through graphical comparisons of simulation output and recorded data compiled for both the X55 and X61. The way this was done was by plotting the auxiliary power's temperature dependency from the simulation and compare this to hourly average power values and temperatures compiled from EREX and SMHI's databases. The hourly average auxiliary power is calculated from from the energy used in EREX and from SMHI hourly temperature data for the different geographic locations the trains have been stabled at was collected.

As the two most common operating modes of the X55 are the *active* mode and the energy saving *parking* mode, these are the ones that would be most interesting to validate. In this case there is an asset in the existence of historic records in the EREX system as previous work routines and settings had the X55 trains parked in an operating mode almost identical, in terms of auxiliary power use, to that of the *active* mode. This was changed in 2014, with the introduction of the energy saving parking mode, but the historic data from before this change provides data that can be used to validate the model for the active mode, corresponding to the operational situation *Idling*, without interference from passengers' or traction energy. The same is then also done for the new parking mode, using more recent data. The recorded data is then plotted together with the simulated power curve for the corresponding situations, here shown in Figures 8.1 and 8.2.

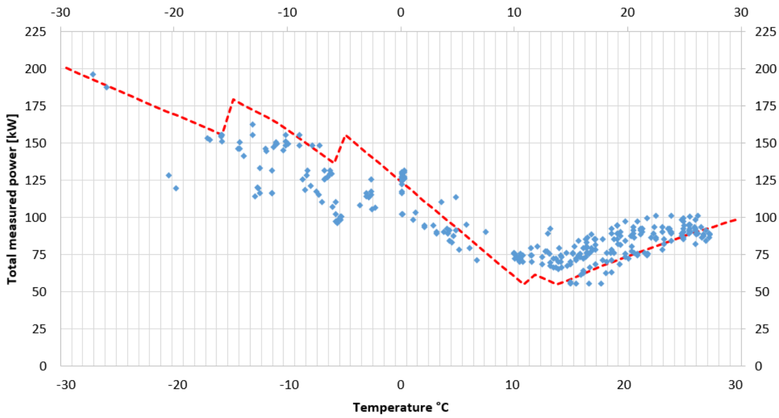

Figure 8.1: X55 Active mode - Recorded total auxiliary power at different ambient temperatures (blue dots) and model power curve (red dashed line)

The "saw-tooth" look of the simulated power curve in Figure 8.1 is due to the ventilation control functions, either stepping down or up the amount of fresh air intake in different temperature intervals. For the X55, this happens at two points below 0°C, having the lowest fresh air intake below -15°C. Figure 8.2 then shows the simulated power curve for the parking mode, whit no fresh air intake. The data for the X55 were compiled from trains stabled and parked on stations Umeå, Sundsvall, Östersund, Stockholm, Göteborg and Karlstad together with local weather data from the corresponding time periods. In the simulated curve, some sun radiation, increasing linearly from 0-600 W/m^2 is also introduced from -10°C to 30°C to take into account that most of the lower recorded temperatures are for night time stabling during winter, while the higher temperature data points were for daytime situations during summer.

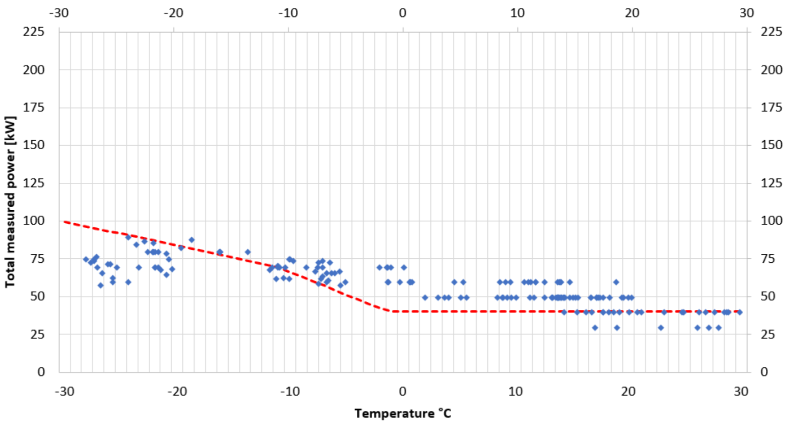

Figure 8.2: X55 Parking mode - Recorded total auxiliary power at different ambient temperatures (blue dots) and simulated power curve (red dashed line)

For the X61 there is an *active parking* mode that is used in most stabling and parking situations[15], which is a operating mode with seemingly similar auxiliary power and energy use as the normal active mode. The same kind of data compilation and comparison done for the X55 is also done here for the *active parking* mode of the X61, shown in Figure 8.3.

The EREX and SMHI data for the X61 were all collected for the same year as the more recent X55 records, the same year later used as reference for all other comparisons and validations.[16] It can also be observed in Figure 8.3 that the temperatures in Göteborg never dropped to quite as low as in Umeå and Sundsvall in the recorded data, with the lowest recorded temperature of -12.2°C. Still, the trend displayed in the data is reflected in the simulated curve.

Face validity and the estimation of goodness-of-fit is in the case of these validations done by graphical comparison between simulated and measured data. For both the X61 and X55, the fits aren't always perfect. And as the auxiliary energy models are based on control func-

[15] According to the driver's instruction manual on what settings and modes are to be used during parking and stabling. [38]

[16] Which year is not to be disclosed in this publication, on SJ's request.

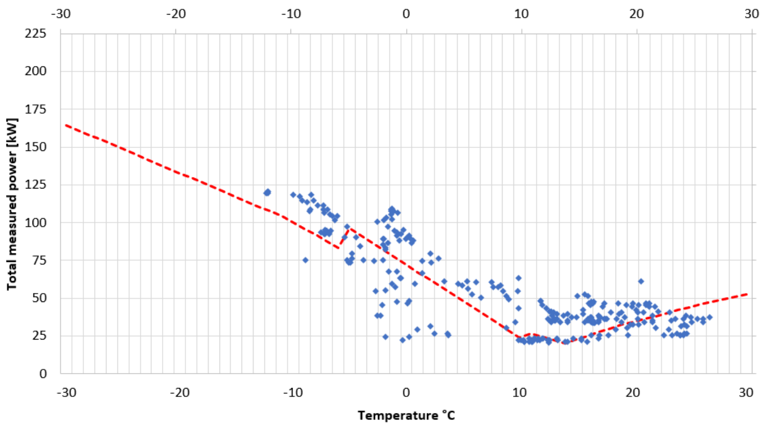

Figure 8.3: X61 Active parking - Recorded total auxiliary power at different ambient temperatures (blue dots) and simulated power curve for the same span (red dashed line)

tions and design parameters found in the technical documentation, the room for calibrations is limited to small adjustments of some uncertain parameters. For example, the X55's ventilation air flows were adjusted down by 5-10% in some temperature ranges, still keeping within the margin of error stated for the initial values in the technical documents of the vehicle. But other than these smaller calibrations the model design and major input parameters are not changed.[17]

As the models are nonlinear and not fitted to the data it's not possible to use any common statistical goodness-of-fit measures. But the graphical comparisons still show that the model captures the trends in power demand, and the model is thus considered to be satisfactory. The main source of differences most probably lies in both the model and the data gathered for comparison. Control functions, such as for ventilation air, are often given as simplified tables in the technical documentation of the trains, giving rise to the "saw-tooth" like curves. It could well be that the ventilation functions in reality regulates the air flow in a more continuous manner, that would result in smoother power curves. The comparison of the instantaneous power

[17] All values given in text and tables are the ones used for model input after the calibrations took place.

need also doesn't capture any transient behaviour that could happen. For instance, an already warm vehicle would require less heating the first couple of hours of stabling or parking. Other weather phenomena, such as rain, heavy wind or snowfall are not taken into account in the model, but will of course affect the data points. Information on the local shading or sun radiation is neither available for the points. And for the X55, which is parked and stabled in many different stations and depots, the weather stations could sometimes be up to 5 km from the yards, adding both a time and space dimension to the differences in local weather.

8.1.2 Comparisons for monthly and annual energy use

With the auxiliary power model validated it's possible to move on and include the traction energy and study the total energy use in the operational cycle of the trains. To make a good evaluation of this complete energy model and simulations, as well as of the method of using an averaged annual operational cycle based on the five type days, the output needs to validated against recorded data. This is here done on macro level, where simulated monthly and annual energy, together with the produced train-km, is compared to recorded data for a reference year.

The compiled results from the simulations of monthly energy use for the X55 and X61 in in their current operation and use are here displayed in Figures 8.4 and 8.5. and based on the distribution of the five different type days according to the numbers previously provided in Table 7.6, and for monthly averages of the 36 different weather inputs summarized in Tables 7.4 and 7.5.

The total annual figures for the simulated energy and run kilometres can then be compared to the recorded figures for the reference year, here shown in Table 8.1.

The simulated produced kilometres agree well on an annual basis, as this was one of the guiding figures used when the five different type days for each train were weighed into a full year. The total energy use also agrees well for both trains. From the simulation results it's also possible to study how a warmer or colder year could impact the total

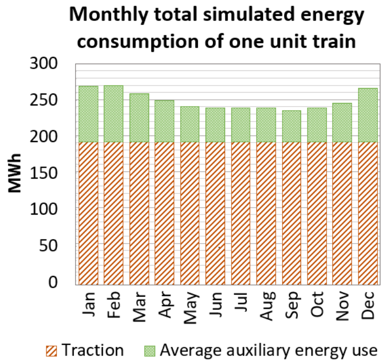

Figure 8.4: Monthly energy use, simulated for one X55 train.

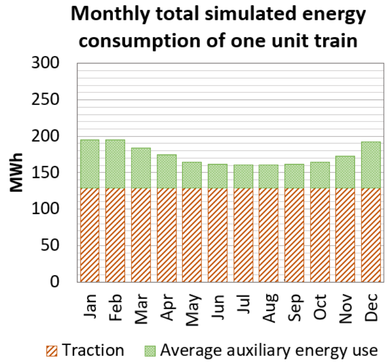

Figure 8.5: Monthly energy use, simulated for one X61 train.

Table 8.1: Simulated annual energy figures for one train, compared to records of the reference year

X55	Gross MWh	Err.%	Train km	Err.%	Gross kWh/km	Err.%
Simulated	2986	-0.46%	295 544	0.04%	10.1	-0.50%
Recorded figures*	3000		295 424		10.2	
X61	Gross MWh	Err.%	Train km	Err.%	Gross kWh/km	Err.%
Simulated	2087	1.68%	165 078	-0.41%	12.6	2.08%
Recorded figures*	2052		165 756		12.4	

*Average energy and run kilometres for one train. Based on the *fleet total* for the reference year.

energy use, as shown previously in Figures 7.13 and 7.14. For the X55, the simulated weather variations give rise to a maximum difference in total energy of 143 MWh per train and year. For the X61 the figure is calculated to be about 147 MWh. These figures give a good indication on how much the weather can affect the annual energy use for the trains, and also help to illustrate the point that some energy saving measure could be hard to distinguish due to these naturally occurring variations.

Also relevant to study is how well the monthly energy use agrees between the simulation and the actual monthly records for the reference year. The monthly records for both train types are compiled from the EREX system and statistics on the accumulated run kilometres for the trains. As the simulations use the same average operational cycle for each month, this means that the simulated amount of train service and kilometres are the same for each month. In reality, the level of service varies between the months, with some month seeing a larger number of train kilometres produced and some lower. These differences become apparent when the simulated kilometres and energy use for each month is plotted against the actual figures for the year used as reference, see Figures 8.6 and 8.7.

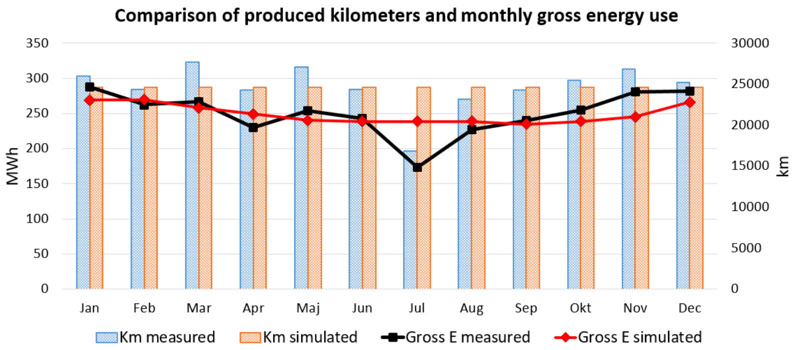

Figure 8.6: X55 - Produced kilometres (bars) and monthly energy use (lines) for simulation and reference year.

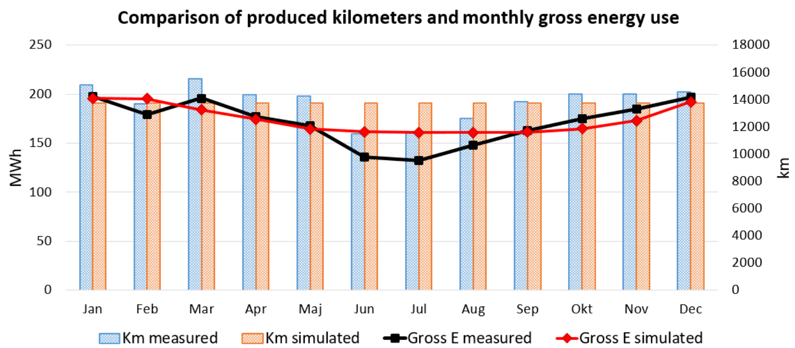

Figure 8.7: X61 - Produced kilometres (bars) and monthly energy use (lines) for simulation and reference year.

The monthly variations in service of the trains result in large differences of both the total energy use and the produced kilometres. The differences between the simulated monthly energy use and the measured figures differ as much as 27% July for the X55 case. But at the same time the difference in produced kilometres between the model and recorded figures also differs with 32% for the same month. Thus the error in the simulated monthly specific energy use [kWh/km] is not that large. Figures 8.8 and 8.9 show the error in simulated total energy, kilometres and the resulting difference in kWh/km on a monthly basis.

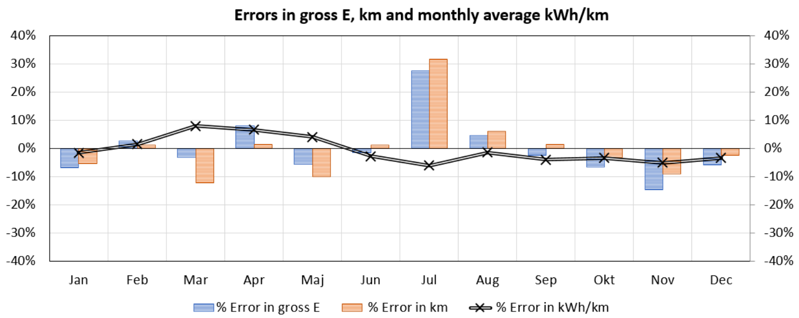

Figure 8.8: Monthly errors in simulated energy, kilometres and kWh/km for one X55 train, compared with reference data

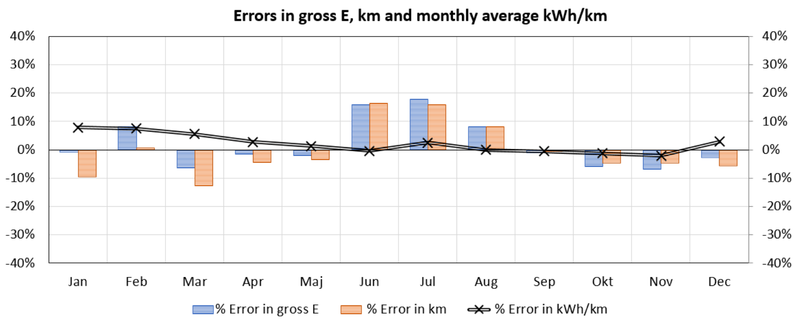

Figure 8.9: Monthly errors in simulated energy, kilometres and kWh/km for one X61 train, compared with reference data

The results from these comparisons show that the error in the simulated kWh/km each month is much smaller than that of the total energy and run kilometres with an absolute average error of 4% for the X55 and 3% for the X61. And with a maximum of 8% for both. Thus the simulations still agree fairly well with the recorded data, despite the many simplifications in both the model and input.

Interesting to note is also that the simulated auxiliary energy is for the average of the *warm*, *cold* and *averaged* temperature years. This simplification does not really capture the fact that the months and seasons themselves change and differ for every year, where in this regard the used reference year was quite a mild year with a somewhat warmer winter and spring followed by a somewhat colder summer. In Göteborg especially, the temperatures were never much lower than -12°C in the early winter, which may give some explanation to why the simulations are getting a higher energy use for the X61 in the early months of the year.

8.2 Discussion on the validations

The results from the validations of the auxiliary power model and the study of monthly and annual energy use show that the energy model is satisfactory and fulfills its intended functions. Sources of error of course still preside in both the assumptions surrounding the input, as well as in the level of detail of the model itself. With the simulated traction energy included, the assumptions surrounding the input in the STEC software play an important role in the total energy use and the results of the validations. Two factors that have been neglected in the traction energy simulations, that could turn out to be of importance, are the effect of temperature dependent air resistance and coupled trains.

The influence of ambient temperature on the air resistance is a factor that in this case has been omitted in the simulations of traction energy, as it would have required the B and C coefficients in the running resistance equation (6.18) to be recalculated for each run with a new temperature. The ambient temperate will cause the air resistance to increase or decrease. For example, going from -30°C to 30°C the resistance coefficient C will decrease with as much as 25%. But assuming the figures for C initially is based on normal temperatures, the maximum deviation decreases, to about $\pm$13%. But the effect is still something worth investigation in a more detailed model.

Another omitted factor is the coupling of multiple EMUs into longer trains, something that is commonly used in rush hours in the commuter service with the X61 trains while in the case studies the two types of trains are only regarded as single EMU trains (with 4 units). The coupling of two EMUs also has the effect of lowered air resistance, compared to two trains running separately. Yet another factor for the X61 is that the simulations were all carried out for quite high intensity commuter services while in reality Västtrafik's X61 trains also occasionally serve as regional trains. This discussion is continued in Section 9.2 on continued works.

8.3 Suggestions for auxiliary energy savings

With the model validated it's possible to move on and show how it can be useful in further analysis of the trains in the case studies. As the focus of this work has been on the auxiliary systems energy use, this will also be the case of this section where the influence on the energy use caused by the operational cycle, the trains performance, settings and modes are studied in order to show some possible measures for savings in the auxiliary energy use.

The most important factors when it comes to energy for the auxiliary equipment are those related to the HVAC operation and choice of vehicle mode in the different operational situations. For the HVAC, lower set-points for interior temperature during parking and better ventilation control functions, such as CO_2 control, are measures that can lead to reduced energy use. Some of the possible measures can also be as simple as just changing the work routines so that existing energy saving operating modes on the trains are used more often. Thus energy could be be saved without the need for new technology and complex solutions as well as with little investments.

8.3.1 Examples of energy saving measures on the X55

As the X55 trains currently are the most modern in SJ's fleet of rolling stock they also are among the most energy efficient. In terms of the two main operating modes of the X55; *active* and *parking*, they are used pretty much optimally in the corresponding operational situations. When stabled or parked, the trains are usually set in their *parking* mode and have an interior set temperature of 15°C and its ventilation turned off. This mode is currently used in the operational situations 2-4, where it helps lowering the energy use quite substantially compared to if the vehicle would have been parked in the *active* mode.[18] In the simulations, the annual auxiliary energy use only stands for 23% of the total energy use of the trains. And of this figure, the heating and cooling energy use for the HVAC only makes up for 25% of the auxiliary energy use, i.e. 5.7% of the total. And the energy use outside of *train service* only makes up for 12.8% of the total, even though these situations correspond to 70% of the operational cycle time.

The biggest sources of energy use in the HVAC are the shell and ventilation heat flows, which together make up 69% (36% and 33% respectively) of the heating and cooling need. Both of these heat flows are affected by the interior set temperature. The ventilation is also greatly affected by the fresh air intake rate. As mentioned in Section 2.5 this is due to the air intake being dimensioned after the number of seats in the trains, leading to excess fresh air intake when the HVAC systems are active and the train is not at full passenger capacity. So two hypothetical energy saving measures in response to these issues would thus be:

- Lowered set-points for the interior temperature while parking and stabling, going from 15°C to 10°C
- Ventilation fresh air intake rate controlled by the passenger demand, i.e. by CO_2 control

In the EAUX software it's easy to then enter a new set temperature in the parking mode, as well as change the control functions for the fresh air intake into one based on the current number of passengers. Ventilation controlled by the number of passenger will always be at its lowest setting when the train is empty, which means that unnecessary ventilation will be eliminated when the train is idling in depots and all other situations when the train is not in service. Table 8.2 shows how these measures affect the simulated annual energy use of one train.

[18] See also the later comparison to older work routines and the active parking used before 2014.

Table 8.2: Energy saving measures on the X55
Simulated annual energy savings for one train

Measure	Absolute savings	Savings in aux. E	Savings in total E	*Possible yearly variation**
1. 10°C parking and stabling	3.83 MWh	0.56%	0.13%	*134 MWh*
2. CO_2-controlled ventilation	67.51 MWh	10.9%	2.3%	*98 MWh*
1. and **2.** combined	70.25 MWh	11.4%	2.4%	*91 MWh*

*For comparison: The absolute difference in annual energy use due to variations in weather conditions (*warm*, *cold* and *average* years)

CO_2-controlled ventilation together with a lowered set temperature while parking would lead to the largest hypothetical energy savings. On the other hand it's noted here that the predicted savings by just lowering the set temperature while parking are very small. So small in fact that they would probably not even be noticeable on an annual scale, as just the possible variations due to the weather is almost 50 times larger.

Even in combination with CO_2-controlled ventilation the savings by lowering the set temperature are small. What this shows is that the existing set temperature of 15°C doesn't use that much extra energy. The higher 15°C set temperature also has some other benefits, such as allowing the trains to reach comfort temperatures faster when going into train service as well as serving as better working environments for crews working in parked and stabled trains. Another interesting note is that the simulated variations in energy use for a *warmer*, *colder* and *average* year becomes less significant with the energy saving measures. This is due to the elimination of some of the weather's influence on the trains' energy use.

As the energy saving measures with CO_2-controlled ventilation would require the rebuilding of the HVAC in trains, the potential energy savings can hardly be considered large enough to warrant such as investment in themselves. But as CO_2-controlled ventilation is becoming more common during refurbishments of older trains. It's likely that the addition of this function will come in the future, during other major refurbishments of the rolling stock fleet. The extra cost for this addition would then likely be marginal.

As mentioned initially, the X55 already uses its existing modes and functions in the different operational situations quite optimally. But this was not always the case, compared to the conditions before 2014 where the trains were kept in an *active* mode during all stabling and parking conditions as well as in work and routine descriptions concerning the train preparations before 2017 when the trains were to remain in an *active* mode in the situation *parked after train preparations*. The change from this previous use of modes and handling of the trains can also be interesting to study to get a grasp of how these changes possibly have impacted on the energy use. Table 8.3 summarizes the simulation results for these "inverse" energy saving measures.

Table 8.3: Comparison to previous sub-optimal use of vehicle modes during parking/stabling situations

Difference in use	Absolute waste	Waste in aux. E	Waste in total E	*Possible yearly variation*
Active during parking / stabling	313 MWh	31.2%	9.5%	*239 MWh*
Active during *parked after train prep.*	119 MWh	14.7%	3.8%	*174 MWh*

These figures are of course assuming the same level of traffic and train-km as those for the reference year, which is not the case for the time before 2014, as the X55 was still being introduced during that time. Thus no direct comparison of the annual energy use from then can be made with available data. For the change in the routines surrounding mode use in the situation *parked after train operation*, this changeover took place too recently for a proper comparison. Still the results are interesting, as they give a hint of the amount of energy that could have been wasted if these changes had not been in place. It can once again be noted that the possible variations due to weather also increases for the more sub-optimal cases.

8.3.2 Examples of energy saving measures on the X61

Just as the X55, the X61 is a modern EMU and is equipped with energy efficient functions and modes. But contrary to the X55 these modes do not always seem to be used in an optimal way. This is shown already in the validation of the auxiliary energy model, where the *active parking* mode shares many similarities with the fully *active* mode of the X55. And during the measurements carried out in Sävenäs, while estimating the thermal parameters and constant loads, it was noted that the X61 trains present were all parked with an interior set temperature of 20°C as well as having some ventilation running. Still, the X61 supposedly has an energy saving parking mode that is meant to both turn off the ventilation's fresh air intake and lower the set temperature to 10°C, according to the technical documentation for the vehicles [38]. So far, the reasons for this mode seemingly not being in use is unclear, and will hopefully be a starting point for any further investigation in possible energy saving measures on the X61.

Moving on to the simulations of the X61, the energy use for the auxiliary equipment make up for 25.8% of the total energy use, and the energy use outside of the *train service* in this case makes up 15.4% of the total. This is not that much larger than for the X55, but there's a much larger difference in how this auxiliary energy is used. As the X61 lack features like catering equipment, as well as some other constant auxiliary loads the X55 has, the heating and cooling needs in the HVAC's instead make up 49% of the auxiliary energy use, i.e. 12.6% of the total energy. The ventilation heat flow alone makes up 57% of this energy use, and the shell heat flow only 17%. And just as for the X55 it would also be interesting to study the effect of CO_2-controlled ventilation.

As the X61 already has a built in energy saving parking mode, it would also be very relevant to study the effect of this mode being used more often than in the two situations *parked before* and *parked after train preparations*. With this mode, the cooling function is turned off, and the set temperature for the interior is lowered to 10°C. As discussed in the case of the X55, 10°C might be a little low from a practical standpoint. There have also been studies on SJ on the issue of low interior temperatures and the build up of humidity in the trains [25] as water may condense if the temperature is allowed to drop to much, and in places inside the vehicles where it may cause direct or long-term damage. Because of this, and also due to the little difference in energy use displayed in the case of the X55, it would also be interesting to study the effect of having a higher set temperature of 15°C for the parking mode in the X61.

To summarize, some hypothetical energy saving measures for the auxiliary energy on X61 would thus be:

- Use of the built-in energy saving parking mode in the parking / stabling situations
- Use of the built-in energy saving parking mode, but with a higher set-point for the temperature of 15°C
- Ventilation fresh air intake rate controlled by passenger demand; i.e. CO_2 control

The effects these measures would then have on the annual energy use are simulated in EAUX and summarized in Table 8.4.

Table 8.4: Energy saving measures on the X61
Simulated annual energy savings for one unit train

Measure	Absolute savings	Savings in aux. E	Savings in total E	*Possible yearly variation*
1. Optimal use of built-in modes	147 MWh	37.7%	7.6%	*103 MWh*
2. Opt. mode use w/ 15°C parking	147 MWh	37.5%	7.6%	*105 MWh*
3. CO_2-controlled ventilation	181 MWh	50.6%	9.5%	*73 MWh*
1. and **3.** combined	193 MWh	55.7%	10.2%	*69 MWh*
2. and **3.** combined	192 MWh	55.5%	10.1%	*71 MWh*

The results show that the largest hypothetical savings would be if CO_2-controlled ventilation could be combined with a more optimal use of the X61's existing energy saving parking mode. But what's also shown is that basically the same energy savings could be had with a new set temperature of 15°C in this parking mode. The hypothetical savings from just using the built-in parking mode in the situations *parked before* and *parked after train preparations* also lead to quite substantial savings in auxiliary energy. And also here it shows that this parking mode at 15°C would be almost equally good, but with the benefits of the higher interior temperature 15°C.

What these results show is that in the case of the X61, there is large potentials for energy savings even without the need for new technology or any major changes to the trains if the existing energy saving parking mode turns out to be possible to use more often, either with its original 10°C set temperature or the more practical 15°C. The necessary investments would possibly only be those involved in the training of crews and drivers in the use of these modes, and perhaps some minor software settings in the trains' HVAC control. Combined with CO_2-controlled ventilation, which would of course require larger investments, the possible energy savings are even more substantial.

The order of magnitude in the energy savings, achieved from better use of the built-in energy saving parking mode, is similar to the differences in the X55's use before 2014. So in this regard the X61 is not alone, as both the X55 and other train types either have had or are still suffering from sub-optimal use of their built-in energy saving features [23]. The reasons why this is the case may be several. A possible explanation may be as simple as a lack of communication between vehicle manufactures and train operators, where the designers of the trains may have another idea of how the operating modes are to be used, compared to how they end up being used. This also ties into the issue of lack in standards for auxiliary systems and operating modes. For example, an energy saving mode may turn out to be *too* effective, turning off systems that will be required for cleaning and basic maintenance of the trains when in depot, thus requiring the operators to leave the trains in an active mode for these kind of tasks. While this is just speculation into possible causes, the real reasons for this sub-optimal use of existing functions and how it could be prevented would be an important continuation of this work. See the further discussion in Section 9.2.

9. Conclusions & further work

The overall results of this master thesis show that the energy use for auxiliary equipment and the time spent outside of train service are both important and worthwhile investigating. The potential for savings found in the simulations of improved HVAC control and use of operating modes, indicates very large possible energy savings compared to necessary investment. It can also be seen as remarkable that existing energy saving operating modes in some trains don't see their full potential use and that energy is seemingly wasted as an effect of excessive auxiliary energy use outside of train service. But this may very well be a result of the fact that auxiliary energy use in these situations has been overlooked until recently.

9.1 Conclusions

Using the operational cycle as a concept proves to be a useful and intuitive way of describing and analyzing the use of passenger trains in their everyday operation. Used alongside the train service profiles (i.e. duty cycles) and climatic input the operational cycle also serves as a useful input in a model for passenger trains' energy use, especially when trying to capture the varying need in energy for the auxiliary systems both during and outside of the train service.

When the developed methodology and model are used in the case studies on the X55 and X61 it's also shown to be possible to use simplified operational cycles for each train type. The operational cycles of each train are described by compiling five different type days, each representing a common daily operational cycle for the train types. When combined into a year, together with monthly climatic data, the model captures recorded trends in monthly variations in specific energy use as well as the total energy use on an annual level.

As the developed model and simulation software also allow for the separation of traction energy from the auxiliary one, it becomes useful in the way that the auxiliary energy can be analyzed separately. And as the trains' HVAC energy use has been described with the help of thermal models of the trains it's also possible to study the influence of the HVAC control functions and different heat flows, making the model and simulation software useful in the investigation of different energy saving methods and measures in the case studies.

Even with the positive results of the case studies, it should be noted that many uncertainties remain and that the results and projected energy savings as of now can't be associated with any strictly determinable error spans. As with this master thesis, the level of detail has been set by the available time and data for the trains used for the case studies. A summary of the main factors that contribute to these uncertainties is given as:

- Differences in the used climate data and the year used as reference in the validation, as well as poor knowledge of climatic conditions locally.
- Simulated HVAC control and functions are simplified to fit available information of vehicle systems.
- Neglected or unknown effects not included in the model.

As the year of recorded data for energy and kilometres was one with a warmer winter and more average summer, the simulation results will naturally deviate. This will always be an issue for this kind of simplification, where averaged yearly weather conditions are used. For the HVAC systems, the available technical documentation did not always provide the exact figures and functions for how the HVAC operates, and simplified expressions and functions were necessary to be used instead. Finally, many factors have been knowingly neglected in the construction of the model, that could prove to be important for an increased level of detail. This brings on the need for further investigation and continued works.

9.2 Further work

This master thesis has only really begun to investigate and model the mechanisms that affect energy use for passenger trains in their operational cycle. For the sake of the subject it's important that further work continues this investigation as many factors and details not covered in this work may still prove important for the bigger picture.

Direct suggestions further work can of course also be provided based on the known assumptions, simplifications and uncertainties in both model and results. To summarize, works following up on this one should include more investigation into:

- Further improvements and generalization of the description of the operational cycle and the operational situations.
- Increased level of detail in the models, to include neglected factors and better describe the different control functions used in the trains.
- Improvements in model input, where assumed or otherwise estimated values can be replaced with measured ones or estimates with a determinable error.

A major aim has been making the operational cycle into a generalized tool for describing the use of passenger trains over time. The same goes for the operational situations that make up the cycle. The whole purpose of the operational cycle is to describe the representative operating conditions for passenger rail vehicles, and that subject in itself deserves more focus. A possible continued work should aim on possibly improving on this concept and these descriptions, and further evaluate the general usefulness of the method.

Another, equally important task would be to improve on the model for auxiliary energy use in the trains. For the auxiliary energy model, the division between constant and varying loads needs to be investigated, as there may be more loads than the heating and cooling need that would need their own dynamic model. For example, the cooling need for equipment such as transformers and power inverters can easily be hypothesized to be influenced by ambient temperatures while in the model used in this work these power loads are assumed as constants. The heat flows in the vehicle thermal model and the way they are expressed could also be improved to include more factors, but of course at the cost of them then needing more input. On this subject there is also room for more work, as the detail of the model input always can be improved. If the model is redesigned to take into account new and more detailed input, it would be interesting to study the effects of ambient wind conditions, rain as well as changes in sun radiation by overcast weather, but also from the sun's motion across the sky and how the sunlight falls on the vehicle. Other effects are keeping doors open at stations, air resistance dependent on ambient temperatures, the effect of coupled trains, etc. The list will probably keep on expanding with the development of a more advanced model.

Gathering more relevant data for input on the trains and operations studied should also be possible. A lot of the work in this master thesis has gone into finding relevant input from the available technical documentation and work descriptions. With more time, and possibly material directly from vehicle manufactures, it would be possible that some unwanted simplifications and assumptions in the input could be avoided. On this subject, measurements and more active monitoring of energy use in the trains is something that should also be carried out, both in the interest of the train operators themselves as well as researchers looking into the matter. With this, more precise figures could possibly be drawn for the actual energy use in the trains during the operation, and would also allow easier validations of any energy models.

It's finally worth mentioning that there are likely many more train types than the X55 and X61 that show similarly large energy saving potential. The trend is reflected in other train types, both on SJ and Götalandståg, as well as in results from previous studies consulted in the literature review. Existing modes are either not used optimally or not designed to be as energy saving as they could be. Surrounding this issue is the need for better standards for auxiliary systems and auxiliary equipment energy use as well as a need for better communication between vehicle manufacturers and train operators so that the train operating modes and functions better suit the many activities and situations in the everyday operation, other than just the train service. Just bringing up the issue and describing it, as has been done in this work, is an important step forward as it brings light to issues that are important in the continued improvement of energy efficiency of passenger rail vehicles.

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1. Terms, definitions and abbreviations

What follows here is a small summary of terms, definitions as well as abbreviations used in this work. Some terms and definitions used here are original to this work, and used to describe the aspects of the method employed. Other definitions are based directly on the UIC vocabulary [42] and terms and phrases used in the *Rail Systems and Rail Vehicles* course material [13].

Terms and definitions

Some particular terms used in this work, that may require further explanation, are here listed in alphabetical order:

- *Deadheading* - Train running without passengers, usually from depot to starting station or from end station to depot
- *Operating mode* - Vehicle and train specific operating modes, depends on vehicle type in question, can be modes such as active, parking-mode, shunting-mode etc.
- *Operational cycle* - Description of the typical utilization of a rail vehicle over a day, including train service, idling, parking, maintenance etc.
- *Operational situations* - The different stages or parts of the operational cycle, i.e. train service, idling, parking, maintenance etc.
- *Rolling stock* - Another term for rail vehicles
- *Rolling stock roster* - Turn round plans for vehicles, used to plan train service assignments as well as maintenance and depot visits
- *Shunting* - Train moving within stations or depots, to change tracks or get to specific maintenance facilities
- *Stabling* - Longer parking intervals, usually in wait for maintenance or during long periods of no service assignments
- *Time outside of service* - Time outside of *train service*, i.e. all that which is not train service
- *Train preparations* - Activation, inspections and verification of the train's different systems before train service
- *Train service* - Train running with passengers, i.e. the commercial exploitation of the train

– *Train service profile* - The typical traffic, in terms of operating speeds, passenger loads, number of stops, i.e. the "duty cycle" of the train service
– *Unit* (vehicle) - A vehicle connected in a multiple-unit (EMU or DMU)

Symbols and units

Symbols and units used in this work are explained where they appear. The following is a list of symbols used, arranged here in their order of appearance:

– E_i - Gross energy use, if nothing else is stated [Wh]
– P_i - Electric power [W]
– $\dot{Q}_i$ -Heat flow, both sensible and latent [W]
– C_i - Heat capacity [J/K]
– T_i - Temperature [°C]
– x_i - Humidity ratio [kg/kg]
– k_i - Heat transfer coefficient per area [W/(m^{2}K)]
– A_i - Area [m^2]
– ρ_i - Density [kg/m^3]
– $c_{p,i}$ - Specific heat [kJ/kgK]
– $\dot{V}_i$ - Volume flow [m^3/s]
– h - Latent heat [kJ/kgK]
– ϵ_i - Irradiance absorption factor
– $\dot{q}_i$ - Irradiance [W/m^2]
– α_i - Irradiance transmission factor
– β - Shading factor
– K_i - Heat transfer coefficient [W/K]
– η_i - Efficiency factor ($\eta_i < 1$)
– A, B and C - Coefficients of running resistance
– v - Speed [m/s]

Abbreviations

Abbreviations used in the text are here listed in their order of appearance:

- HVAC - Heating Ventilation and Air Conditioning
- LCC - Life Cycle Cost
- EMU - Electric Multiple Unit
- KPI - Key Performance Indicator
- EN - European Norm (Standard)
- CLC/TS - CENELEC Technical Specification (Standard)
- UIC - Union International des Chemins de fer (Standard)
- PEM - Prediction Error Method
- AC - Alternating Current
- DC - Direct Current
- GTO - Gate Turn Off, thyristor type
- IGBT - Insulated Gate Bi-polar Transistor
- DMU - Diesel Multiple Unit