University of Southern Denmark

Field of Study: Energy Technology

Bachelor Thesis - 6^{th} Semester

Design of a Siemens eHighway System Implemented across Funen

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Preface

This paper is a bachelor thesis in Energy Technology Engineering produced at the University of Southern Denmark. It is intended for peers and others who find interest in the transition from fossil fuels to renewable energy in the transport sector. The study examines the implementation of Siemens eHighway across Funen, using overhead power lines to which heavy-duty vehicles with pantographs will be able to connect. The paper consists of several parts of data analysis of traffic and power aspects, as well as a mathematical model.

The authors would like to thank the following people for helping provide data and information; Jesper Knudsen, Uffe Ærboe Christiansen, Nina Christensen, Michael Lehmann, Benjamin Wickert and Lise Jonasen. Lastly, a special thanks to our supervisor Lars Yde as well as to Henrik Wenzel and Abid Rabbani for guidance during supervisor meetings.

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Abstract

The Danish Parliament is committed to change the Danish energy system into a completely renewable energy system by 2050. This implies that all non-renewable production will be phased out over the next decades. One of the sectors lacking behind in this transition is the transport sector, being a relatively heavy fossil fuel consuming sector.
Based on the current development in freight transportation, the thesis finds that the increase from 2016–2050 in heavy duty traffic is 60 %, meaning that the consumption from the transportation sector will not likely be reduced during these upcoming years.

Furthermore, the thesis looks into one of the possible solutions that can accelerate the transition to renewable energy in the transport sector: The chosen solution is the Siemens eHighway concept, and the highway across Funen is used as a case study. The eHighway is a system where heavy duty vehicles, hybrids with pantographs on top, connect to overhead cables in order to receive power from the electricity grid.
The eHighway system will likely be connected to the 10 kV power grid and include traction substations for down-transforming the voltage to 600 or 750 V. This thesis compares the performance of both voltage levels and concludes that 750 V causes lower requirements to the traction substations than 600 V.

The costs of the traction substations, whose purpose is to deliver power to the heavy duty vehicles, depend heavily upon how close the substations need to be placed to each other in order to provide sufficient voltage to the vehicles. This placement distance is analysed and it has been concluded that the costs vary from 83.4 million € to 152.0 million €, depending on a number of input conditions.
Finally, if the eHighway system was implemented today, and the entire heavy duty traffic was electrified over-night and immediately connected to the eHighway system, the power grid on Funen would be able to handle the extra amount of load. However, by 2050, the traffic is expected to have grown enough to make it necessary for an extra 60/10 kV transformer to be installed near the eHighway.

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Nomenclature

Acronyms

BEL	Bellinge
BHM	Broholm
DK1	Jutland and Funen
DK2	Zealand
DSO	Distribution System Operator
DST	Danish Statistics
DYR	Dyrup
EJB	Ejby
EU	European Union
FGD	Fraugde
GDP	Gross Domestic Product
GEL	Gelsted
GPS	Global Positioning System
GRP	Gaderup
HDV	Heavy Duty Vehicle
HJS	Odense
ISO	International Standards Organization
ITF	International Transport Forum
KRT	Kratholm
LAN	Langeskov
LHM	Nyborg
LIV	Lindved
MLA	Middelfart
MØH	Middelfart
NBG	Nyborg
NBY	Njørre Åby
ODL	Odense

$OECD$	Organisation for Economic Co-operation and Development
OTB	Thornbjerg
SKR	Middelfart
SoS	Security of Supply
TSA	Transport Stream Analyser
TSO	Transmission System Operator
ULL	Ullerslev
VDE	Vindeinge
VSB	Vissenbjerg
$ÅRP$	Årup

Symbols

Δ	Delta
γ	traffic Density
ρ	Resistivity
ρ_{copper}	Resistivity Copper
A_{Line}	Overhead Line Cross Area
C°	Degree Celsius
d	Distance
E_{HDV}	Energy Consumption per Length
I	Ampere
I_{In}	Input Current
l	Length
L_D	HDV Distance (pantograph-to-pantograph)
L_V	Connection Point
L_{Limit}	Maximum Sustained Distance in one Direction
N_{HDV}	Number of Heavy Duty Vehicle
P_T	Drawn Power per Vehicle
P_{HDV}	Power Consumption of Heavy Duty Vehicle
P_T	Drawn power per vehicle
R	Resistance
r	Annual Traffic Growth
R_D	Line Resistance between Heavy Duty Vehicles
R_T	Resistance of Heavy Duty Vehicle
R_V	Line Resistance between Heavy Duty Vehicle and Connection Point
R_{eq}	Equivalent Resistance for one Overhead Line Section

R_{Feeder}	Feeder Cable Pair Resistance
R_{Line}	Resistance in a Line
U	Voltage
U_{Front}	Voltage of the HDV in front
U_{In}	Input Voltage from Substations
U_{Limit}	Minimum Voltage Level
U_{Max1}	Input Voltage from Substations (ISO)
U_{Min1}	Minimum Voltage Level (ISO)
U_{Nom}	Nominal Voltage Delivery to Lines
v	Vehicle Speed
V_{HDV}	Input Voltage for the Heavy Duty Vehicle
v_{HDV}	Velocity of HDV

Units

€	Euro
Ω	Ohm
AC	Alternating Current
AMP	Ampere
DC	Direct Current
h	Hour
kA	kilo ampere
km	Kilometre
kV	Kilo volts
kWh	Kilowatt Hours
m	Metre
MVA	Mega Volt Ampere
MW	Megawatt
MWH	Megawatt Hour
PJ	Petajoule
t	Tonnes
TJ	Terajoule
tkm	Tonnes Kilometre
V	Volts
yr	Year

Chapter 1

Introduction

Denmark is on its way towards a future without any fossil fuels in the energy system. To achieve the goal of independence from fossil fuels, all energy consumption and production industries need to be reformed. This transition has been ongoing since the oil crisis in 1979. For example, a lot of wind turbines have been placed in Denmark during the last few decades. In fact, 56 % of the total Danish electricity consumption was covered by wind turbines in 2015 [5].

However, some industries have not yet begun this transition or are in the initial stages of phasing out fossil fuels. One of these industries is the transport sector. For many years the manufacturers have been trying to make their vehicles more efficient and change the type of fuel from fossil to renewable. However, a paradigm shift has not yet occurred.

1.1 Challenges in the Transportation Subsector

The Danish energy sector can be divided into four subsectors, each representing a different type of consumer/purpose:

- Households
- Industry and Production
- Commerce
- Transportation

In Figure 1.1, the four subsectors are presented with their respective 2015 energy consumptions as well as a flow chart that shows how much energy that is provided to the respective subsectors from a variety of energy sources.
The flow chart shows an interesting point: Not only does the transportation subsector consume the most energy in comparison to the other sectors, but almost the entirety of the energy consumption for transportation relies on oil products, while the other subsectors use renewable energy to a wider extent.
Therefore there is an urgent need for changes to be conducted in the transportation subsector in order to fulfil the energy goals, which are described further in 3.1.1.
As approx. 56 % of the electricity production is already based upon renewable energy, it seems to be a viable solution to use electricity for powering vehicles, and this is where the eHighway concept can prove useful.

1.2 The Transport Situation Today

This section will highlight the transport sector today and which challenges that might be faced in the transition to a completely renewable energy sector by 2050.

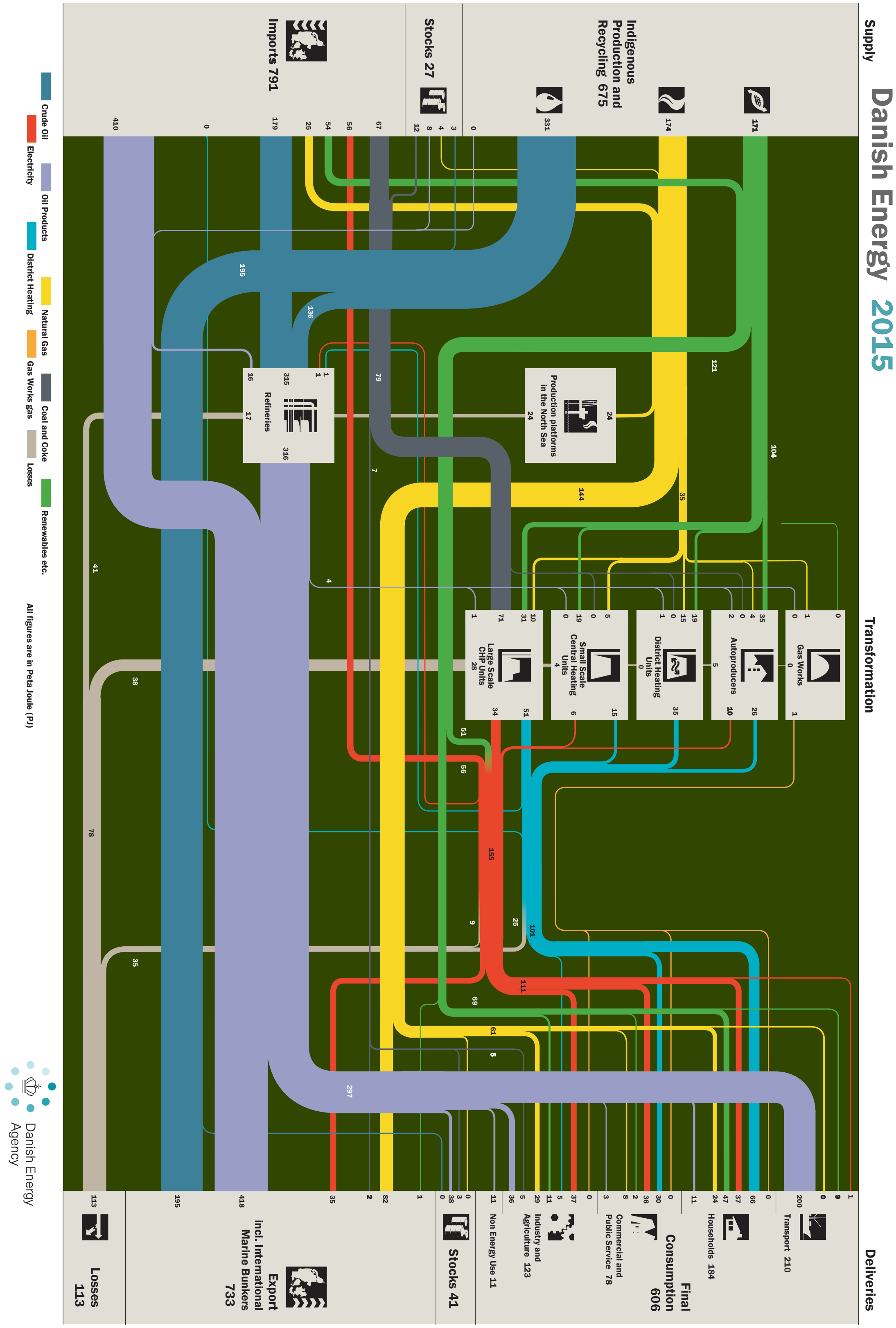

Figure 1.1: *Flow chart of the total Danish energy flow from supply to demand sub-sectors during 2015.*

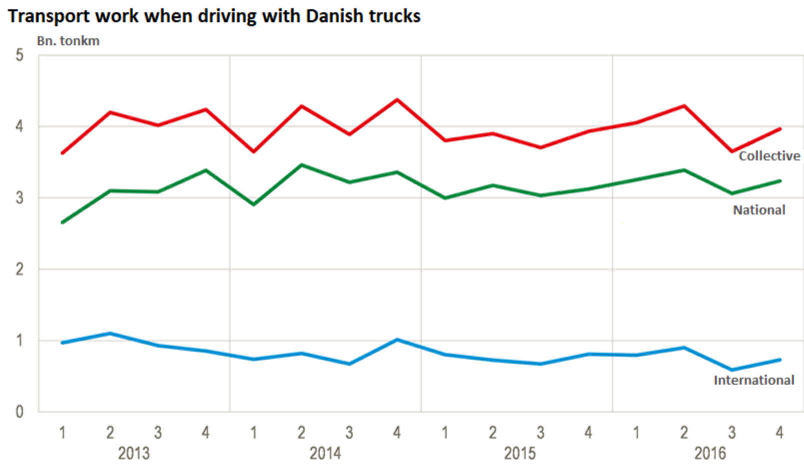

Figure 1.2: *Graph describing freight volumes for Danish HDV's above 6 t[15]*

Tendencies associated with increases in the transport sector will be explained as well. This is to get a better understanding of why there are increases and decreases year to year, although looking at the transport sector over decades, there is an increase in freight moved [11].

The correlation between surface freight and economic wealth is strong. *It is well established that surface freight (road and rail) volumes grows with the gross domestic product (GDP)* -(Garcia et al., 2008; Meersman and Van de Voorde, 2005; Bennethan et al., 1992). Because of the strong correlation, road freight volumes have been affected by economic crisis. This is elaborated in Section 4.3.1.

"Road and freight volumes have remained more or less the same In the European union since 2010..."

– ITF TRANSPORT OUTLOOK 2017 © OECD/ITF 2017

The national road freight accounts for a large portion of the collective Danish freight with Danish heavy duty vehicles (HDV). International freight with Danish HDV's accounted for 18.4 % of the collective Danish transport in 4th quarter of 2016, as seen in Equation (1.1) and in Figure 1.2.

$$\frac{729\,\text{tkm}}{3235\,\text{tkm} + 729\,\text{tkm}} = 0.1839 \tag{1.1}$$

The input variables for Equation (1.1) are from "Godstransport med danske lastbiler 4. kvt. 2016" [15].

A report from DST (Denmark's Statistics) suggests that there is an increase in Danish road freight with Danish HDV's. The increase was 5 % from 4th quarter 2015 to 4th quarter 2016. With a total freight volume of 3.24 billion tkm in the 4th quarter of 2016 [15].
A look at Denmark's energy usage for the transport sector will give an overview of how large a portion of the total Danish energy usage goes to moving freight on the roads.

The graph in Figure 1.3 shows that the energy consumption of HDV's weighing more than 6 tonnes has decreased by 3.4 % since 1990, but there was an increase from 2014–2015. The decrease can be explained both by economic crisis as well as more energy efficient heavy duty vehicles. The latter could be due to low oil prices and an increase in national demand.

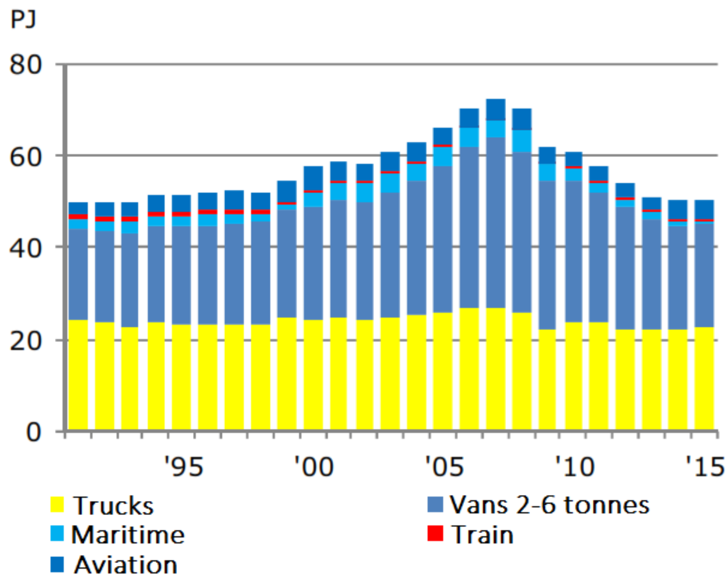

Figure 1.3: *The energy usage of freight transport distributed on different means of transportation. [3]*

HDV's account for 44.6 % [5] of the collective energy usage for freight transport equivalent to 22.4 PJ (1.2).

$$50.243\,\text{TJ} \cdot 44.6\ \% = 22.408\,\text{TJ} \approx 22.4\,\text{PJ} \tag{1.2}$$

The number, 50,243 TJ [5], is the collective energy used consumed by freight transport in 2015, out of which a share of 44.6 % is used for HDV's.
The actual energy usage in the transport sector for 2015 was close to 210.1 PJ [5] of which freight with HDV's heavier than 6 t account for 10.66 % (1.3).

$$\frac{22.4\,\text{PJ}}{210.1\,\text{PJ}} = 0.1066 \tag{1.3}$$

Figure 1.4, which is a cut-out from the flowchart *Danish Energy 2015* (Figure 1.1), depicts the distribution of the Danish energy production and consumption. It is worth noting that the transport sector is the largest consumer of oil.
The red line represents electricity, the green line represents renewables (biogas, biomass, etc.), the yellow line represents natural gas and the purple line represents oil.
By 2050 the purple bar should be gone and the others should increase enough to cover the future demand. This, however, requires continuous conversion from fossil fuels to e-fuels (electricity) produced from renewables and CO2 neutral fuels.
The total energy usage in the transport sector was 210.1 PJ in 2015, and out of that, 9 PJ came from renewable energy and 1.43 PJ from electricity. The energy from these two sources corresponds to 4.96 % of the total energy usage in the transport sector, see Equation (1.4). By 2050 the purple bar is expected to be completely gone. The three other bars will then cover the demand completely.

$$\frac{9\,\text{PJ} + 1.43\,\text{PJ}}{210.1\,\text{PJ}} = 0.0496 \tag{1.4}$$

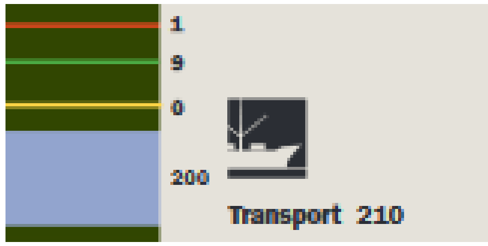

Figure 1.4: *Picture depicting part of the Danish energy flow in PJ (2016)[3].*

The number, 9 PJ, is a summation of bioethanol, biodiesel, bio-natural gas and pure natural gas while the number 1.43 PJ is the electricity usage in the transport sector. Both inputs are gathered from *Energistatistik 2015* [5].

1.3 Problem Identification

The overall purpose of this study is to show a way for the Danish HDV industry to go from fossil fuels to renewable energy. The desired outcome of the project is to:

Investigate the overall design of a Siemens eHighway System Implemented across Funen.

The motivation for this project is primarily a common interest in finding a possible solution that helps moving Denmark towards a completely renewable system by 2050, focussing on the transport sector. Furthermore, getting an opportunity to consider the eHighway concept and which challenges this solution might bring in regards to designing an electrical network and connecting it to the existing Danish power grid. The transport sector being the biggest sinner when it comes to greenhouse gases emissions has awoken the authors' interest as well. This project will prepare the writers to work with similar tasks in the future.

1.4 Problem Statement

This study will consider the implementation of Siemens eHighway across Funen using overhead power lines to which HDV's with pantographs will be able to connect.
Relevant data needs to be gathered, both regarding traffic across Funen and regarding suitable points where the cables can be connected to the cables on the existing Danish power grid. This data is expected to be obtained from the following partners and data distributors.

Partners:

- Siemens AG

Data Distributors:

- EnergiFyn
- TREFOR El-net
- The Danish Road Directorate

1.4.1 Goals

The goals of this study are listed in bullet points below.

1. Study the amount of traffic and electricity demand across Funen
    - Project the electricity demand at high-voltage transformers near the Funish highway
    - Explore future profiles for the heavy-duty traffic and the resulting electricity demand
    - Relate the future capcacity on the Funish electricity grid to the demand and the upcoming demand from the eHighway
2. Examine the infrastructure of the electricity grid on Funen and the implementation of the power supply for the eHighway concept
    - Determine the dimensioning of the eHighway system on Funen
    - Determine the grid connection of the eHighway system
    - Estimate costs of the traction substations and the complete eHighway system

1.4.2 Scope

This study will focus on the implementation of a Siemens eHighway system across Funen, specifically the technical part of the implementation. A solution using overhead power lines and pantographs fitted on the heavy duty vehicle has already been chosen, other possibilities will therefore not be included in this study.
The study will not specify how the system should be operated nor how the billing should work when it is in operation.

Chapter 2

Methods

The following chapter will give a review of the prerequisites for this project. Furthermore the chapter will give a walkthrough of the assumptions made for the project.

2.1 Prerequisites

In this section, all prerequisites such as assumptions and input variables are listed and explained.

2.1.1 Assumptions & Delimitations

The following list shows the assumptions made in the calculations conducted throughout this study.

- The length of the HDV's are from 12.5 m and above
- There will be overhead cables on the whole stretch across Funen.
- eHighway is available for the HDV's to use
- All the HDV's are hybrids and able to use eHighway.
- The expected consumption of the HDV's is 1.45 kWh/km.
- The traffic will increase constant towards 2050.
- All HDV's drive at 80 km/h
- It is most likely that the eHighway will be connected to 60/10 kV transformer stations.[1]
- There will not be looked at the transmission losses from the 60/10 kV transformers to the eHighway.
- The current load is purely active, so it can be compared and combined with the data from EnergiFyn.
- The eHighway is split into four stretches, being separated at the exit closest to the midpoint between two measuring points.
- The measured traffic passes from one end of a stretch to the other end. To visualise, see Figure 4.2 in Section 4.1.3.

[1]From an email correspondance with Klaus Winther, see Appendix G.3

Variable name	Value	Notes/equations
Minimum voltage (U_{Limit})	500 V	From Siemens, differs with scenarios
Vehicle speed (v)	80 km/h	Speed limit
Vehicle consumption per length (ETL)	1.45 Wh/m	From Siemens (28.5 T HDV)
Overhead line resistivity (ρ)	$172 \times 10^{-6}\,\Omega \cdot \mathrm{m}$	Table value
Overhead line cross-area (A_L)	$120 \times 10^{-6}\,\mathrm{m}^2$	From Siemens
Feeder cable pair resistance (R_{Feeder})	$5.5 \times 10^{-3}\,\Omega$	
Annual traffic growth (r)	1.4 %	From the Danish Road Directorate

Table 2.1: *List of expected input values for the distance calculations for the traction substations in the eHighway installation*

2.1.2 Input Variables

Table 2.1 highlights the different input variables used in the model made in Chapter 5 that is used to find the maximum allowable distance between traction substations on the four different eHighway stretches across Funen. The numbers are calculated or described further throughout the pre-mentioned chapter.

2.1.3 Other Prerequisites

The analysis prerequisites from Energinet.dk [10] was used in the projection of the total electricity consumption across the 23 60/10 kV transformers towards 2050.

All negative power measurements from the transformers have been changed to absolute values, this is because the negative number still accounts for load on the transformer, the negative power simply implies that power is transformed from 10 kV to 60 kV instead of 60 kV to 10 kV. This can be caused by excess power from small production facilities.

A catalogue from The Danish Road Directorate *Statistikkatalog, Indeks 2* [8] was used in order to project the expected growth in traffic for the coming years.

No security measures in form of physical damage or faults in the eHighway system are taken into account in this project. This is mainly done because the simulation would be far more complex than it is with the above prerequisites.

2.2 The Procedure

1. The initial phase of this project was to gather relevant data and information. This came from:
    - EnergiFyn - hourly load on transformers near the highway for 2016
    - TREFOR El-net - hourly load on transformers from Middelfart for 2016
    - The Danish Road Directorate - hourly heavy duty traffic on the highway across Funen
    - Siemens - workshop, test reports and key numbers for the project
    - International Transport Forum - *ITF Transport Outlook 2017* report
    - The Danish Energy Agency - *Climate politics and energy flows* report
2. The next step was to process the data and information. The data processing went as follows:

- Separation of the Funish highway into four stretches with associated transformer stations
- Creation of a frequency analysis to determine characteristic of the traffic on the road
- Creation of graphs for yearly, monthly, weekly and hourly traffic and loads
- Processing of data in Excel, making it more manageable for MATLAB
- Employment of MATLAB to create traffic and load profiles

3. The last step was to create a model in order to use the processed data for:
    - Determining the optimal distance between the traction substations
    - Considering the costs of the traction substations

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Chapter 3

General Aspects and Background Information

This section covers a brief and general description of the eHighway system as well as some renewable energy plan-based reasoning for installing it on the Danish highways.

3.1 Justification of the eHighway System

Before it makes sense to undergo a technical design description of the eHighway system and its installation (see Chapter 5), it is necessary to get an understanding of the challenges that the Danish energy sector faces.

3.1.1 Energy Goals

The Danish energy goals can be divided into three milestones, the goals towards 2020, 2030 and 2050 respectively. The goals towards 2020 have been defined in collaboration with all the members of the European Union (EU). Each country has committed themselves to achieve national energy goals [6].

Since not all members of the EU have the capability to fullfill equal goals, Denmark has agreed to overdo its own goals. The Danish energy goals for 2020 can be seen below [4]:

- 10 % of the energy used in the transport sector has to come from renewable energy.
- The green house gas emissions from buildings, agriculture and transport has to be reduced by 20 % compared to 2005.
- 30 % of the total energy consumption has to come from renewable energy by 2020.

The general goals towards 2030 have also been made through collaboration within the EU and are as follows [4]. All of the goals are compared to 1990:

- The EU's combined emissions have to be reduced by 40 %.
- Large greenhouse gas emitters, such as power plants and the oil/gas industry, have to reduce their emission by 43 %.
- The greenhouse gas emissions from buildings, agriculture and transport have to be reduced by 30 %.
- 27 % of the total energy consumption has to come from renewable energy.

- The energy efficiency has to be increased by 27 %.

However, note that specific national targets for Denmark have not yet been set.
The last energy milestone is set for 2050 and has been made by the Danish Parlament in 2015. The goal is simple, however challenging to achieve, as it requires 100 % renewable energy consumption by 2050 [4].

3.2 The Siemens eHighway Concept

The Siemens eHighway is, in its simplest sense, an electrical power line that is installed alongside the highway, see Figure 3.1. Vehicles can connect to the line, receive the electricity and convert it to mechanical energy in order to drive. This provides an important step towards reducing the usage of fossil fuels and emissions of greenhouse gasses in the transport sector, as most of the electricity production already comes from renewable energy sources at the present time, as explained in Section 1.1.

Figure 3.1: *The setup of the Siemens eHighway. Vehicles connect to the overhead lines by using pantographs and receives electrical power [18].*

3.2.1 Heavy-Traffic Roads

While being a rather low-cost solution when compared to other ways of relocating the energy consumption in the transport sector to renewable alternatives, the eHighway system still requires very considerable investments to be made. It has to deliver power to a large number of vehicles in order to be feasible and is therefore not suitable for less trafficked roads.

An analysis of the traffic flow in the German road infrastructure system was performed in 2012, and it was estimated that 60 % of the total emission by heavy-duty transportation vehicles in Germany happened on 2 % of the entire road network, namely the main highways [17].

	DK1	DK2
Geographical area	Jutland and Funen	Zealand
Synchronized with	European electricity grid	Nordic electricity grid
Transmission voltage level	400 kV, 150 kV	400 kV, 132 kV

Table 3.1: *The differences between DK1 and DK2*

3.3 Power Grid

In this section the structure of the Danish power grid will be explained. At first, a national overview will be given, after which a more detailed view of the power grid on Funen follows. The main focus in this section will be the 60/10 kV transformer stations on Funen.

3.3.1 Danish Power Grid

The Danish power grid is divided into two regions, Western Denmark (DK1) and Eastern Denmark (DK2). DK1 covers Funen and Jutland, and DK2 covers Zealand. The regions differ in frequency synchronization. DK1 is synchronized with Germany and thereby the rest of Europe. DK2 is synchronized with the Nordic electric grid. In addition to the synchronization difference, DK1 and DK2 also differ on the transmission system voltage levels. In Table 3.1 all the differences are shown.
The national grid is based on the transmission grid which is owned by Energinet.dk[1]. From the transmission grid, the power goes to the distribution grid, which is owned by private companies or municipalities.

3.3.2 Funen Power Grid

The distribution grid on Funen is based on the transmission grid at 400 kV, which goes from Middelfart to Fraugde (and to Fynsværket) and then through an underground cable to Zealand. From 400 kV the voltage is transformed to 150 kV. Stations which converts power from 400 kV to 150 kV can be seen in Figure 3.2. Then the voltage is transformed further from 150 kV to 60 kV. At 60 kV, the power is distributed to the many cities on Funen. In Figure 3.2, it is possible to see where the 150/60 kV transformers are located, as well as the 60 kV cables.

The distribution network on Funen is mainly owned by EnergiFyn, however a small part of the grid is owned by TREFOR El-net. This means that EnergiFyn owns all but three 60/10 kV transformer stations on Funen, Energinet.dk owns two 400 kV stations where one of them also functions as the connection to Zealand, TREFOR El-net owns three stations in Middelfart (MLA, MØH and SKR). All the transformer stations can be seen in Figure 3.2.
In order to know whether the eHighway concept can be implemented on Funen or not, it is important to know the capacity on Funen. Since the system will be connected to 60/10 kV transformers, this study will not take the complete capacity on Funen into account. A 10 kV cable will only deliver power in a distribution network, and therefore power cannot be transmitted via a 10 kV cable to the eHighway, as an example, from Svendborg.

The maximum capacity is therefore considered as the capacity of all 60/10 kV transformers located near the highway from Middelfart to Nyborg. In Figure 3.3 all transformers near the highway are shown.
In total there are 23 60/10 kV transformer stations placed close enough to highway, so they can be connected to the eHighway system. In Table 3.2, relevant data is shown for these stations [2]. The total capacity for the highway can be calculated from Table 3.2

[1] Thereby the government
[2] The table matches the map if the map is read from left to right

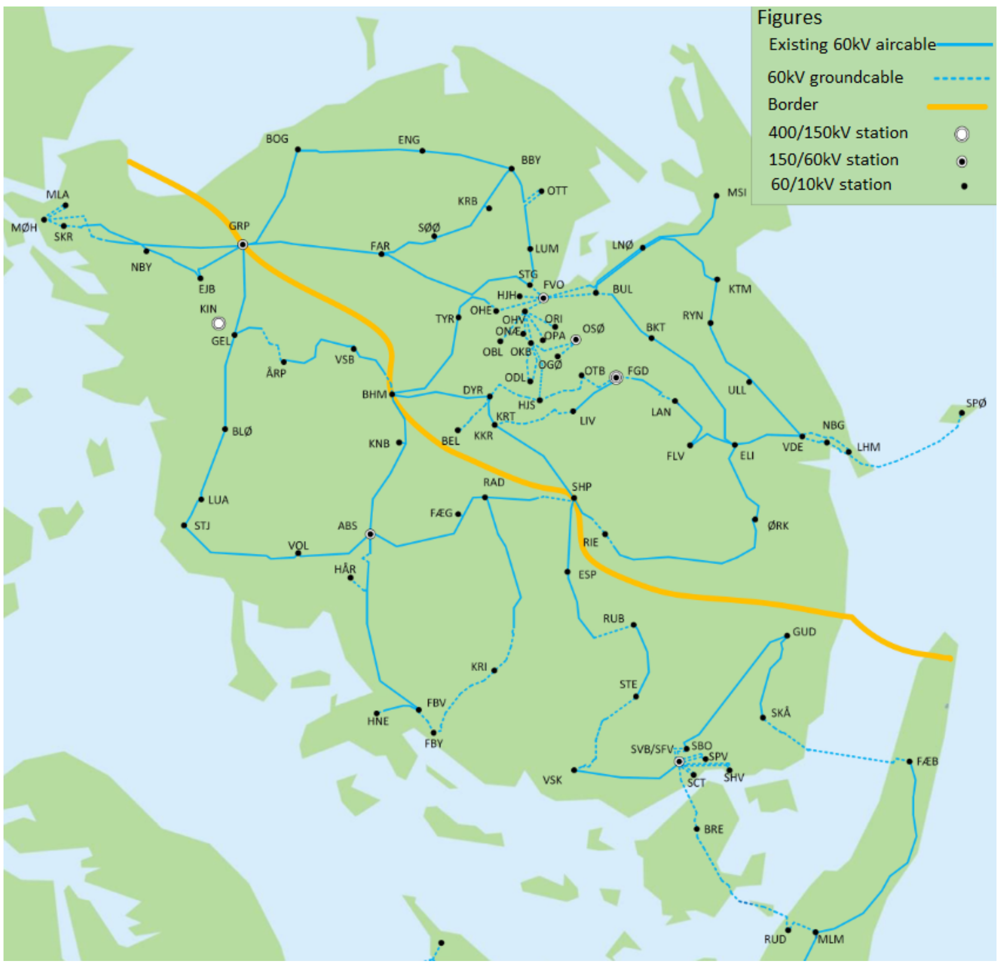

Figure 3.2: *60 kV power grid on Funen, including 400/150 kV and 150/60 kV transformer stations.*

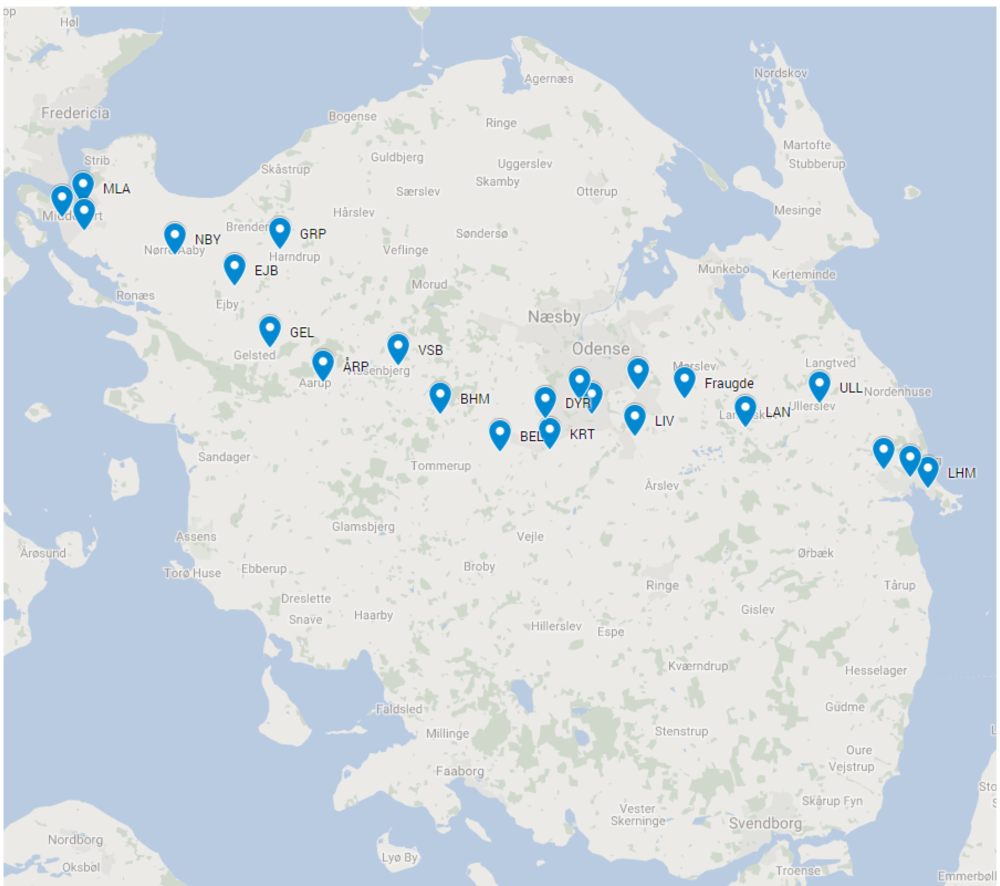

Figure 3.3: *60/10 kV transformer stations placed near the Funish highway*

Station name	Location	Max. effect transformed [MVA]
MØH	Middelfart	22
MLA	Middelfart	32
SKR	Middelfart	16
NBY	Nørre Aaby	10
EJB	Ejby	10
GRP	Gaderup	10
GEL	Gelsted	10
ÅRP	Årup	10
VSB	Vissenbjerg	10
BHM	Broholm	20
BEL	Bellinge	16
DYR	Dyrup	32
KRT	Kratholm	40
ODL	Odense	40
HJS	Odense	40
LIV	Lindved	10
OTB	Tornbjerg	40
FGD	Fraugde	30
LAN	Langeskov	32
ULL	Ullerslev	10
VDE	Vindeinge	28
NGB	Nyborg	32
LHM	Nyborg	32

Table 3.2: *Information about the different transformers along the highway*

$$Totalcapacity = 532\,\text{MVA} \tag{3.1}$$

Many of the transformer stations have the same capacity, which is due to standardization. Normal distribution transformers come in the size of 6, 8 ,10, 16, 20 or 25 MVA. Normally, 6 and 8 MVA transformers will not be used since 10 MVA transformers are cheaper to manufacture [3]. If the capacity of a transformer station does not match with the standard transformer dimensions, it is because two transformers are placed at that station. For example, at VDE (Vindinge) there is one 12 MVA and one 16 MVA transformer.

3.3.3 Loads Connected to 10 kV Grid

As mentioned in section 2.1.1 the eHighway concept will be connected to the already existing 10 kV grid. This means that there is already an electricity load on that part of the grid. Wind turbines on land and energy consuming factories are normally directly connected to the 10 kV grid. Furthermore, all households are connected through a transformer which reduces the voltage to 400 V. This means that the full capacity of the grid is not available to the eHighway system.
Therefore, load data for each of the transformers have been collected hour by hour for 2016 by EnergiFyn and TREFOR El-net. These data are listed in Table 3.2 and will be described in section 4.1.

[3] Due to mass production

Year	DK1 Consumption [GWh]	Annual growth [%]
2016	18,860	1
2017	19,564	3.73%
2018	20,425	4.40%
2019	21,282	4.20%
2020	21,940	3.09%
2021	22,518	2.63%
2022	23,211	3.08%
2023	24,008	3.43%
2024	24,195	0.78%
2025	24,401	0.85%
2026	24,757	1.46%
2027	24,757	0.99%
2028	25,155	0.61%
2029	25,307	0.60%
2030	25,749	1.75%
2031	25,920	0.66%
2032	26,110	0.73%
2033	26,221	0.43%
2034	26,337	0.44%
2035	26,458	0.46%
2036	26,619	0.61%
2037	26,844	0.85%
2038	27,034	0.71%
2039	27,197	0.60%
2040	27,536	1.25%

Table 3.3: *The annual growth in electricity consumption for DK1 [10]*

3.3.4 Projection of Electricity Consumption towards 2050

This study works with two scenarios, one where all heavy duty traffic is electrified in 2016, and one where all heavy duty traffic is electrified in 2050. In order to create the scenario for 2050, the general electricity consumption (load at the transformers without eHighway) is needed for 2050. To find the data for the consumption, the report, *Energinet.dk's analyseforudsætninger 2016*, from Energinet.dk[10] is used. The report estimates the yearly electricity demand at the consumer, including net losses, for DK1. The report from Energinet.dk only projects the electricity consumption to 2040. In order to get the electricity consumption for 2050, three projections based on the report have been made, see Section 3.3.5.
In Table 3.3 the expected consumptions from 2016 to 2040 can be seen, and in Figure 3.4 the expected yearly growth can be seen. From the graph in the figure, it is clear that the electricity consumption will increase until 2020. From 2020 and onwards, the yearly growth in electricity consumption slows down. Furthermore, in 2030 and around 2035, the electricity consumption increases more than usually. This is due to the energy goals that were explained in Section 3.1.1

3.3.5 Projection from 2040–2050

In order to make a projection of the electricity consumption from 2040 to 2050, the report *Energinet.dk's analyseforudsætninger 2016* from Energinet.dk is used [10]. Three projections have been made and they are called *Projection Low*, *Projection Medium* and *Projection High*, respectively.
The first projection, *Projection Low*, is based on the average growth from 2024 to 2040, which is 0.81 %. This projection is made since Figure 3.4 shows that the growth decreases after 2023 and then stabilizes until 2040. The projection will therefore assume that the growth will keep

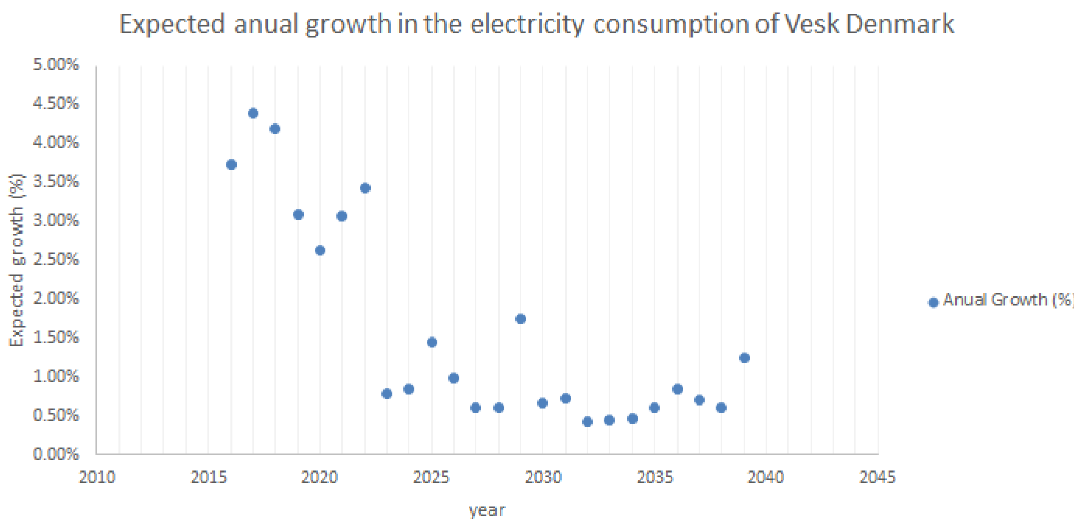

Figure 3.4: *Energinet.dk's projection of the future growth in electricity consumption for DK1*

stable until 2050.
The second projection, *Projection Medium*, is based on the average growth from 2016 to 2040, which is 1.6 % per year. This projection assumes that the yearly growth will be the same from 2040 to 2050 as it is from 2016 to 2040.
The last projection, *Projection High*, is based on the average growth from 2016 to 2023, which is 3.51 %. This projection is made under the assumption that the rise from 2016 to 2023 is due to the energy goals set for 2020. Therefore, it is likely that the electricity consumption will rise again before 2050 in order to reach the goal of 100 % renewable energy.
The three projections can be seen in Figure 3.5 combined with the projection from Energinet.dk for 2016–2040. The projection called *Projection High* has been chosen.

The two projections, *Projection Low* and *Projection Medium*, are used for comparison in the sensitivity analysis, see Section 6

3.4 Security of Supply

The security of supply (SoS) in Denmark is known to be very high. When a consumer plugs a cable into a socket they expect electricity. This high SoS comes at great expenses, however. Consumers have a high willingness to pay for these expenses, since almost no ordinary consumer has a back-up power supply.
Many initiatives are made by the Danish transmission system operator (TSO) in order to secure a high SoS. Likewise, distribution system operators (DSO), such as TREFOR El-net and EnergiFyn, are also working towards a high SoS. All 60/10 kV transformers on Funen follow the so called *n-1 rule*. This rule states that at any given moment transformers should be able to supply enough power if one of the neighbouring transformers in that area fails.

In Table 4.2, the transformers are allocated to different areas near the highway. The capacity of each transformer is also listed. From that table, the transformer with the highest capacity is extracted and listed in Table 3.4.
According to the *n-1 rule*, the system should still be able to cope with peak demand when all of the transformers from Table 3.4 are out of order.

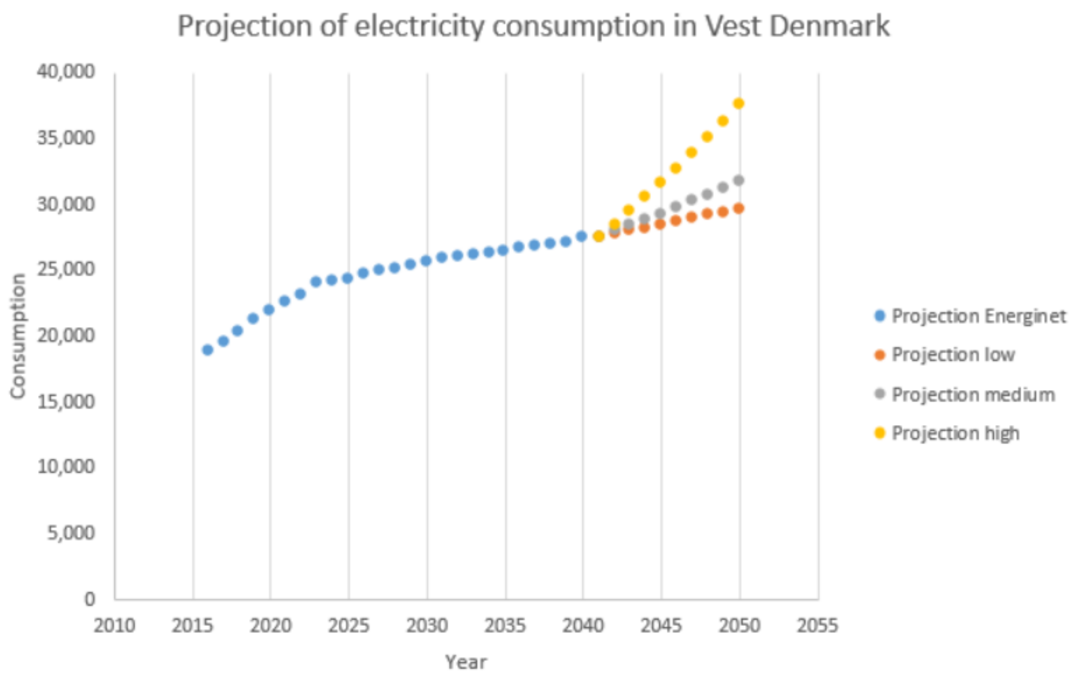

Figure 3.5: *Three possible projections for 2040–2050 combined with Energinet.dk's projection from 2016–2040*

Area	Station	Capacity [MVA]
TSA58b	MLA	32
TSA55	BHM	20
TSA51	HJS	40
TSA45	LHM	32

Table 3.4: *The transformer station with the highest capacity for each area*

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Chapter 4

Scenarios and Analyses

This chapter looks into the gathered data for the project and explain traffic and power profiles for 2016 and towards 2050

4.1 Data

The main part of this study relies on a lot of data. Fortunately, The Danish Road Directorate, EnergiFyn, TREFOR El-net and Siemens AG have been willing to provide the needed data. The data providers are listed below:

The Danish Road Directorate: Uffe Ærboe Christiansen has delivered traffic data for HDV's above 12.5 m in length on a hourly basis for the entire year, 2016[1]. The data has been measured at four different points on the highway across Funen. Each point is on the middle of a stretch. The different measurement points can be seen in Figure 4.2. The data are provided in Appendix F.2.

EnergiFyn: Jesper Kudsen has delivered data from 20 transformer stations near the highway across Funen. These data represent the load for each station measured hourly for 2016. EnergiFyn had not finished their analysis of the data, therefore it was only possible to get the active loads and not the reactive or apparent loads of the transformer stations. The data are provided in Appendix F.1.

TREFOR El-net: Nina Christensen has delivered data from three transformer stations in Middelfart. These data includes current load for each transformer station measured hourly for 2016. In order to convert the current load to power load, it has been assumed that the voltage is constant at 10 kV[2]. A detailed list of the specific stations that are used in this study can be seen in Table 3.2 in Section 3.3. A map of the locations of the stations are can be seen in Figure 4.3 in the same section. The data are provided in Appendix F.1.

Siemens AG: Siemens AG provided key numbers for the project as well as material such as a report from a research project, ENUBA 1 [2] (short for *Electromobility in heavy commercial vehicles to reduce the environmental impact on densely populated areas*) and two Powerpoint presentations from a workshop with Siemens AG.
The representatives from Siemens AG were:

- **Michael Lehmann** - Senior Engineer, Mobility Division
- **Benjamin Wickert** - Head of Business Development, Mobility Division

[1] There are some missing data, this is described in Section 4.1.2.
[2] It will fluctuate a bit due changing loads

	ÅRP [MW]	NBY [MW]	EJB [MW]	GEL [MW]
01-01-2016 00:00	2,3	1,9	1,4	1,0
01-01-2016 01:00	2,3	1,7	1,3	0,9
01-01-2016 02:00	2,1	1,8	1,3	1,0
01-01-2016 03:00	2,0	2,2	1,3	1,0
01-01-2016 04:00	1,9	1,8	1,3	0,9
01-01-2016 05:00	2,0	1,8	1,3	0,9
01-01-2016 06:00	2,0	1,8	1,3	0,7
01-01-2016 07:00	2,0	2,2	1,3	0,7
01-01-2016 08:00	2,1	2,4	1,5	0,9
01-01-2016 09:00	2,2	2,8	1,6	1,2
01-01-2016 10:00	2,3	3,2	1,7	1,4

(a) *Data excerpt of the EnergiFyn data*

	Max	
	MLA-TR1-AMP	MLA-TR2-AMP
01-01-2016 00:00	214.85	0.00
01-01-2016 01:00	197.98	0.00
01-01-2016 02:00	197.63	0.00
01-01-2016 03:00	203.25	0.00
01-01-2016 04:00	192.35	0.00
01-01-2016 05:00	177.90	0.00
01-01-2016 06:00	192.00	0.00
01-01-2016 07:00	203.25	0.00
01-01-2016 08:00	223.29	0.00
01-01-2016 09:00	227.86	0.00
01-01-2016 10:00	252.47	0.00

(b) *Data excerpt of the TREFOR El-net data*

Figure 4.1: *Representation of the numerical data provided by Energi Fyn and TREFOR El-net*

- **Lise Jonasen** - Business Developer Professional, Mobility Division

The key numbers are:

- The energy consumption per length for a HDV, 1.45 kWh/km
- The maximum amount of time the eHighway system can be overloaded by 200-300%, 3 hours
- The length between traction substations, 1 – 3 km
- The size of the traction substations, 1–3 MW

4.1.1 Used Data

This subsection explains data errors and which parts of the different data that were used.

EnergiFyn and TREFOR El-net

Figure 4.1 is an excerpt from the data sheets from EnergiFyn & TREFOR El-net. At the top, the different transformer stations are listed, and to the left, the first hour continuing to the last at hour number 8760. This data is later used to create a load profile for the highway across Funen. It was not possible to get the reactive power data on the mentioned stations, hence the denotation of MW and AMP and not MVA.

Measurement Errors

There are some outliers in the collected data. An example is the transformer station, Lindholm (LHM), which measured 62 MW in an hour, the $28^t h$ of May 2016. This is simply an error. The adjacent hours measured 0.1 MW and -0.1 MW. The outliers are clearly visible in Figure 4.11 in Section 4.4.

4.1.2 The Danish Road Directorate

The data from The Danish Road Directorate have been measured at four different measurement station on the highway across Funen. The data provided is from 2016 and contains hourly data of heavy duty vehicles above 12.5 m in length. There are missing entries in some of the data sets. This is due to errors at the measurement stations, called transport stream analysers (TSA). The largest holes with missing data are present in the data sets from the measurement stations, TSA45 and TSA58b. TSA55 is missing data from $1^s t$ of January to $8^t h$ of February and TSA58b is missing data from $1^s t$ to $18^t h$ of January. The missing data had a large impact on January in Figure 4.8, showing the average monthly heavy duty traffic for 2016.

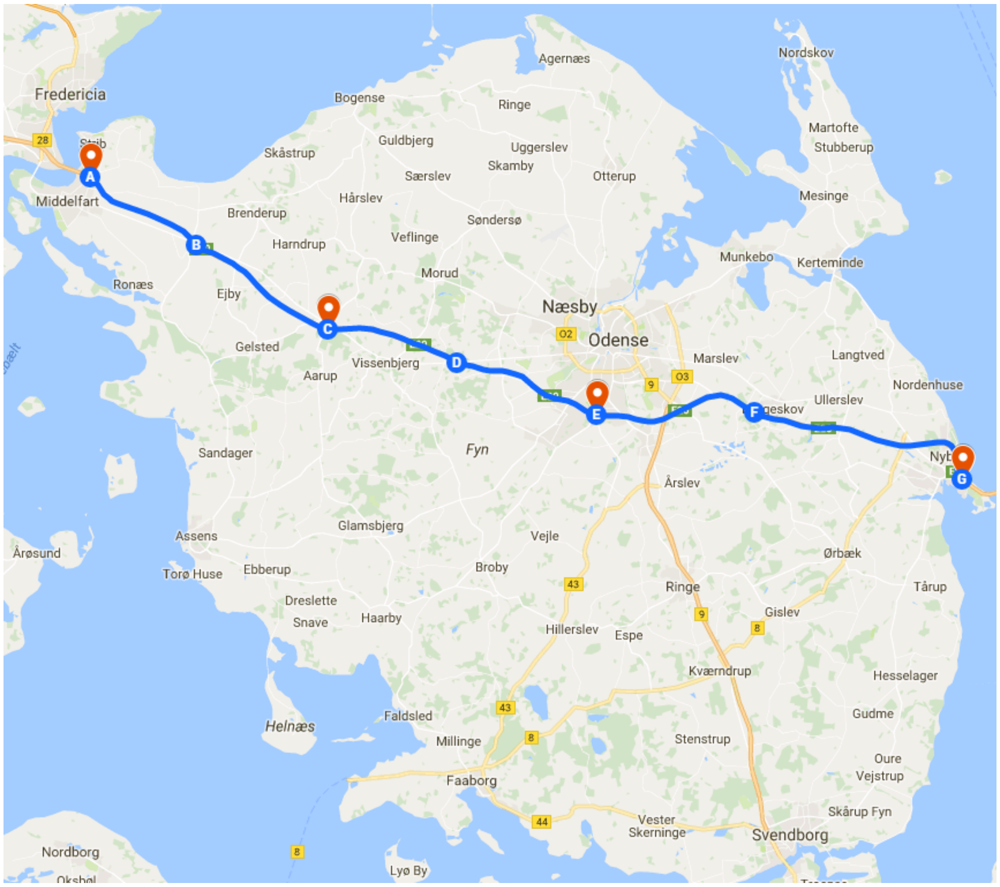


Figure 4.2: *Distance travelled by the HDV's. The four red markers represent the places where the traffic is measured.*

4.1.3 Stretches on the Funish Highway

Traffic Characteristics

The Data provided for the transport profile has been given for four positions across the Funen highway. The four positions are placed with approximately same distance between each other. Each of the four measurement points are placed near a highway exit, respectively exit 58b (Middelfart), 55 (Aarup), 51 (Odense S) and 45 (Nyborg Ø). The data includes all HDV's above 12.5 m. In Figure 4.2 a map of Funen is shown. On the map, the four collection points are included.
With the assumptions from Section 2.1.1, it is possible to calculate the stretch lengths, which are shown In Table 4.1. The traffic measured at exit 58b (Middelfart) travels from point A to point B or from point B to point A. The traffic measured at exit 55 (Aarup) will travel from point B to point D or from point D to point B. The traffic measured at exit 51 (Odense S) travels from either point D to F or from F to D. Finally, the traffic measured at exit 45 (Nyborg Ø) travels from point F to point G or from point G to point F. For visualisation, see Figure 4.2.

Power Characteristics

The 60/10 kV transformer capacities along the Funish highway have already been explained in Section 3.3. This subsection will go more in depth with the capacity at each stretch of the highway. This is done since a transformer station in Middelfart will not deliver power to a HDV driving at Odense or Nyborg, because the power losses would be too immense. In this study a

Measuring point	Stretch length [km]
TSA58b (Middelfart)	9.79 (A to B)
TSA55 (Aarup)	22.1 (B to D)
TSA51 (Odense S)	24.2 (D to F)
TSA45 (Nyborg Ø)	18.0 (F to G)
Total distance	74.09

Table 4.1: *Distance for each measuring point*

Stretch	Station	Capacity [MVA]
TSA58b	MØH	22
	MLA	32
	SKR	16
	NBY	10
TSA55	EJB	10
	GRP	10
	GEL	10
	ÅRP	10
	VSB	10
	BHM	20
TSA51	BEL	16
	DYR	32
	KRT	40
	ODL	40
	HJS	40
	LIV	10
	OTB	40
	FGD	30
TSA45	LAN	32
	ULL	10
	VDE	28
	NBG	32
	LHM	32

Table 4.2: *Dividing the transformers to each stretch*

transformer station will therefore only deliver power to the nearest stretch.
By allocating the transformer stations from Table 3.2 to the different stretches, it is possible to make a table which shows the transformer stations at each stretch as well as their capacities.
In Section 3.4 the SoS has been described, including the *n-1 rule*. When applying the rule, the transformer with the highest capacity for each stretch will be considered out of order. These transformers are listed in Table 3.4. When removing those transformer stations, the available capacity of the area is found. This is done in Table 4.3.

4.2 Scenarios

In this section, the two scenarios of the following sections will be explained:

The first scenario: In this scenario, the entire heavy duty traffic that is on the roads today choose to shift from conventional HDV's to hybrid HDV's tomorrow because of the eHighway. With the extra consumers connected in the form of HDV's, it has to be considered whether or

Stretch	Station	Capacity [MVA]
TSA58b		
	MØH	22
	SKR	16
	NBY	10
	Total	**48**
TSA55		
	EJB	10
	GRP	10
	GEL	10
	ÅRP	10
	VSB	10
	Total	**50**
TSA51		
	BEL	16
	DYR	32
	KRT	40
	ODL	40
	LIV	10
	OTB	40
	FGD	30
	Total	**210**
TSA45		
	LAN	32
	ULL	10
	VDE	28
	NBG	32
	Total	**102**

Table 4.3: *Transformer capacity for each stretch*

not there will be enough capacity, as of 2016, to have the eHighway up and running and in use right away.

The second scenario: A projection towards 2050 where all fossil fuels are phased out of the Danish energy system and a constant increase of traffic will happen from 2016 at a rate of 1.4 % per year.

With a tendency showing a continuous increase in freight moved by HDV's over the last years, see Figure 4.3, the traffic profiles for 2050, in addition to the power profiles for 2050, will help determine whether or not additional capacity is needed in order to supply the eHighway system with sufficient power.

4.3 Traffic Profile

This section gives an overview of the amount and distribution of heavy duty traffic on the highway across Funen. Data for each of the four measuring points was collected for 2016 to realise the traffic profiles in this section.
The overview consists of yearly, monthly, weekly and hourly distribution of said traffic.

4.3.1 Traffic Estimation Towards 2050

This section explains the tendency in the amount of HDV's in Denmark and estimates what the traffic numbers might look like towards 2050. Data used from The Danish Road Directorate only dates back to 2008 in this section.
The data for the graph in Figure 4.3 is collected from all over Denmark at The Danish Road Directorate's monitoring stations. The monitored vehicles are HDV's above 12.5 m in length and only data for workdays is taken into consideration. The index starts at 100 % in year 2008. The dip at the beginning of the graph can be correlated to the financial crisis at the time. The crisis had an impact in such a way that there were less products being bought and therefore the freight decreased. From the International Transport Forum (ITF) report *Transport Outlook 2017*[11], it is noted that there is a strong correlation between the GDP of a country and amount the of freight moved by road in that country, as mentioned in Section 1.2.
Over the last 6–7 years, since 2010, a general increase in traffic can be seen each year. It increases at an average rate of 1.4 % per year, see Equation (4.1). This number is used to create the traffic profile for 2050, with the assumption that freight transport will continue to increase and without any occurrence of a financial crisis.

$$\frac{98.1\ \% - 89.7\ \%}{6\,\text{yr}} = 1.4\ \frac{\%}{\text{yr}} \tag{4.1}$$

The number 98.1 is the index number for the year 2016 and 89.7 is for 2010 [8].
The transport analysis is made in order to later determine the capacity needs of the Funen eHighway system.

4.3.2 2016 Traffic Versus 2050 Traffic

This section is divided into four smaller subsections, three of them depicting different traffic profiles for 2016 and 2050, and the last providing a frequency diagram of the traffic in 2016.

Hourly Traffic Profiles

The profiles are used to get an overview of the amount heavy duty traffic that used the highway across Funen in 2016.

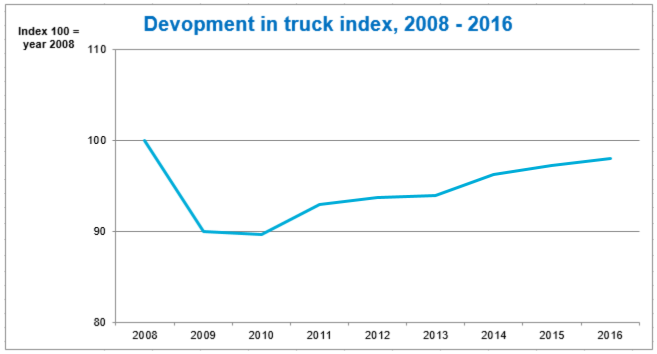
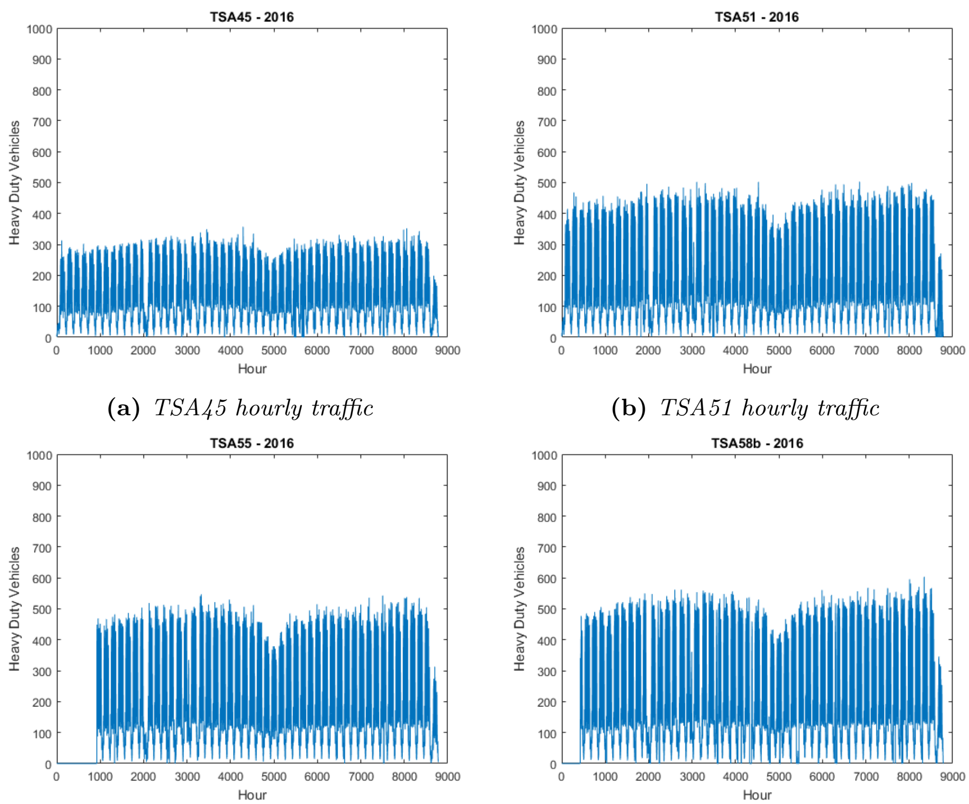


Figure 4.3: *Development in heavy duty traffic index since 2008 [8]*



(a) *TSA45 hourly traffic*

(b) *TSA51 hourly traffic*

(c) *TSA55 hourly traffic*

(d) *TSA58b hourly traffic*

Figure 4.4: *Hourly traffic on each of the four stretches for 2016 - TSA45, TSA51, TSA55 and TSA58b.*

The traffic profiles show how much heavy duty traffic that is on the roads at any given hour throughout 2016.
It can be seen that there are not many variations in the graphs. There are a few dips in the traffic, but overall the tendency is roughly the same for each stretch throughout the year.

To further explain what goes on in the graphs, the first drop near April (hour 2000) is caused by the Easter holidays. The second drop in July (hour 5000) is caused by the industrial holidays in Denmark, spanning weeks 28, 29 and 30. The third drop (hour 8500) is caused by the Christmas holidays.
The measurement station, TSA55, has not collected data for January and is therefore not a part of the graph. The same goes for TSA58b which is missing a part of January.

Figure 4.5 shows the expected traffic in 2050. The factor, 1.4%, is multiplied to the data from 2016 for each year towards 2050 in order to project the numbers to 2050. This is shown in Equation (4.4). The variable, *Factor*, denotes the total percentage increase from 2016 to 2050.

$$Traffic_{2050} = Traffic_{2016} \cdot 0.014^{2050-2016} \tag{4.2}$$

$$Factor = \frac{Traffic_{2050}}{Traffic_{2016}} - 1 \tag{4.3}$$

$$Factor = 60\% \tag{4.4}$$

The results of the equation are seen in Figure 4.5 which depicts the expected amount of hourly traffic in 2050 on the four stretches.
The plot in Figure 4.6 shows the collective average amount of traffic per hour per day in 2016. The years 2030 and 2050 have been projected in the same figure. The projection to 2030 is used in Chapter 5 to analyse the traction substations in the eHighway system. It is elaborated in the same section why a dimensioning of the system is carried out towards 2030 instead of 2050.

Weekly Traffic Profile

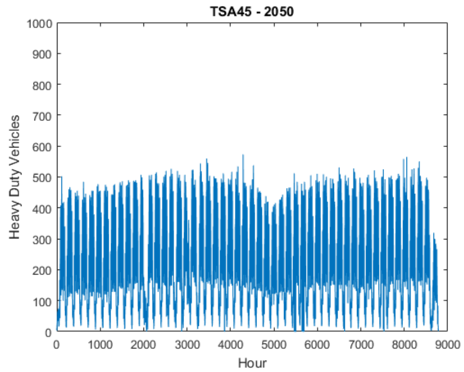
The bar plot in Figure 4.7a is made to get a closer look at what an average week looked like in 2016. The bar plot is a summation of all the data from the four stretches. All Mondays were summed and divided by the total number of Mondays in 2016. The same method was used for the rest of the weekdays.
The weekly tendency shows some busy first four days and a less busy Friday. Tuesday is the day with the most traffic in general. The traffic in the weekends is significantly lower than in workdays.
The factor from Equation (4.4) was used to make the bar plot for 2050. The MATLAB code used for making the plot can be found in Appendix E.1.

Monthly Traffic Profile

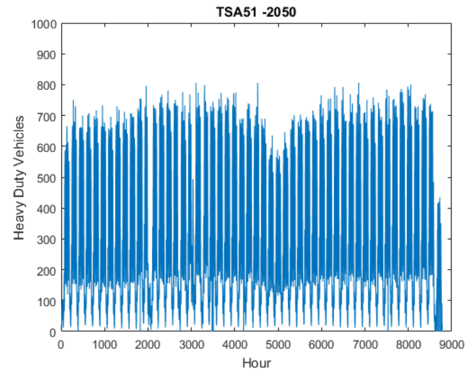
The bar plot in Figure 4.8 shows the average monthly traffic on the Funish highway. This bar plot is a summation of monthly data from each of the four stretches. The dips are caused by the same events as for the weekly profiles. The rest of the months do not show any major tendency changes. The factor from Equation (4.4) was used to make the bar plot for 2050. The MATLAB code for the plot can be seen in Appendix E.1.

Frequency Functions

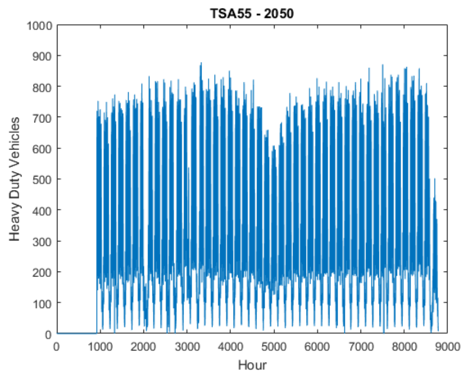
The frequency functions produce graphs to help map how much time there are more than x amount of HDV's on the road. An example on how to read Figure 4.9a is used:



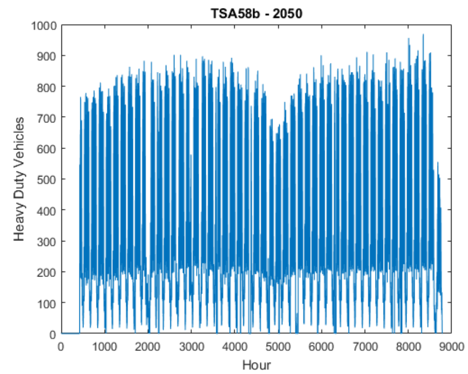
(a) *TSA45 hourly traffic*



(b) *TSA51 hourly traffic*



(c) *TSA55 hourly traffic*



(d) *TSA58b hourly traffic*

Figure 4.5: *Hourly traffic on each of the four stretches for 2050 - TSA45, TSA51, TSA55 and TSA58b.*

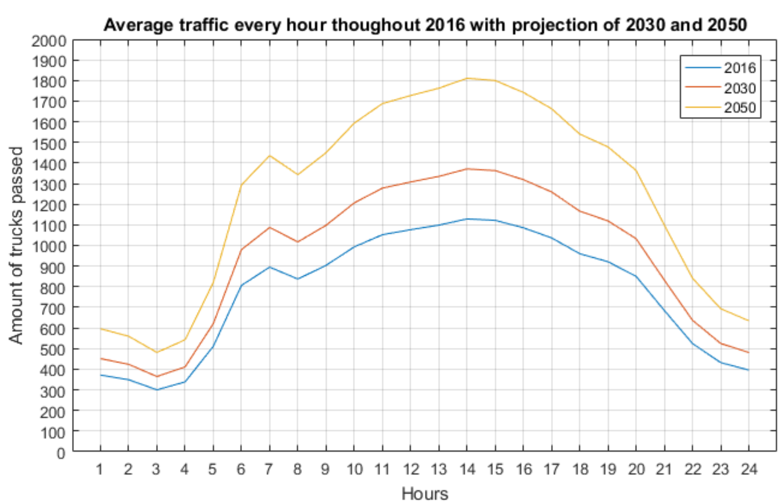
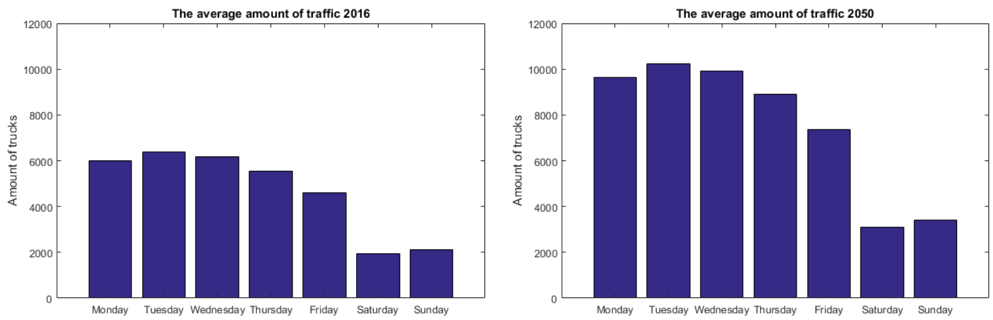
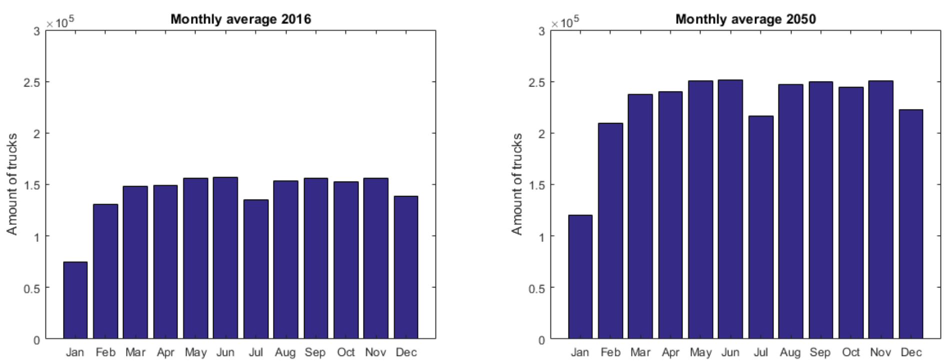


Figure 4.6: *Traffic for 2016 and projections to 2030 and 2050*



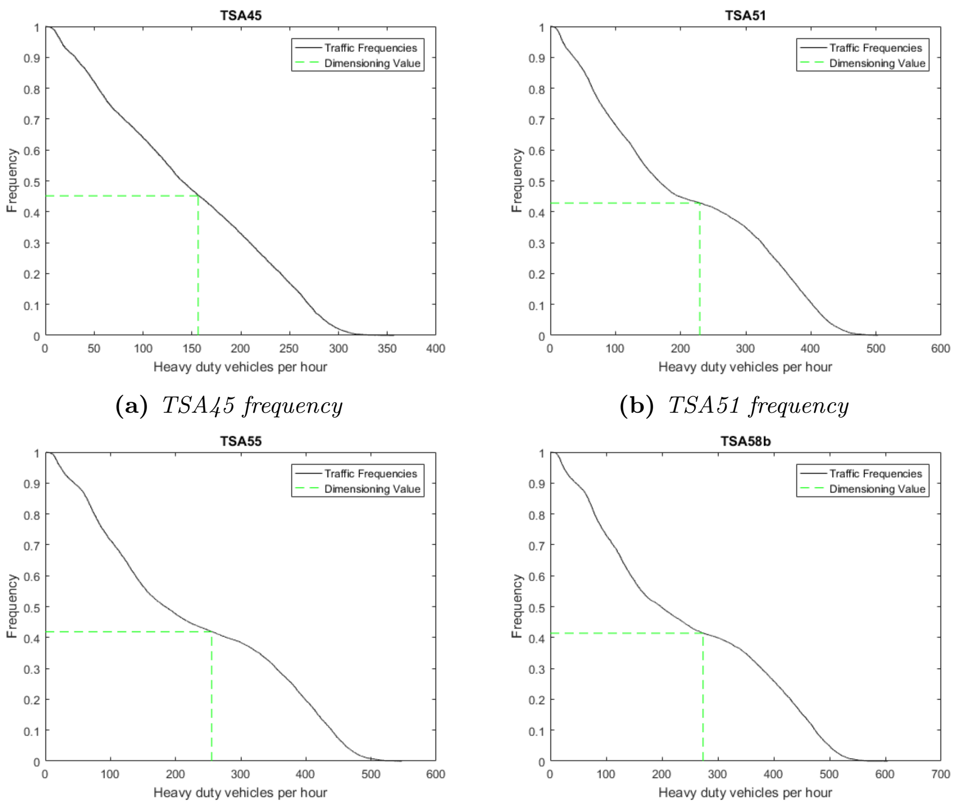
(a) *Traffic 2016* **(b)** *Traffic 2050*

Figure 4.7: *Average weekly traffic on the highway across Funen for 2016 and 2050*



(a) *Traffic 2016* **(b)** *Traffic 2050*

Figure 4.8: *Average monthly HDV traffic for 2016 and 2050*



(a) *TSA45 frequency*

(b) *TSA51 frequency*

(c) *TSA55 frequency*

(d) *TSA58b frequency*

Figure 4.9: *Traffic frequencies on the four stretches at a maximum overload of 200 %*

Name	Length [km]	Capacity Needed at 200%[MW]	Capacity Needed at 300%[MW]	Peak Load [MW]
TSA45	18	4.08	2.72	8.17
TSA51	24.2	8.05	5.37	16.11
TSA55	22.1	8.19	5.46	16.37
TSA58b	9.79	3.88	2.59	7.76

Table 4.4: *Total traction substation power capacity needed on each of the four stretches*

The black curve denotes how large a percentage of the total time, given by the y-axis, that the measured amount of traffic is above the value on the x-axis.
The frequency functions make it easier to analyse the system. It is considered that the system is able to handle an overload of 200–300 % for three consecutive hours [3]. Since this is the case, the system does not need to be dimensioned after the peak load.
Table 4.4 lists the substation capacity needed on each of the four stretches. This capacity is found using the consumption of the HDV's, 1.45 kWh/km, the length of the stretch, Table 4.1, and the *dimensioning value* of HDV's on the given stretch. The reason for it being calculated without the velocity of the HDV's is because of the assumption made in 2.1.1, that the vehicles drives the full length of the stretch. Equation (4.5) is used as an example for TSA45.

$$Capacity_{TSA45} = DimensioningValue_{TSA45} \cdot Length_{TSA45} \cdot \ E_{HDV} \tag{4.5}$$

$$Capacity_{TSA45} = 104.33 \text{ HDV/h} \cdot 18.00 \text{ km} \cdot 1.45 \text{ (kWh/km)/HDV} = 2.72 \text{ MW} \tag{4.6}$$

The frequency diagrams for 2050 look similar, since the factor from Equation 4.4 is multiplied to the data. Therefore the only change is the numbers on the x-axis.

4.4 Power Profiles

In this section, the power profile for the transformers close to the Funen highway will be found. Two profiles are made and combined in order to get the correct power profile. The first profile, called *Consumption without eHighway*, is made based on the existing load at transformers located near the highway. To clarify, the profile made for the consumption (or production) does not includes all loads and productions except forthe eHighway system. The second profile, called *Consumption eHighway*, is, as the name says, the consumption which comes from eHighway. This profile has been made from the traffic profile where the electricity consumption for each HDV has been added (1.45 kWh/km) as well as the distance the HDV drives in each stretch. The distance travelled in each stretch can be seen in Table 4.1.

Both profiles will be projected towards 2050 so the expected development can be seen including upcoming bottlenecks in the system. The two profiles will at first be handled separately, and at the end of this section they will be combined and compared. From this comparison a conclusion will be made: Is the capacity of the 60/10 kV transformers large enough to sustain the additional load from the eHighway?

4.4.1 Construction of Power Profiles

The first profile, *consumption without eHighway*, is made from individual transformer load profiles provided by EnergiFyn and TREFOR El-net. The transformer stations have been grouped into the stretch, TSA45, TSA51, TSA55 and TSA58b. For each area the transformer

[3]Michael Lehmann

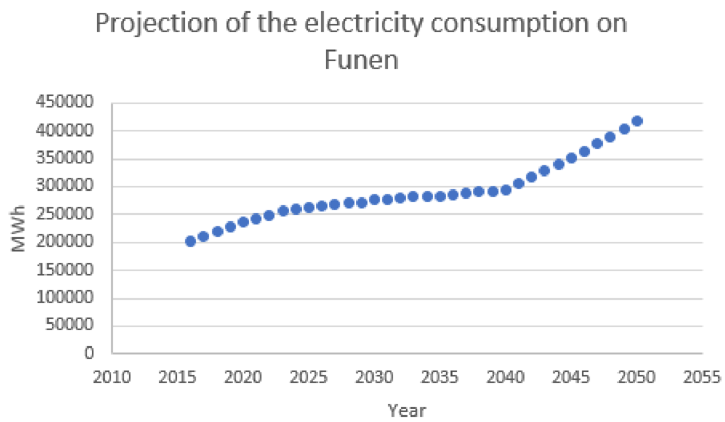


Figure 4.10: *Projection of the non-eHighway electricity consumption near the Funish highway towards 2050*

loads are combined into a total load.

The second profile, *consumption eHighway*, has been made based on the traffic profile described in Section 4.3. The traffic profile is multiplied with the electricity consumption for the HDV's, 1.45 kWh/km. This gives the eHighway consumption per km for each stretch. Finally, the distances from 4.1 are multiplied to the consumption per km, which gives the total electricity consumption for each stretch of the eHighway.
Both profiles have been made in MATLAB, the scripts are shown in Appendix E.2

4.4.2 Power Towards 2050

In Section 3.3.5 a projection of the future electricity consumption for DK1 from 2016 to 2050 was made. It is assumed that Funen and especially the transformers located near the eHighway will follow the same tendency, without the eHighway concept installed. In Figure 4.10 the projection towards 2050 for the transformers located near the highway can be seen. According to the projection, the non-eHighway consumption will increase from 202,290 MWh in 2016 to 417,003 MWh in 2050. The increase is equal to a percentage rise of 206.1 %

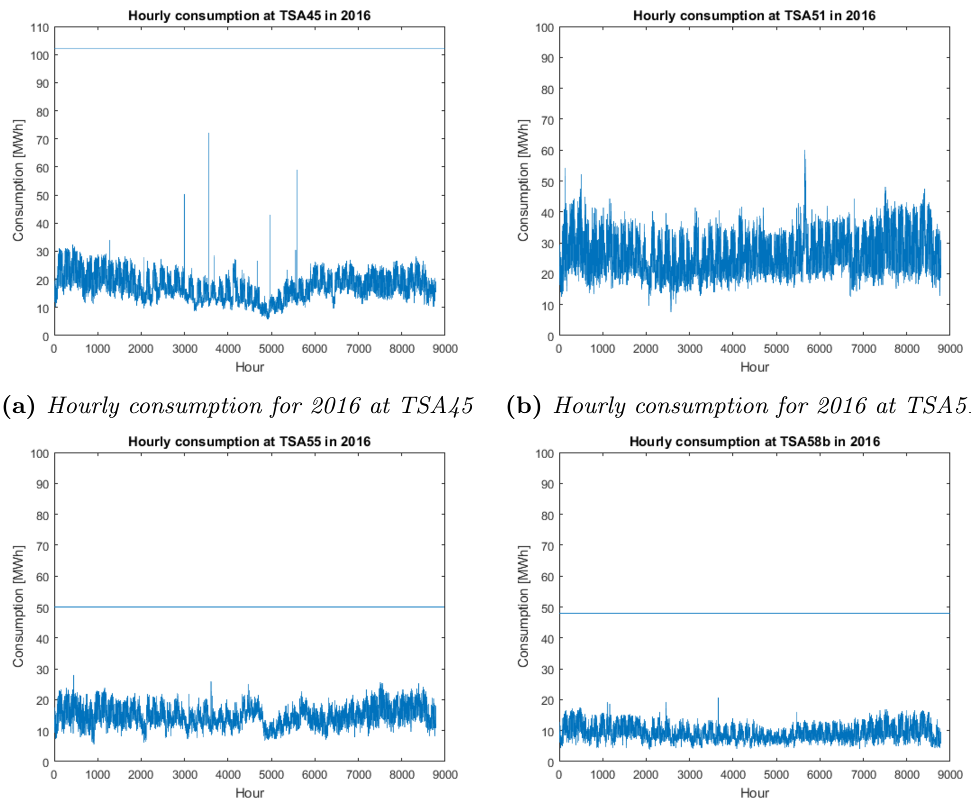
4.4.3 Power 2016 vs 2050

This section is divided into three smaller subsections: One where the power profile without the load of the eHighway is considered, then one that considers the load from the eHighway system and finally a combined profile for the entire load near the ehighway on Funen. For each profile, the graphs for 2016 and 2050 will be shown and described.

Load from Transformers Without eHighway Connected

Figure 4.11 shows the complete load for all transformers near the highway for 2016. On each of the four subfigures, a horizontal line is shown. This line represents the transformer capacity for that area. The horizontal line cannot be seen in Figure 4.11b, since the capacity is very large, 208 MW.
In Figure 4.11a, there are some clear outliers that have been measured at the LHM transformer station. As the installed capacity at LHM is 32 MVA, the measured value of 60 MW must therefore be an error[4].

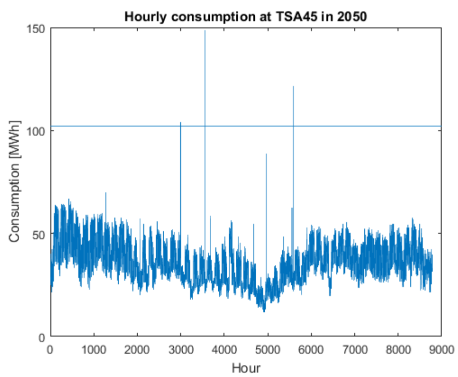
[4]This has been discussed with Jesper Knudsen, who confirms that it is an error at the transformer station.



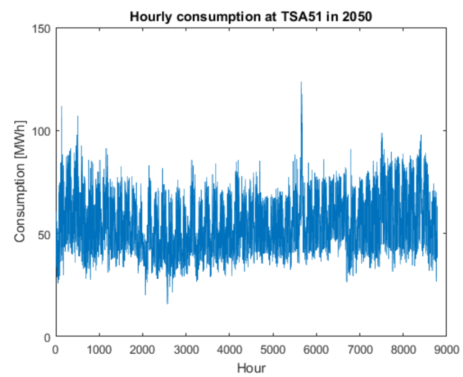
(a) *Hourly consumption for 2016 at TSA45* **(b)** *Hourly consumption for 2016 at TSA51*

(c) *Hourly consumption for 2016 at TSA55* **(d)** *Hourly consumption for 2016 at TSA58b*

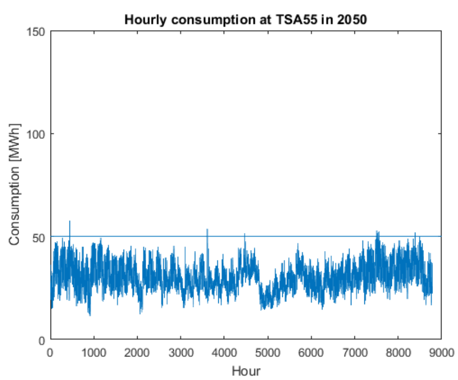
Figure 4.11: *Hourly power profile for each of the four stretches, without the eHighway concept*



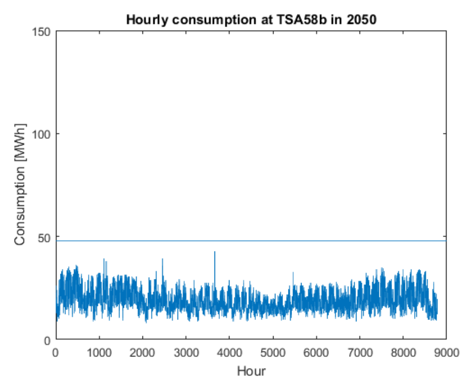
(a) *Hourly consumption for 2050 at TSA45*



(b) *Hourly consumption for 2050 at TSA51*

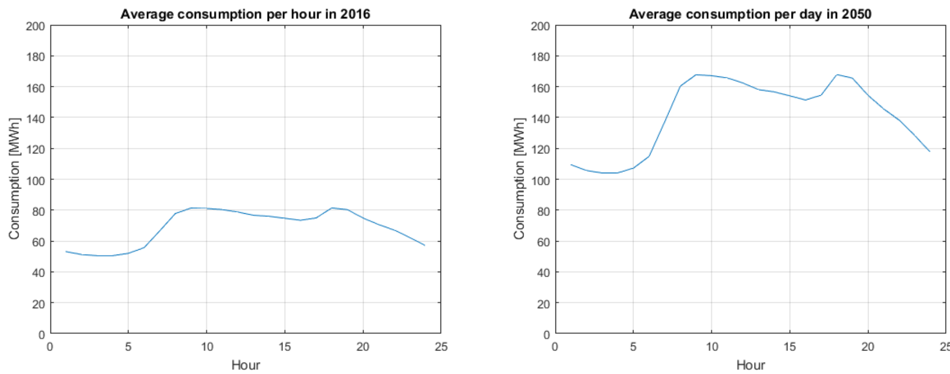


(c) *Hourly consumption for 2050 at TSA55*



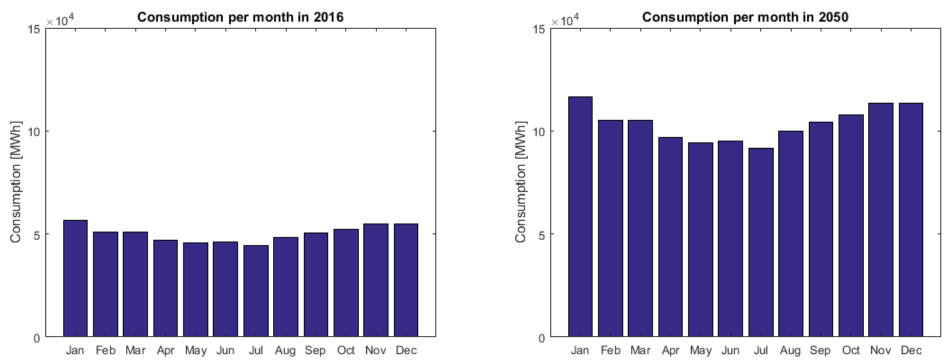
(d) *Hourly consumption for 2050 at TSA58b*

Figure 4.12: *Hourly power profile for each of the four stretches for 2050 (without the eHighway concept)*



(a) *Average daily consumption for 2016* **(b)** *Average daily consumption for 2050*

Figure 4.13: *Average daily consumption for all four stretches for 2016 and 2050 without the eHighway concept.*

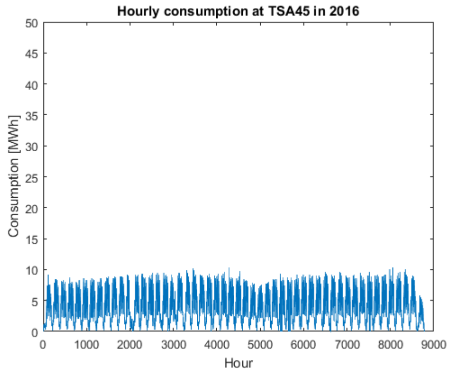


(a) *Monthly consumption for 2016* **(b)** *Monthly consumption for 2050*

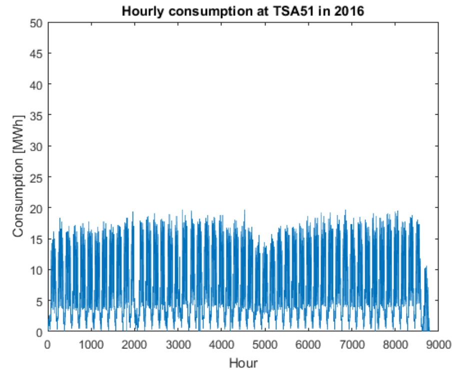
Figure 4.14: *Monthly consumption for all four stretches for 2016 and 2050 without the eHighway concept*

In Figure 4.12, the load at the transformers without the eHighway concept connected have been projected to 2050. The visualization shows that the consumption is still well within the maximum capacity for each stretch except at TSA55, which touches the maximum capacity of the transformers in that area a few times.

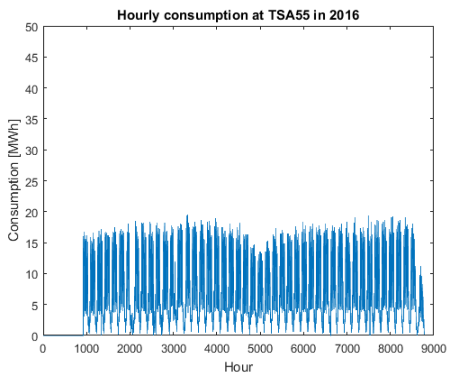
In Figure 4.13 the daily load curve is shown. This curve follows the common consumption curve, where the consumption increases heavily between 06:00 and 09:00. This is due to the fact that factories start operating heavy energy consuming machines, and the household consumer wakes up, turns on the light and starts the coffee machine. From 09:00 the consumption will slowly decrease until 17:00 where everybody returns home from work and starts making dinner. At 19:00 the consumption will decrease rapidly until midnight where it will somewhat stabilize until 06:00 the next morning.
In 2050, these gradients will increase and decrease even more according to the projection. This results in greater fluctuation between peak and off-peak periods.
In Figures 4.11 and 4.12 it can be quite hard to see how the consumption is distributed during the year, since there are so many point on the figures. Therefore, Figure 4.14 has been made, which shows the total consumption for all four strethces on a monthly basis.



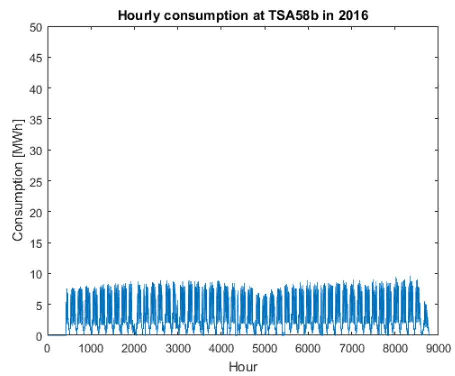
(a) *Hourly consumption eHighway at TSA45 in 2016*



(b) *Hourly consumption eHighway at TSA51 in 2016*



(c) *Hourly consumption eHighway at TSA55 in 2016*



(d) *Hourly consumption eHighway at TSA58b in 2016*

Figure 4.15: *Hourly power profile for each of the four stretches for 2016 (for the eHighway concept).*

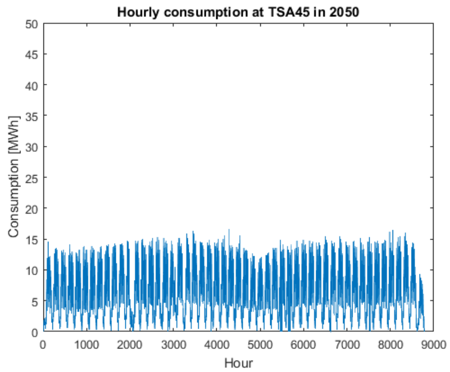
Loads from eHighway

In Figure 4.15, the consumptions from the eHighway for all four stretches are shown. The figure uses vehicle data from 2016 on an hourly basis. Some data entries are missing (see 4.1, giving rise to some uncertainities. This also results in an incomplete graph as the consumptions from the eHighway are zero for a complete month for TSA55 and for a little more than two weeks for TSA58b.
The dives and fluctuations are caused by the same events as described in Section 4.3.2.

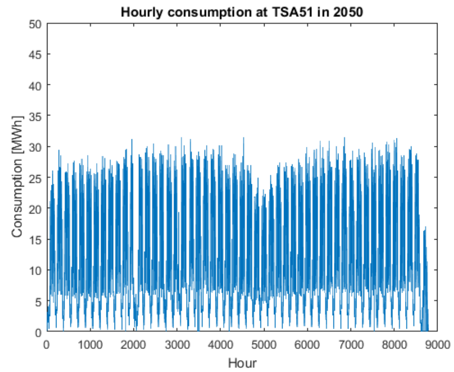
Figure 4.16 shows the consumption of the eHighway for 2050 at different stretches on the highway. When comparing Figure 4.15 with Figure 4.16, it is clear that there is a significant increase. From 2016 to 2050 the consumption will rise with about 50 %.

In Figure, 4.17 an average day is shown for all four stretches combined. The figure shows the consumption from the eHighway, both for 2016 and 2050. The base load (the load between 23:00 and 04:00) does not increase substantially over the years, however the peak consumption from 10:00 to 18:00 increases a lot. This will result in a larger gradient between off-peak and peak periods. The average peak in 2016 is 35 MWh/h and in 2050 it will have increased to 55 Mwh/h.

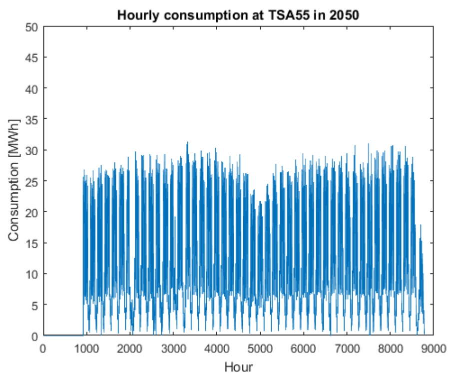
In Figure 4.18, the monthly consumption from the eHighway is shown. If looking away from July due to the industrial vacation, the consumption is lowest in the winter time and then rises towards summer.



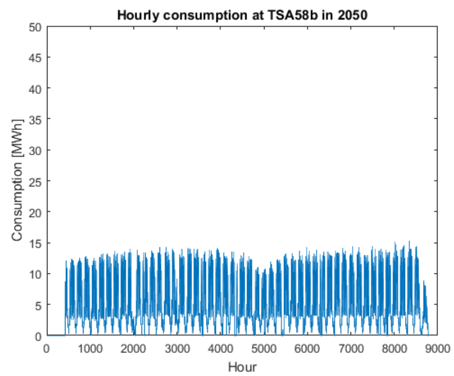
(a) *Hourly consumption eHighway at TSA45 in 2050*



(b) *Hourly consumption eHighway at TSA51 in 2050*

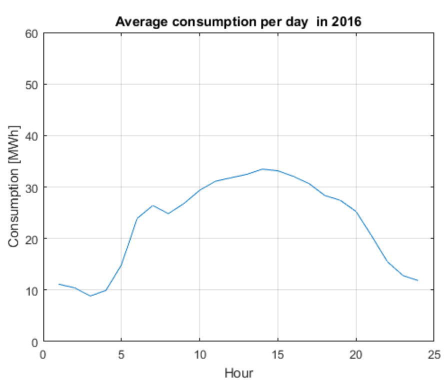


(c) *Hourly consumption eHighway at TSA55 in 2050*

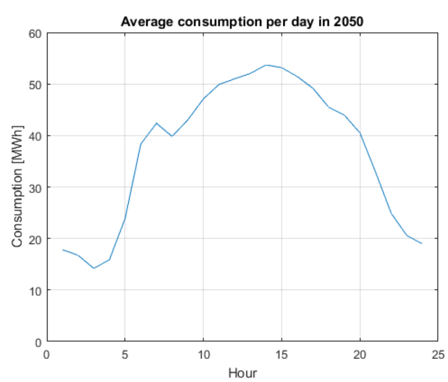


(d) *Hourly consumption eHighway at TSA58b in 2050*

Figure 4.16: *Hourly power profile for each of the four stretches for 2050 (for the eHighway concept)*

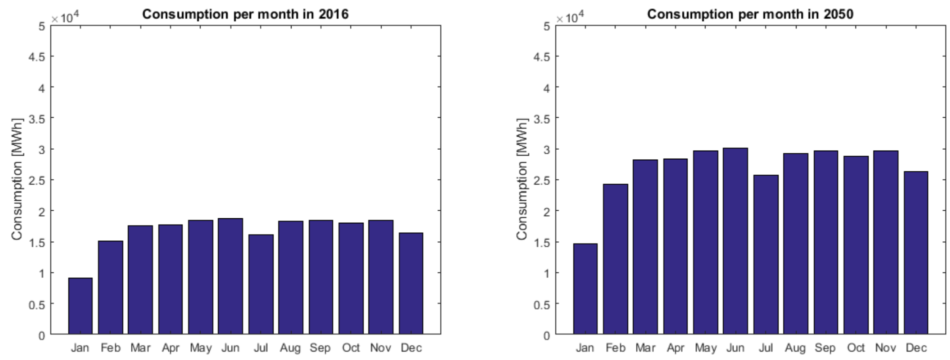


(a) *Average daily consumption eHighway 2016*



(b) *Average daily consumption eHighway 2050*

Figure 4.17: *Average daily consumption from the eHighway for all four stretches for 2016 and 2050*



(a) *Monthly consumption eHighway 2016* **(b)** *Monthly consumption eHighway 2050*

Figure 4.18: *Monthly consumption from the eHighway for all four stretches for 2016 and 2050*

Combination of Ordinary Load and eHighway Load

Now a comparison of the loads from the eHighway and the general loads at the consumption will be made. The structure will follow that of the other subsections, meaning that initially, the yearly consumption per hour for all four stretches in 2016 will be shown and then they will be shown for 2050. After this, a graph of an average day for both 2016 and 2050 will be shown. Finally the consumption on a monthly basis will be shown for both 2016 and 2050.

Figure 4.19 shows the total consumption of the transformers for all four stretches. It should be noted that the consumption is below the maximum capacity at all four stretches. However, for TSA55 the consumption is quite close to the maximum capacity.

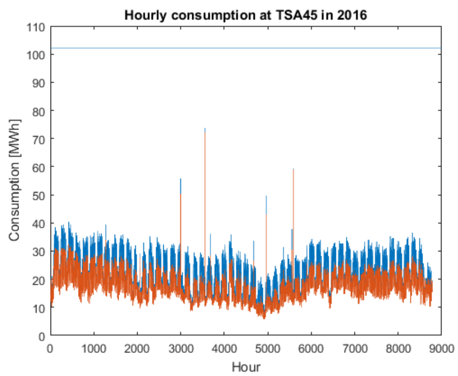
In Figure 4.20, the consumption has increased as expected. At TSA55, the consumption is now above the capacity in peak times. The other stretches are still well within their capacity.

Figure 4.21 shows how the consumption is distributed over an average day. Both the eHighway consumption and the general consumption at the transformers somewhat have the same load curves. This could be a problem for the TSO and DSO as well as the power production operator since there is a high fluctuation over the day.
In Figure 4.22 the monthly consumptions is shown, the eHighway use more power in summer time and less in winter time, whereas the general consumption use more in the winter and less in the summer. This results in a year with almost no fluctuations on a monthly basis.

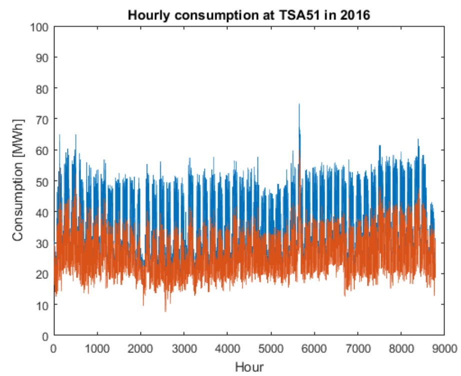
4.5 Chapter Summarization

4.5.1 Traffic Profile

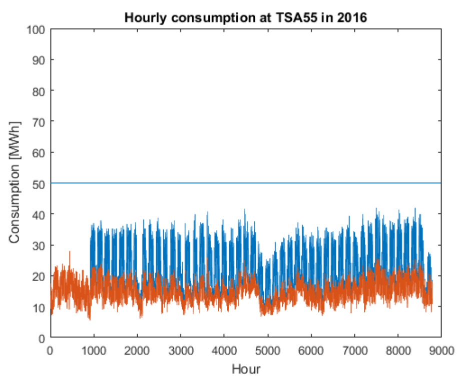
With an increase in traffic of 1.4 % per year, the traffic on the roads in 2050 is expected to have increased by 60 % in total since 2016.
The hourly traffic profiles show that there are two peaks during a 24 hour cycle. The first peak happens between the hours 05:00 and 08:00 in the morning. The second peak is gradually built up through the day and reaches its maximum around 14:00 in the afternoon, see Figure 4.6.
The weekly traffic profiles determined that Tuesday is the day of the week with the most amount of traffic.
The monthly profiles shows an evenly distributed amount of heavy duty traffic every month throughout the year, with the exceptions of July and December because of summer and Christmas holidays.



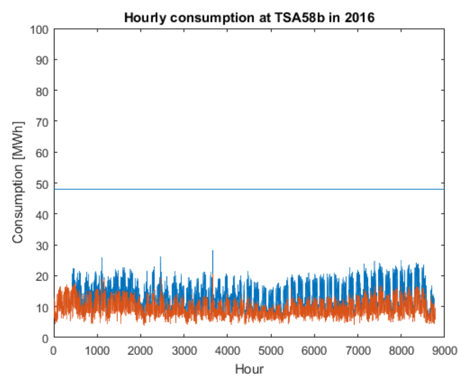
(a) *Total hourly consumption at TSA45 in 2016*



(b) *Total hourly consumption at TSA51 in 2016*

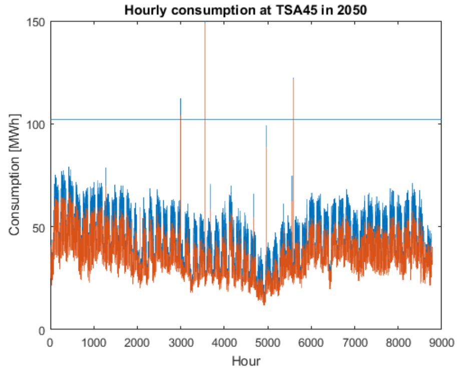


(c) *Total hourly consumption at TSA55 in 2016*

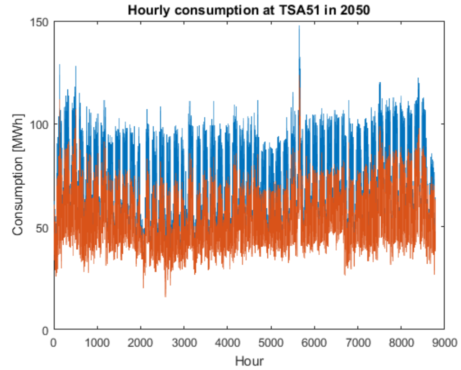


(d) *Total hourly consumption at TSA58b in 2016*

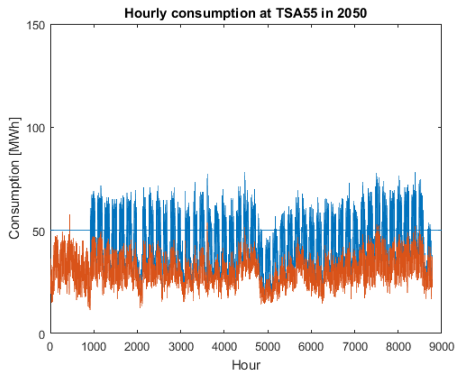
Figure 4.19: *Hourly consumption for the eHighway and the normal consumption for 2016*



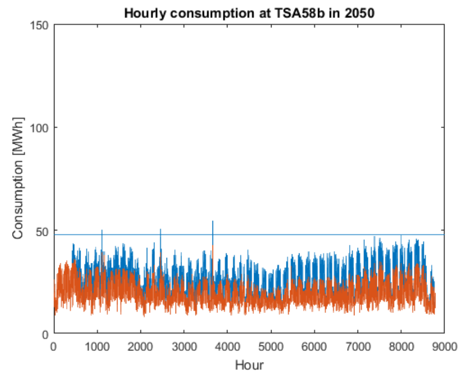
(a) *Total hourly consumption at TSA45 in 2050*



(b) *Total hourly consumption at TSA51 in 2050*

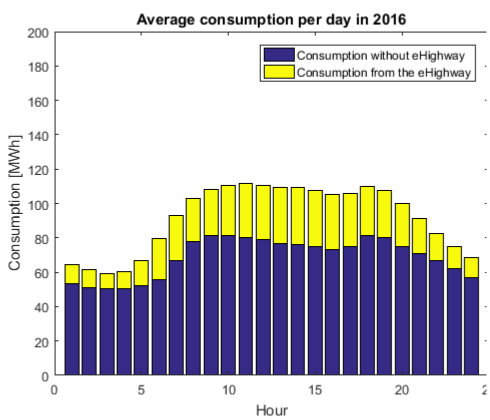


(c) *Total hourly consumption at TSA55 in 2050*

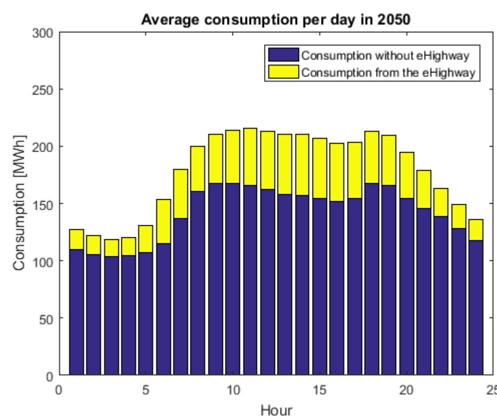


(d) *Total hourly consumption at TSA58b in 2050*

Figure 4.20: *Hourly consumption for the eHighway and the normal consumption for 2016*

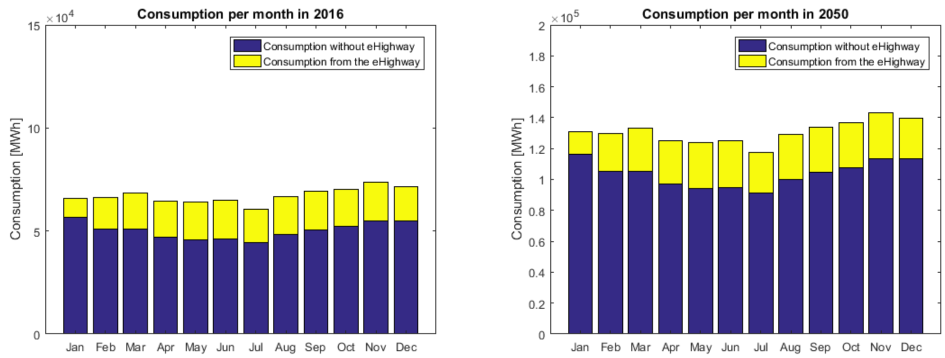


(a) *Collective average daily consumption in 2016*



(b) *Collective average daily consumption in 2050*

Figure 4.21: *Average daily consumption for all four stretches for 2016 and 2050.*



(a) *Monthly consumption for 2016* **(b)** *Monthly consumption for 2050*

Figure 4.22: *Monthly consumption for all four stretches for 2016 and 2050*

The frequency functions showed the dimensioning value on each of the four stretches. They were used to create Table 4.4. From the table it can be concluded that the capacity needed for each of the stretches is significantly lower if the system is dimensioned to be overloaded to 300 % than 200 %.

4.5.2 Power Profile

From Figure 4.19 it is clear that the capacities at all four stretches are high enough to handle the eHighway combined with the general load, under the assumption that the eHighway would have been constructed and implemented in 2016.

In 2050, the picture has changed a bit: The loads have increased a lot, and for the TSA55 stretch the consumption will be higher than the capacity during peak hours, as can be seen in Figure 4.20. This means that at least one additional transformer should be placed in the area before 2050.

The daily demand curve will change a bit due to the eHighway. In Figure 4.21 the demand curves for both 2016 and 2050 are shown. On the figure it can furthermore be seen how the demand has shifted a few hours, as the general demand rises around 07:00, and the eHighway demand rises around 04:00.

The eHighway concept uses more electricity in the summer time, where the consumption normally is low, as it can be seen in the yearly demand curve in Figure 4.22. It can therefore be concluded that the eHighway concept will help smooth out the yearly demand curve.

Chapter 5

The DC Substations and Overhead Line Voltages

In this chapter, the optimal distance between the positions of the traction substations that are to be placed along the eHighway is analysed and determined. That includes two different types of connections between the traction substations and the overhead lines as well as comparisons between input parameters based on present day technology and traffic and future ditto.

5.1 System Components

In order to properly conduct a reasonable analysis on the placements and distances between the traction substations, the different parts of the local power system that contribute to supplying energy to the vehicles have to be identified and understood to a sufficient degree, as the first step. That includes identifying the relevant specifications of the components. These specifications, which will, to a far extent, be rather generic as the specific components are unknown at the given time due to the eHighway concept still being in its development phase. Note, that in order to keep the system simple enough to work with, only the most crucial and basic components are considered in the network:

- The substation (5.1.1)
- The substation feeder cables (5.1.2)
- The overhead lines (5.1.2)
- The vehicles (5.1.3)

All of the above components are treated as regular ohmic resistors, except for the substation, which represents the input voltage source. Even though the output voltage level can be regulated in the substation, it is treated as an ideal DC voltage source, keeping a constant voltage level. The components along with their most basic and relevant traits are briefly considered in the subsections that are noted beside the respective list entries. During reading of the subsections, Figure 5.4 can be used as a reference for the placement of the components in the system.

5.1.1 The Traction Substations

In order to deliver the necessary power to the overhead lines, ultimately transferring it to the HDV's that use the eHighway, a number of traction substations have to be placed along the highway. They play the role as the very last electricity conversion step before the power is delivered to the HDV's. A traction substation is shown in Figure 5.2.

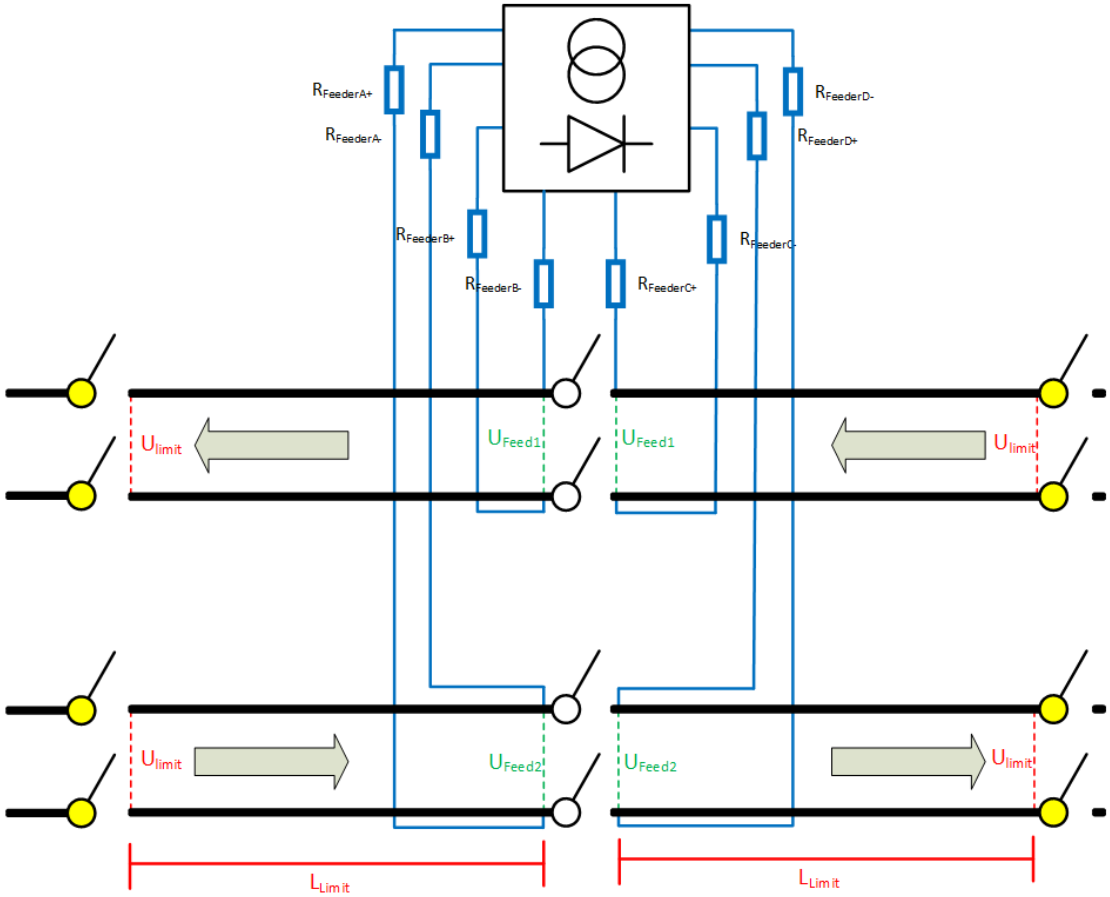


Figure 5.1: *A single section of the eHighway with both driving directions included. The blue lines represent feeder cables, the black lines represent overhead lines and the transformer/rectifier box represents the traction substation that converts the power from the grid to DC power at a suitable voltage level.*

Figure 5.2: *A traction substation [13]*

Voltage Levels

The main purpose of the traction substations is to transform the voltage from the electricity grid down to a level that is applicable for the HDV's.
In the case of implementing Funen eHighway, the input voltage level is most conveniently set to match the voltage level used for larger electricity customers, e.g. industrial complexes and nurseries, which are connected directly to the distribution level of the grid. The input voltage level is therefore expected to be 10 kV.
The output voltage level of the traction substations, U_{In} is set to equal the voltage level for which the HDV's are designed with an additional 10 % added (Appendix G.1). For instance, if the HDV are designed to receive 600 V, the actual no-load voltage fed into the system by the substations is 660 V. This is done to compensate for voltage losses in feeder cables (see Section 5.1.2), and while the HDV's might sometimes receive higher voltages than they are designed for, the excess voltage is still sufficiently low for the vehicles to handle without any failures.
Calculations using the slightly higher voltage level of 750 V (with 825 V at no-load) will also be conducted (see Appendix G.1 for more information).
In addition to down-transforming the voltage level supplied to the eHighway system, another purpose of the traction substations is to convert the power from three-phase AC to a two-pole DC output. For more information about the reasons for this, see Appendix A.

Substation Costs

A very important aspect to consider when dealing with the installation of infrastructure is the actual costs of the project. In this case, it does not make a lot of sense to just find a number of substations that have to be installed along the eHighway if their costs are not considered, even if only briefly.

The purchase price for a 10/0.660 kV AC/DC traction substation that was used for the installation of a tramway system in Aalborg was estimated to be approx. 700,000 € per unit, with each unit being able to handle 900 kW through the rectifier [16]. Based on rough estimations provided by Siemens, approx. 1–3 MW of capacity is required for the eHighway[13].
In order to include a reserve capacity, the actual capacity is quadrupled to get a capacity of 3600 kW, and the cost equally quadrupled to 2,800,000 €.
The installation costs are not multiplied, as it is assumed that the same installation work has to be done regardless of substation capacity, so it is set to 180,000 € making for a total of 2,980,000 € per substation[16].
The 10 kV cables costs are not included in this estimation, as the circumstances for their installation differ slightly from the Aalborg tramway system, and because they are most likely going to be placed along the eHighway regardless of the exact distance between the substations. Furthermore, the cables are not directly part of the substation themselves.

It is assumed that the 600 V traction substation will have approx. the same costs as the 750 V version.

5.1.2 Cables and Lines

The cables that are used for the construction of the eHighway system can be divided into two categories, each described in its own subsection: Feeder cables and overhead line cables.

Feeder Cables

The feeder cables are marked by the blue lines and boxes in Figures 5.4 - C.5, and their purpose is to deliver the power from the traction substation to the two overhead lines. For each station, there will be installed four pairs of feeder cables: Two pairs for each highway direction track (eight in total), one delivering to the overhead line section to the east of the connection point and one delivering to the western section.

It is expected that a very high amperage will be transferred through the feeder cables, as 600 V (or 750 V) is not a very high input voltage for HDV's that require power inputs as high as 116 kW (see Section 5.1.3). With several HDV's connected to the system, the amperage can easily reach well above a few kA. It has not been possible to find a suitable cable model for the feeder cables that can transfer that high currents. An alternative is to use several smaller parallel-connected cables instead of a single large one. This, however, leaves a decision to be made between an incomprehensible number of combinations, which is not the purpose of this study. Instead, the resistance per length of the feeder cable has been set to $0.05\,\Omega/\text{m}$, which is relatively low, in order to accommodate the fact that thicker cables generally provide lower resistances (see Equation (C.4)).
The typical length of feeder cable that is required per connection between the substation and the overhead lines has to be determined as well. The substation delivers power to both driving direction tracks through separate cables. The distance to the track farthest away from the substation is used to determine the feeder cable length, as the cables providing power to line above this track will make for a higher resistance when compared to the cables providing power to the closer track. Thus, with higher losses, the farthest track sets the requirement.
The width of one highway track, including emergency lane, is approx. 12 m, giving a 24 m span across both tracks[7]. The central reservation varies a little in its width, but it is set to be approx. 2 m wide, and it is assumed that the substation is placed at a decent distance of 20 m away from the highway. Finally, the cables runs vertically up the eHighway line poles in order to reach the overhead lines. This vertical distance is set to 5.30 m [2].
Summing all the above lengths and multiplying the result by two because of the electrical pole pair, the total length of feeder cable to the overhead line at the track farthest from the substation is approx. 102.6 m, which is rounded to 100 m. The actual resistance found in the feeder cables is then:

$$R_{Feeder} = 102.6\,\text{m} \cdot 0.05\,\frac{\Omega}{\text{m}} \approx 5.1 \times 10^{-3}\,\Omega \tag{5.1}$$

Note that in Figures 5.4 – C.5, the feeder cables are split up into unique pairs. This is done for illustrative purposes, but for this study, all of these resistances are equal if they go to the same driving direction track (so $R_{FeederA+}$ is not equal to $R_{FeederB+}$ in Figure 5.4). Likewise, a pair of feeder cables in Figures C.1 – C.5 represents the R_{Feeder} resistance, meaning for instance that:

$$R_{FeederA+} + R_{FeederA-} = R_{FeederD+} + R_{FeederD-} = R_{Feeder} = 5.1 \times 10^{-3}\,\Omega \tag{5.2}$$

Overhead Lines

The overhead lines are the last step before the power is delivered to the HDV's. The overhead lines are suspended in pairs of two (one for each pole) above the right side lane of each driving direction track at the highway. The resistances found in these lines are the most important contributors to the decrease in input voltages as the HDV's move away from the connection point near the substation. Without resistances in the overhead lines, the vehicles could simply be considered connected in parallel to each other in the system and would thus receive the same voltage regardless of their positions and the traffic density.
The parameters set for the overhead lines are as follows:
A standard cross-sectional area, A_{Line} of $120 \times 10^{-6}\,\text{m}^2$ is deemed sufficient for carrying the required power to the HDV's at the given voltage levels. The wires are made of grooved copper [13]. This gives a resistivity, ρ, of approx. $1.72 \times 10^{-8}\,\Omega \cdot \text{m}$ at $20\,^\circ\text{C}$[12]. The resistance per metre of length thus becomes:

$$\frac{\Delta R_{Line}}{\Delta l} = \frac{\rho}{A_{Line}} = \frac{1.72 \times 10^{-8}\,\Omega \cdot \text{m}}{120 \times 10^{-6}\,\text{m}^2} = 143.3 \times 10^{-6}\,\frac{\Omega}{\text{m}} \tag{5.3}$$

5.1.3 Vehicles

The HDV's can largely be regarded as the main load of the system. Power is delivered to the vehicle by connection between a pantograph on the HDV and each pole of the overhead line. Figure 5.3 depicts a HDV that can connect to the eHighway.

Figure 5.3: *An electrical HDV with a pantograph [1].*

The actual mechanics and circuitry inside the HDV is beyond the scope of this project. Instead the HDV's are considered as simple ohmic resistances, whose sizes are to be determined in this section, based on a few assumptions.

5.1.4 Voltage Input and Power Consumption

According to Siemens most electrical HDV's are presently designed to receive an input of 600 V at the pantograph, and it is also known that they are able to operate properly at voltage levels down to 500 V. Below that level, they will cease to function (see Appendix G.1.
Furthermore, it is assumed that an electrical HDV consumes approx. 1.45 kWh /km, when it travels at a velocity of 80 km/h, a velocity which is expected to be kept steady most of the time. By knowing the velocity, v_{HDV}, and energy consumption per distance, E_{HDV}, the typical power consumption can be calculated as:

$$P_{HDV} = v_{HDV} \cdot E_{HDV} \tag{5.4}$$

$$P_{HDV} = 80 \times 10^3 \, \frac{\mathrm{m}}{\mathrm{h}} \cdot 1.45 \, \frac{\mathrm{W} \cdot \mathrm{h}}{\mathrm{m}} = 116 \times 10^3 \, \mathrm{W}$$

Knowing the power consumption and input voltage, V_{HDV} allows for the calculation of the total resistance in the HDV by using the power equation:

$$R_T = \frac{{V_{HDV}}^2}{P_{HDV}} \tag{5.5}$$

$$R_T = \frac{(600\,\mathrm{V})^2}{116 \times 10^3\,\mathrm{W}} = 3.103\,\Omega$$

The resistance, R_T from Equation (5.5) is used to represent the resistance in a HDV for the rest of the study, even though internal resistance regulation might be present in some vehicles.
Considering the HDV resistance to be constant at all times is done in order to avoid that the problem becomes too complex to analyse and solve. However, this also means that the HDV's will not receive the required 116 kW of power at voltage levels below 600 V, but that the input power can fall to a level of 80.55 kW at the lowest possible input voltage of 500 V.

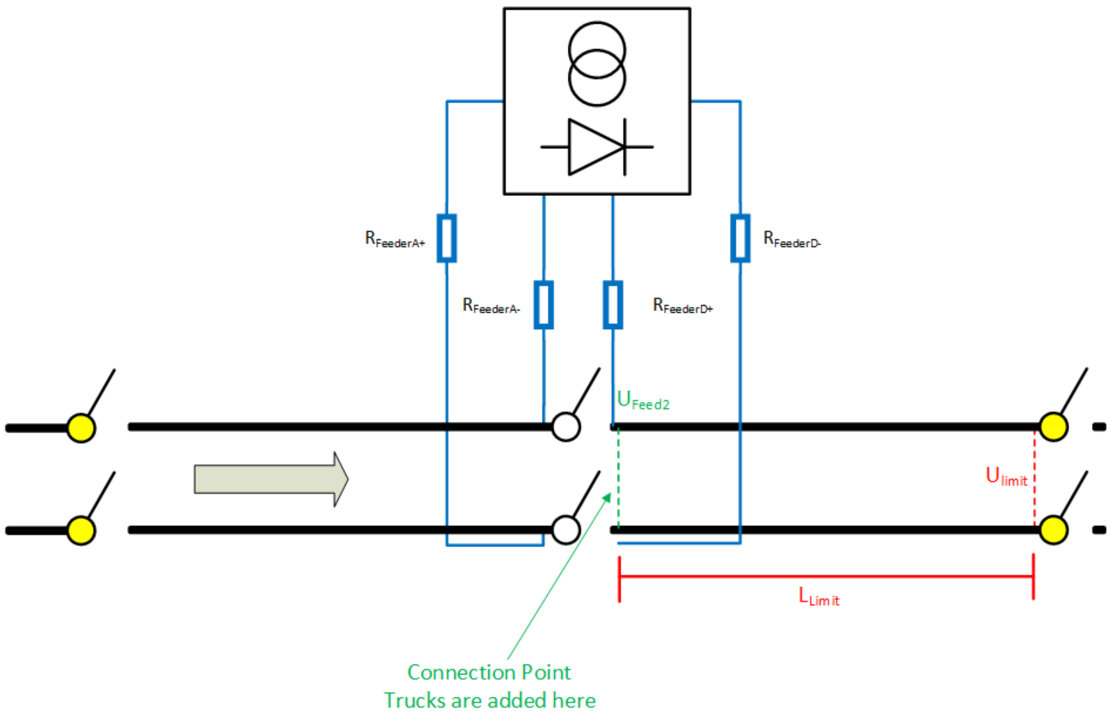


Figure 5.4: *Excerpt of Figure 5.1, showing only one driving direction*

5.2 System Topology

Now that the overall components of the eHighway system has been described, it is time to look at perhaps the most important part when correctly determining the voltage losses in the eHighway system: The network topology of the system.
While it is quite simple, it still provides some challenges due to its dynamic nature. Two types of topology will be described in Section 5.2.1 and Appendix B. The actual descriptions of the calculation approaches as well as the comparisons of performance between the two solutions can be found throughout Section 5.3.

5.2.1 The Single-feeder Solution

Figure 5.4 shows a simplified circuitry depiction of the actual eHighway network and is referred to throughout this section. Only one of the two driving direction tracks is considered, but the opposite direction is designed and connected in a completely identical manner (see Figure 5.1).

The power system is a two-pole system, where each pole starts out at the substation, providing the voltage difference that is output by the substation, noted by U_{In} in the figure. One of these poles is considered grounded at the connection point to the substation. The poles are then transferred through a pair of feeder cables that connect to their respective overhead line cables. The connection points are considered to be geographically positioned exactly opposite each other above the highway, thus rendering the two poles fully identical to each other from the overhead lines and onwards.
The first voltage and power losses occur in the feeder cables due to resistances, $R_{FeederA+}$, $R_{FeederA-}$, $R_{FeederD+}$ and $R_{FeederD-}$, thus the voltage level delivered to the overhead lines, denoted by U_{Nom}, is slightly lower than U_{In}.

The next part of the system is constituted by the overhead cables. Without any vehicles on the

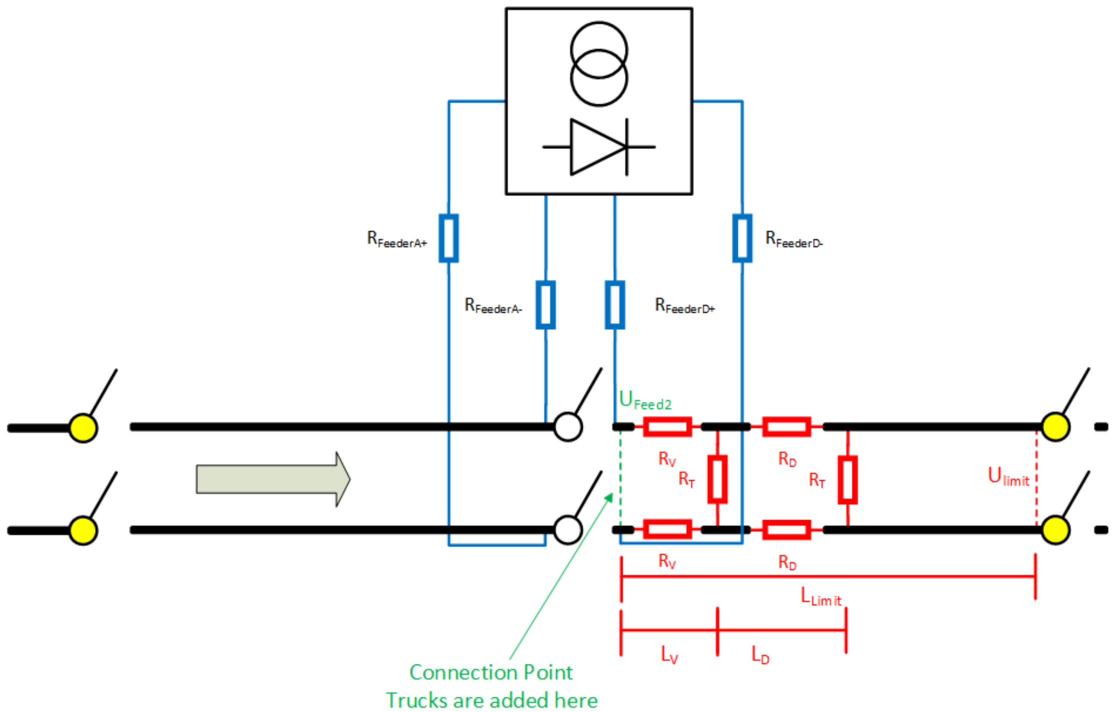


Figure 5.5: *The single-feeder solution with two HDV's inserted, represented by the red R_T resistances. A line resistance between two HDV's is represented by R_D, and a line resistance between a HDV and the connection point is represented by R_V.*

highway, the two overhead line poles are separated, and no current flows through the network at all. The line section to the west of the connection point is separated from the eastern section by the two open switches shown in the middle of the figure. A single substation therefore delivers power to two separate sections of overhead lines. Furthermore, the substation and its two line sections are completely separated from the adjacent substations by the four yellow opened switches.

Now, each vehicle that is present in the system provides a connection between the poles, as it can be seen in Figure 5.4, and the vehicles are connected in parallel connections to each other, each providing the load, R_T. As the vehicles drive with a constant distance, L_D, between each other (see the reasoning behind this statement in Section 5.4), the resistance of the overhead lines between two vehicles will always be the same, R_D.
There is one exception to this statement: If the vehicle is the one that is closest to the connection point, the resistance in the line depends on the distance between that given vehicle and the connection point, L_V. This resistance is thus variable and is called R_V.

At some point, when enough vehicles are connected to the system and the distance between the vehicle farthest from the substation and the connection point , the voltage received from that vehicle drops down below the minimum voltage level, U_{limit}. The actual maximum distance, L_{Limit}, that can be sustained in one direction by one substation has then been determined.

Another solution called the double-feeder is described in Appendix B.

Name	Density [HDV/m]	Length between HDV's [m]
TSA45	0.0048	208.34
TSA51	0.0056	178.57
TSA55	0.0055	180.17
TSA58b	0.0062	162.94

Table 5.1: *Substation capacity needed on each of the four stretches.*

5.3 Determining the Distance

In this section, the basic considerations and equations used for the calculation approach in the model are given. The more technical part of the model description, where vehicles are incrementally added to the system, can be found in Appendix C. Additionally, the model is provided in the two MATLAB scripts in Appendices, E.5.1 and E.5.2.
Thereafter, the results that are gained from using the model with inputs from 2.1 and the maximum measured traffic densities at each stretch are listed.

5.4 Traffic Density and Absolute Traffic Peaks

In order to place the traction substations with the right intervals at the right places on the four stretches, the traffic densities at each of the four stretches need to be found.
The term, traffic density, denotes how many vehicles that can be found per length on a road stretch. At the same time, the reciprocal of the traffic density denotes the distance between two vehicles.
Equation (5.6) is used to find the traffic density.

$$\gamma = \frac{N_{HDV}}{T \cdot v_{HDV}} \tag{5.6}$$

Here, γ denotes the traffic density, T denotes the period of each measurement (or time detail), $v_H DV$ denotes the vehicle velocity, which is kept constant, and N_{HDV} denotes the number of HDV's measured during a measurement period. For instance, the traffic data set used for determining the distance between the placements of the traction substations is based on half hours. Furthermore, projection towards 2030 of the highest measurement made during the entire year at stretch A58b was 247 vehicles. Assuming that the vehicles travel at 80 km/h, the density can be calculated, which is shown in Equation 5.7.

$$\gamma = \frac{247}{\frac{1}{2}\text{h} \cdot 80 \times 10^3\,\text{m/h}} \approx 0.0062\,\frac{1}{\text{m}} \tag{5.7}$$

Then, the reciprocal to the density is calculated in (5.8) in order to determine the distance, L_D, between two vehicles.

$$L_D = \frac{1}{\gamma} = \frac{1}{0.0062\,\frac{1}{\text{m}}} \approx 162.94\,\text{m} \tag{5.8}$$

The above method is used to find the maximum traffic density and minimum distances between vehicles on each of the four highway stretches. The densities and distances are listed in Table 5.1.
The reason for choosing the half measurement hour with the highest amount of HDV's present for each stretch, is to dimension the system to handle the highest traffic density. This is done, so that vehicles on the given stretch will still be able to run on the eHighway, even though traffic is very high.
A special case that represents the maximum traffic that can be stuck onto the eHighway is also considered in this study. Due to the braking distances that a typical HDV needs to stall entirely,

there is a lower limit to the distance that is allowed between two HDV's. This lower limit is set to 95 m, corresponding to a traffic density of 0.0105 m^{-}1 [9]. The vehicles will never drive closer to each other than 95 m, unless a chauffeur wants to break the law, so the traffic density of 0.0105 m^{-}1 is considered to be the highest that can ever occur at the eHighway.

5.4.1 Calculation Approach

Before heading for the actual calculations, a calculation procedure/model is constructed. This model is based on a number of theoretical foundations as well as system characteristics and generalizations.
This section can be considered a continuation to section 5.2.

Initial Considerations

Firstly, a few points that are vital in the construction of the model are mentioned.

As the vehicles are connected in parallel to each other, they will not directly decrease the voltage level of each other. However, the farther a vehicle is from the feeder connection point, the larger the resistance in the overhead lines becomes, and consequentially, the lower the actual input voltage to the vehicle becomes.
More vehicles connected to the line result in a decreased equivalent resistance in the system. The reduced resistance causes an increase in the current drawn from the substations and thus increased voltage drops through the cables closest to the substation. This ultimately causes even lower input voltages for the vehicles farthest from the source.

Summarizing the above considerations, the voltage that is delivered to a specific vehicle depends on the distance between the vehicle and the feeder cable/overhead line connection point and the number of HDV's connected to the line.
It naturally does not make any sense to consider every single vehicle on the highway, as the one furthest away from the connection point receives the lowest voltage. *The input voltage level at the vehicle farthest from the connection point is therefore exclusively considered, as it will be the first one to drop below U_{Limit}.*

Basic Equations

Only three equations are used for analysing the system:
The resistance equation:

$$R_D = \frac{\rho_{copper} \cdot L_D}{A_{Line}} \tag{5.9}$$

$$R_V = \frac{\rho_{copper} \cdot L_V}{A_{Line}} \tag{5.10}$$

Ohm's resistance law:

$$U = R \cdot I \tag{5.11}$$

The equivalent series and parallel (respectively) resistor resistance equations:

$$R_{eq_S} = R_1 + R_2 \tag{5.12}$$

$$R_{eq_P} = \frac{R_1 \cdot R_2}{R_1 + R_2} \tag{5.13}$$

And the current divider equation:

$$I_{out} = \frac{R_1}{R_1 + R_2} \cdot I_{in} \tag{5.14}$$

The rest of the calculation approach is described in Appendix C.

5.4.2 Substation Distance Results

In this section, the results of the traction substations distance analyses, using the calculation approaches described in the previous sections, are given. The results describe expectations for the year of 2030.

The curves in Figure 5.6 show the voltages that the vehicle farthest away (the front vehicle) receives at different distances from the substation(s).
By looking carefully at the figure, it can be seen that the curve makes very small jumps and increase in steepness at regular intervals. These jumps represent the distances where a new vehicle is added to the connection point. For instance, when the front vehicle reaches the 95 m L_D milestone in Figure C.3, a vehicle is added at the connection point, causing more current to be drawn through the feeder cables and thus a larger voltage drop in these, resulting in the small jump downwards in the voltage received by the front vehicle.
It is *very* important to note that the curve does *not* say anything about the voltages received by the vehicles apart for the front vehicle. It only tells the story of the front vehicle driving from the connection point and to a point where the received voltage has dropped below a minimum acceptable level, in this case 500 V.
A summary of the optimal distances between the substations, including the number of vehicles expected to be present on each line section at the given distance and traffic density, is shown in Table 5.2. Note that the distances are doubled from the distances shown in the figures, as there are actually two line sections between two substation, one for connected to each station. Furthermore, the results from the double-feeder solution are included in the table. A full walk through of the double-feeder results can be seen in Appendix C.1.2.

Single-feeder Results

The red curves in Figures 5.6 - 5.7 (the latter two being found in Appendix D.1) represent the single-feeder solution, and they are provided for each of the four highway stretches as well as the situation where the most dense vehicle traffic that may legally occur is present. Furthermore, they are given for 600 V vehicles and 750 V vehicles.
The figures in this section represent the single-feeder solution. The x-axes denote the distance between the front vehicle and the connection point near the substation connected to the overhead line section (see Figure 5.4 for reference). The curves only apply for one of the two overhead line sections that the substation is connected to, but can be applied equally to the other section as well. The y-axes denote the voltage level, which the front vehicle receives at the given distance.

5.4.3 Substation Numbers and Costs

Now that the distances between the substations are gained for the four stretches at various conditions, it is time to calculate the required number of substations for the entire eHighway system across Funen as well as the resulting costs.

The individual lengths of the four highway stretches (found in Table 4.1) are divided with their respective distances between the substations (found in Table 5.2), in order to get the number of substations at each stretch. Afterwards, the total number of substations at the four stretches is multiplied with the substation cost identified in Section 5.1.1, and the total cost for the substations is found. Using the results from Table 5.2, the calculation for the single-feeder

	TSA45	**TSA51**	**TSA55**	**TSA58b**	**Max. allowable traffic density**
Max. traffic (half hour)	192	224	222	247	-
Traffic density [vehicle/m]	0.0052	0.0045	0.0045	0.0041	0.0105
Vehicle-to-vehicle distance [m/vehicle]	208.4	178.9	179.9	162.2	95
Single-feeder ***660/600 V***					
Distance between substations [m]	2139	1991	1996	1908	1486
Number of vehicles on each section	6	6	6	6	9
825/750 V					
Distance between substations [m]	3869	3602	3612	3434	2658
Number of vehicles on each section	10	11	11	11	15
Double-feeder ***660/600 V***					
Distance between substations [m]	2299	2140	2145	2026	1544
Number of vehicles on each section	11	11	11	13	17
825/750 V					
Distance between substations [m]	4039	3739	3749	3566	2716
Number of vehicles on each section	19	21	21	21	29

Table 5.2: *Single and Double-feeder system distances at different voltage levels and input traffic data. The voltages represent the substation no-load output and the nominal vehicle input, respectively. A single vehicle section covers half of the distance between two substations.*

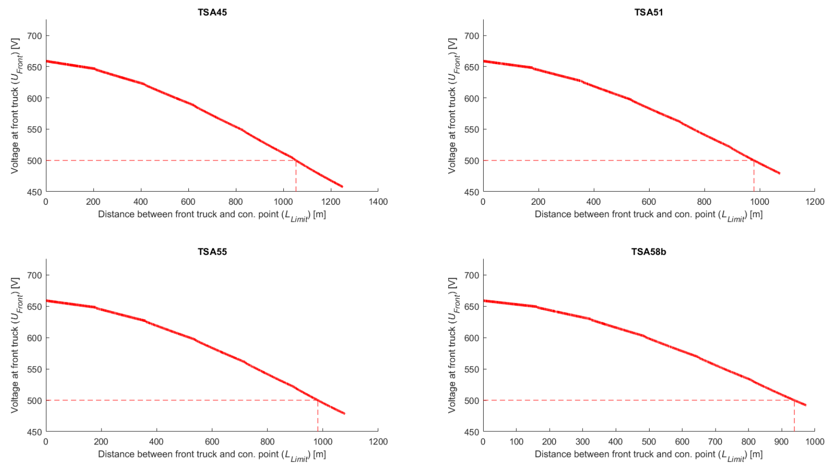


Figure 5.6: *The input voltage to the front vehicle at increasing distances from the substation using the maximum measured traffic densities at each of the four highway stretches as inputs - Nominal vehicle voltage: 600 V; Solution: Single-feeder; Traffic: Max. measured at stretches*

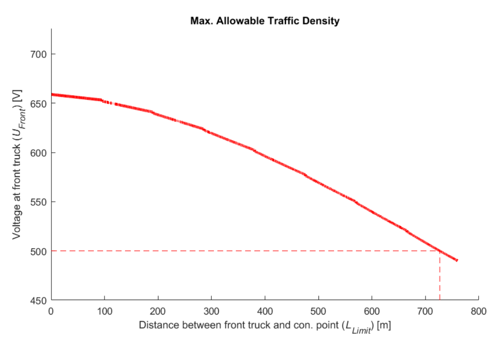


Figure 5.7: *Nominal vehicle voltage: 600 V; Solution: Single-feeder; Nominal vehicle voltage: 600 V; Solution: Single-feeder; Traffic: Max. allowed in lane*

	Single-Feeder		*Double-Feeder*	
	Cost	**Amount**	**Cost**	**Amount**
***600* V**	113.2×10^6 €	38	104.3×10^6 €	35
***750* V**	62.5×10^6 €	21	59.6×10^6 €	20

Table 5.3: *Number of substations and their total cost at four different conditions*

solution with 600 V vehicles is carried out as follows:

$$N_{Substations.Single.600V} = \frac{18 \times 10^3\,\text{m}}{2106\,\text{m}} + \frac{24.2 \times 10^3\,\text{m}}{1958\,\text{m}} + \frac{22.1 \times 10^3\,\text{m}}{1963\,\text{m}} + \frac{9.79 \times 10^3\,\text{m}}{1875\,\text{m}} \approx 38 \tag{5.15}$$

$$Cost_{Substations.Single.600V} = 38 \cdot 2\,980\,000\,€ \approx 113.2 \times 10^6\,€ \tag{5.16}$$

The above calculations are done for each of the two feeder solution and for each of the two voltage levels. The required numbers of substations are always rounded up to nearest whole number in order to ensure that the sufficient voltage level is present everywhere. The results can be seen in Table 5.3.
It is clear that a higher voltage level for the vehicles is preferable, presumed that the vehicles are still able to operate all the way down to 500 V. This means that even though the technology generally limits the voltage that the vehicles are able to handle as input to 600 V [13], developing vehicles for higher voltage levels greatly increases the distance that can be allowed between two substation. Furthermore, the increased voltage input decreases the current drawn by the vehicle if the power input is unchanged, thus lowering the requirements to the conductors in terms of amperage.
It also seems that the double-feeder solution is marginally better than the single-feeder solution, but the difference does not seem noteworthy.
A final aspect to be considered in this section is the way that the substation costs relates to the total costs of constructing the eHighway across Funen.

The actual cost per direction and per kilometer of eHighway is estimated by Siemens to be in the range of 1.0×10^6 €–1.5×10^6 €. An average of the range is used, so the construction of the eHighway is assumed to cost 2.5×10^6 € per km for both tracks. This means that the entire investment cost of the eHighway across Funen will be approx.:

$$Cost_{Total} = 74.09 \times 10^3\,\text{m} \cdot 2.5 \times 10^3\,\frac{€}{\text{m}} \approx 185.2 \times 10^6\,€ \tag{5.17}$$

If it is assumed that $Cost_{Total}$ is the total budget of implementing the eHighway structure, then it can be calculated how big a share that the substations contribute to the budget. However, because Siemens has estimated their costs from using this voltage it only makes sense to compare the 600 V input results.
The 38 traction substations that will be installed if the single-feeder solution is used the nominal voltage level of 600 V will cost approx. 113.2×10^6 €, contributing to a share of 61.1 % of the total investment costs for the eHighway system. Similarly, the double-feeder solution cost, 104.3×10^6 €, will contribute to a share of 56.3 %.

5.5 Discussion of Results

In this section, a discussion regarding the results along with possible conditions and omissions that might cause some failures in the results from Section 5.4.2 is given. Furthermore, a variety of interesting aspects that influence or are relevant to the traction substations distances and the eHighway concept in general are discussed here.

U_{min1}	U_{Nom}	U_{max1}
500 V	600 V	660 V
500 V	750 V	825 V

Table 5.4: *The Siemens voltage ranges*

5.5.1 Comparison to Expectations by Siemens

A reference that is suitable for comparison with this study is the presentation given by Michael Lehmann. This presentation was largely based upon the experiences from an eHighway test track project carried out in Germany and its corresponding report, ENUBA2 [1]. The conditions are far more similar to the assumptions and conditions used for this study: The nominal line voltage is 600 V and the electricity consumed by an average sized vehicle per driven km is likewise set to 1.45 kWh (this study got the value from the ENUBA2). While the transportation density is not defined in the presentation, the 2–3 km distance expectation fits remarkably well with the results from this study (except for the results from the max. allowable traffic density scenarios). These results are presented in the 660/600 V part of Table 5.2.

5.5.2 Extra Voltage and Substations

According to the ENUBA2 report, the traction substations will be designed in a way that supports a rather effortless installation of modules capable of delivering higher voltages than 600 or 750 V [1]. For instance, a 1500 V module can be installed, should the opportunity/need arise in the future with the combination of more advanced technology and heavier load on the eHighway system.
Another way to accommodate a higher load is to install extra substations at sections where the traffic density often reaches exceptionally high levels. This “emergency hole closure” should be rather easy to implement due to the prefabricated and easily-installable design of the substations.

If the dimensioning carried out in this study holds true, there will not be any urgent need for the pre-mentioned improvements and extensions caused by lack of voltage before 2030. However, the desire to upgrade the eHighway system with the newest technology to gain some other benefits, for instance improved efficiency, or as a part of a planned highway extension/maintenance can of course still lead to significant changes to the system before 2030.

5.5.3 Siemens Voltage Limitations and International Standards

The voltage levels and their corresponding upper and lower boundaries that are used in this study are in accordance with the voltage levels set by Siemens (see Section 5.1.1 and Appendix G.1). These levels are reproduced in Figure 5.4

U_{Nom} denotes the optimal input voltage to a vehicle, U_{min1} denotes the minimum acceptable voltage input to a vehicle and U_{max1} denotes the maximum acceptable ditto, which is also the no-load input voltage from the traction substation.
However, the nominal voltage levels and boundaries that are set by the International Standards Organization (ISO) are slightly different, as shown in Table 5.5 [14]:

U_{min1}	U_{Nom}	U_{max1}
400 V	600 V	725 V
500 V	750 V	900 V

Table 5.5: *The ISO standards voltage ranges [14]*

Carrying out the distance analysis after inserting U_{max1} as the no-load input from the substation, while setting U_{min1} to represent the operation limit U_{Limit} for both 600 V and 750 V as nominal voltages, the results comes up as shown in Table 5.6.

	Single-Feeder			***Double-Feeder***		
	Cost	**Amount**	**Difference**	**Cost**	**Amount**	**Difference**
***600* V**	71.5×10^6 €	24	-37 %	68.5×10^6 €	23	-34 %
***750* V**	56.6×10^6 €	19	-10 %	56.6×10^6 €	19	-10 %

Table 5.6: *Number of substations and their total cost at four different conditions using ISO voltage boundaries. Differences are found by comparing to Table 5.3.*

By comparing these results with the numbers found in Table 5.3, it is clear that the need for substations at 600 V vehicle voltage, and thus the costs, are much lower if the ISO voltages are used instead of the Siemens voltages. The impact is especially significant at 600 V nominal voltage compared to the 750 V voltage, as the lower boundary is lowered to 400 V instead of 500 V for the 600 V nominal input. At the same time, it is not lowered at in the 750 V case, but remains at 500 V.

5.5.4 Comparison between Single- and Double-Feeder Solutions

From the Table 5.2, it can be seen that the double-feeder system gives a longer distance between the traction substation than the single-feeder solution. However, the advantage is not very significant as it only increases the distance by approx. $3 - 10$ %, depending on the specific case. The double-feeder system proves to be more resilient against failures. This is because the substation at one end of an overhead line section can feed the entire section in case the other substation drops out due to a fault or maintenance. It should, however, be noted that the substation remaining in operation is only able to sustain a voltage level above the minimum limit on the entire section of the overhead line if light traffic is present. It cannot sufficiently provide voltage if the traffic is heavy or even moderate.

5.6 Chapter Summarization

Topologies were set up for the Siemens eHighway installation. Two solutions were identified, the single-feeder and the double-feeder. The double-feeder proved to be a little more effective, because it yielded a longer distance between the substations. Even though this advantage was only between 3 % and 10 %, the double-feeder also allowed for more resilience against of failures. The system was analysed using two nominal voltage levels for the HDV's, 600 V and 750 V.
As it can be seen in Table 5.3, 750 V proved far better than the 600 V, requiring only 21 traction substation units to be placed along the Funen eHighway system as opposed to 38 units. The lower voltage limit was kept at 500 V in both cases.
Knowing the required number of units, a rough estimation of the total traction substation costs could be made. This estimation gave a substation cost of 113.2×10^6 € for 600 V, while the cost was only 58.0×10^6 € 750 V.
Finally, it seems that the costs from the traction substations will contribute with a rather large share of the total investment for the implementation of the eHighway system across Funen.

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Chapter 6

Discussion

Key assumptions and numbers used to create this thesis will be discussed in this chapter. Furthermore, the goals of the project (see 1.4.1) will be assessed and evaluated.

The possibilities of a system like the Siemens eHighway are numerous. Simultaneously, the electrification of parts of the transport sector, in this case HDV's, is encouraged by the energy goals set for 2050 which Denmark strives to accomplish.

Even though it is considered to happen in this study, the implementation of a system like the eHighway is not likely to be conducted overnight, nor is it sure that every haulier will have the capital to invest in a hybrid HDV capable of using the eHighway system.

A possible alternative could be a tractor system that is available for hauliers who would like to reduce their diesel expenses. This system would have conventional HDV's that connects to tractor trucks. Then the conventional HDV's would pay a fee to get pulled from location A to location B. These locations would act as pick-up and drop-off points and would be located along the eHighway stretch. With the case of the eHighway system across Funen, the points could be positioned near Middelfart and Nyborg.

Traffic Profile: No comparison was made with the numbers representing the increase in HDV traffic from The Danish Road Directorate, which is a reliable source of information. However, an increased amount of uncertainty is still added to the data when there has not been any verification of the data through comparison to other sources.

The number of traffic measuring points on a highway has a significant impact on the detail of the traffic data for the highway. More measuring points mean more knowledge of how many vehicles that passes where, which is crucial for establishing an international eHighway with optimal capacities. As an alternative to the traditional measuring points, data sent from a GPS system installed into the individual vehicle, will provide a very detailed data set.

Since a concept like the eHighway system is likely to be implemented on larger stretches at a time, for instance from Sweden through Denmark and further to Germany, the idea of dividing the stretch into many sections will help keep a high SoS.

The same considerations go for the time detail level. For instance, if the traffic data was measured on a minute scale, it would be much easier to predict local short-term traffic peaks. This would eventually help avoid traction substation overloads or too large voltage drops in the overhead lines.

Power Profile: As was the case with the data used for the traffic profile, the data received by Energinet.dk has not been verified by a second source. Energinet.dk, being the Danish TSO, they can be considered one of the most reliable sources of data regarding electricity consumption projections.

Security of Supply: As explained in Section 3.4, the HDV's will be hybrids vehicles with electricity as their main energy source. When the HDV's are not in areas where the eHighway is implemented, they will have to use a secondary energy source.
The fact that HDV's have an alternative to using electricity gives rise to some interesting discussions about the wanted SoS at the eHighway. The HDV operator will probably be willing to receive a lower SoS, if compensated with lower electricity prices. However, most of the initiatives to ensure a high SoS are implemented to the general grid. Therefore it is not possible to lower the SoS for some consumers while still keeping it unchanged for other consumers.

There is an exception that can lower the SoS for HDV operators while maintaining the high SoS for the rest of the grid. The exception is the opportunity to shut down the supply to the eHighway system when the grid is under too much stress. So far, the *n-1 rule* has been applied to the distribution grid. This means that each part of the grid is able to handle peak demand if one transformer in that area goes out of order. Due to this rule the grid is over-dimensioned in normal operation, so that a reserve capacity is always present.

With some change in legislation, the eHighway could be allowed to operate using the reserve capacity. If a transformer cuts out while the demand from non-eHighway consumers is high, the eHighway will immediately turn off in that area to free reserve capacity. In this situation, the HDV's will have to drive using their secondary energy source.

Substation Costs: As the eHighway concept is still in its development phase, and as the specific components inside the substation, apart from a 10/0.660 kV (or 10/0.825 kV) transformer and a rectifier for converting the AC to DC, are not known, it is hard to gather any actual component costs and thus to make any reasonably precise cost calculations. This means that the calculated costs for substations in this report can only be used as vague guidelines for getting an impression of the substation costs as well as their share in the total cost of the eHighway installation across Funen.

Furthermore, it should be noted that the actual substation costs will likely be lower due to the substation being delivered as a prefabricated concept, seemingly ideal for acquiring some economy of scale in their production. At the same, it is easily installable, thus lowering the installation costs. However, these discounts are not known and are therefore not considered in this report.

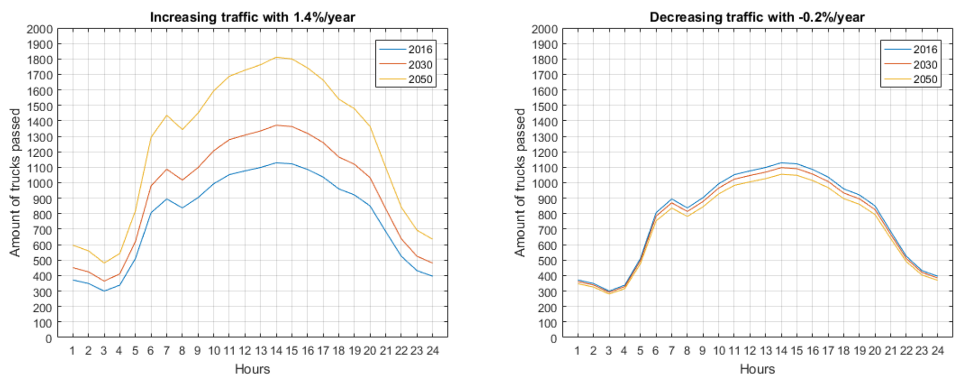
Sensitivity Analyses

In this section sensitivity analyses will be conducted to estimate the sensitivity of key numbers that are deemed prone to change.

Traffic Estimation The system in the thesis has been dimensioned after how much traffic that is expected to be in 2030. This estimation was made using a projected annual increase rate of 1.4 % in the HDV traffic. This rate was found using numbers from the index *Udvikling i lastbiltrafikindekset, 2008 – 2016* [8].
What would the traffic numbers for 2050 look like if the traffic was decreasing annually, as is the case if the factor is found using 2008 as the starting year, making it the index year?
The new annual rate is calculated in Equation (6.1).

$$\frac{98.1\ \% - 100\ \%}{8\,\text{yr}} = -0.2\frac{\%}{\text{yr}} \tag{6.1}$$

Figure 6.1 shows the difference of the 1.4 % increase per year and the 0.2 % decrease per year towards 2050.



(a) *Increase in traffic* **(b)** *Decrease in traffic*

Figure 6.1: *Average traffic every hour throughout 2016 with projection of 2030 and 2050*

As can be seen in Figure 4.6 in Section 4.3.2, the impact of the annual 0.2 % decrease is relatively small in comparison to the annual 1.4 % increase. So, in the 0.2 % decrease case, the dimensioning of the system can be limited to the traffic numbers of 2016.

Projection of Consumption In this study, the electricity consumption for West Denmark has been projected to 2050. A projection towards 2040 made by Energinet.dk was used to make three projections, spanning from 2040 to 2050. Of those three projection, *Projection High* was chosen since the authors of this study deemed it to be the most accurate. However, since a lot factors that have an impact on the electricity consumption in 2050 might change, it is likely that the chosen projection is not that accurate. Therefore, it is analysed what would happen in 2050 if the electricity consumption will follow one of the other two projections.
In Figure 6.2, the expected general consumptions for 2050 (excl. the eHighway consumption) are based on the three projections. On the figure it can be seen that *Projection Medium* and *Projection Low* are quite close to each other.
Furthermore, in Figure 6.3 the total consumption in 2050 is shown for TSA55. The figure shows that even if the *Projection Low* was used, the consumption would still exceed the capacity of the 60/10 kV transformers at TSA55. Therefore the installation of an additional 60/10 kV transformer station is required.

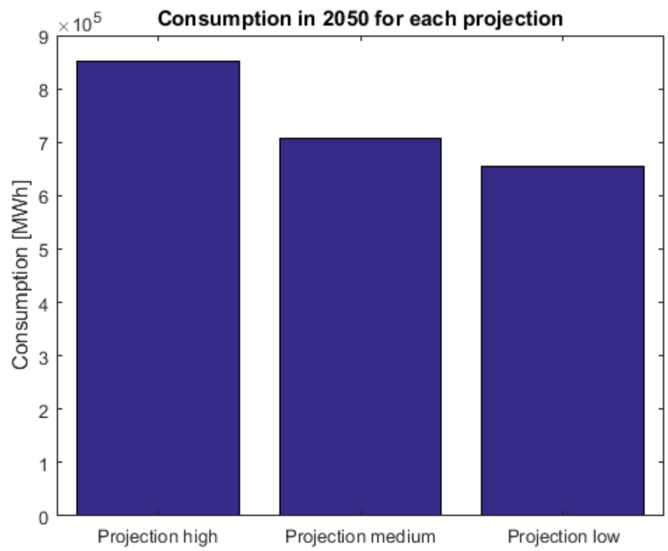
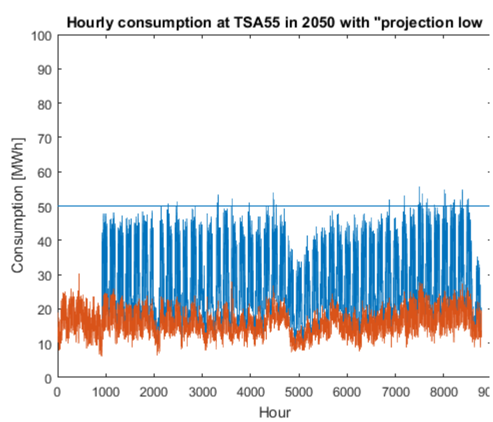
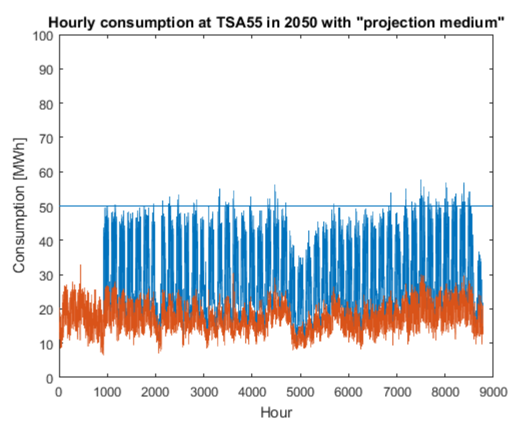


Figure 6.2: *Total consumptions in 2050 for all three projections, excluding eHighway consumption*

From the above, it can be said that the power profile is not sensitive to smaller fluctuations in the electricity consumption.



(a) *Hourly consumption in 2050 - based on "Projection Low"*



(b) *Hourly consumption in 2050 - based on "projection medium"*

Figure 6.3: *The hourly consumption in 2050 - based on the two projections, "Projection Low" and "Projection Medium"*

Feeder Cable Resistance Impact The feeder cable model was not specified in the analysis of the distance between the substations that was conducted in Chapter 5, specifically in Section 5.1.2. This made it necessary to choose a resistance that was assumed reasonable. This way of just settling with a self-chosen specification without support from any reference naturally causes a considerable uncertainty in the results of the analysis. In order to consider the actual extent of this uncertainty, the sensitivity of the feeder cable resistance is estimated.

In order to consider the sensitivity of the feeder cable resistance, two scenarios are considered: A tenfold increase in the resistance ($R_{Feeder} = 51 \times 10^{-3}\,\Omega$) and a reduction to a tenth of the resistance, ($R_{Feeder} = 0.51 \times 10^{-3}\,\Omega$). Using the calculation procedure described in Chapter 5 with all other input variables kept the same, the results from decreasing the feeder cable resistance to a tenth or increasing it to tenfold; they are shown in Tables 6.1 and 6.2, respectively. Change factors represent the relationship between results from those two tables and the results from Table 5.3.

	Single-Feeder			***Double-Feeder***		
	Cost	**Amount**	**Difference**	**Cost**	**Amount**	**Difference**
***600* V**	113.2×10^6 €	38	0 %	104.3×10^6 €	35	0 %
***750* V**	62.5×10^6 €	21	0 %	59.6×10^6 €	20	0 %

Table 6.1: *Number of substations and their total cost for four different conditions with a tenth of the orignial feeder resistance The numbers are compared to Table 5.3.*

	Single-Feeder			***Double-Feeder***		
	Cost	**Amount**	**Difference**	**Cost**	**Amount**	**Difference**
***600* V**	134.1×10^6 €	45	18 %	122.2×10^6 €	41	17 %
***750* V**	68.5×10^6 €	23	10 %	65.6×10^6 €	22	10 %

Table 6.2: *Number of substations and their total cost for four different conditions with feeder resistance multiplied by ten. The numbers are compared to Table 5.3.*

It seems that changes in the feeder cable resistance have virtually no impact at small resistance values, as shown in Table 6.1. This can be explained by the number of substations being rounded up to nearest whole number, nullifying the much smaller effect from the resistance change.

On the contrary, if the resistance is increased by the same factor rather than being decreased, the impact becomes noteworthy as seen in Table 6.2. However, it is still not very significant as a substation amount/cost increase by 10–18 % of the original values seems minuscule when compared to the 900 % resistance increase. Furthermore, a lower nominal HDV voltage seems more sensitive to resistance changes, while there is almost no difference between the single-feeder and double-feeder solution.

From the above considerations, it can be concluded that changes in the feeder cables resistance do not affect the outcome of the project in a noteworthy way, especially if the feeder cable resistance is small compared to the overhead line and HDV resistances. Therefore, the uncertainty caused by setting the feeder cable resistance to an assumed value is quite small.

Maximum Traffic Density Case The eHighway system has to be capable of handling any traffic situation that might arise. The level of detail for hourly measured data can be deemed insufficient, as it does not say anything about sudden short-term peaks in HDV traffic. A way to make sure that the eHighway system is always capable of delivering the sufficient voltage is to consider the heaviest traffic that may legally occur. At this traffic density the distance between the vehicles is set to be 95 m (see Section 5.4 for further details). Note, that the 95 m distance scenario does not consider smaller vehicles also driving in the eHighway lanes, so the actual vehicle-to-vehicle distance is going to be slightly greater.
The number of substations and their total costs at the two voltage levels, using the two feeder solutions, are summarized in Table 6.3. These values are found by using Equations (5.15) and (5.16), inserting the same vehicle-to-vehicle distance of 95 m for all four highway stretches.
With increases of 37.1 %–40.0 %, the maximum traffic density that the ehighway can physically handle, makes for some significant extra costs to the project. However, the system is prepared for virtually every traffic situation that might occur.

The lack of voltage caused by short-term events with extraordinarily heavy traffic is partially solved by the vehicles being able to run on their alternative energy source, such as the on board battery or a combustion engine (bio- or fossil fuel).

	Single-Feeder			***Double-Feeder***		
	Cost	**Amount**	**Difference**	**Cost**	**Amount**	**Difference**
***600* V**	152.0×10^6 €	51	34.2 %	143.0×10^6 €	48	37.1 %
***750* V**	86.4×10^6 €	29	38.1 %	83.4×10^6 €	28	40.0 %

Table 6.3: *Number of substations and their total cost at four different conditions at the maximum vehicle density that can legally occur (95 m between two vehicles). The requirements and costs are significantly higher than in Table 5.3.*

Considering the 95 m scenario also has another advantage: If the amount of heavy-duty traffic continues to increase steadily at the rate of 1.4 % per year, even after 2030, the eHighway is able to deliver the sufficient voltage all the way until the 95 m mark is reached [1].

[1] Which has been calculated to happen at the TSA58b stretch in a rather distant future, more specifically, the year of 2070

Chapter 7

Conclusion

Firstly, the traffic and related electricity demand was found for 2016 and 2050.
Then it was determined that the eHighway system should connect to 60/10 kV transformer stations owned by EnergiFyn and TREFOR El-net. These connection points are shown in Figure 7.1.
The electricity demand at the 60/10 kV transformers near the Funish highway was projected and is visualised by the blue bars in Figure 7.3.
Then, future profiles for heavy duty vehicles and their electricity demand were found. Figure 7.2 shows the estimated heavy duty traffic with Danish HDV's in 2030 and 2050, with 2016 as starting point. With an increase in traffic of 1.4 % per year, the traffic on the roads is expected to have increased by a total of 60 % in 2050 relative to 2016.

The frequency functions showed the dimensioning value on each of the four stretches. They were used to create Table 7.1. From the table it can be concluded that the capacity needed for each of the stretches is significantly lower if the system is dimensioned to be overloaded to 300 % than 200 %.
The capacity is high enough at all four stretches to sustain the demand from the eHighway combined with the general load under the assumption that the eHighway would have been constructed and implemented in 2016. The specific capacities and demands can be seen in Figure 7.3.

The infrastructure of the electricity grid on Funen and the implementation of the power supply for the eHighway concept were then examined. It was found that there is no need to install new 60/10 kV transformer stations in order to supply eHighway across the Funen highway, if implemented in 2016.

In 2050, the picture has changed a bit: The loads have increased a lot, and for one of the four stretches the consumption will be higher during peak hours than the capacity. This means that at least one additional transformer should be placed in the area before 2050. Figure 4.20 shows that the consumption for stretch TSA55 is higher than the capacity.

Name	Length [km]	Capacity Needed at 200%[MW]	Capacity Needed at 300%[MW]	Peak Load [MW]
TSA45	18	4.08	2.72	8.17
TSA51	24.2	8.05	5.37	16.11
TSA55	22.1	8.19	5.46	16.37
TSA58b	9.79	3.88	2.59	7.76

Table 7.1: *Total traction substation power capacity needed for each of the four stretches*

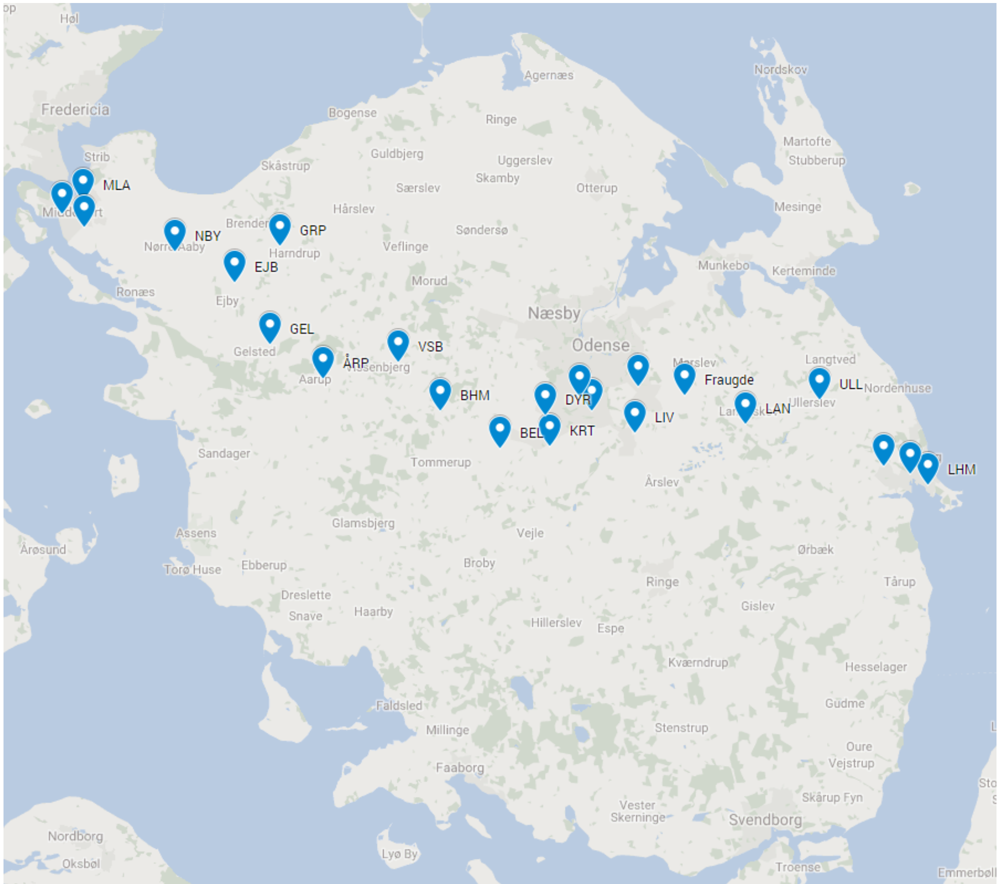


Figure 7.1: *60/10 kV transformer stations placed near the Funish highway*

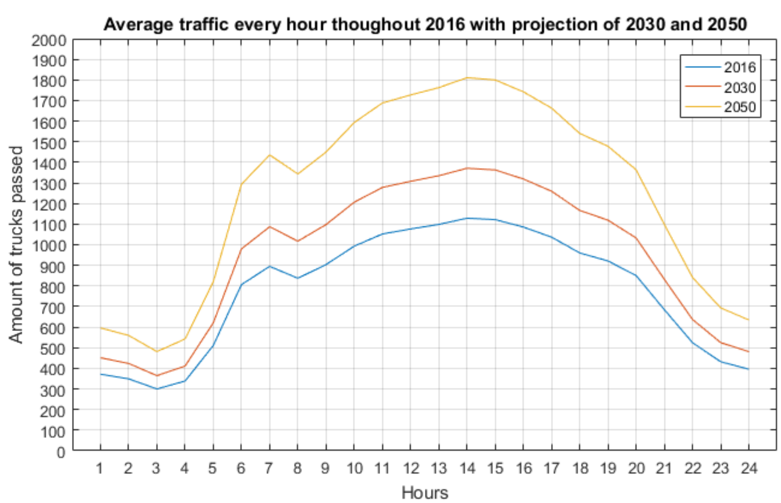
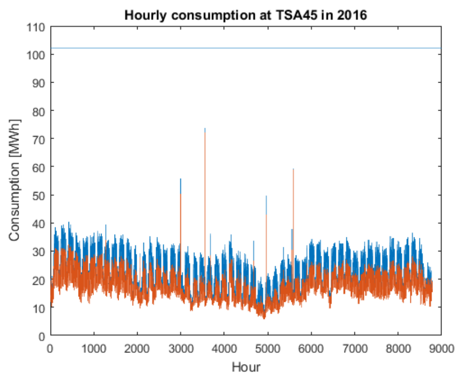
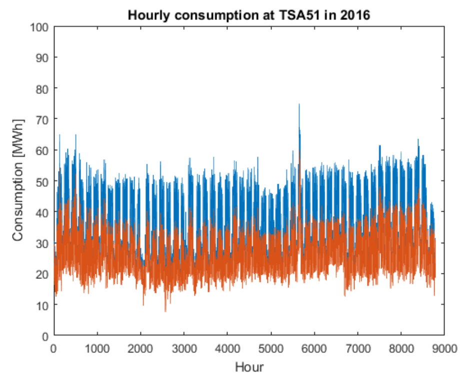


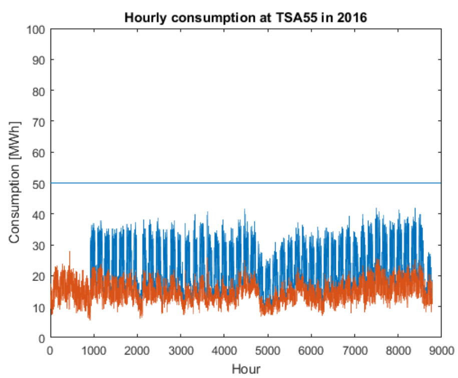
Figure 7.2: *Traffic for 2016 and projections to 2030 and 2050*



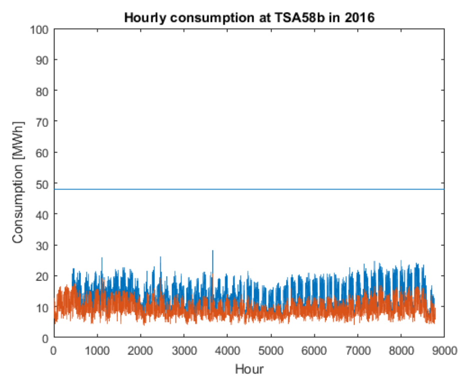
(a) *Total hourly consumption at TSA45 in 2016*



(b) *Total hourly consumption at TSA51 in 2016*

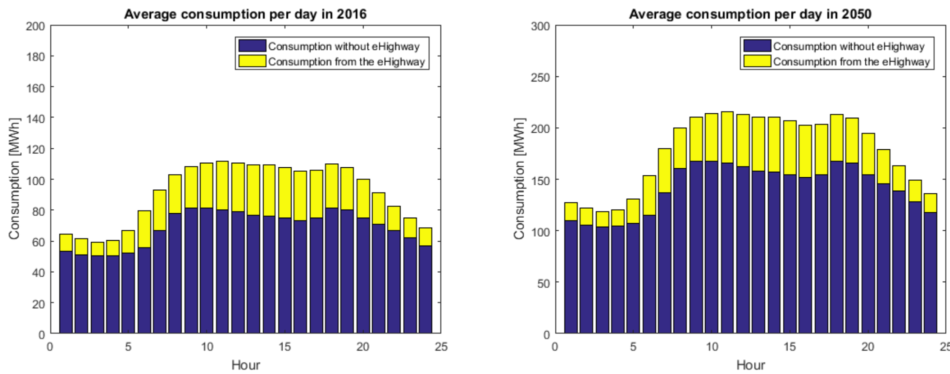


(c) *Total hourly consumption at TSA55 in 2016*



(d) *Total hourly consumption at TSA58b in 2016*

Figure 7.3: *Hourly consumption for the eHighway and the normal consumption for 2016*



(a) *Collective average daily consumption in 2016*

(b) *Collective average daily consumption in 2050*

Figure 7.4: *Average daily consumption for all four stretches for 2016 and 2050.*

The daily demand curve will change a bit due the eHighway, in Figure 7.4 is the demand curve for both 2016 and 2050 shown. On the figure can it be seen how the the demand has shifted a few hours. The traditionally demand rises around 07:00, and the eHighway rises around 04:00.

In Figure 4.22 the yearly demand curve can be seen. The eHighway concept uses more electricity in the summer time, where the traditional consumption is low. It can therefore be concluded that the eHighway concept will help to smooth out the yearly demand curve.

The dimensioning of the eHighway system on Funen was found using data for the traffic density. A table showing the maximum distances between substations required at different voltage levels and with two different types of feeder systems was created, see Table 7.2.

By multiplying the distances between the substations of each stretch with the respective stretch length, the total number of required substations was found. For 600 V nominal HDV input to the system, the number was found to be 38. The costs of those 38 traction substations as well as for the complete eHighway were found. The 38 traction substations that will be installed if the single-feeder solution is used, with a nominal voltage level of 600 V will cost approx. 113.2×10^6 €, contributing to a share of 61.1 % of the total investment costs for the eHighway system across Funen. This is a rather large share, however, certain conditions might help reduce the substation cost per unit, such as economy of scale and low installation costs. These advantages can be gained if the substations will be produced as prefabricated units.

	TSA45	**TSA51**	**TSA55**	**TSA58b**	**Max. allowable traffic density**
Max. traffic (half hour)	192	224	222	247	-
Traffic density [vehicle/m]	0.0052	0.0045	0.0045	0.0041	0.0111
Vehicle-to-vehicle distance [m/vehicle]	208.4	178.9	179.9	162.2	95
Single-feeder 660/600 V					
Distance between substations [m]	2139	1991	1996	1908	1486
Number of vehicles on each section	6	6	6	6	9
Single-feeder 825/750 V					
Distance between substations [m]	3869	3602	3612	3434	2658
Number of vehicles on each section	10	11	11	11	15
Double-feeder 660/600 V					
Distance between substations [m]	2299	2140	2145	2026	1544
Number of vehicles on each section	11	11	11	13	17
Double-feeder 825/750 V					
Distance between substations [m]	4039	3739	3749	3566	2716
Number of vehicles on each section	19	21	21	21	29

Table 7.2: *Single and Double-feeder system distances at different voltage levels and input traffic data. The voltages represent the substation no-load output and the nominal vehicle input, respectively. A single vehicle section covers half of the distance between two substations.*

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Chapter 8

Basis for Further Study

This chapter provides a brief walkthrough of different possibilities and points of interest in regards to looking further into transportation.

8.1 Future Use of the Calculation Model

The calculation model consists of two parts, one for the single-feeder solution and one for the double-feeder solution (they are found Appendices E.5.1 and E.5.2, respectively). While being rather simplified, it is useful for the specific task of gaining a rough overview of the distance between the substations in a DC traction system along with a few other core attributes. Potentially, it can be used at any highway where the eHighway concept is planned to be installed, as long as the traffic data is provided. The singular input values can then be set and adjusted according to the specific needs of the project.

Furthermore, additional functionalities can be added to the model in order to integrate new tasks and aspects into the model as the demand arises.

8.2 Traffic Safety

A system like the eHighway would likely help increase traffic security by having software installed into the vehicles, so that they could communicate and measure the voltage drops. By measuring the voltage drop a vehicle would be able to determine the distance to the vehicle behind it and send a signal to slow down in order to keep the statutory braking distance.

8.3 Different Transportation Means

With the ongoing development in drone technology and other freight transportation methods, like privatising parcel deliveries in form of applications on the smart phone, might reduce the expectations for the growth in the HDV transport sector. It could be interesting too look into how such alternative transportation methods will affect the transport energy sector in the future.

8.4 Shifting Peak Hours for HDV's

The fluctuating demand in electricity is one of the major challenges in the electricity grid. A system with a smooth demand curve makes for fewer and relatively smaller consumption peaks, and thus does not cause very high requirements for reserve production capacity.
Therefore, it is a problem that the daily demand curve for the eHighway falls close to the daily demand curve of the general consumer load, causing higher peaks when they are summed.

From a political point of view, it could therefore be an idea to insert a grid congestion tax or reduce the price of electricity significantly in off-peak hours (late afternoon, night and early morning). To illustrate the effect of such a tax or price reduction, a new figure, Figure 8.1, has been made, relating the total consumption from eHighway and the general consumption. However, the consumption from the eHighway has been shifted by 15 hours, meaning the eHighway peak begins at 20:00 instead of 05:00. Now the peak remains until 12:00 instead of 09:00.

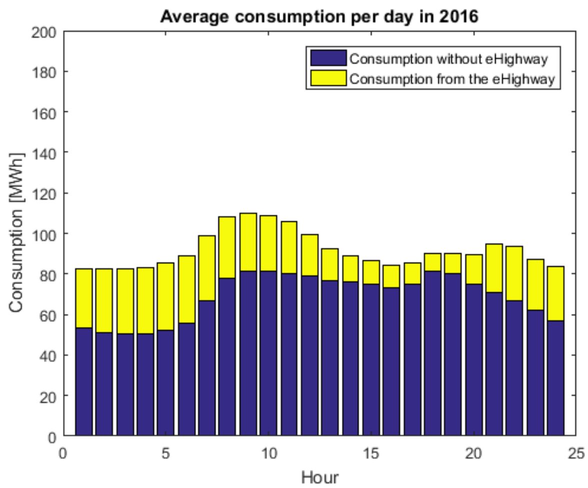

Figure 8.1: *New demand curve, after the load from the eHighway has been shifted 15 hours. The figure has been made using MATLAB, see Appendix E.3*

.

In Figure 8.1, the new demand curve can be seen. It is clear that the demand curve is much smoother than the original demand curve from Figure 4.22. Regarding the power, it can therefore be a good idea to either add a congestion tax for vehicles on the eHighway or lower the electricity price substantially at night/off-peak periods.

8.5 Payback Period

It could prove interesting to look more into the economic feasibility of the eHighway concept. For instance, it is useful to know which revenues that helps the system to recover and break even, and how long it will take for that to happen.

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Appendices

Extensive data has been used in this project (more than 300,000 values). Therefore has an online appendix been made, in the following paper version of appendixes are the different appendixes described, however if the reader wants to see MATLAB scripts or data values the reader has to go the online appendix.

The online appendix can be found at:

`https://studentsdudk-my.sharepoint.com/personal/krkvi14_student_sdu_dk/_layouts/15/guestaccess.aspx?folderid=05f82316648294e4daa4c6b10ab655667&authkey=AZLjl1asiauAjAJn3mlms_Y`

For the reader who has the printed version of the study, the online appendices can also be found at:

`kortlink.dk/qnm5`

Appendix A

Comparison between AC and DC

The reasons for using DC rather than AC are [2]:

- To reduce creepage distance between the conductors in the lines
- To allow for simpler on board electrical systems in the vehicles and thus lighter and cheaper HDV's, as fewer conversions of the energy are necessary

A further discussion of the differences between AC and DC can be found in However, there are some down-side effects to using DC as well, effects that are very relevant when considering the minimum allowed distance between the traction substations [2]:

- The voltage losses in the cables of a DC system are slightly higher than for an AC system. This is especially negative in systems that employ high voltage levels, such as a typical railway system that uses 25 kV.
- The traction substations are slightly more complex and expensive when conversion to DC is required.

In short, the AC solution is suitable for larger high voltage traction systems that are used by fewer and heavier vehicles, while the DC solution is better used for lower voltage level systems to which numerous comparably smaller vehicles, such as HDV's, are connected. The eHighway concept definitely belongs to the latter category, and thus DC is used for the system.

Another noteworthy point is the fact that the AC solution entails heavier investment and operation costs for the vehicle owners/operators due to increased machinery complexity and weight put into the vehicles and the resulting increase in energy consumption. On the other hand, the DC solution sport greater operation and especially investment costs for the traction power system operator, due to increased transformer complexity, cable losses and voltage regulation requirements.
Finally, in order to simplify the substation distance analysis, the power that might be "produced" by the HDV's due to regenerative braking is not considered to be sent back into the eHighway infrastructure or the grid. Instead, the power is considered to be stored into an internal battery on board the HDV and that power is thus considered to be "outside" of the eHighway installation.

Appendix B

The Double-feeder Solution Topology

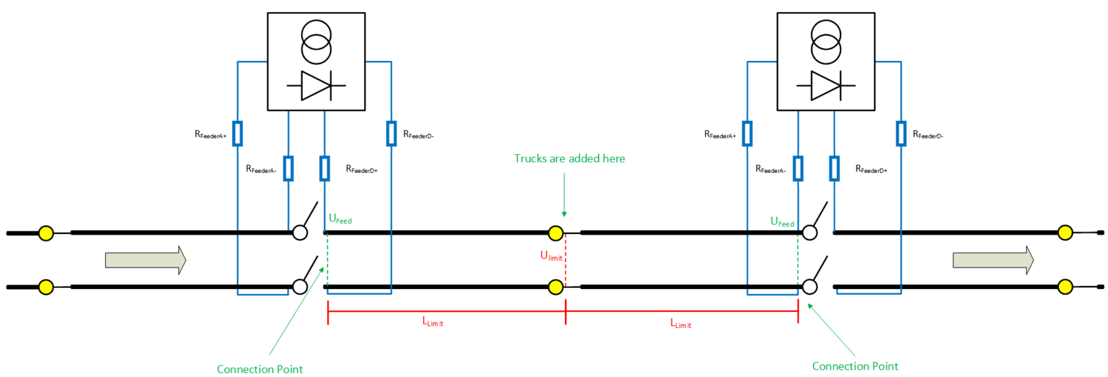

Figure B.1: *The double-feeder solution without any HDV's inserted. Each section of overhead lines is connected to the substations at each end.*

The solution described in the previous section (Section 5.2.1) considered each single stretch of overhead line to be connected to only a single substation, with each of the substations connected to two separate line stretches. The substations are therefore disconnected from each other through the overhead lines, which means that the two line stretches connected to a specific substation will be completely offline in case the substation fails.

Alternatively, it is possible to close the yellow switches in Figure 5.4, thereby giving the line voltage inputs from both ends. This results in each section of overhead lines being connected to the substations at both ends, as shown in Figure B.1. The advantage of using this kind of network comes from the way that the voltages delivered by the two substations can be added to each other at any given point on the overhead lines between them. This results in a greater allowable distance between the substations. Furthermore, it contraries the single-feeder solution, where the residue voltage below U_{Limit} is not used because the overhead line section is simply disrupted after that point.

Appendix C

Calculation Approach - Continued

C.1 Adding Vehicles to the System

With all the required parameters, equations and network topologies defined and ready, it is time to make the actual analysis of the distance between the traction substations. The analyses are made separately for the single-feeder network solution and the double-feeder network solution, respectively. Note that no numerical calculations are performed in this section, as only the method of calculation are shown here. The actual results can instead be found in Section 5.4.2.

C.1.1 The Single-Feeder Solution

Using Figure 5.4 as the starting point, a single vehicle is added at the connection point, resulting in Figure C.1. The only voltage reduction that comes from cable losses are the ones caused by the feeder cables, which means that the voltage input to the vehicle is:

$$R_{eq} = R_{FeederD+} + R_{FeederD-} + R_T \tag{C.1}$$

$$I_{In} = \frac{U_{In}}{R_{eq}} \tag{C.2}$$

$$U_{Front} = I_{In} \cdot R_T \tag{C.3}$$

First, the equal resistance of the entire system is found by Equation (C.1). The system just consists of three resistances at the given moment, so it is not very complex. Then, the total input current is found by using Ohm's law in Equation (C.2). And finally, the voltage difference over the HDV is calculated by using Ohm's law once again in Equation (C.3). Note that the current divider equation is not necessary for this simple network, but it becomes usable in a moment.

Now, the HDV is moved incrementally forward, gradually increasing L_V, causing a voltage drop along the overhead lines to come into play, as shown in Figure C.2. The voltage received by the vehicle is now calculated as follows (note that the feeder voltage is shortened to R_{Feeder} from now on, see Equation (5.2)):

$$R_V = \frac{\rho_{copper} \cdot L_V}{A_{Line}} \tag{C.4}$$

$$R_{eq} = R_{Feeder} + 2 \cdot R_V + R_T \tag{C.5}$$

$$I_{In} = \frac{U_{In}}{R_{eq}} \tag{C.6}$$

$$U_{Front} = I_{In} \cdot R_T \tag{C.7}$$

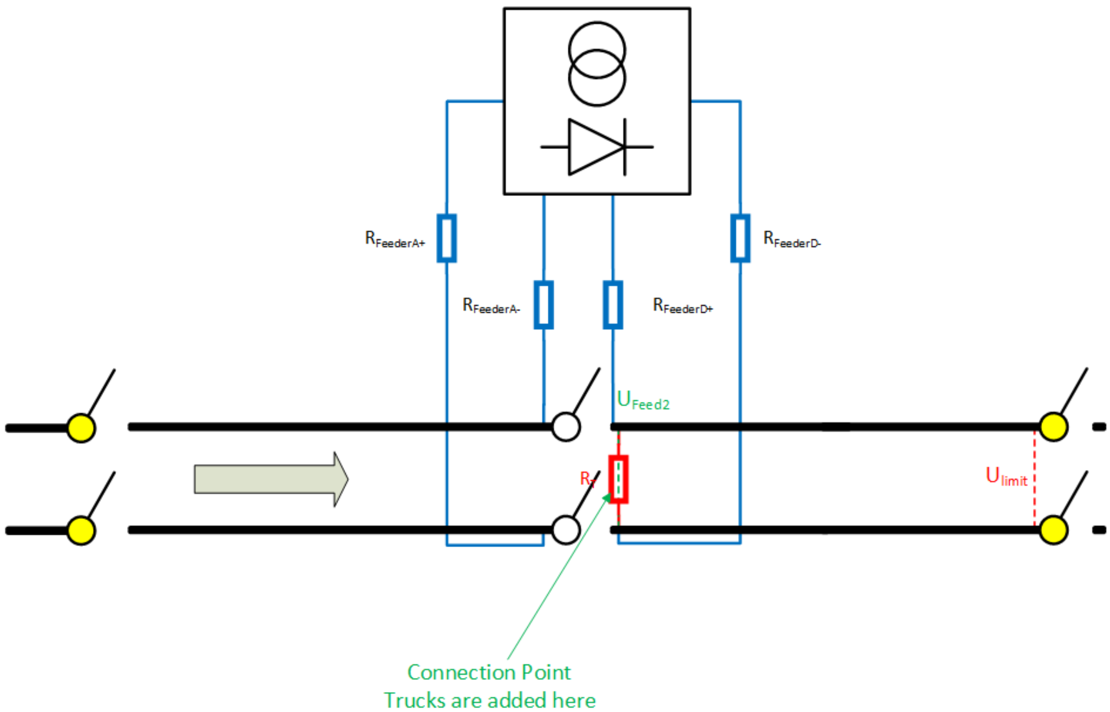

Figure C.1: *The single-feeder solution with one vehicle added at the connection point*

Note that the variable resistance, R_V, increases as L_V increases.
The above equations are used until the length reaches the distance between the HDV's, L_D (see Section 5.4). At this point, the line resistances switches to R_D, and another vehicle is added, as can be seen in Figure C.3.

$$R_{eq} = R_{Feeder} + \frac{(2 \cdot R_V + R_T) \cdot R_T}{(2 \cdot (R_V + R_T)} \tag{C.8}$$

$$I_{In} = \frac{U_{In}}{R_{eq}} \tag{C.9}$$

$$U_{Front} = I_{In} \cdot \frac{R_T}{2 \cdot (R_T + R_D)} \tag{C.10}$$

Now, the current divider equation is used, as noted by Equation (C.10). The addition of a single vehicle adds greatly to the complexity of the equations. In Figure C.4, the entire vehicle caravan is once again moved incrementally, thus gradually increasing R_V:

$$R_V = \frac{\rho_{copper} \cdot L_V}{A_{Line}} \tag{C.11}$$

$$R_{eq} = R_{Feeder} + \frac{(2 \cdot R_V + R_T) \cdot R_T}{2 \cdot (R_V + R_T)} + 2 \cdot R_V \tag{C.12}$$

$$I_{In} = \frac{U_{In}}{R_{eq}} \tag{C.13}$$

$$U_{Front} = I_{In} \cdot \frac{R_T}{2 \cdot (R_T + R_D)} \tag{C.14}$$

In Figure C.5, the caravan has been moved even further, and another vehicle has been inserted. The equation set for this system is more complex than the previous set, and it is therefore *not* shown in this report. A model that automatically update the equation

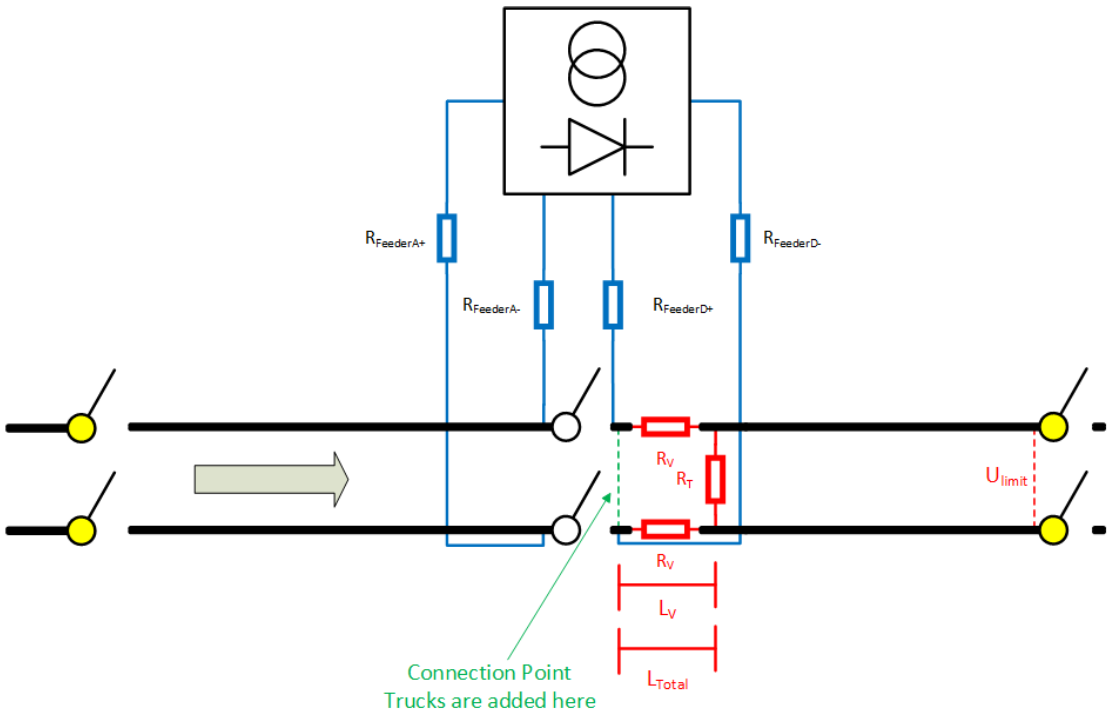

Figure C.2: *The single-feeder solution with one vehicle moved forward from the connection point*

set properly when more vehicles are added to the circuit has been developed as part of the model.

The above procedure of incrementally moving the caravan of vehicles forward while adding a new vehicle each time the caravan has been moved by a distance of L_D is repeated until the point where U_{Front} has dropped below U_{Limit}. When this happens, the distance, L_{Limit}, between the front vehicle and the connection point represents the range of the substation. Furthermore, the number of vehicles connected to the system and L_{Limit} are related by the following equation:

$$N_{HDV} = \frac{L_{Limit} - L_V}{L_D} + 1 \tag{C.15}$$

The overhead line section to the left of the open switches in the middle is analysed using the exact same method; the vehicle caravan is just moved leftward (or backward) instead of rightward. As the feeder resistances are identical for both sides, the substation will have the same range, L_{Limit}, in both directions.

C.1.2 The Double-Feeder Solution

The analysis of the double-feeder system is largely reminiscent of the analysis of the single-feeder system. This time, however, instead of adding vehicles near the substation and moving them towards a point where the voltage level drops below a certain limit, two substations are initially placed at exactly the same position. A vehicle is then added at their shared connection point, and hereafter, the substations are incrementally moved away from each other, increasing the length of the overhead line section while always keeping the vehicle perfectly at the midpoint between them.
After each substation has moved the distance that is expected to be between the vehicles, L_D, two new vehicles are added, one at each substation. After that, the substations continue to move away from each other, until a point is reached where the vehicle at the midpoint (the first

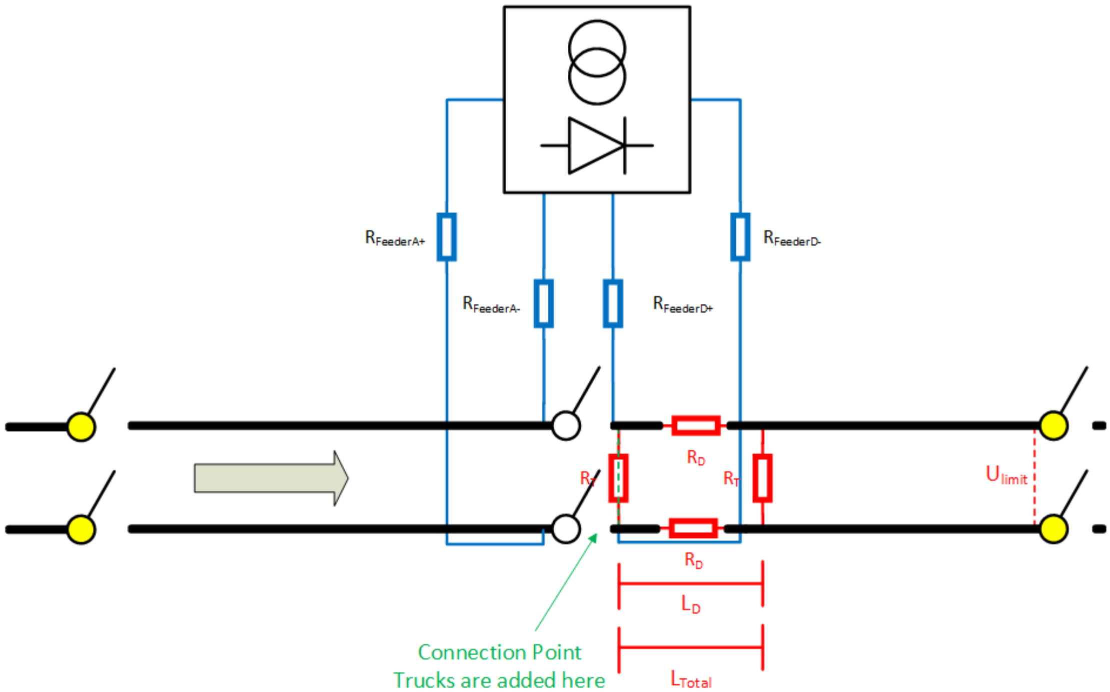

Figure C.3: *The single-feeder solution with two vehicles*

vehicle added) receives a voltage level below U_{Limit}.
The actual equations are largely reminiscent to the ones used for the single-feeder solution and they too increase in complexity with the addition of more vehicles. They are also based on the equations mentioned in Section 5.4.1.

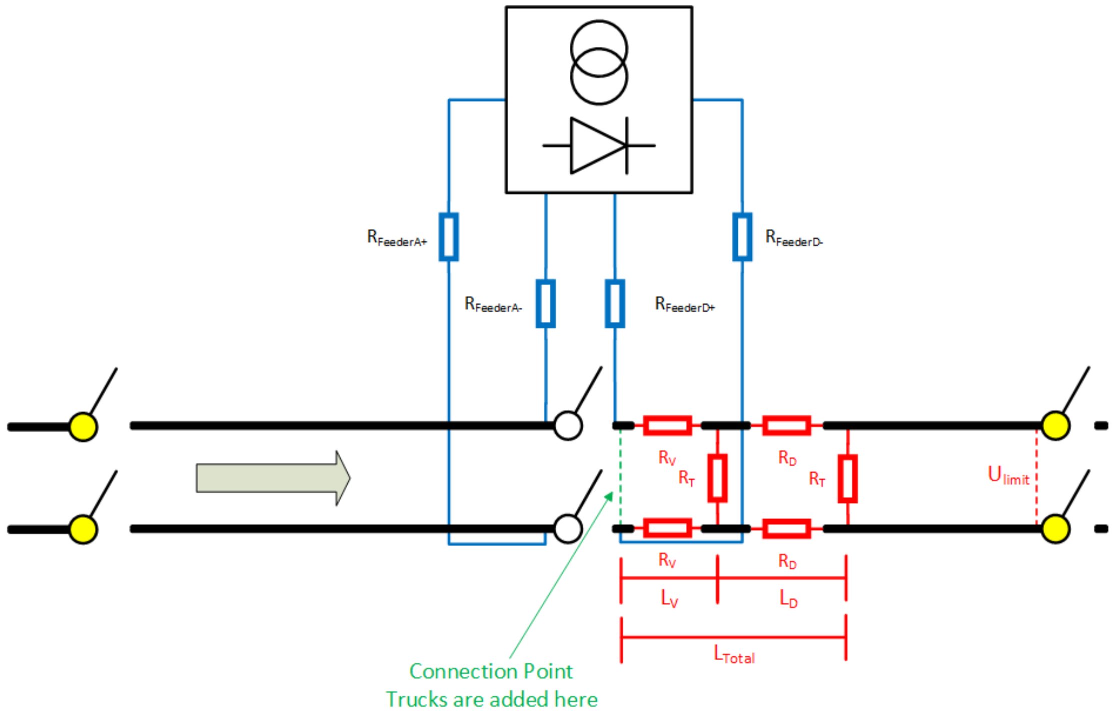

Figure C.4: *The single-feeder solution with two vehicles, moved from the connection point*

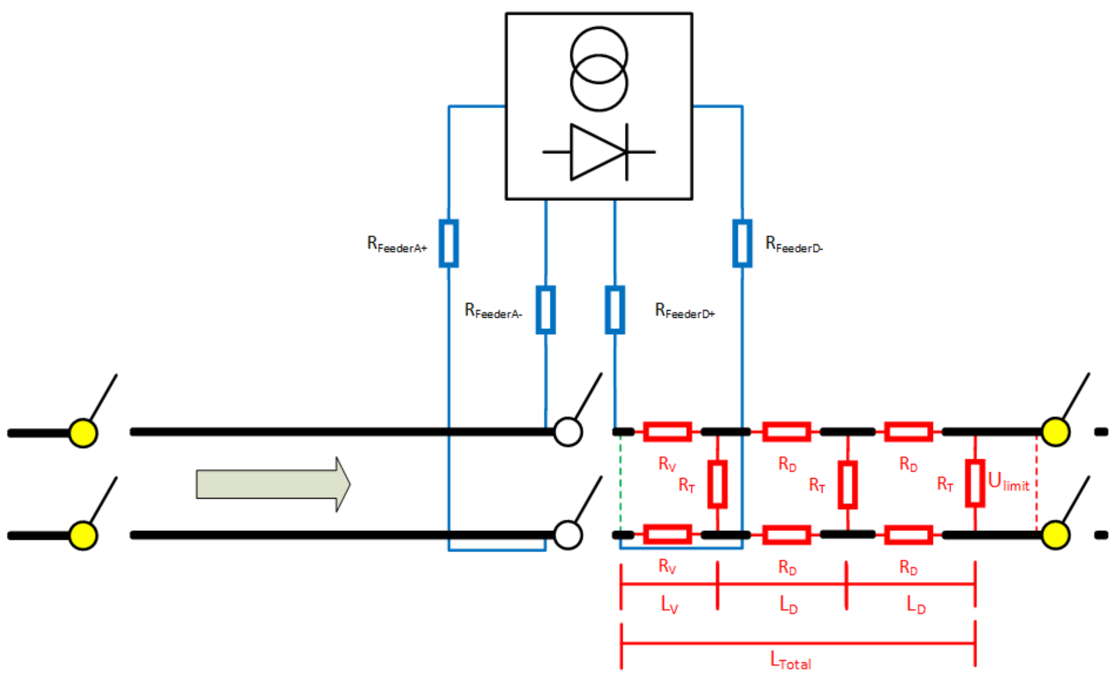

Figure C.5: *The single-feeder solution with three vehicles, moved from the connection point*

Appendix D

Additional Graphs

D.1 Single-Feeder Results

The red curves in Figures D.1 and D.2 represent the voltage level input to the front vehicle at different distances from the connection point. The solution is single-feeder, and the nominal voltage is set to 750 V. The curves figures represent the maximum traffic densities at the four stretches as input and the maximum allowable traffic density as input, respectively.

D.2 Double-Feeder Results

The blue curves in Figures D.3 - D.6 represent the double-feeder solution, and they are provided for each of the four highway stretches as well as the situation where the most dense vehicle traffic that may legally occur is present. Furthermore, they are given for 600 V vehicles and 750 V vehicles.
The x-axes denote the distance between the front vehicle and both of the connection points near the substations that are connected to each end of the overhead line section (see Figure B.1 for reference). The distances between the vehicle and the connection points are equal to each other, as the vehicle is always positioned at the midpoint between the substations, and the substations are completely identical as well. The y-axes denote the voltage level, which the front vehicle receives at the given distance.

A summary of the optimal distances between the substations, including the number of vehicles expected to be present on each line section at the given distance and traffic density, is shown in Table 5.2. Note that the distances are doubled from the distances shown in the figures, as there is an equal length from the front vehicle towards the substations at each direction.

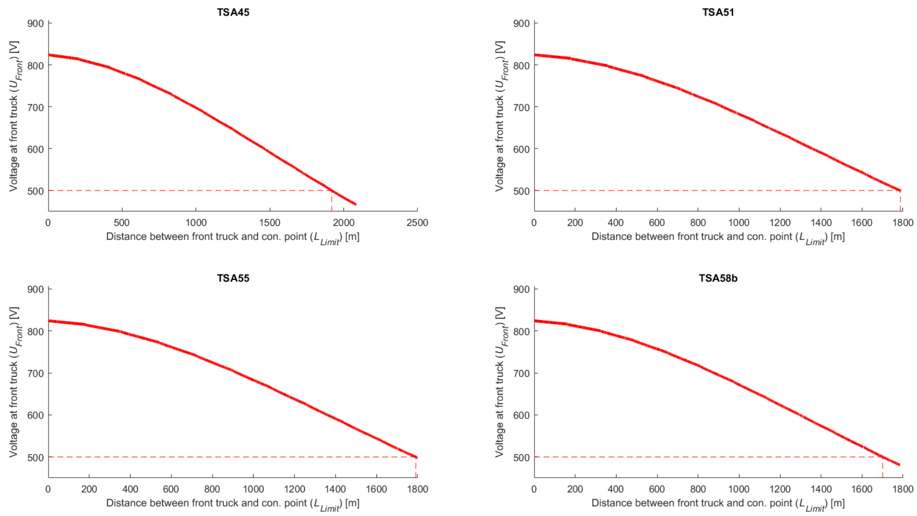

Figure D.1: *Nominal vehicle voltage: 750 V; Solution: Single-feeder; Traffic: Max. measured at stretches*

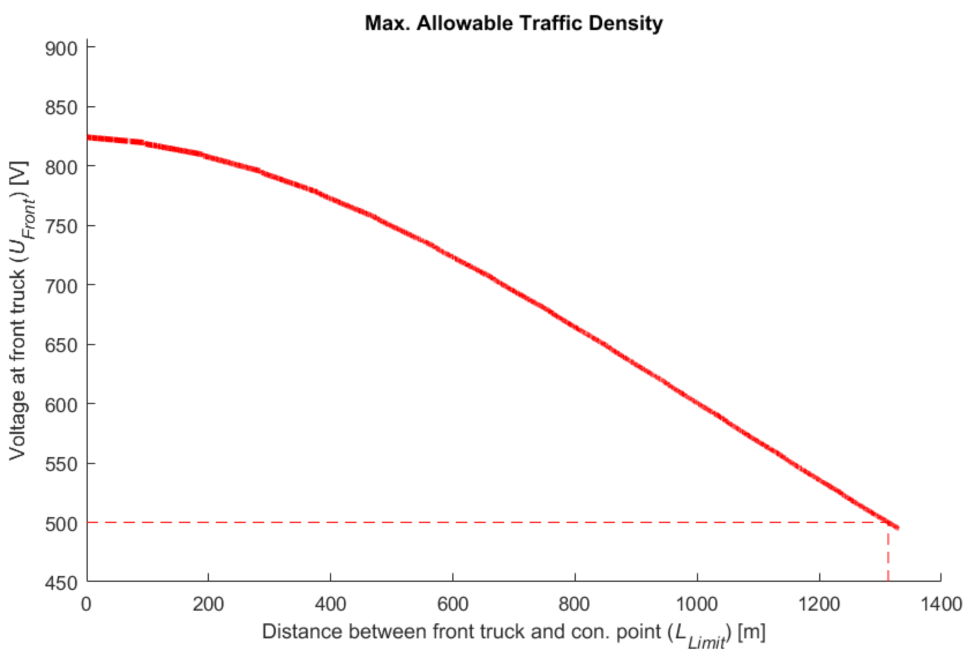

Figure D.2: *Nominal vehicle voltage: 750 V; Solution: Single-feeder; Traffic: Max. allowed in lane*

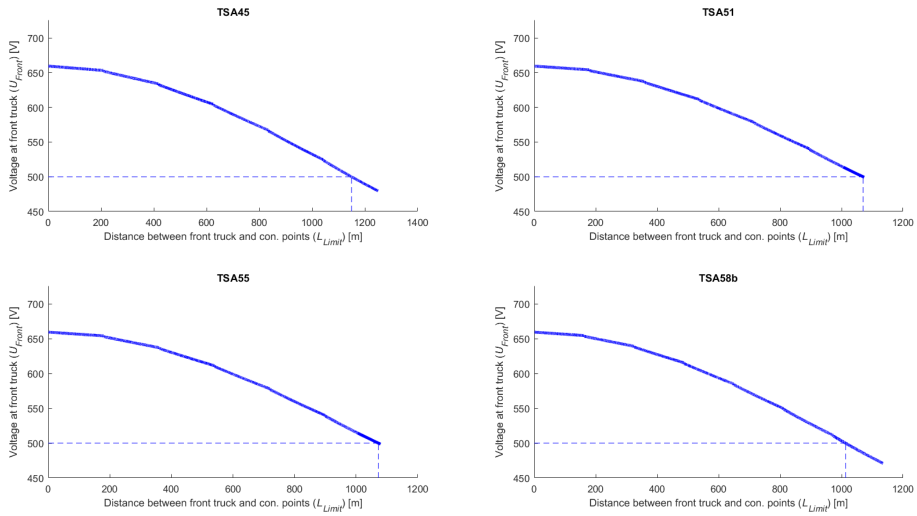

Figure D.3: *Nominal vehicle voltage: 600 V; Solution: Double-feeder; Traffic: Max. measured at stretches*

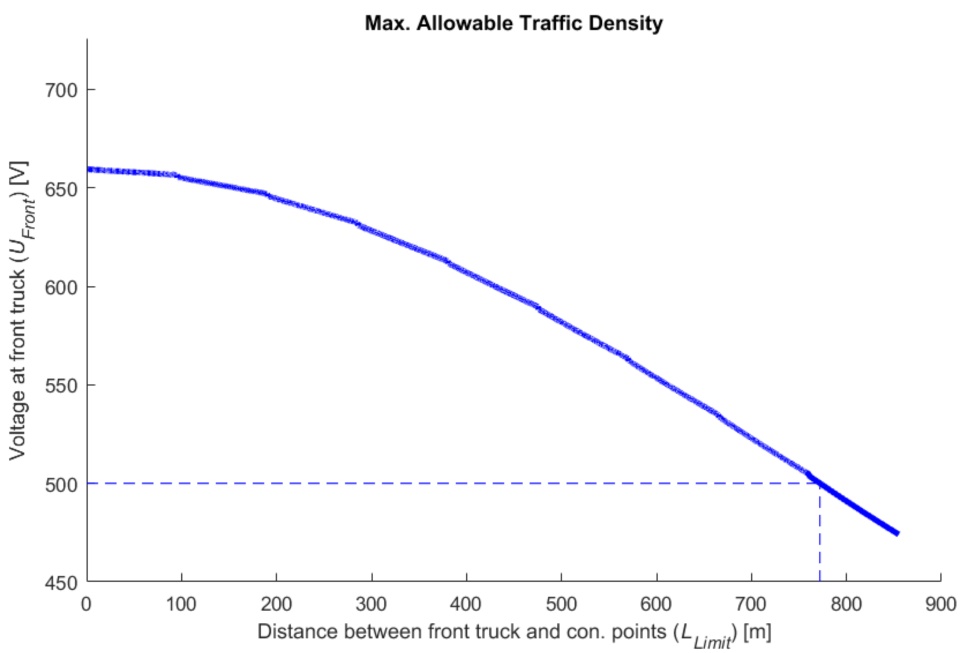

Figure D.4: *Nominal vehicle voltage: 600 V; Solution: Double-feeder; Traffic: Max. allowed in lane*

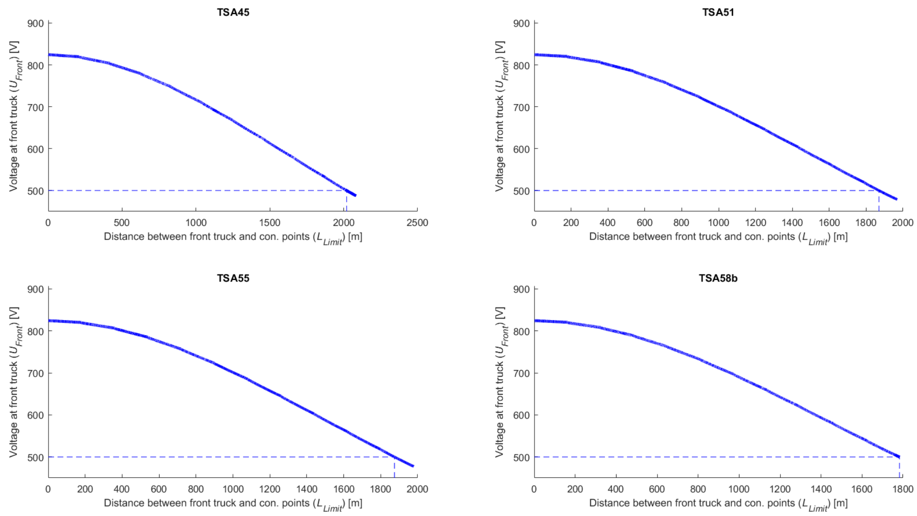

Figure D.5: *Nominal vehicle voltage: 750 V; Solution: Double-feeder; Traffic: Max. measured at stretches*

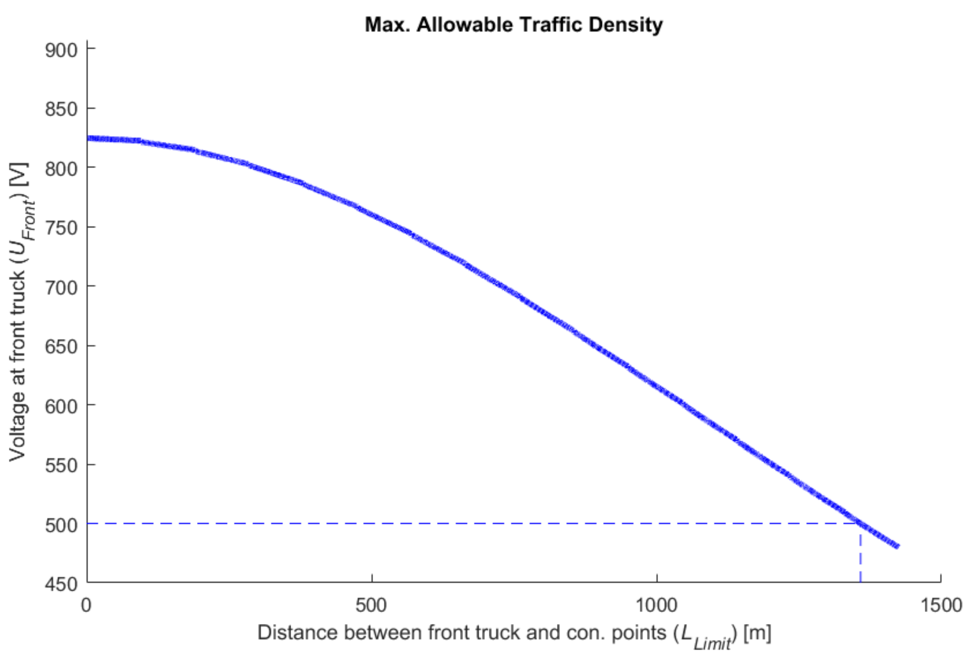

Figure D.6: *Nominal vehicle voltage: 750 V; Solution: Double-feeder; Traffic: Max. allowed in lane*

Appendix E

MATLAB

The scripts can be found in the online Appendix

E.1 Traffic Profiles

This MATLAB script is used to calculate the traffic profiles, both for 2016 and 2050. The script includes the following:

- Weekly average traffic for 2016
- Monthly average traffic for 2016
- 24 hour average traffic for 2016, 2030 and 2050
- Traffic load for 2016 and 2050

E.2 Power Profiles

A series of small MATLAB scripts used to calculate the eHighway consumption, the general consumption and compare them for both 2016 and 2050. The Scripts includes the following:

- Hourly power from eHighway in 2016 and 2050
- Hourly power from the general consumption in 2016 and 2050
- Total hourly power from the eHighway and the general consumption in 2016 and 2050
- Average hourly consumption for a day from eHighway in 2016 and 2050
- Average hourly consumption for a day from the general consumption in 2016 and 2050
- Average hourly consumption for a day combined from eHighway and general consumption
- Monthly consumption eHighway in 2016 and 2050
- Monthly consumption general consumption in 2016 and 2050
- Monthly consumption from eHighway and geneal consumption combined in 2016 and 2050

E.3 eHighway Load Shifting

MATLAB script used to shift the consumption from eHighway 15 hours, in order to get a smoother daily demand curve.

E.4 Frequency Function

Script used to create the frequency function, which can tell how many HDV's (x) there atleast are (y) of the time.

E.5 Traction Substation Distance Model

Scripts used for the model determining the optimal distance between the traction substations.

E.5.1 Single Feeder Model

Script for analysing the single-feeder solution:

E.5.2 Double Feeder Model

Script for analysing the double-feeder solution:

E.5.3 Traffic Data Assembler

Script for projecting the assembling traffic data and projecting them to future years:

Appendix F

Data

The exact data can be found in the online Appendix

F.1 Transformer Data

EnergiFyn provided hourly load data on 20 60/10 kV transformers near the Funish highway TREFOR El-net has provided hourly load data on three 60/10 kV transformers located in or around Middelfart.

F.2 Traffic Data

The Danish Road Directorate, provided the amount of traffic for vehicles between 12.5 m and 22 m and the amount of traffic over 22 m on a half hourly basis for 2016. The traffic has been measured in four placed and in both directions on the Funish highway.

Appendix G

Mails

This chapter will highlight the most important mail replies during the project.

G.1 Siemens

Question
We would like to know if you have an approximate price for the substations used in Siemens eHighway, both 600V and 750V at 1-3MW?
We will use it to estimate the costs of substations for the whole stretch, both at 600V and 750V.

Answer
- *Michael Lehmann*
we do not have/give detailed numbers for the subsystems / components. As a good average you can take 1-1.5 Million EUR per direction and per km for the whole infrastructure, which was give in several publications and newspapers. This accounts for both contact line and substation ... and some add-ons (like crash barriers). A unit price per substation is hard to give.

Question
Hi Michael,
I am writing you on behalf of the bachelor group working with the technical dimensioning of the Siemens eHighway system across Funen.

We would like to know whether or not we have chosen the right way to calculate the distance between substations.

The method we are going to use is as follows:
We are going to use the traffic density on a stretch (we have four different stretches) to find the distance between each truck. By knowing the distance between the trucks and assuming that they keep a constant velocity of 80 km/h, we can find how much current the trucks draw from the overhead lines and thus how large voltage drops that will be present in the lines.
These voltage drops will help us determine a reasonable distance between the positions of the rectifier substations along the highway in order to keep the voltage at a sufficient level for the trucks.

Answer
- *Michael Lehmann*
What you need to know is:

- the specific resistance (ohm/km) of the chosen contact line including return

- the permissible voltage drops (check EN 50163 for nominal voltage ranges of 600 V DC or 750 V DC systems)
- typically substation no-load voltage is at 110 % of the nominal voltage (660 V @ 600-V-system, 820 V @ 750-Vsystem)
- presently the vehicles are limited in the voltage range (600 V system) and may just be operated down to 500 V

maybe it is worth showing the difference from the standardized ranges to the present limits

G.2 Danish Road Directorate

Question
Vi arbejder med et projekt sideløbende med en anden bachelor gruppe omkring Siemens eHighway.
De har tidligere haft skrevet til dig omkring trafik data for lastbiler og modulvogntog over 12.5 m.
I vores projekt bruger vi dataene til at dimensionere det elektriske system der skal bruges til eHighway.
Vi har et par spørgsmål omkring dataene som vi håber du kan hjælpe os med.
Hvor bliver trafikken målt?

- Er det under en motorvejsbro?
- Midt på en motorvejsstrækning?

Der mangler store mængder data fra et par at målepunkterne.

- Hele Januar for målepunkt TSA55
- 1-18 Januar for målpunkt TSA 58b

Hvad er grunden til dette?

Er det muligt at få timevis data for Juli måned 2016 på følgende strækninger?

- TSA 45
- TSA 51
- TSA 55
- TSA 58b

Answer
- *Uffe Ærboe Christiansen*
Jeg skal forsøge at svare på jeres spørgsmål:

- Trafikken bliver målt imellem tilslutningsanlæggene (TSA) – altså midt på motorvejsstrækningerne. Dvs. fx imellem tilslutningsanlæg 44 og 45. Så I burde kunne gå ind på Google maps eller lignende og finde de enkelte målepunkter.
- Der mangler desværre noget data, men sådan er det bare med vores målinger. Nogle målestationer måler ikke hele året rundt. Men med så meget data I har vil det ikke svække datagrundlaget, hvis I bruger gennemsnitsdata for de dage.
- Jeg kan godt se, at det ser ud ti, at jeg har glemt juli måned. Jeg skal se om jeg ikke kan lave et udtræk til jer i næste uge.

G.3 EnergiFyn

Question
Efter at have arbejdet med dataene er der et par ting der undrer os.
Hvorfor har man valgt at installere transformer effekt, der er noget højere end det aktuelle

forbrug?
- Et eksempel: For Gelsted er maks. forbruget i en time 3MW ud af den installerede 10MW
Kan det passe at de negative værdier er effekt sendt fra 10-60kV?

Answer
- *Jesper Knudsen*
Den ratede effekt på 60/10 kV krafttransformere er standardiseret, og kommer i størrelserne 6, 8 10, 16, 20, 25 MVA, (der kan være andre mindre størrelser, men dem er jeg ikke bekendt med). Typisk er den mindste transformerstørrelse der anvendes 10 MVA, hvorfor denne i mange tilfælde er billigere at fremstille end de mindre transformere. Der er dermed et økonomisk incitament for at vælge denne størrelse.

Energi Fyn har ligeledes valgt kun at anvende 10 og 16 MVA transformere, da vi dermed har en standardiseret population, og vi har mulighed for at "flytte rundt" på transformerne mellem de enkelte stationer.

Det tekniske argument er, at krafttransformerne er dimensioneret efter, at skulle kunne forsyne det tilsluttede forbrug i en normal driftssituation, men også kan forsyne nabostationerne, i tilfælde af fejl på en krafttransformer i en af disse. Dette kaldes en n-1 situation.

N-1 kommer af, at der skal kunne opretholdes forsyning af alle kunder ved intakt net (n) og ved fejl på en vilkårlig komponent (n-1). Der regnes i dette tilfælde altid med den komponent der har den største konsekvens for det samlede net. Stationen i Gelsted levere dermed ca. 3 MW ved normal drift, men skal samtidig have kapacitet til at kunne forsyne eksempelvis Årup, Ejby eller Barløse.

Angående målingerne er det korrekt, at en positiv værdi betyder at effekten leveres fra 60 kV nettet til 10 kV nettet, og en negativ værdi betyder at effekten leveres fra 10 kV nettet til 60 kV nettet.

Question
Vi har brug Kabelspecifikationer, El-kort over hvor de forskellige ledninger ligger samt load profiler for Fyn

Answer
- *Klaus Winther*
Jeg har dog et billede af at forbruget til e-highways vil være så stort at de skal tilsluttes direkte i 60 kV stationer.

Vi eftersender forbrugskurver for Fyn og den fremtidige 60 kV-struktur.

I modtager data fra Jesper Knudsen, somogså i rimeligt omfang vil kunne hjælpe jer med yderligeredata.

G.4 TREFOR El-net

Question
Vil det også være muligt at få data fra TREFOR's stationer i Middelfart for 2016?

Answer
- *Nina Hedegaard Christensen*
Hermed data på transformerne i Middelfart for 2016

Question
Kan jeg også få at vide hvad maks effekt/strømmen er??

Answer
- *Nina Hedegaard Christensen*
Nedenfor har jeg indsat et skema med data.
Det er vigtig at sige at der på MØH og MLA er stationsreserve

Question
De data jeg har brug for er, timebelastningen over et år (hvis muligt 2015) for de 3 60/10kV transformere i har placeret i Middelfart.

Answer
- *Nina Hedegaard Christensen*
Jeg har vedhæftettre Excel filer med maksimal strøm pr. time for transformeren i Middelfart i 2015.
De første seks dage ved MLA er der ikke målt data på, pga. renovering på stationen.
Jeg håber derfor du selv kan finde ud af hvordan du vil udfylde disse dage.