Applying the Flow Optimization Model: Dynamic Charging on the Dutch National Roads

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## Management summary

## Introduction

In 2015, the 21ste session of the Conference of the Parties to the United Nations Convention took place in Paris. This session was initiated to come to a climate agreement and succeeded in doing so. An important result is an overall commitment to limiting greenhouse gas emissions. Yet this is not an easy task. In this report, we specifically look at reducing greenhouse gas emissions of heavy duty transportation. One of the most efficient ways to reduce greenhouse gas emissions in transportation is using electricity as an energy source. To overcome the problem of high energy consumption that heavy duty transportation has, we look at the possibility of using dynamic charging.

#### **Problem statement**

One solution for electrifying heavy duty transportation could be the use of dynamic charging as is the results of the first exploration of Rijkswaterstaat towards dynamic charging. The question remains, how should dynamic charging be combined with the current practice of static charging and battery capacity. That has resulted in the following research question:

How can we compute a combination of dynamic charging infrastructure, static charging infrastructure and truck battery capacity, in order to present a competitive case for electrifying heavy duty transportation?

To be able to answer this question we look at heavy duty transportation in the Netherlands. We look at the different dynamic charging possibilities available at this moment. We look at possibilities to optimize the combination of dynamic charging, static charging and battery capacity. We also look at the technological developments that take place and finally we look at the costs and the benefits of the shift that is proposed.

#### Approach

In this research, we have taken a five step approach. These five steps are:

1. Situation analysis – What is the situation of heavy duty transportation in the Netherlands, what technologies are available etc.

- 2. Literature review on optimization models An important part of the research concerns the optimization, therefore a literature review takes place to be properly informed.
- 3. Building the optimization model In this step, the optimization model is created based on the literature of step 2 and adapted to our specific case.
- 4. Social cost benefit analysis (SCBA) this step creates an overview of the costs and benefits involved in the realization of electrifying heavy duty transportation via dynamic charging. The costs and benefits are based on a variety of reports on specific issues and comparable social cost benefit analyses.
- 5. Execution Both the optimization model as well as the SCBA are together combined to get an insight in the overall result.

### Results

For dynamic charging three possible technologies are available. Induction charging, pantograph charging with overhead lines and the drop down pantograph. Of these three technologies, only the pantograph had data available to make calculations possible and therefore we focused, for now, on the pantograph. This does not mean that, in the future, the other technologies should not be considered.

How trucks are going to use dynamic charging comes in two approaches. The two approaches are, (i) driving hybrid: a truck drives electric when dynamic charging infrastructure is available and on conventional fuel on other moments and (ii) full electric driving, a truck drives electric when dynamic charging infrastructure is available, at the same time it charges its batteries. When no infrastructure is available it uses the stored energy of the battery.

These two approaches are combined with different truck energy usages and battery capacities to come to 10 different scenarios. Of these 10 different scenarios, the scenario in which all trucks drive fully electrically with a battery of a 100 km range shows the best results. The results have been calculated over a time period of 100 years with a discount rate of 4.5%. The results are (with the map showing in red the location of the proposed infrastructure) in million euros:

#### **Direct costs:**

-	Infrastructure including	- 2,268
	maintenance	
-	Truck adjustments	- 2,940



# Conclusion

Dynamic charging shows promising results in allowing electric trucks to drive electrically, and this research has shown a method of determining the locations dynamic charging should take place. One should note that the approach used so far is rather theoretical and that only a comparison has been made with conventional techniques but not with other innovative techniques.

v

# Preface

The report that is currently in front of you, forms my thesis and final project for the master industrial engineering and management, specifically the track production and logistics at the University of Twente. During my studies, I came into contact with Rijkswaterstaat and their work with innovation in smart mobility and I got triggered by the world of possibilities. In the end, I was asked to put a proposal on paper for a thesis that had a fit with my master program and could be interesting for Rijkswaterstaat. Even after months of working on my thesis, I am still happy that we found a match with dynamic charging.

During the execution of my thesis and this report specifically, I have had the pleasure to work with- and receive help from others to be able to finish my work. Therefore, I take the opportunity to thank those who have been directly or indirectly involved in the process for their support.

Specifically, I would like to thank Frank ten Wolde for his guidance during my thesis. It has been an honor and a pleasure to work together on this topic. Special thanks for involving me in subjects, directly and indirectly, related to the topic of dynamic charging. It has broadened my horizon both for my personal development and for the benefit of my thesis.

I also need to thank my university supervisor, Peter Schuur for his never ending enthusiasm and interest in the topic. It has always been a pleasure to travel to Enschede to share knowledge and ideas concerning the topic of my thesis and many others.

Finally, I need to thank my direct colleagues at Rijkswaterstaat for their warm welcome and direct inclusion. I am furthermore grateful for the many insights I have been able to receive from all of them during the many conversations and discussions.

Giel van Erp

# Table of contents

Coloph	on i
Manag	ement summaryii
Preface	<b>e</b> vi
1. Int	roduction
1.1.	Problem statement
1.2.	Research question
Mai	n question5
Sub	p-questions
1.3.	Method 7
Ste	p 1, situation analysis7
Ste	p 2, literature review on optimization models
Ste	p 3, building of the optimization model
Ste	p 4, social cost-benefit analysis
Ste	p 5, execution of the optimization & SCBA
1.4.	Overview of deliverables
1.5.	Thesis outline
2. Situ	uation Analysis
2.1.	Dynamic charging technologies11
Ind	uction
Pan	tograph12
Dro	p-down pantograph12
Con	clusion13
2.2.	Energy sources13
Die	sel: Combustion engine13
Elec	ctricity: Battery14
Hyd	Irogen: Fuel cell
Con	clusion16
2.3.	Transport sector
2.4.	Conclusion
3 Lite	erature review on mathematical optimization19
3.1.	Optimization methods, an overview19
3.2.	Optimization methods, the flow-based models19
3.3.	Optimization methods, linear programming21
3.4.	Optimization methods, heuristics23
3.5.	Optimization methods, exact optimization methods24
3.6.	Conclusion25
4. Mat	thematical optimization model27
4.1.	Mathematical optimization model: hybrid27
4.2.	Mathematical optimization model: full electric29
4.3.	Conclusion
5. Soc	cial cost-benefit analysis
5.1.	What is a social cost-benefit analysis
5.2.	Null alternative & scenarios41

5	.3.	Overview of costs and benefits involved	42
	Direc	ct costs	43
	Direc	ct benefits	44
	Indir	rect effects	44
	Exter	rnal effects	44
5	.4.	Conclusion	45
6.	Appl	lication, results & sensitivity analysis	47
6	1.	Application	47
	Appli	ication of the mathematical optimization method	47
	Appli	ication of the SCBA	48
6	.2.	Quick results of all scenarios	48
	Meth	nods for determining quick results and eliminating unpromising scenarios	48
	Quicl	k results of all the scenarios	50
6	.3.	Detailed results of best scenario including sensitivity analysis	52
6	.4.	Conclusion	57
7.	Disc	cussion	59
7. 8.	Disc Conc	cussionclusion & Recommendation	59 61
<b>7.</b> <b>8</b> . 8	Disc Conc 1.	cussion	59 61 61
<b>7.</b> <b>8.</b> 8	Disc Conc .1. .2.	cussion clusion & Recommendation Conclusion Recommendations	59 61 61 62
7. 8. 8 8 Apt	Disc Cond 1. 2. Dendi	cussion clusion & Recommendation Conclusion Recommendations lix A: Mathematical models	59 61 62 62
7. 8. 8 8 Apj Apj	Disc Cond .1. .2. Dendi	cussion clusion & Recommendation Conclusion Recommendations lix A: Mathematical models lix B: Infrastructure costs	59 61 61 62 69 76
7. 8. 8 Apj Apj Apj	Disc Cond .1. .2. Dendi Dendi Dendi	cussion clusion & Recommendation Conclusion Recommendations lix A: Mathematical models lix B: Infrastructure costs lix C: Energy usage	59 61 62 69 76 77
7. 8. 8 Api Api Api	Disc Cond .1. .2. Dendi Dendi Dendi	cussion clusion & Recommendation Conclusion Recommendations lix A: Mathematical models lix B: Infrastructure costs lix C: Energy usage	
7. 8. 8 Api Api Api E	Disc Cond .1. .2. Dendi Dendi Dendi Dendi Dendi	cussion clusion & Recommendation Conclusion Recommendations lix A: Mathematical models lix B: Infrastructure costs lix C: Energy usage y usage	
7. 8. 8 Api Api Ei Api	Disc Cond .1. .2. Dendi Dendi nergy nergy Dendi	clussion         clusion & Recommendation         Conclusion         Recommendations         lix A: Mathematical models         lix B: Infrastructure costs         lix C: Energy usage         y usage         y costs         lix D: Energy supply	
7. 8. 8 App App Ei App App	Disc Conc .1. .2. Dendi Dendi Dendi Dendi Dendi Dendi	clusion & Recommendation Conclusion Recommendations lix A: Mathematical models lix B: Infrastructure costs lix C: Energy usage y usage y costs lix D: Energy supply lix E: Driving on non-national roads and static charging infrastructure	
7. 8. 8 Apr Apr E E Apr Apr Apr	Disc Cond .1. .2. Dendi Dendi Dendi Dendi Dendi Dendi	clussion         clusion & Recommendation         Conclusion         Recommendations         lix A: Mathematical models         lix B: Infrastructure costs         lix C: Energy usage         y usage         y costs         lix D: Energy supply         lix E: Driving on non-national roads and static charging infrastructure         lix F: Network & Routes	
7. 8. 8 App App Ei App App App App	Disc Cond .1. .2. Dendi Dendi Dendi Dendi Dendi Dendi Dendi	clusion & Recommendation Conclusion Recommendations lix A: Mathematical models lix B: Infrastructure costs lix C: Energy usage y usage y costs lix D: Energy supply lix E: Driving on non-national roads and static charging infrastructure lix F: Network & Routes lix G: Emissions	
7. 8. 8 Apr Apr Apr E Apr Apr Apr Apr L	Disc Cond .1. .2. Dendi Dendi Dendi Dendi Dendi Dendi Dendi	clusion & Recommendation Conclusion Recommendations lix A: Mathematical models lix B: Infrastructure costs lix C: Energy usage y usage y costs lix D: Energy supply lix E: Driving on non-national roads and static charging infrastructure lix F: Network & Routes lix G: Emissions on independent emissions	

## 1. Introduction

In the framework of completing my master Industrial Engineering & Management, Production & Logistics Management at the University of Twente, I performed a research at Rijkswaterstaat, the National Road, Water system & Waterway authority in The Netherlands in the direction of electrifying heavy duty transportation via dynamic charging.

In 2015, the 21ste session of the Conference of the Parties to the United Nations Convention took place in Paris. This session was initiated to come to a climate agreement and succeeded in doing so. It resulted in a "twelve-page text, made up of a preamble and 29 articles, provides for a limitation of the temperature rise to below 2°C and even to tend towards 1.5°C. It is flexible and takes into account the needs and capacities of each country. It is balanced as regards adaptation and mitigation, and durable, with a periodical ratcheting-up of ambitions." (COP21, 2016). Although all of the articles have their importance, article 4 is specifically important for this research and covers all sorts of measures and policies intended to limit greenhouse gas emissions.

Limiting greenhouse gas emissions is not an easy task. We have created a society practically based on the use of fossil fuels and the emission of greenhouse gasses that accompany this use. Changing that requires the use of new and often unproven technologies and vast amounts of investments. Therefore governments around the world are involved in the change towards a more sustainable economy. So are the Dutch Government and other institutions in the Netherlands. In the SER-energy-agreement one of the goals was the following: "A reduction of the  $CO_2$  –emission by 60% in 2050 compared to 1990 in transportation" (Ministry of Infrastructure and the Environment, 2014). It is clear that achieving such an enormous reduction while demand for mobility increases, requires extensive changes in all possible ranges. Practically, this means that we have to reduce the emission for the entire mobility sector from 1100Mton today to 320Mton in 2050. Excluding aviation and shipping, the hardest forms of transportation to reduce emissions, the emission space in 2050 for other forms of transportation is close to zero (Ministry of Infrastructure and the Environment, 2016).

One of the most efficient ways to reduce greenhouse gas emissions in transportation is using electricity as an energy source (given that the electricity is produced in a sustainable way). At this point, the development of electric vehicles goes rather fast and it is expected that in the near future both the range as the price of the vehicle is comparible with if not preferable over conventional vehicles. For heavy duty transportation, this is not necessarily the case. Heavy duty uses much more energy per kilometer while space used for batteries should be minimized to maximize the loading capacity. Transportation vehicles furthermore have a much higher utilization rate than passenger cars do, leaving less time to charge, especially when in the future autonomous driving becomes available. Therefore other solutions are being explored at this point. One of these solutions is dynamic charging. Charging a vehicle with electric energy while it drives. The preference towards electricity as an energy source in mobility is further underlined by the minister of economic affairs: "Voor alle modaliteiten waar elektrificatie mogelijk is zou dit moeten worden nagestreefd" (Kamp, 2016, p. 59).

#### 1.1. Problem statement

"Rijkswaterstaat is responsible for the design, construction, management and maintenance of the main infrastructure facilities in the Netherlands. This includes the main road network, the main waterway network and water systems." (Rijkswaterstaat, 2016). Rijkswaterstaat is furthermore partly responsible for reducing greenhouse gas emission as is every government organization. The first step was reducing greenhouse gas emission as a result of the own organization, the second step is doing this for contracted organizations as well. The final and most complicated step is reducing greenhouse gas emission for the user of the product. In the case of Rijkswaterstaat, the user of the roads and waterways. As was discussed before, the challenge to focus on now is the reduction of greenhouse gas emissions by heavy duty transportation.

As was stated, Rijkswaterstaat had issued a report that evaluated the current options for dynamic charging which was delivered in December of 2016. This report briefly discusses the current techniques available, market developments in Europe and the view from a variety of stakeholders. It also discusses the different roles that Rijkswaterstaat could play: knowledge partner, policy advisor, road authority and operator. At this moment, the first two roles are important and in that role, at this point, the economic feasibility requires further research. The economic feasibility is the result of the optimization of investments in dynamic charging infrastructure, static charging infrastructure and battery capacity (EVconsult & Movares, 2016).

Some calculation on the economic perspective towards the application of dynamic charging has already been done. TU Dresden in cooperation with Siemens (2014) worked on the adjustment costs of trucks as well as the infrastructure. These costs form a good indicator to further work upon yet they are far from the eventual optimization we seek. We have translated the data of TU Dresden and Siemens to the Dutch environment, the report stated

that the infrastructure can be cost efficient if 2600 trucks per working day use it. This is the case for over 4400 kilometers of our national road network spread across the entire country This number does not include provincial roads or municipal roads, including these roads, would increase the total amount of kilometers even further. Building infrastructure on all of these kilometers is costly considering infrastructure investment costs between 0.25 up to 2.5 million per kilometer (EVconsult & Movares, 2016), the report by TU Dresden and Siemens (2014) used 2 million per kilometer, making the total investment costs 8.8 billion euros. If we want the technology to be a realistic option, the investment costs should go down. Once again referring to the national energy plan, investments must be made in the most cost-effective way to reduce CO2 emissions, "het beleid voor duurzame mobiliteit wordt geïntensiveerd met als uitgangspunt kosteneffectief CO2 besparen" (Ministry of Economic Affairs, 2016).

#### 1.2. Research question

This section specifically addresses the main question of this research. It furthermore puts more detail on the sub-questions that need to be answered in order to be able to properly answer the main research question. Finally, we give an overview of the deliverables of this research project.

#### Main question

The lack of knowledge we have today leads to the following research question:

How can we compute a combination of dynamic charging infrastructure, static charging infrastructure and truck battery capacity, in order to present a competitive case for electrifying heavy duty transportation?

The first point that arises from this question is that we are going to discuss how to compute instead of what the actual result is. Since we work with new technology, improvements or new insights change the optimum. Therefore, it is much more useful to develop a method of computing instead of giving a combination of numbers that is the expected optimum at this moment. Of course, we do compute an expected optimum, yet the main value is the possibility to update this optimum based on new developments.

# Sub-questions

To be able to answer the main question, we need to answer a set of sub-questions first. These questions help to shape the optimization and acquire the correct input for the optimization model. These questions are:

- What are the transportation needs for heavy duty transport in the Netherlands?
   It is important to get an understanding of the market to make sensible decisions.
   We want to get an understanding what heavy duty transportation practically needs for a transition towards the use of electric powered vehicles.
- 2. What are the features of the different possible technologies for dynamic charging?
  - What are the costs to build the infrastructure for the different technologies?
  - What are the costs to add the new technology to the truck?
  - How much energy can be transported to and from the vehicle per time/distance unit?

To be able to compute correct calculations on the technology, we need to acquire in-depth knowledge of the different technologies available. Since we have the goal to create a competitive case, costs are important, but also what are the technological characteristics so we understand how to use it.

- 3. What optimization method is suited?
  - What different forms of optimization models exist?
  - What heuristics are available to ease the optimization?

Optimization models come in a variety of forms. Here we look at this variety and look at what would be most suitable for our goal. We also look at heuristics, it is likely that the optimization becomes too complex to practically calculate. A heuristic is a simplified version that comes close to the optimum.

- 4. How are technologies expected to develop?
  - How are the different possible technologies for dynamic charging expected to develop?
  - How is static charging expected to develop?
  - How are batteries expected to develop?

Even though the main goal is to develop a form for analysis, acquiring an idea what, given the knowledge of today, is expected to be the result in the future, gives an idea how to handle this innovation.

- 5. What are the benefits of the new technology?
  - What are the expected costs per km for conventional heavy duty transportation?
  - What are the expected costs per km for electric heavy duty transportation?
  - $\circ$  What is the expected decrease in CO<sub>2</sub> emissions?
  - What is the value of decreasing CO2 emissions?

A part of our goal is to present a competitive case, to get to that point we worked towards minimizing the costs through question one to four. Question five discusses whether these cost minimizations were actually good enough. Therefore we need to start looking at the benefits of using the new technologies, we furthermore should not only look at hard cash but also at the social benefit (or costs) that results from the new technology.

# 1.3. Method

This section discusses the proposed method for this research. We discuss the different steps to be taken and how the research questions link to these steps.

## Step 1, situation analysis

The first step is to increase our knowledge of the context of the research. This research step first focuses on research question 1: "What are the transportation needs for heavy duty transportation in the Netherlands?". This part of the study is partly a literature study on transportation and transportation needs in general and partly the application of this general literature to the situation in the Netherlands. To make this application one needs a variety of data. A lot of data is available with the organization (Rijkswaterstaat). If data is not available within Rijkswaterstaat yet essential for a good understanding of the situation, the network of Rijkswaterstaat needs to be used for other sources. Important other sources are (among others) CBS: Statistics Netherlands and Topsector Logistiek (top sector logistics).

The second part in this research step is to discuss research question 2. Several techniques for dynamic charging are available at this moment. The report by Moveres et al. (2016) discusses a set of these different techniques. This report forms a good start for our research on the different techniques of dynamic charging. At the same time, it should not be

seen as more than the start. The research is rather limited on their perspective on the different technologies. This might be the result of the unavailability of the information on the different technologies, whether or not this is the reason, in this case, one needs to strive for more extensive knowledge. Two different methods are used: first a more extensive research on the different technologies, this can be done on via a variety of publications that has been made on the subject or in cooperation with the suppliers/developers of the new technology. Second, if no data is available on the specific technology, an estimate is made based on corresponding technology in different applications. We also look at research question number four, how are these techniques expected to develop.

#### Step 2, literature review on optimization models

The second research step focusses on answering research question three: "What optimization method is suited?". This question is answered via a systematic literature review. To do so, the five-step approach for a systematic review described by Khan, Kunz, Kleijnen & Antes (2003). Even though the five-step approach may seem to be a linear approach, every next step being done, may lead to new insights that require stepping down to a previous step making it an iterative approach.

## Step 3, building of the optimization model

This step is in principle rather straightforward yet at the same time also the most challenging. Here we combine the knowledge acquired in step one and step two to be applicable in our specific situation and translate that to an optimization model. Looking at the research question, the optimization model is the optimization between dynamic charging infrastructure, static charging infrastructure & battery capacity (or hybrid technology range). Therefore we have a cost optimization which, of course, needs to be minimized.

Unfortunately combining all of these variables into one optimization is computationally undesirable. Therefore we only optimize (minimize) the amount and locations of the dynamic charging infrastructure and determine the other factors via scenarios.

## Step 4, social cost-benefit analysis

To properly assess the results of the location optimization and understand what the financial and social implications of dynamic charging on the Dutch national roads are, we execute a social cost-benefit analysis (SCBA). In such an analysis we get an overview of all the costs and benefits involved including external effects. The results of the analysis allow us to judge which scenario is most desirable. To properly execute the SCBA, a multitude of

different sources is used to determine the correct values of the different costs and benefits. These sources include but are not limited to government reports,

# Step 5, execution of the optimization & SCBA

Once an optimization model has been developed and the SCBA structure is determined, the problem can actually be optimized. The optimization is made not just once but for a variety of input variables. The variables in the model need to be treated as well to make the optimization practically calculable.

The optimization model can be used for the three different dynamic charging techniques: induction charging, drop-down pantograph (sleepcontact) and the use of the pantograph. Practically our calculations focus on the pantograph simply because this technology is the furthest in its development and is, therefore, able to provide reliable data (as is further discussed in chapter two). Scenarios differ based on the use of the dynamic charging infrastructure and, as discussed in step 4, on the other factors influencing the total social costbenefit analysis.

Important in this step is the execution of a sensitivity. This case especially needs a good sensitivity analysis since the input variables are doubtful at best and a good insight on how a shifting in the input affects the result is valuable.

## 1.4. Overview of deliverables

During this research, a combination of deliverables has been created. Most important is this report with the findings of our research. Here is an overview of all the deliverables:

- ArcGIS models to create network and routes

ArcGIS is a program used at Rijkswaterstaat for geographical analysis. This research consists of a strong geographical component and uses ArcGIS for that. During this research a flow optimization model is used, an important input for this model is a network of roads and routes that use the network. This network and the routes have been made in ArcGIS.

- Excel macros to transfer ArcGIS output to LINGO input The output of the ArcGIS models cannot directly be used in the optimization that takes place during this research. There a couple of macro's have been written to do the work for us.
- LINGO optimization models

The mathematical optimization takes place with LINGO solver software, the models are a deliverable. The models itself are part of this report as well to allow for the use of other solvers in the future.

- Excel calculation sheets for the social cost-benefit analysis and sensitivity analysis The combination of all factors that make up the social cost-benefit analysis is shown in a set of excel sheets as well as the sensitivity analysis. The results of the sheets are included in this report.
- Report

*Of course, the final report is the most important deliverable since it gives an overview of the entire research and gives the most important insights.* 

# 1.5. Thesis outline

This thesis starts with the situation analysis in chapter 2, the different dynamic charging techniques are discussed as well as alternative energy sources and the transport sector. Then we discuss the literature study on optimization techniques in chapter 3. Chapter 4 uses these techniques to make a mathematical optimization model for our specific application. Chapter 5 discusses the social cost-benefit analysis. Chapter 6 combines the mathematical optimization model of chapter 4 with the SCBA of chapter 5 to compute the results of the impact of dynamic charging on the Dutch national roads. Finally, in chapter 7 the main conclusions, as well as recommendations are presented.

# 2. Situation Analysis

In this chapter, we discuss the context of this research. First and perhaps most important, we discuss the available technologies for dynamic charging in section 2.1. Furthermore, we cannot use dynamic charging infrastructure everywhere, so we need alternative energy sources such as batteries, we do so in section 2.2. Finally, we look at the transportation sector in section 2.3. This research is focused on heavy duty transport, so we need an overview of the needs in the heavy-duty transportation sector.

# 2.1. Dynamic charging technologies

At the moment, three different options for dynamic charging are available: induction charging, pantograph charging and the drop-down pantograph charging. The costs and the charging speed are important for each of these technologies. We consider each of these technologies in this section.

#### Induction

Induction charging is described in patent US 5311973 A as "A battery of an electric vehicle is inductively charged while the electrical vehicle is moving, using a magnetic field along different portions of an extended linear distance and an inductive coil mounted on an electric vehicle, by having the electric vehicle, as it traverses the different portions of the extended linear distance, move within the influence of the magnetic field. An apparatus senses progress of the electric vehicle along the extended linear distance. The apparatus produces the magnetic field by a power switch bank connected to an array of inductive coils." (Tseng & Tseng, 1992). Since then, further innovation has taken place and on this moment field testing takes place, for example in Belgium. Nevertheless, at this moment only small scale projects are present and the costs involved in these projects are rather high and we are furthermore not able to make a sound estimate on what the costs are for a large scale application. Finally, the energy transfer possible is still low about 22kW, especially considering it for the application with heavy duty transportation. On the other hand, we do not have any infrastructure visible and all vehicles can use this technology.



Figure 1, Induction Charging (EVconsult et al. 2016)

# Pantograph

It is easier to make a representation of a pantograph. Pantograph charging is already used in different cases, both trains and trams use the system for electric power. The difference is that trams and trains ride on predefined rail tracks while trucks are more free in how they behave on the road (EVconsult & Movares, 2016). Another example are the trolley busses, for example in Arnhem, in this case, the route is also predefined and the connection between the bus and the electric wires is made in a different way than is done via a pantograph. One of the benefits of the pantograph is the experience with the technology that already exists at this moment due to the applications in rail. Therefore we are also able to make a good estimation of the costs (Appendix A) and also the energy transfer is much higher up to 450 kW.



Figure 2, Pantograph charging (EVconsult et al. 2016)

# Drop-down pantograph

The last technology for dynamic charging we include is the 'pick-up' pantograph or 'upside down' pantograph. In this case, we do not have electric wires above the roads, but we have power strips built in the road. 'The charging lanes are intended to be open to all traffic and the strips would be built in sections, with only one at a time being live as the vehicle passes, so ensuring safety for other road users. Its design incorporates leeway to allow for the truck not being driven precisely over the strips at all times.' (ITS International, 2014). The main advantage for this changes is that we eliminate the problem of height differences of vehicles and therefore allow every vehicle on the road to be connected to the system.



Figure 3, Pantograph charging (EVconsult et al. 2016)

## Conclusion

All of the three technologies can, or have the potential to allow heavy-duty transportation to become full electric. At the same time, none of the technologies are proven and a lot is still unknown both on the cost side of the technologies as well as the features of the different technologies. At this point, we can only present realistic data on the pantograph. Therefore we use the data from the pantograph in our calculations. This does not mean that the other technologies are no longer considered. The development of the different technologies should, in the end, determine which is most suited.

# 2.2. Energy sources

Dynamic charging is not available at every moment, therefore some other form of energy must be available. At the moment many different options are available, diesel is most common at the moment, yet not renewable, therefore we also look at other options, such as storing electrical energy in a battery or using hydrogen and a fuel cell to provide energy when no dynamic charging is available.

#### Diesel: Combustion engine

Currently, the most standard engine in a truck is the diesel combustion engine. Apart from the obvious environmental problems that result from the diesel combustion engine, it does have a set of advantages. The most important one being that it is the status quo. OEM's provide many choices in diesel combustion engines as well as trucks using those engines. Furthermore, diesel is available throughout the world on almost every corner.

# Electricity: Battery

One of the most obvious ways of storing electric energy is in a battery. Yet actually doing so is a bit more complicated and costly, although prices have dropped significantly in recent years and are expected to drop even further. "The average price of lithium-ion battery packs used in EVs fell 65 percent over the period 2010–15 – from \$1,000/kWh to \$350/kWh – and continues to drop, driven by scale, improvements in battery chemistry and better battery management systems. Costs have fallen further and faster than many had expected. They are now forecast to drop below \$100/kWh in the next decade, and could possibly fall as low as \$50/kWh–\$60/kWh in the longer term" (McKerracher et al. 2016). Similar expectations, although with different numbers have been proposed by Goldman Sachs (2016), See figure 4, also in this case the expectation is that in the near future, the cost per kWh is around a 100 dollars. Another important point that comes forward in the report by Goldman Sachs, is the increased energy density. If batteries become cheaper, the space and weight of the batteries become an increasingly more important factor in decision making on battery size (in kWh).

Even though these reports are positive about the development of batteries, and McKinsey and Bloomberg (McKerracher et al. 2016) expect battery prices to drop even further after the 100 dollar milestone has passed, some are more critical, Goldman Sachs (2016), explicitly states that to get to the 100 dollar mark, a technological breakthrough is needed. When we can expect such a breakthrough is hard to predict and if one comes around, it is unknown when and if it reaches mass scale. "Start-ups with novel chemistries tend to falter before they reach full production." (Martin, 2016). Even though we should take a critical standpoint towards the costs of batteries, using a 100 dollars per kWh is reasonable with the currently available information. The uncertainty that does exist should be tested later on in the sensitivity analysis.



Figure 4, battery price development (Goldman Sachs, 2016).

## Hydrogen: Fuel cell

Technically, the energy source for the engine is electricity as well. Yet contrary to storing the electric energy in a battery, electricity is stored in hydrogen. "Unlike traditional combustion technologies that burn fuel, fuel cells undergo a chemical process to convert hydrogen-rich fuel into electricity. Fuel cells do not need to be periodically recharged like batteries, but instead, continue to produce electricity as long as a fuel source is provided." (FCHEA, 2016). To be able to provide in such a fuel source, hydrogen needs to be produced, this can be done via as many energy sources as is the case with electricity and can also come from renewables such as wind or solar power (IPHE, n.d.). Transforming hydrogen into electricity results in the following products: water, electricity and heat and no harmful byproducts (Hydrogenics, 2016) making it a clean option. Yet hydrogen does have its challenges, "The production and transportation of hydrogen in a cost-effective, environmentally friendly manner is one of the major challenges to the development of the hydrogen economy." (IPHE, n.d.). At the moment using hydrogen for transportation is a lot more expensive than other fuels such as diesel, not even to mention the difference with electricity. The expectation is that in the future, due to, among others, increased production efficiency, hydrogen can close the gap with fossil fuels such as diesel. Yet if closing the gap with electricity is possible, in whichever form it is produced, remains questionable (DeMorro, 2014).

# Conclusion

At the moment diesel is the most common energy source, yet it is not renewable and does not provide cutting down greenhouse gas emissions. If we go full electric, the battery is probably the most cost efficient at this moment, yet it limits the driving range of the vehicle, a problem that could be solved by strategically placing dynamic charging infrastructure. Finally, hydrogen seems a suitable alternative for diesel in the future yet the enormous costs at this moment make it not a realistic option.

#### 2.3. Transport sector

"The Netherlands plays a key role in our globalized economy, by connecting producers and consumers worldwide. Our success is based on an alignment of cutting-edge infrastructure and world-class service providers, and our coastal location at the heart of Europe." (Nuffic, 2016). An important part is played by freight transport by road. At this moment 6.8 billion kilometers are made in the Netherlands by trucks, roughly 90% of these kilometers are made by Dutch vehicles and 10% is made by foreign vehicles. The 134 thousand Dutch trucks make 2/3 of their kilometers in the Netherlands and 1/3 abroad (CBS, 2016). Mainports in the Netherlands are the harbor in Rotterdam and Amsterdam Schiphol airport. The top three logistical hubs can be found in Venlo/Venray, West Brabant & Tilburg/Waalwijk (Dijkhuizen, 2016).

# 2.4. Conclusion

Our goal in this research is 'to compute a combination of dynamic charging infrastructure, static charging infrastructure and truck battery capacity, in order to present the competitive case for electrifying heavy duty transportation', with the ultimate goal of reducing greenhouse gas emissions. From the different dynamic charging options available at this moment, the pantograph has the most information available, making it most suitable for further calculations. This does in no way mean that the other options cannot become the preferred alternative in the future.

Looking at the forms of alternative energy, while keeping future calculations in mind, we can distinguish two scenarios. In each scenario, you drive electric while dynamic charging infrastructure is available, if not another source of energy needs to be used. In this chapter, we discussed three possibilities. Most straightforward are diesel or hydrogen, of which we now focus on diesel since the costs involved with hydrogen are not yet competitive. At the point, hydrogen becomes competitive with diesel, a switch can be made. This forms scenario one, scenario two results from the more complicated case in which we choose a battery as the alternative source of energy. A battery means a limited range and therefore more complicated calculations.

# 3 Literature review on mathematical optimization

This chapter discusses the theoretical mathematical options for the optimization. We start with a short overview of the possible mathematical optimization techniques in section 3.1. We then take a closer look what our specific optimization problem looks like in section 3.2. We then differentiate in exact optimization methods and heuristics to be able to solve the optimization in sections 3.3, 3.4 and 3.5.

# 3.1. Optimization methods, an overview

Discussing an optimization we discuss a combinatorial optimization which is "To select the best solution from a finite number of alternatives, which are measured/valued by a certain criterion (objective)" (Schutten, 2014). The criterion is either a minimization or a maximization, the best solution is described by a selection of decision variables. The space of solutions is determined by a set of restrictions or constraints and parameters or input data. An overview of elements of an optimization model is given in figure 5.

Model elements:

- · Parameters, input data
- Objective; formulated as a min/max function

there can be multiple (conflicting) objectives!

- Decision variables (integer, continuous)
- Restrictions/constraints (soft vs. hard)
- · (Restrictive) assumptions

#### Figure 5, Modeling a CO problem (Schutten, 2014)

# 3.2. Optimization methods, the flow-based models

So far, the theory discussed is rather general and can be applied to a large number of optimization problems available and while the general theory is helpful to get an understanding of how to read and understand optimization models and how to adjust them, an enormous amount of options still exist to optimize our specific problem. So at this point, we look at a more specified method of optimization.

Upchurch and Kuby (2010) used optimization models for locating alternative-fuel stations. To do so they have used the p-median model and the flow refueling model. The p-median model is one of the most commonly used location models. This model has a given number of facilities and places them in such a way that the total distance traveled to the facilities is minimized (Hakimi, 1964; Revelle and Swain, 1970). The flow refueling location model (FRLM) is more recent and more specifically applied. The FRLM was developed by Kuby and Lim (2005). It uses flows or round trips as restrictions. A flow is only refueled and therefore permitted if a combination of stations exists on the path of the flow. This model is specifically interesting since it incorporates driving ranges to and from the refueling stations. As an example, we look at the route network shown in figure 6.



Figure 6, Exemplary route network

Refueling is needed after each 400 kilometers. Flows (or routes) under 400 kilometers do not need to be refueled. Flows over 400 kilometers (AD, AF, BD, BF, CE, CF, DE, both ways) would not be permitted of no refueling option is placed in the network. These routes are only permitted if we place refueling options in B, C, D and F. If we want to reduce the number of refueling options while still being able to reach each individual destination, we could decide that non-optimal flows are just as good as the direct flow. This would half the number of refueling locations to B and C. In this case, getting from D to E and from C to F takes a longer flow. Even though this optimization model is already challenging on a bigger scale, the model cannot be directly applied since, in the case of dynamic charging, refueling stations are not a point on a path, they also have a distance. Solving this optimization model can be done via exact methods or heuristics depending on the needs of the solution.

Bapna, Thakur & Nair (2001) developed an integer linear programming approach (linear programming further discussed in section 3.3.) for optimally locating refueling stations. They presented a model that optimized the balance between coverage and costs. They optimized given the existing road network, given the traveling population and given the location of existing facilities. They formulated the Maximum covering/shortest spanning subgraph problem, an alteration of the maximal covering location problem of Church &

ReVelle (1974) and the more specific maximum covering/shortest path problem by Current, ReVelle & Cohon (1985).

The FRLM is only one example of the different flow based models available today. Li & Huang (2014) described the different flow based optimization models as is shown in Table 1. For our model, the main objective is to minimize the costs of the of the refueling stations (in our case in the form of dynamic charging infrastructure). The major constraints are to satisfy all travel demand and the vehicle range. We furthermore only look at the shortest path since the new approach should not further complicate vehicle planning and routing than it already does.

# 3.3. Optimization methods, linear programming

A common method of describing and solving an optimization method is via linear programming. Linear programming (LP) can be defined as "maximizing or minimizing a linear function subject to linear constraints" (Ferguson, 1958). An LP problem is described in the same manner as other combinatorial optimization problems, an objective function with restrictions, that are described via parameters and variables. An example is the following:

*Maximize*  $x_1 + x_2$ 

Subject to:

- 
$$x_1 + 2x_2 \le 4$$
  
-  $4x_1 + 2x_2 \le 12$   
-  $-x_1 + x_2 \le 1$   
-  $x_1 \ge 0$   
-  $x_2 \ge 0$ 

This example shows a maximisation with five constraints and two variables:  $x_1 \& x_2$ . The parameters are not specifically described but the numbers are directly given. Due to the simple nature of this example, we can show the solution space that is allowed under the constraints. The answer is the maximum value that lies within that solution space, see figure 7.

	$model_6$	Wang's			DFRLM5			$FRLM_4$			FILM-D <sub>3</sub>			$FIFLP_2$		1	MPRLM	Models
charging	stations locations	Minimize the costs of			Maximize covered flows			Maximize covered flows	inconvenience	or minimize expected	Maximize covered flows		flows	Maximizes covered	stations	locating refueling	Minimize the Cost of	Objectives
1		ı			ı			I			ı			ı	I		ı	Major
Vehicle range	travel demand	Satisfy all	station	charging	Number of	station	charging	Number of		facilities	Number of		facilities	Number of	Vehicle range	travel demand	Satisfy all	Constraints
		One shortest path	paths	including deviation	At most one path			One shortest path	paths and deviation	including pre-planned	Multiple paths			One shortest path	and deviation paths	including shortest paths	Multiple paths	Paths considered between an O-D pair
		No			Yes			Yes			No			Yes			Yes	Travelers Routing choice
- Hydrogen stations	stations	- Ev charging	- Hydrogen stations	stations	- Ev charging	- Hydrogen stations	stations	- Ev charging		service facilities	- Discretionary	stations	inspection	- Billboard		stations	- EV charging	Applications
$_1$ Li	i & F	Huan	g, 20	)14							4 <b>K</b>	Kuby	& L	im, 2	2005			I
$_2\mathbf{B}$	erma	ın, La	arsor	n & I	Fousk	ta 199	92; F	lodg	son,	199(	) <sub>5</sub> K	Kim d	& Ku	ıby, 2	2012			
3 Berman, Bersimas & Larson 1995;								<sub>6</sub> V	Vang	g 200	7,200	08; W	ang	& Li	n, 2009			



Figure 7, graphical representation of solution space (Ferguson, 1958).

This solution space is not so clear for larger amounts of variables and constraints. Furthermore, if we have variables that are only allowed to be an integer (integer linear programming), the solution space becomes even more complicated.

# 3.4. Optimization methods, heuristics

A common solution to large and complicated problems for which retrieving exact solutions might seem difficult if not impossible are heuristics. Heuristics are algorithms and methods to determine a feasible solution that comes close enough to the optimal solution. The common heuristics are:

o LP-relaxation

Making a model simpler to compute by removing a restriction. In the case of an integer linear programming model (ILP), solve as a linear programming model without integer variables.

- Constructive methods
  - Greedy approach
    - Add a building block in every step
  - Adaptive search Heuristic is a combination of dispatching or priority rule heuristic and a random search method
- o Local search methods
  - Simulated annealing

Simulation method that starts as a random search, almost all change are accepted later only improvements are accepted. Acceptance is based on probability.

Tabu Search

Local search method with the option to escape a local optimum. All neighbor solutions are evaluated, the best is selected even if this one is not better than the current solution.

Li & Huang (2014) used the greedy approach to construct the solution for the flow optimization model. The basics of the algorithm are as follows:

- Step 0: Set all infrastructure to 0
- Step 1: Check if all routes can be covered by the placed infrastructure. If yes, stop and we have the final solution; otherwise continue with step 2.
- Step 2: determine for each possible stretch of infrastructure the weight.
- Step 3: Add the stretch of infrastructure with the highest weight. Go to step 1

To get even better results, Li & Huang (2014) described three possible extensions, preselection, substitution and solution refining. In the pre-selection, the possible stretches that have to be executed with infrastructure are identified. Substitution is used to create alternative solutions apart from the solution created in the original greedy approach. Finally, in the solution refining, possible stretches that could be deleted are deleted.

The seam algorithm was used to ease the FRLM problem by Lim and Kuby (2009). They implemented a set of heuristic algorithms. They have used greedy-adding, greedy-adding with substitution and genetic algorithms. The genetic algorithm was used to further optimize this problem since it had proved to perform well compared to tabu search and simulated annealing.

# **3.5.** Optimization methods, exact optimization methods

Exact methods intend to find the exact optimum of an optimization problem. While the precise answer is always desirable, it is not always practically possible to come to such an answer because it requires large amounts of processing time. In the case of *explicit enumeration*, each possible answer is being generated and the best solution is chosen. One can

imagine that for larger problems with many possible solutions, the computation time becomes undesirably large. Therefore some other techniques are available that are able to limit that computation time:

o dynamical programming (DP)

Dynamic programming breaks down a complex problem into smaller problems, the result of such a smaller problem is solved just once and stored for later use in the bigger overall problem.

 $\circ$  cutting plane methods

These methods intend to reduce the initial problem, the cutting plane method uses the result of the relaxation, if the relaxation is a feasible solution, this solution is used, if not the method searches for an option to 'cut a plane' from the current formulation reducing the solution space. This process is repeated until either a feasible solution is reached or another stopping criterion is met (Bertacco, 2005).

 $\circ$  branch-and-bound

A method in which the solution space is split into different branches with the hope that certain branches can be eliminated thus reducing the computation time of the problem. A branch can be eliminated if the result is either already bigger (in a minimization) than the upper objective bound (the best feasible solution so far), or lower (in a minimization) than the lower bound (the first lower bound is the LP relaxation, the lower bound is then increased (in a minimization) if no lower solutions are possible anymore).

# 3.6. Conclusion

The flow optimization models give us plenty of insight to create a mathematical optimization model that is able to help us answer the main question of this research. We also got tools and techniques to be able to optimize the model. Most desirably, it would be an exact optimization, yet it is likely that (parts of) a heuristic are needed. We use the flow optimization model to create a model specifically for our case. The mathematical optimization model used in this research is discussed in chapter 4. To apply the model we need different techniques both exact and from the heuristics, to be able to optimize our problem. This is discussed in more detail in chapter 6.

## 4. Mathematical optimization model

Optimizing the new technology cannot only be done for a set of different technologies, also the way in which these technologies are applied differ. We look at two different options, the hybrid option and the full-electric option. Different forms of application also mean a different form of optimization. Chapter 4 first discusses the hybrid optimization in section 4.1 and then the full electric optimization in section 4.2. This chapter only discusses the models that are applied in this research, other models: the optimization method with a limited budget and the theoretically desirable optimization, are shown in Appendix A.

#### 4.1. Mathematical optimization model: hybrid

The hybrid approach is rather straightforward. In this case, trucks have an engine with two different energy sources, one is electric energy supplied by dynamic charging infrastructure and another source that can easily be transported and is broadly available. At the moment this is most likely diesel, but in the future renewable options might become viable such as bio-diesel or hydrogen.

Practically this means that a truck drives electric when dynamic charging is available and at any other moment, the truck uses a different energy source to drive. Since we like to take a rather conservative point of reference, we take diesel as the different energy source. First, it is readily available and therefore likely to be the first choice by the industry. Second, diesel is the cheapest option available at this moment. In other words, the competition for electric charging is hardest to win if the alternative, in this case, diesel, is cheap.

The hybrid approach itself is rather straightforward and the mathematical optimization is that as well. The value created with dynamic charging is the difference in electricity price per km over the diesel price per km. This results in the following optimization:

#### **Indices:**

b Interval, The network of Dutch national roads is divided into intervals, these intervals are based on the so-called 'baanvakken'.

 $b = \langle b1, b2, b3, \dots bN \rangle$  with N the maximum interval number.

## **Parameters:**

We have two sorts of parameters, one describing the network of so-called 'baanvakken' and its characteristics and the other describing the costs and benefits of driving electric.

etmaal3 <sub>b</sub>	The number of trucks driving over interval b on average per day in
	2016.
lengtebaankmeter <sub>b</sub>	The length of each interval b in kilometers.
profitperkm	The profit of driving one truck for one kilometer electrically. (profit is the comparison of driving electric vs diesel and is calculated for the entire time horizon that is considered including a possible increase in trucks based on the 2016 level).
infracostperkm	The cost of constructing and maintenance of one kilometer of dynamic charging infrastructure. (costs are calculated for the time horizon that is considered including the replacement of infrastructure at the end of its lifecycle
Decision variables:	
<b>REVENUE</b> <sub>b</sub>	Possible profit made per interval b (profit is of course only made
	if dynamic charging infrastructure is placed).
COST <sub>b</sub>	Possible cost made per interval b for the dynamic charging
	infrastructure (costs are of course only made if dynamic charging
	infrastructure is placed).
Y <sub>b</sub>	Integer variable, 1 if the infrastructure is placed on interval b and 0 if no infrastructure is placed on interval b.

**Objective function:** 

$$Maximize \ \sum_{b} Y_{b} * (REVENUE_{b} - COST_{b})$$
(1)

(For all b)

Subjected to:

 $REVENUE_b = etmaall3_b * 365,25 * profitperkm * lengtebaankmeter_b$  (2)

(For all b)

 $COST_b = lengtebaankmeter_b * infracostperkm$ (3)

(For all b)

 $Y_b = \{0, 1\}$ (4)

(For all b)
These Dutch national roads are split up in so-called 'baanvakken' represented in the optimization with 'b'. A 'baanvak' is a part of the road on every point a driver can make a decision (stay on the road or leave for example) a (or more) new 'baanvak' begins. The goal is to maximize the profit by placing dynamic charging infrastructure on the different 'baanvakken' (1), a 'baanvak' is executed with dynamic charging infrastructure if  $Y_b = 1$  and it is not executed with the infrastructure if  $Y_b = 0$  (4). Practically, every single 'baanvak' that has a positive profit (revenue – costs) is executed with dynamic charging infrastructure. The revenue per 'baanvak' (2) is calculated using the difference in costs between driving one kilometer on diesel, the profit is the combination of the difference in energy costs, emissions, maintenance costs etc. That is the profit that results from one truck passing by on one kilometer. To get the total revenue for the 'baanvak', we multiply the total amount of trucks per day, we multiply it by the days of the year and the length of the 'baanvak'. The costs for each 'baanvak' (3) are the costs per kilometer for the dynamic charging infrastructure multiplied by the length of the 'baanvak'. This includes both investment costs of the infrastructure and maintenance of the chosen time period.

The mathematical optimization model is a simplified representation of reality. To do so, a set of decisions have been made. The most notable decisions are:

- In the model, we look at revenue, this is not revenue specific for the one providing the dynamic charging infrastructure, but the total value created with the application of dynamic charging infrastructure. How revenues are divided among the different parties involved is a policy issue that is not considered at this point.
- The costs that are calculated so far are only the costs of the infrastructure. Other costs, such as adjustment costs to adapt the trucks, are not taken into account simply because they do not influence the results of the optimization model, considering the main result are the locations the dynamic charging infrastructure is placed. Such costs are included in the overall cost-benefit-analysis.

#### 4.2. Mathematical optimization model: full electric

The full electric approach is more difficult than the hybrid approach since energy levels play a role now. On the other hand, it allows us to make more specified decisions and define smarter locations to place the dynamic charging infrastructure. In this case, a truck drives electric all the time. The truck charges at beginning and end points of a trip, but also during the trip via dynamic charging infrastructure. In reality, it might be impossible or not desirable to create dynamic charging infrastructure to allow all trucks to become full electric since heavier trucks have a higher energy consumption. Therefore the model consists of two parts, the full electric truck and the hybrid truck. In which the hybrid trucks functions as the truck in section 4.1. and the electric truck consists of an electric engine and a battery to supply energy during the moments no dynamic charging is available. The size of the battery can differ as well as the percentage of the trucks we want to be able to become full electric. These differences are not included in the optimization model, these differences are options for which the optimization model is executed.

Including energy levels makes the optimization considerably more difficult than the optimization in section 4.1. We furthermore have a different perspective in this case. In the previous section, we included as many parts with dynamic charging infrastructure as was economically possible and so maximizing the profit. In this case, making a profit is not the main concern, here we have the goal to allow trucks to go around full electric while minimizing the costs. The model is based on the Flow Optimization Models as discussed in chapter 3. This means we have a road network, in our case the Dutch national roads, and an extensive set of routes created on these roads to define the locations of the dynamic charging infrastructure.

The model we present in this section is not the perfect model we wish to use. But the adaption (the theoretical desirable model is shown in Appendix A). The main reasons for adaption are:

- It is impossible to divide the national roads in stretches of equal length (it might be possible for short stretches, yet that would not improve calculability), so we needed to adjust the model so non-equal stretches are possible and dealt with correctly.
- Energy usage is not equal across different trucks, we partly cover this problem by creating scenarios for which a different percentage of the trucks drives fully electric, but using ranges instead of energy level makes the calculation considerably easier.
- The final problem is the cost calculation for the infrastructure itself. Unfortunately, the data we have available on the costs of the infrastructure is not detailed enough to create a realistic vision via the theoretical model. we only know an estimation of the costs per kilometers. To prevent the model from including extremely small

stretches of infrastructure, we use a minimum stretch of consecutive infrastructure of five kilometers

Since the model is much more complicated than the model in 4.1, we use a rather extensive form the write down the model. We first explicitly explain the indices, parameters and variables before describing the objective function and the corresponding restrictions.

#### **Indices:**

The model uses two indices, one to indicate the interval and one to indicate the route number. The indices are used throughout the model to indicate the network in which we optimize the costs that we optimize for and the routes that form the constraints.

i Interval, The network of Dutch national roads is divided into intervals, these intervals together form the network on which the routes are being created, each interval has a number so:

 $i = \langle i1, i2, i3, \dots iN \rangle$  with N the maximum interval number.

r Route number, each combination of destination and starting point forms a route, each route has a number so:

 $r = \langle r1, r2, r3, ..., rM \rangle$  with M the maximum route number.

#### **Parameters:**

The model consists of many different input parameters, they can be categorized into two categories, the first set of parameters discusses the routes and their energy levels and are so setting the restrictions of this optimization but also creates information on the network itself. The second set of parameters discusses the costs of the dynamic charging infrastructure.

routes<sub>r,i</sub> Routes composed of a route number r and an interval i, if route r uses interval i, routes (r,i) = 1 otherwise 0, using the example network (note: the example network is just to show how the parameters, variables and indices work, it is not big enough to test the model), the routes(r,i) input results in the following table:

A 1 2 B 3 5 C Example network	D	• i1	• i2	• 13	• i4	• i5
A-B	<b>R1</b>	1	1	0	0	0
A-C	R2	1	0	1	1	0
A-D	R3	1	0	1	0	1
B-C	R4	0	1	1	1	0
B-D	R5	0	1	1	0	1
C-D	R6	0	0	0	1	1

Note: For the example, we only include the routes in one direction, of course, you should include two directions for a correct result.

routeorder<sub>r,i</sub> A number representing the i index of the previous interval in a route. Parameter routes(r,i) gives the combination of the intervals that are used, yet it does not give the order in which the intervals are used in the route. We need to know the order of used intervals to be able to properly calculate the energy levels in of each route on each interval. High, useless numbers (at least higher than iN) indicate that it is the first used interval of a route. Using the same example network, the order(r,i) input results in the following table:

		i1	i 2	i 3	i 4	i 5
AB	<b>R1</b>	1000	1	n.v.t.	n.v.t.	n.v.t.
AC	R2	1000	n.v.t.	1	3	n.v.t.
AD	R3	1000	n.v.t.	1	n.v.t.	3
BC	R4	n.v.t.	1000	2	3	n.v.t.

BD	R5	n.v.t.	1000	2	n.v.t.	3
CD	R6	n.v.t.	n.v.t.	n.v.t.	1000	4

Previous<sub>i</sub> A number representing the i index of the previous interval on a road. Next to routes, we also have roads in our case road (1,2), road (3) and road(4,5). Roads are needed to properly calculate the costs of the infrastructure.

i1	i 2	i 3	i 4	i 5
1000	1	1000	1000	4

Once again we use a value greater than iN to identify the first interval of a road. Note: once again, in reality, the routes have two directions, for the example, we use only one.

distance<sub>i</sub> Unfortunately, not every interval is the same length, therefore, we include the distance of each interval.

i1	i 2	i 3	i 4	i 5
200	198	206	206	4

Lastinterval<sub>r</sub> The last interval of each route, so we can calculate the minimum level of range at the end of each route.

r 1	r 2	r 3	r 4	r 5	r 6
2	4	5	4	5	5

lastrestriction<sub>r</sub> The minimal amount of range that needs to be left in the last interval (further explanation in Appendix E)

r 1	r 2	r 3	r 4	r 5	r 6
2	4	5	4	5	5

maxrange A battery cannot grow without a limit. Therefore the range can also not grow without a limit. Possible energy can only be stored up to this limit.

intensity<sub>i</sub> Number of trucks per day on interval i.

i 1	i 2	i 3	i 4	i 5
1200	1300	1000	1000	400

pricemeter The costs for constructing the dynamic charging infrastructure per meter.

rangesupply Multiplicator of range so the amount of range added per unit of distance.

benefit	The benefit of having one truck drive electrically for the entire time horizon of the calculation for one unit of distance compared to driving diesel.			
benefitRUR	Location specific benefit of having one truck drive electrically for the entire time horizon of the calculation for one unit of distance in a rural area compared to driving diesel.			
benefitURB	Location sp entire time area compa	pecific benefit of having one truck drive electrically for the horizon of the calculation for one unit of distance in an urban ared to driving diesel.		
benefitHUR	Location specific benefit of having one truck drive electrically for the entire time horizon of the calculation for one unit of distance in a highly urban area compared to driving diesel.			
bigM	Large value	e used for linearization		
Decision variables	o 0			
INFRA <sub>i</sub>		1 if infrastructure is placed on interval i, 0 otherwise		
RANGE <sub>r,i</sub>		Energy level of route r in interval i (cannot be less than 0 or more than battery capacity)		
INTERVALINARO	DW(i)	Length of all consecutive intervals with infrastructure up until interval i		
PRICE <sub>i</sub>		Price of infrastructure in i, depending whether infra is placed on previous intervals of i or not		
BENEFIT <sub>i</sub>		Direct economic benefit resulting from the trucks that do not drive fully electric on each interval		
LBENEFIT <sub>i</sub>		Extra benefits that result from a specific location (PMx)		
$D_i/X_i\!/Y_i\!/\!Z_i$		Dummy variable to solve linearization		

**Object function:** 

 $Minimize = \sum_{i} INFRA_{i} * PRICE_{i} - INFRA_{i} * BENEFIT_{i} - INFRA_{i} * LBENEFIT_{i}$ 

(1)

Subject to:

$RANGE_{r,i} = MAXRANGE - routes_{r,i} * distance_i + routes_{r,i} * INFRA_i * distance_i$	(2)
$+ routes_{r,i} * INFRA_i * range supply * distance_i$	
(For all <i>r</i> and all <i>i</i> , if order <sub>r,i</sub> =1000)	
$RANGE_{r,i} = MIN \{ 1, 2 \}$	(3)
1. $RANGE_{r,order_{r,i}} - routes_{r,i} * distance_i + routes_{r,i} * distance_i * INFRA_i$	
+ routes <sub>r,i</sub> * distance <sub>i</sub> * $INFRA_i$ * rangesupply	
2. MAXRANGE	
(For all <i>r</i> and all <i>i</i> , if order <sub>r,i</sub> $\neq$ 1000 AND routes <sub>r,i</sub> = 1)	
$RANGE_{r,i} \ge 0$	(4)
(For all <i>r</i> and all <i>i</i> , if order <sub>r,i</sub> $\neq$ 1000 AND routes <sub>r,i</sub> = 1)	
$RANGE_{r,lastinterval} \ge lastrestriction_r$	(5)
(For all <i>r</i> )	
$INTERVALINAROW_i = INFRA_i * distance_i$	(6)
(For all i, if previous = 1000)	
$X_i \leq bigM * INFRA_i$	(7)
(For all i, if previous $\neq 1000$ )	
$X_i \leq INTERVALINAROW_{previous_i}$	(8)
(For all i, if previous $\neq 1000$ )	
$X_i \ge INTERVALINAROW_{previous_i} - (1 - INFRA_i) * bigM$	(9)
(For all i, if previous ≠1000)	
$X_i \geq 0$	(10)
(For all i, if previous $\neq 1000$ )	
$INTERVALINAROW_i = X_i + INFRA_i * distance_i$	(11)
(For all i, if previous = 1000)	
$Z_i \leq bigM * D_i$	(12)
(For all i, if previous $\neq 1000$ )	
$Z_i \leq INTERVALINAROW_{previous_i}$	(13)
(For all i, if previous $\neq 1000$ )	
$Z_i \geq INTERVALINAROW_{previous_i} - (1 - D_i) * bigM$	(14)

(For all i, if previous ≠1000)	
$Z_i \geq 0$	(15)
(For all i, if previous $\neq 1000$ )	
$Y_i \leq 2 * D_i$	(16)
(For all i, if previous $\neq 1000$ )	
$Y_i \leq INTERVALINAROW_{previous_i}$	(17)
(For all i, if previous $\neq 1000$ )	
$Y_i \ge INTERVALINAROW_{previous_i} - (1 - (2 * D_i))$	(19)
(For all i, if previous $\neq 1000$ )	
$Y_i \geq 0$	(20)
(For all i, if previous $\neq 1000$ )	
$INFRA_i \leq bigM * (1 - D_i)$	(21)
(For all i, if previous $\neq 1000$ )	
$INFRA_i \geq 0.5 * (1 - D_i)$	(22)
(For all i, if previous $\neq 1000$ )	
$Z_i \geq Y_i * 5000$	(23)
(For all i, if previous $\neq 1000$ )	
$INTERVALINAROW_i \geq 5000 * INFRA_i$	(24)
(For all i, if last =1000)	
$D_i \in \{0, 1\}$	(25)
(For all i)	
$PRICE_i = pricemeter * distance_i$	
(For all i)	(26)
$BENEFIT_i = benefit * distance_i * intensity_i$	(27)
(For all i)	
$LBENEFIT_i = benefitRUR * distance_i * intensity_i * rur + benefitURB$	(28)
* $distance_i * intensity_i * urb + benefitHUR * distance_i$	
* intensity <sub>i</sub> $*$ hur	

(For all i)

In this case, the objective function (1) is a minimization of the total costs of the infrastructure. The objective function takes the costs of the infrastructure (26) as a basis. We also compensate for possible hybrid driving since that might create extra benefits. The

benefits are based on driving electric instead of diesel (different energy costs per kilometer, different maintenance costs per kilometer, lower climate and environmental impact) (27) and the location-specific benefits (mostly comprising of the economic value of fine dust reduction) of driving electric instead of diesel (28). The model is furthermore subjected to a large set of restrictions. The range level of the first interval of a route is a full battery minus the range used in the first interval, plus possible energy supply (2). The other range levels are the previous range level minus range usage, plus possible range supply, which cannot exceed the battery range (3). The range can also not go below 0 (4). The last interval of a route has a different minimum energy level since the truck drives more than the route we consider in the optimization. Finally, restrictions 6 to 25 determine that we need at least 5 kilometers of infrastructure for each instance it is applied. We need this many restrictions to overcome linearization problems.

#### 4.3. Conclusion

In this chapter, we have discussed two different approaches in order to determine the needed locations for dynamic charging infrastructure. The first optimization model is rather straightforward and uses the benefit of driving electric with the intensity to determine the profitable locations in the case of hybrid driving. The second optimization model is more complicated but provides more information as a result, it uses energy levels of different routes to determine where recharging should take place to serve all of the different routes. This model is needed in the case of driving fully electric with a battery. The two optimization models are used to determine the costs of the infrastructure in the following chapters.

#### 5. Social cost-benefit analysis

Chapter 4 discussed the method of determining the location and as a result the costs of the infrastructure. Yet only minimizing the infrastructure that needs to be built (or maximizing the infrastructure with a positive return), gives a limited view. Therefore this chapter looks at the broader picture of the cost and benefits involved in electrifying heavy duty transport via dynamic charging. Executing a complete social cost-benefit analysis (SCBA) is a time-consuming undertaking and combined with the rather big uncertainty concerning the data, one should see the SCBA we use as a 'quick scan'.

We first discuss the SCBA in general in section 5.1, we then continue with the scenarios we use in this research, discussed in section 5.2. Finally, we walk through the most important costs and benefits that occur during the project of electrifying heavy duty transport via dynamic charging in section 5.3.

## 5.1. What is a social cost-benefit analysis

Applying dynamic charging does require a significant budget. Whether this is financed by the government or any other party, resources are limited and should, therefore, be used most effectively. To be able to make sensible decisions on the allocation of resources, information is needed that provides the insights to be able to do so. The SCBA provides in this need by answering the following question, "How changes affect the total social prosperity" (Romijn & Renes, 2013). It, therefore, does not only look at the direct economic result but looks at the wider perspective. Three different effects can be distinguished:

- Direct effects Direct effects are the effects for the owner/operator of the project. In this specific case it is, on the one hand, the costs of construction and maintenance of the dynamic charging infrastructure and on the other hand the benefits of operating a truck under the new condition.
- Indirect effects Indirect effects occur as a result of the project in other markets. A classic example comes forward during projects that realize an improved travel time.
  Commuters can potentially reach better-paying jobs with the same travel time.
- External effects External effects are effects for which no market exists and therefore also no prices. Examples, in this case, are emissions and noise disturbance. Important to notice is that CO2 emissions also fall in this category. Even though the EU Emissions Trading System exists, it does not set a proper price (European Commision, 2017) and it does not hold for heavy duty transportation.

According to the "Kader KBA bij MIRT,-verkenning" (Ministry of infrastruttre and the Environment, 2012), a couple of standard rules apply concerning a SCBA. These rules are:

- Definition of the project A project is defined as "the smallest possible collection of related investments that are expected to be technically and economically feasible."(Romijn & Renes, 2013) In this case, it, therefore, does not only concern the investments in dynamic charging infrastructure but also the investment in trucks. Since those two can not be separated.
- Null alternative The cost or benefits of a project are determined in comparison to a reference scenario called the null alternative. This alternative represents the most likely alternative if no further actions are taken. This does include expected developments outside the project. This definition gives some room for interpretation, section 5.2. discusses the null alternative for this specific research in more detail.
- Future scenarios One should use at least two future scenarios: a low growth scenario and a high growth scenario. Our growth scenarios are focused on the total amount of kilometers that trucks drive to properly calculate the benefits and the costs. But another option is looking at low and high technological development. Due to the complexity of possible future scenarios, we only look at one scenario that represents a conservative point of reference.
- Time period The effects of an investment need to be calculated at least until 2030.
  Years after 2030 can be derived from those calculated values. The entire time period is theoretically without an end. Practically the time period needs to be at least a 100 years after the start of the project.
- **Taxes** According to the guidelines, taxes should be included in the costs as well as the benefits. This holds for all possible taxes. In our case, taxes form a significant part of the costs since diesel forms a significant part of the cost and diesel exist for the bigger part out of taxes. We have decided to not include taxes in our calculations and with that deviate from the guidelines for two reasons. The first reason is that applying dynamic charging cannot be done by one country alone and to come to a consensus a lot of information needs to be generated and shared, to be able to properly share information, country-specific differences need to eliminated as far as possible and taxes are one of them. The second reason is that SCBA calculates the benefits for the

'by Nederland', if dynamic charging allows for avoiding a form of tax, the avoided taxes result in a benefit in the SCBA, yet in the end, no overall benefit is generated. The tax benefit in the project is directly counterbalanced by a lack of income for the government.

- **Specifically for excise duty (accijns)**, we do not include them as well in the calculation for the same reason as other taxes are not included.
- Discount rate The guidelines prescribe a discount rate of 5.5%, yet in since April 2016, a revision of the discount rates has been published. As of April, 3% should be used except for significant public physical investments then it is 4,5% both for the costs as the benefits (Steunpunt economische expertise, 2017).
- Sensitivity analysis Every project, and this project, in particular, has uncertainties.
  By addressing these uncertainties and showing how changes affect the outcome, we create stronger and therefore more valuable information. The following aspects are recommended:
  - *Costs*, what are the effect of higher and lower costs.
  - *Construction period*, how is the result affected by an increase in construction time.
  - *Phasing*, the effect of executing the project in phases. This aspect is not included in the scope of this project, nevertheless, a location optimization model is included in Appendix A concerning dynamic charging to implemented with a limited budget and therefore in phases.
  - Spatial development The limiting effect of other spatial developments as a result of this project. At this point, no significant effects on spatial development are expected.

#### 5.2. Null alternative & scenarios

The null alternative is the alternative that occurs when no extra measures are taken. In our case, it means that trucks continue with diesel as their energy source and the development of diesel trucks continues according to expectation.

The other scenarios result from the different approaches we have available and discussed in the previous chapters. The clearest distinction that can be made is between hybrid driving (electric when dynamic charging infrastructure is available and diesel in all of the other options) and full electric driving (using a battery as an energy source when no dynamic charging infrastructure is available).

These two options, hybrid and full electric can also be combined, this is the case because different truck categories have different energy usages. In this case, we consider three truck categories. We present more specified information on the different truck categories in Appendix C. This gives the following four options:

- All trucks drive hybrid.
- Truck category one drives full electric, truck category two and three drive hybrid.
- Truck category one and two drive full electric, truck category three drives hybrid.
- All trucks drive full electric.

Furthermore, those trucks that drive fully electric, have a set of options as well. As said, the trucks use batteries as an energy source. The amount of infrastructure needed is likely to be influenced by the range the batteries have. Therefore we distinguish three possible battery ranges: 100 km, 200 km and 400 km. This results in the following 10 possible scenarios:

All hybrid	Scenario 1					
	Range: 100 Km	Range: 200 Km	Range: 400 Km			
Cat 1 full electric,	Scenario 2	Scenario 3	Scenario 4			
Cat 2-3 hybrid						
Cat 1-2 full electric,	Scenario 5	Scenario 6	Scenario 7			
Cat 3 hybrid						
All full electric	Scenario 8	Scenario 9	Scenario 10			

#### Table 2, Overview of scenarios

## 5.3. Overview of costs and benefits involved

To make sure we involve all the possible costs and benefits, we look at a reference case. The reference case, we use, is the SCBA of the electrification of the railway line Arnhem –Doetinchem – Winterswijk (Vervoort & Peters, 2015). Although dynamic charging is not focused on rail but road transport, electrification of transportation is precisely what we

do. In this section we first discuss the direct cost, then the direct benefits, then we discuss the indirect effects and finally the external effects.

#### Direct costs

We consider two important groups of direct costs. On the one hand the investment in infrastructure and the maintenance of that infrastructure and on the other hand the costs of the truck adjustments. Maintenance of the trucks is not included since it actually is a direct benefit.

- Investment in infrastructure The first direct cost that occurs is the investment in infrastructure. The amount of this investment depends greatly on the scenario. The larger the battery the less infrastructure is expected to be needed. Therefore we use infrastructure cost per meter (or km) this comes at a cost of  $1.200 \notin$  per meter (or 1.200.000  $\notin$  per km). More details on how we got this number can be found in Appendix B.
- Maintenance and operation of the infrastructure Besides the initial investment costs of the infrastructure, yearly costs occur for the maintenance and operation of the infrastructure. These costs are often presented as a percentage of the initial investment costs. The percentage present our reference case is 1%, we use a percentage of 2% as is stated by Siemens and the TU Dresden (2014) to be on the conservative end.
- Extra investments Hybrid A hybrid truck requires a more expensive engine because it needs to be able to run both on diesel as on electric, it furthermore also requires a pantograph (or other systems, for now, we focus on the pantograph) to extract electricity. These costs have been stated to be € 50.000 at the start and reduce with € 2.500 per year until € 25.000 according to Siemens & TU Dresden (2014).
- Extra investment full electric We have less specific information on what the extra costs for a fully electric truck are. The main cost component of electric cars is the battery and we do have a couple of predictions of the price development of batteries as discussed in chapter 2. We use the average price stated by the two reports to calculate the costs of the batteries. We do not calculate other extra costs since an electric engine is generally cheaper than a combustion engine and by adding the costs of the batteries we already take a more conservative standpoint. Especially since Bloomberg expects the total upfront investment costs of an electric car, so including the battery, to be cheaper than a conventional vehicle by 2025 (Shankleman, 2017).

#### Direct benefits

As stated, a direct benefit is a reduction in maintenance costs of the trucks driving electrically. Another cost saving is the reduction of energy costs that is created by driving electrically instead of on diesel.

- Reduction in maintenance costs Maintenance costs form an important factor in the total costs of driving a vehicle and electrically driven kilometers have significantly lower maintenance costs. What the difference is for an electric truck is difficult to estimate at this point. Therefore we use the experience of electric vehicles that exists so far. The ANWB (2017) states that the cost of maintenance of an electric vehicle is approximately 40% of that of a comparable conventional vehicle meaning a reduction of 60% of the maintenance costs.
- Energy usage costs The energy costs of driving an electric vehicle is considerably less than driving with a conventional diesel engine. Every kilometer that is driven electrically shows a certain benefit. The benefit is the result of the combination of the energy usage in a diesel engine, the energy usage of an electric engine and the cost of a liter of diesel and the costs of one kWh of energy. For the electric energy, we use two different numbers, the costs of renewable electric energy, specifically wind power, and the costs of the mix of electric energy as is present in the Netherlands. More details on the energy usage and energy costs are given in Appendix C.

#### Indirect effects

Indirect effects are the effects that come forward in other markets. A possible positive effect is an improved flow of traffic due to trucks being able to pull up faster. A negative effect might be that trucks use the road parts that are executed with the dynamic charging infrastructure more intensively actually creating problems for the traffic flow.

At this point, we do not have enough insights to make a sensible judgment on this subject. Furthermore, comparisons with another electrification SCBA teaches us that the indirect effects are positive but too insignificant to include. For those two reasons, we decided to not include indirect effects into our SCBA at this point.

#### External effects

The most important external effect is the reduction of emissions. This reduction is the main reason for starting this project and is, therefore, the most important external effect. Other

external effects possible due to electrification are a reduction in noise disturbance and a reduction in water and soil contamination.

- Emissions As stated creating a reduction in emissions is the main reason for this research. Emissions have a negative effect on climate change and the environment. CO2 emissions are specifically important for their effect on climate change and are priced as such. But CO2 emissions also affect the air quality, as do NOx, and PM<sub>2,5</sub> and PM<sub>10</sub>. These effects on the air quality fall under the negative effects on the environment. Important to notice is that the comparison with the null alternative is not based on the current average emissions of trucks, but is based on future emissions of trucks as is required by the SCBA, more on emissions in Appendix G.
- Noise disturbance If all road traffic would become electric, a noise reduction of 3-4 decibel is possible in urban areas according to the RIVM (Verheijen & Jabben, 2010), which could result in a significant benefit. Unfortunately, noise reduction is primarily significant for speeds under 20 km/hour and the biggest benefits are reached within urban areas, areas where heavy-duty vehicles only make up about 2% of total traffic. This (and the expectation of the RIVM that trucks do not become fully electric) is the reason that no further insights exist for the noise reduction and the accompanying benefits of heavy duty vehicles. Therefore, for now, we do not include the possible benefits of noise reduction.
- Water and soil contamination Based on the standard numbers of the "Externe en infrastructuurkosten van verkeer" external infrastructure costs of traffic (Schroten, van Essen, Aarnink, Verhoef & Knockaert, 2014), once again no standard numbers exist for electric trucks in comparison to diesel trucks and also not for electric cars. We do have the numbers for trains, both diesel and electric. These numbers do show a decrease in water and soil contamination cost for electric trains in comparison to diesel trains, but this decrease only holds for passenger travel. The numbers for freight transportation are roughly the same which is why we do not include water and soil contamination as a factor in our SCBA.

## 5.4. Conclusion

Chapter five discussed the social costs and benefits of dynamic charging on the Dutch national roads. Important financial benefits are energy usages cost reduction and maintenance

cost reduction. Emission reductions are important external benefits. Costs are made for the dynamic charging infrastructure and the extra costs made when buying a truck.

### 6. Application, results & sensitivity analysis

This chapter discusses the results of the combined application of the mathematical model in chapter 4 and the social cost-benefit analysis (SCBA) in chapter 5. To do so we first briefly discuss the quick application of the models in our specific case in section 6.1. We then discuss the results of the different scenarios in section 6.2. Finally, we go into more detail about the best results in section 6.3.

#### 6.1. Application

The application consists of two parts. First, the mathematical optimization is calculated for the different scenarios as discussed in section 5.2. The results of the mathematical optimization are then used in the SCBA. Therefore we first discuss the application of the mathematical optimization model and then the application of the SCBA.

## Application of the mathematical optimization method

In the mathematical model, we have used the Dutch national roads as the input network. Routes have been created on this network that covers all of the existing roads except for the n62. The reason for that is that this road is not connected to the rest of the national roads. More details about the road network that is the input for the mathematical optimization is shown in Appendix F.

Besides the road network and all the information about the road network, each scenario has its own set of information. Most notably is, of course, the difference in battery range. Also the amount of range that is added per unit of distance dynamic charging infrastructure differs. More about this in Appendix D.

Finally, the mathematical optimization is executed with the Lingo solver. Which uses many different techniques to increase the speed of the calculation such as 'cutting' routines specifically in integer problems. Furthermore, the main optimization technique is branch & bound.

To further increase the speed of calculation we do two things. First, we cut a set of solutions ourselves. We only allow the main lane (hoofdrijbaan) to be executed with dynamic charging infrastructure. This already decreases the amount of computation time dramatically. We furthermore have the expectation that the total costs of the infrastructure have a certain maximum. So to cut off branches of the branch and bound tree easier, we set a maximum objective value. It takes a bit longer to get the first feasible solution, but that first feasible solution is much better than in other cases and we get to that objective value much faster.

Finally, we get a feasible solution rather fast. Further improving this solution requires significant computation time. Therefore we take the rather fast feasible solution and further improve this single solution specifically with the same mathematical optimization model, yet now only allowing the stretches of the fast solution to be executed with the dynamic charging infrastructure.

### Application of the SCBA

In the SCBA we make one big assumption, all trucks are included. Every kilometer driven is part of this new method. Of course, we do include the effect if not all trucks adapt to electric driving (hybrid or full electric) in the sensitivity analysis. For the rest, we use the guidelines as suggested. We make one exception from the guidelines on taxes and excise duty as was indicated.

#### 6.2. Quick results of all scenarios

Using the mathematical optimization method to calculate all of the ten scenarios is time-consuming and unnecessary if we use smart exclusion methods. This means that we use for each (set) of scenarios a quick calculation method to determine whether the scenario should be considered in more specific calculations.

# Methods for determining quick results and eliminating unpromising scenarios

In total, we have ten scenarios. Preferably we reduce the number as far as possible with quick calculations. Therefore we group the scenarios according to the different quick calculation options. We eliminate on the expectation that having all trucks drive fully electrically is most desirable. This expectation is based on the following:

- 1. Since the total amount of kilometers driven electrically is maximal by all trucks driving fully electrical, the most profit is made if all trucks drive fully electrical.
- 2. It is also expected that the battery costs outweigh the excessive amount infrastructure costs needed while driving hybrid or at least outweigh the difference in benefits.

Since the elimination primarily focusses on the hybrid/full electric characteristic of the scenarios, we present the following groups:

- Full hybrid, scenario 1 The hybrid calculation is rather straightforward and is, therefore, fully calculated.
- Truck category 1 full electric, truck category 2 & 3 hybrid: scenario 2, 3 & 4 For this set of scenarios a full calculation of the mathematical model as presented in 4.2. seems necessary. Nevertheless, since truck category 1 represents only a small portion of the trucks, 11%, and requiring a small amount of energy, less than half of category 3, it might be smart to first look at the needs of the hybrid component individually. The optimal amount of infrastructure for the hybrid part is expected to be sufficient for truck category one, independent of the battery size. Scenario 2, 3 and 4 are not relevant if the total profit (assuming category 1 does not require extra infrastructure) is less than any of the other scenarios. If the assumption is not correct, extra infrastructure is needed, increasing the costs, making the scenario even less desirable.
- Truck category 1 & 2 full electric, truck category 3 hybrid: scenario 5, 6 & 7 We cannot be as straight forward for this set of scenarios as we could have been in the previous set. Therefore we start with the calculations of the mathematical model as presented in 4.2. and use the objective bound (the minimal infrastructure costs) based on the limited calculations done as our initial investment costs. If the objective bound is lower than the initial investment costs that result from the hybrid optimization, we use the initial investment costs of the hybrid optimization. Whichever one we choose for the initial investment, we use the amount of hybrid driven kilometers maximally and so maximizing the possible benefit of driving hybrid. If under these extreme assumptions the result is still less than any other scenario, we can eliminate these scenarios.
- All trucks full electric, scenario 8, 9 & 10 The last category is expected to provide the best results both from the SCBA and in reducing overall emissions. Having these results fast furthermore, helps (is at least the expectation) to eliminate the other scenarios. Furthermore, we here have no other option than to fully use the mathematical model presented in 4.2. and ideally, we should do this for all of the three scenarios to determine the most desirable battery option. To ease the calculation, we yet make another assumption, the costs of dynamic charging infrastructure outweigh the cost of batteries. In that case, the scenario with a 100 km range is most desirable, if the other cases show inferior results even if we take the infrastructure costs to be zero, we know we only have to fully calculate the one scenario.

#### Quick results of all the scenarios

This section discusses the quick results via the method as described in the previous section. Since this is merely a method of determining the most desirable scenario, we pay little attention to the specific results since the results of most desirable scenario are further discussed in section 6.3. One exception is scenario 1, all trucks drive hybrid, this scenario is fully discussed since it might be considered as a method to smoothen the transition to electrically driving trucks.

#### Overview of all the results

Using the method discussed in 6.1, the 10 different scenarios have the results presented in Table 3.

All hybrid	€ 4,586,000,000		
	Range: 100 Km	Range: 200 Km	Range: 400 Km
Cat 1 full electric, Cat 2-3 hybrid	€ 6,231,000,000	€ 6,058,000,000	€ 5,713,000,000
Cat 1-2 full electric, Cat 3 hybrid	€16,425,000,000	€15,258,000,000	€12,925,000,000
All full electric	€29,756,000,000	€29,084,000,000	€23,203,000.000

Table 3: Overview of quick results of the scenarios

Clear is that the assumption we made, have proven to be correct. The most desirable scenario exists when having all trucks drive fully electric. This is, as expected, the result of having benefits on every kilometer driven instead of only the kilometers that included dynamic charging infrastructure. It is also the case that the amount of infrastructure needed even with smaller batteries proves to be limited.

#### Results of the hybrid scenario

The previous section already showed the overall result of the hybrid scenario. This section shows more details about that result because the hybrid scenario might be considered for the transition period. Table x shows the specific numbers that result from the SCBA. Figure 8 shows the parts of the national roads that are planned with dynamic charging infrastructure in this scenario.

# Table 4, Overview results scenario All Hybrid

## **Direct costs:**

- Infrastructure including maintenance	-8,853,000,000
- Truck adjustments	-10,429,000,000
Direct Benefits:	
- Truck maintenance	993,000,000
- Energy usage	9,689,000,000
External effects:	
- $CO_2 - Climate$	10,017,000,000
- CO <sub>2</sub> – Environment	2,498,000,000
- NO <sub>x</sub>	570,000,000
- Pm <sub>x</sub>	102,000,000

Total

€ 4,586,000,000



Figure 8, Planned locations (red) of dynamic charging infrastructure in the case of hybrid charging

# 6.3. Detailed results of best scenario including sensitivity analysis

As was already shown by the quick calculations, the scenario in which all trucks drive fully electrically with a battery providing in a range of 100 kilometers shows the best results. The SCBA is further specified in table 5, figure 9 shows how the infrastructure is planned.

# Table 5, overview of results scenario all electric 100 km battery range

## **Direct costs:**

-	Infrastructure including maintenance	- 2,268,000,000
-	Truck adjustments	- 2,940,000,000
Direc	t Benefits:	
-	Truck maintenance	1,325,000,000
-	Energy usage	11,425,000,000
Exter	nal effects:	
-	CO <sub>2</sub> – Climate	17,930,000,000
-	$CO_2 - Environment$	3,400,000,000
-	NO <sub>x</sub>	765,000,000
-	Pm <sub>x</sub>	118,000,000

Total

€ 29,756,000,000



Figure 9: Planned locations (red) of dynamic charging infrastructure in the case of driving full electric

We already did put emphasis on the importance of conducting a sensitivity analysis in 1.3 and the guidelines as discussed in 5.1 underline the importance. According to the guidelines, the following three factors should be considered: costs, construction period and phasing. Yet we also consider technical problems. Therefore we look at the impact of problems with the battery range and energy usage.

**Costs**, to get an understanding of the impact of changes in costs on the overall result we look at two important cost factors: dynamic charging infrastructure costs and battery costs. For each of the two cost factors, we calculate two values to get the insight of the sensitivity of the costs. We calculate how much the result decreases if we use the high-end costs (absolute and percentage) and how big the average increase of the costs are allowed to be in order to break-even on the end of the time horizon. The results of these calculations are given in Table 6.

Table 6, overview of the impact of cost increases.

		Result	Percentage	Percentage
			difference	difference
			result	cost
Dynamic charging	High-end costs	€ 27,298,000,000	-8.26%	150%
infrastructure	Break-even	0	-100%	1816%
Batteries	High-end costs	€26,816,000,000	-9.88%	100%
	Break-even	0	-100%	1012%

The second point that requires sensitivity analysis is the **construction period**, how is the result affected by a delay. Calculating the effect of delay might seem irrelevant since we do not incorporate construction time in the SCBA. Nevertheless, we do include the effect of a 1, 3 and 5 years later start of the results. A delay means that the costs for infrastructure are being made, yet no benefit is created, furthermore, the costs of batteries only start once the project actually starts.

Table 7, overview of the impact of a longer construction period

	Result	Percentage
		difference
		result
1 year delay	€ 28,351,000,000	-4.72%
3 year delay	€ 25,719,000,000	- 9.28%
5 year delay	€ 23,310,000,000	-17.78%

The final point standard is **phasing**, one might see the different scenarios as phasing, although one should, in that case, ignore the costs and the benefits of hybrid driving. In this sensitivity analysis, we consider the adoption of electric driving and dynamic charging as the

biggest concern in phasing. What is the impact if the total adoption decreases and so how much can the adoption decrease so that in the end of the time horizon a break-even is reached.

Table 8, overview of the impact of a lower adoption rate

	Result	Percentage
		difference
		result
95% adoption	€ 28,155,000,000	-5.38%
90% adoption	€ 26,553,000,000	-10.76%
75% adoption	€ 21,750,000,000	-26.91%
50% adoption	€ 13,744,000,000	-53.81%
7,1% adoption	0	-100%

The **energy usages** we have calculated with means that also trucks exist that use more energy which likely results in an increase in infrastructure needed to be able to properly charge the truck with a higher energy usage. Therefore we increase the highest energy usage with 25% and 50%. We do not fully recalculate the model, yet we use the feasible objective bound providing in the worst case.

Table 9, overview of the impact of an increase in energy usage

	Result	Percentage	
		difference	
		result	
25% increase	€ 29,311,000,000	-1.50%	
50% increase	€ 29,013,000,000	-2.50%	

The final point is the effect of a decrease in **battery range**. Calculations on the effect are quite a bit more complicated. Because it directly affects the mathematical optimization as well. Nevertheless, to get an insight in the result we optimize the mathematical model while having a shorter range, to make sure that it is still possible to travel. We do relax the day constraint, at this point it is only needed to drive to one destination. We have not driven the optimization as far as possible, but given the 1.37 billion infrastructure in the basic case, we would need at least 1.51 billion and at most 1,61 billion in infrastructure. When we use the most costly case, the result reduces to  $\notin 29,360,000,000$  a relative decrease of 1.33%.

## 6.4. Conclusion

This chapter discussed the results of the ten different scenarios. The main conclusion is that the more trucks drive fully electrically the higher the benefits, the possibility to drive more of the kilometers electrically, outweighs the investments in batteries. This does not mean that batteries are automatically the way to go, if all trucks drive fully electrically, the smallest practical battery of a 100 km range, is most desirable (smaller batteries might provide even better results but a 100 km range is already on the low end that is practical for trucks).

### 7. Discussion

During this research, we have worked towards an answer for our research question within reasonable bounds. This does mean that we have made decisions on how extensive certain parts of our research have been. To properly value the results of this research, it is important to take notice of the possible shortcomings of this research.

The first point is the uncertainty concerning the data that is used in the optimization and the SCBA. Although the data is often verified via different sources, it does still leave uncertainty. Especially data predicting the future, which is a considerable amount of this specific research, needs to be handled carefully. We did do a sensitivity analysis to get an insight into the impact changes in the data could give to overcome this problem. Yet it stays important that changes in the data are monitored and the impact is analyzed in the future.

The second point we wish to discuss is the 'unlikely case'. In this research, we have calculated with range levels of trucks. These range levels are based on average energy usage of trucks. To get more accurate numbers, we have diversified the kind of trucks according to their energy usage. Yet the problem still exists in the category with the highest energy usage. Making it possible that a truck with a rather high energy usage is not able to make its route. Of course, this likely only occurs in more extreme cases because in all of the other points such as destinations and routes we have taken the maximum possible option that is likely to be used only on small occasions. We also included the problem in our sensitivity analysis. And at this point, it is also not possible to make more accurate results since we have no insights on how energy usage is diversified. Nevertheless, we would recommend, as a second step in the research on dynamic charging, to increase the knowledge on how energy usages are with electric trucks.

Finally, one should see this research in a broader context than dynamic charging alone. During this research, we have compared the case of electric trucks with dynamic charging with conventional diesel engines. Yet other possibilities also exist that might give even better results in the future, think about fast charging or hydrogen technology. To properly assess the value of dynamic charging, we need to properly assess other options for zero emission heavy duty transportation in a similar way to make an equal comparison what looks most promising. While still taking into account the inaccuracy of data describing the future. The value of 30 billion should therefore not be used as an accounting based number, but as a number to compare the option with alternatives, to assess what is expected to be best.

## 8. Conclusion & Recommendation

This chapter reflects on the report, first via the conclusion in 8.1 and the recommendations in 8.2.

#### 8.1. Conclusion

This research started with the following research question: '*How can we compute a combination of dynamic charging infrastructure, static charging infrastructure and truck battery capacity, in order to present a competitive case for electrifying heavy duty transportation.*' To be able to properly answer this question, we have looked at the following questions:

First is heavy duty transportation. Heavy duty transportation can take different modalities, such as road, rail or water transport. In this research, we have focused on heavyduty road transport, and one of the main advantages of road transport is the enormous flexibility in routes and destinations, contrary to rail and water. To not compromise this advantage and since rather soon in our research we discovered that the main challenge was probably not going to be how to present a competitive case, but how to present the most competitive case, we have decided that in the principle, a truck should be able to reach every destination as it would always do. What percentage of the trucks that are able to do that has become a variable in this research and has been included in the different scenarios.

Second in our research is, of course, dynamic charging. For dynamic charging three possible technologies are available. Induction charging, Pantograph charging with overhead lines and the drop down pantograph. Of these three technologies, only the pantograph had data available to make calculations possible and therefore we focused, for now, on the pantograph, this does not mean that, in the future, the other technologies should not be considered.

To provide an answer to the main research question we have done a variety of calculations on ten different scenarios. The scenarios have been the result of driving fully electric and hybrid (electric if dynamic charging is available, diesel otherwise). In the scenarios, a differentiation has furthermore been made between truck energy usage categories and battery ranges. The calculations consisted of a social cost-benefit analysis that consists out of direct costs, direct benefits and external effects in which the focus is on emissions. The calculations also consisted of an optimization of the necessary infrastructure. This has been done via a linear model.

The results of these calculations have shown, that indeed, being able to compute a competitive case is not the biggest challenge, all scenarios we considered showed a competitive case compared to the current practice. The most competitive are the scenarios in which all trucks drive fully electric since in those cases, the most kilometers are driven electrically and so the biggest profit is generated. It then is most desirable to keep battery sizes minimal, since the costs of placing more infrastructure do not outweigh the cost of batteries.

#### 8.2. Recommendations

Finally, we can, based on this research, give a set of recommendations. The main recommendation is that the research has shown that dynamic charging shows potential in electrifying heavy duty transportation and as such further steps are justified. Accept from practical steps we recommend the following:

- Dynamic charging shows promising results in allowing electric trucks to drive electrically, and this research has shown a method of determining the locations dynamic charging should take place. Nevertheless, this method is theoretical. A good validation would be using a set of random trucks and their driving habits and check whether they would be able to drive fully electrically or not. One could change nothing and validate whether it would work, but one could also reschedule based on the dynamic charging infrastructure and validate if that is possible. This is especially interesting concerning trucks with higher energy usages and trucks that only make limited kilometers on the national roads.
- The second thing we recommend is to look at a broader scope. The calculations in this research have been focused on the Netherlands, yet as was stated in chapter two, Dutch trucks do not stop at the border and neither do foreign trucks. Therefore, we recommend to do the same calculation but on a European level (although reducing complexity might be required).
- Finally, we recommend offsetting the options of dynamic charging infrastructure to other options for reducing CO2 emissions. In that way, a proper assessment is possible of the possibilities.

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# **Appendix A: Mathematical models**

As said, ideally the model would look a bit different, to avoid misunderstandings, we present the entire model. The model uses two indices, one to indicate the interval and one to indicate the route number. The indices are used throughout the model to indicate the network in which we optimize the costs that we optimize for and the routes that form the constraints.

i Interval, The network of Dutch national roads is divided into intervals of 200 meter. The smaller an interval is the more accurate the results of the optimization are.

 $i = \langle i1, i2, i3, ..., iN \rangle$  with N the maximum interval number.

r Route number, each combination of destination and starting point forms a route, each route has a number so

 $r = \langle r1, r2, r3, \dots, rN \rangle$  with N the maximum route number.

## **Parameters:**

The model consists of many different input parameters, they can be categorized into two categories, the first set of parameters discusses the routes and their energy levels and so setting the restrictions of this optimization. The second set of parameters discusses the costs of the dynamic charging infrastructure.

- energyuse Energy usage per interval i (for each i, yet we use equal intervals so use is the same for each i). Energy use differs per truck, as discussed, we optimize for different scenarios, for each scenario the highest energy use is used in this case.
- energy supplyEnergy supply per interval i if dynamic charging infrastructure is available(for each i yet we use equal intervals so energy is the same for each i).

energystart Energy level at the start of each individual route

- batterycapacity Maximum level of energy storage. As different trucks have different energy usages, we also include different battery capacity levels in the scenarios that are included.
- routes(r,i) Routes composed of a route number r and an interval i, if route r uses interval i, routes (r,i) = 1 otherwise 0, using the example network (note: the example network is just to show how the parameters, variables and indices work, it is not big enough to test the model), the routes(r,i) input results in the following table:

A 1 2 B 3 5 5 Example network	D	• i1	• i2	• i3	• i4	• 15
A-B	<b>R1</b>	1	1	0	0	0
A-C	R2	1	0	1	1	0
A-D	<b>R</b> 3	1	0	1	0	1
B-C	<b>R4</b>	0	1	1	1	0
B-D	<b>R</b> 5	0	1	1	0	1
C-D	<b>R6</b>	0	0	0	1	1

For the example we only include the routes in one direction, of course, you should include two directions for a correct result.

routeorder(r,i)

Number representing the i index of the previous interval in a route. Parameter routes(r,i) gives the combination of the intervals that are used, yet it does not give the order in which the intervals are used in the route. We need to know the order of used intervals to be able to properly calculate the energy levels in of each route on each interval. High, useless numbers (at least higher than iN) indicate that it is the first used interval of a route. Using the same example network, the order(r,i) input results in the following table:

		i 1	i 2	i 3	i 4	i 5
AB	<b>R1</b>	1000	1	n.v.t.	n.v.t.	n.v.t.
AC	R2	1000	n.v.t.	1	3	n.v.t.
AD	R3	1000	n.v.t.	1	n.v.t.	3
BC	R4	n.v.t.	1000	2	3	n.v.t.

	BD	R5	n.v.t.	1000	2	n.v	v.t.	3		
	CD	R6	n.v.t.	n.v.t.	n.v.t.	10	00	4	_	
last(r)	Repre	sents 1	the last	interval	number	r of	eac	h route	<b>:</b>	
	R1	F	R2	R3	R4		R	5	<b>R6</b>	
	2	4		5	4		5		5	
minimumend(r)	The m	ninimu	im ener	gy level	at the	end	of e	each in	dividual r	oute, calculation
	metho D1		wn in $A$	ppendix			D	-	D/	]
	KI	P	(2	КЭ	K4		K:	5	KO	
	250	2	00	200	200		20	00	250	
previous(i)	Numb	er ren	resentii	ng the i	index o	f the	e pr	evious	interval o	on a road. Next to
	routes	, we a	lso hav	e roads	in our c	case	roa	d (1.2)	1, road (3)	and road $(4,5)$ .
	Roads	are n	eeded t	o proper	ly calc	ulate	e th	e costs	of the inf	frastructure.
	i 1	i	2	i 3	i 4		i 5	5		
	1000	) 1		1000	1000	)	4			
	Once road	again	we use	a value	greater	tha	n iN	I to ide	entify the	first interval of a
basisprice	Basic	price	per inte	erval for	the cor	nstru	ictic	on of tl	ne infrastr	ucture. The costs
cusispire	of con	struct	ing the	infrastru	ucture of	on ai	n in	terval	i is the res	sult of a basic
	price t	that is	the san	ne for ev	very int	erva	ıl (a	ssumii	ng equal l	ength),
startprice	a start	price	that on	ly needs	s to be p	baid	on	the fir	st interval	of a consecutive
	set of	interv	als that	is exect	uted wi	th d	yna	mic ch	arging inf	frastructure and
quantumprice	a quar	ntum p	orice, a	price for	r infras	truct	ture	that d	ecreases v	with every
	conse	cutive	interva	l that is	execut	ed w	vith	dynan	nic chargi	ng. This equals
	the qu	antum	n price f	for the fi	irst inte	rval	in	a cons	ecutive ro	w of intervals and
discountrate	decrea	ises w	ith the	speed of	t the dis	scou	nt r	ate for	each foll	owing interval
trucks(1)	Numb	er of t	trucks p	ber day $c$	on inter	val 1	that is the	at do n	ot drive fi	ally electric:
	11	1	2	13	14		13	)		
	1200	) 1	300	1000	1000	)	40	00		
benefit(i)	Benef	it for l	having	one truc	k drivii	ng e	lect	ric on	interval i	(only the case for
	the pa	rt of t	he truck	ks that d	o not d	rive	full	ly elec	tric) per ti	ruck (economic
	benefit of decreased cost per km as well as environmental (for example									
	better	air qu	ality ar	ound de	nse urb	an a	irea	s)).		_
	i 1	i	2	i 3	i 4		i 5	5		
	1	1	,2	0,1	0,9		0,4	4		
bigM	Value	alway	ys large	r than q	uantum	pric	e			

**Decision variables:** 

INFRA(i)	1 if infrastructure is placed on interval i, 0 otherwise
E-LEVEL(r,i)	Energy level of route r in interval i (cannot be less than 0 or
	more than battery capacity)
PRICEINFRA(i)	Price of infrastructure in i, depending whether infra is placed
	on previous intervals of i or not
Z(i)	Dummy variable to solve linearization
QUANTUMDISCOUNT(i)	Discount based on the amount of consecutive i's that are (on which dynamic charging is realized)

**Object function:** 

$$\begin{aligned} \text{Minimize} &= \sum_{i} PRICEINFRA_{i} - trucks_{i} * benefit_{i} * INFRA_{i} \end{aligned} \tag{1} \end{aligned}$$

$$(For all i)$$

Subject to:

$$E - LEVEL_{r,i} = energystart - routes_{r,i} * use + INFRA_i * energysupply$$
(2)  
(For all user d all is if order = 1000)

$$E - LEVEL_{r,i} = \min \begin{pmatrix} \text{(For all } r \text{ and all } i, \text{ if order}_{r,i} = 1000) \\ E - LEVEL_{r,order_{r,i}} - routes_{r,i} * use + INFRA_i * energy supply \\ battery capcity \end{pmatrix} (3)$$

(For all *r* and all *i*, if order<sub>r,i</sub> 
$$\neq$$
1000 AND routes<sub>r,i</sub> = 1)

$$E - LEVEL_{r,i} \ge 0 \tag{4}$$

(For all *r* and all *i*, if order<sub>r,i</sub> 
$$\neq$$
1000 AND routes<sub>r,i</sub> = 1)

$$E - LEVEL_{r,last_r} \ge minimumend_r \tag{5}$$
(For all r)

$$Z_i \le bigM * INFRA_i \tag{6}$$

(For all *i* if previous<sub>i</sub>
$$\neq$$
1000)

$$Z_i \le QUANTUMDISCOUNT_{previous_i} * discountrate$$
(7)

(For all *i* if previous<sub>i</sub>
$$\neq$$
1000)

$$Z_i \ge QUANTUMDISCOUNT_{previous_i} * discountrate - (1 - INFRA_i) * bigM$$
(8)
(For all *i* if previous\_i \neq 1000

$$Z_i \ge 0 \tag{9}$$

(For all *i* if previous<sub>i</sub>
$$\neq$$
1000

$$QUANTUMDISCOUNT_{i} = INFRA_{i} * quantum start - Z_{i}$$
(10)
(For all *i* if previous\_i \neq 1000)

$$QUANTUMDISCOUNT_{i} = INFRA_{i} * quantum start$$
(11)

(For all *i* if previous<sub>i</sub>=1000)

$$PRICEINFRA_{i} = INFRA_{i} * basisprice + INFRA_{i} * start + QUANTUMDISCOUNT_{i}$$
(12)  
(For all *i* if previous<sub>i</sub>=1000)

# $PRICEINFRA_{i} = INFRA_{i} * basisprice + INFRA_{i} * start - INFRA_{previous_{i}} * start + QUANTUMDISCOUNT_{i}$ (13) (For all *i* if previous\_i ≠ 1000)

This mathematical optimization does not use 'baanvakken' as the actual optimization does, ideally, we use intervals of 200 meters or even smaller. In the objective function (1), we minimize the total costs. This is a minimization of the costs of the infrastructure needed for the selected group of trucks with the selected battery range to drive fully electric. Since only the selected set of trucks drive fully electric, another set of trucks can take the hybrid form and create extra benefits. These extra benefits are included in the objective function. The energy levels form the main restriction. The energy level is calculated for the first interval (2) and every consecutive interval after that (3). An energy level is the result of the energy level of the previous interval, minus the energy use in the current interval, plus the possible energy supplied in that interval. An energy level can furthermore not become more than the battery capacity and cannot become less than zero (4). And the last interval cannot become less than a previously decided upon number. The price of each interval of infrastructure (12) (13) is the result of three parts, a standard price that is determined by the length of the interval, a start price that occurs every time a new consecutive set of intervals starts and a quantum discount: a price that decreases for every new consecutive interval. The quantum discount for each *i* is calculated in restriction seven to eleven.

The second model we also want to present is the model in which the optimization is done under the constraint of a maximum budget. We see the importance in that because it is likely that no budget is available to create the entire network at once.

Once again we have a different approach. We no longer want to minimize the costs, the costs are given as the stated budget, we now want to maximize the number of possible trips, to get a fast adoption of the new technology among transporters and generate the most benefit the earliest. We still use focus on full electric trucks and a part of the trucks being hybrid. This, of course, means that the model needs be extended. This means that on top of the existing parameters and variables presented in the previous model, the following set of parameters and variables need to be added:

## **Parameters:**

maxbudget As was discussed, this case does not focus on minimizing the costs but

maximizing under a given budget. Maxbudget represents the maximum amount of costs that can be made. We only consider investment costs in this case. This means that external benefits can no longer be included.

importance r In this flow refueling optimization model, we work with routes, yet not every route is equally important. A route that represents a bigger group of actual trips is more important and therefore more desirable.

intervalnumber r The total number of intervals used in a route,

**Decision variables:** 

- POSITIVE  $_{r,i}$ Binary variable indicates whether a route r on interval i, has a positive<br/>energy level (1) or a negative energy level (0).
- SUMPOSITIVE <sub>r</sub>, Variable representing the sum of all intervals with positive energy for each route.
- DIFFERENCE r Variable representing the difference between all intervals with a positive energy level of a route and the total number of intervals on a route for each route.
- ALLOWED<sub>r</sub> Binary variable indicates whether a route is allowed for each route. A route is allowed if the energy level is positive in each interval of the route.

These extra parameters and variables combined, allow us to formulate the following model:

**Object function:** 

$$Maximize = \sum_{r} importance_{r} * ALLOWED_{r}$$
(1)

(For all i)

Subject to:

$$maxbudget \geq \sum_{i} PRICEINFRA_{i} - trucks_{i} * benefit_{i} * INFRA_{i}$$
(2)  
(For all i)

$$E - LEVEL_{r,i} = energystart - routes_{r,i} * use + INFRA_i * energysupply$$
(3)

$$E - LEVEL_{r,i} = \min \begin{pmatrix} \text{(For all } r \text{ and all } i, \text{ if } \text{ order}_{r,i} = 1000) \\ E - LEVEL_{r,order_{r,i}} - routes_{r,i} * use + INFRA_i * energy supply \\ battery capcity \end{pmatrix}$$
(4)

(For all *r* and all *i*, if order<sub>r,i</sub>  $\neq$ 1000 AND routes<sub>r,i</sub> = 1)

$E - LEVEL_{r,i} < BigM * POSITIVE_{r,i}$	(5)
(For all <i>r</i> and all <i>i</i> , if routes <sub>r,i</sub> = 1)	
$0 \leq E - LEVEL_{r,i} + BigM * (POSITIVE_{r,i} - 1)$	(6)
(For all <i>r</i> and all <i>i</i> , if routes <sub>r,i</sub> = 1)	
$SUMPOSITIVE_r = \sum_i POSITIVE_{r,i}$	(7)
(For all $r$ )	
$DIFFERENCE_r = intervalnumber - SUMPOSITIVE_r$	(8)
(For all $r$ )	
$DIFFERENCE_r < BigM * ALLOWED_r$	(9)
(For all $r$ )	
$0 \leq DIFFERENCE_r + BigM * (ALLOWED_r - 1)$	(10)
(For all $r$ )	
$Z_i \leq bigM * INFRA_i$	(11)
(For all <i>i</i> if previous <sub>i</sub> $\neq$ 1000)	
$Z_i \leq QUANTUMDISCOUNT_{previous_i} * discountrate$	(12)
(For all <i>i</i> if previous <sub>i</sub> $\neq$ 1000)	
$Z_i \ge QUANTUMDISCOUNT_{previous_i} * discountrate - (1 - INFRA_i) * bigM$	(13)
(For all <i>i</i> if previous <sub>i</sub> $\neq$ 1000	
$Z_i \ge 0$	(14)
(For all <i>i</i> if previous <sub>i</sub> $\neq$ 1000	
$QUANTUMDISCOUNT_i = INFRA_i * quantum start - Z_i$	(15)
(For all <i>i</i> if previous <sub>i</sub> $\neq$ 1000)	
$QUANTUMDISCOUNT_i = INFRA_i * quantum start$	(16)
(For all <i>i</i> if previous <sub>i</sub> =1000)	
$PRICEINFRA_i = INFRA_i * basisprice + INFRA_i * start + QUANTUMDISCOUNT$	T <sub>i</sub> (17)
(For all <i>i</i> if previous <sub>i</sub> =1000)	
$PRICEINFRA_i = INFRA_i * basisprice + INFRA_i * start - INFRA_{previous_i} * start$	t +
<i>QUANTUMDISCOUNT<sub>i</sub></i>	(18)
(For all <i>i</i> if previous <sub>i</sub> $\neq$ 1000)	

As discussed, this model does not optimize for the cost but under given maximum costs. This means that we have a different objective function (1). In this case, we maximize the possible use and so we maximize the number of allowed routes multiplied with the

importance of each route. A higher utilized route is considered to be more important. The first restriction is then the maximum cost being allowed (2) and then we have restrictions (3)(4) calculating the energy level for each route on each interval. This model allows energy levels to become negative contrary to the previous optimization model. Restrictions (5)(6)(7) determine the total number of intervals with a positive energy level for each route. Then, the difference between the number of intervals with a positive energy level and the total number of intervals per route is determined (8). If the difference is 0 or less, a route is allowed, and if the difference is more than zero a route is not allowed (9)(10). For the infrastructure itself, we use the same cost structure as the previous optimization (11 - 18).

# **Appendix B: Infrastructure costs**

An important factor as input for the optimization model are the costs of the infrastructure. Of the three technologies, the least is known on the drop-down-pantograph. The report by EVconsult & Movares (2016), states that the costs start at 750,000 up to an unknown number.

A bit more is known for induction charging although the report states that the costs for induction charging are unknown. We do have numbers on some pilot projects. The project in Malaga had total costs of 3.7 million, yet that did include the costs for an electric bus and two points for static charging, leaving approximately 2 million of costs for the induction infrastructure. Since the length of the induction was only a 100 meters, the costs per kilometer are around 20 million. Another example can be found in South Korea, here the route was around 12 kilometers of which 5% to 15% included induction charging infrastructure. With project costs of 4 million, the costs per kilometer are around 3.3 million (Kelion, 2013, Dorrier, 2013). Even though we do have numbers on the costs per kilometer in the pilot projects, these costs are most likely not a good representation of the actual costs that occur with a large application of induction charging infrastructure. So from that point, the report by EVconsult & Movares (2016) is correct that we do not have a good cost indication for induction charging.

The clearest are the costs for the pantograph charging infrastructure although the report by EVconsult & Movares (2016) still estimates the costs between 250,000 and 2.5 million, leaving quite some options for what the costs actually might be. At the same time, quite same examples exist at this point in time for the costs of pantograph charging infrastructure. Since the technology is already widely applied in the rail industry, we do have

some recent examples from which we can extract the costs. The best representation probably is the electrification of the railway line between Zwolle and Wierden. With costs of 49 million for 40 kilometers, the cost per kilometer is approximately 1.2 million (Jorna & van der Vliet, 2014). The TU Dresden & Siemens (2014) have presented a cost estimation of what the costs are. Their estimation for the pantograph charging on motorways is 2.2 million per kilometer for both directions. Yet we need the costs for the infrastructure on just one side of the road. Looking more detailed at the costs of 2.2 million, we expect, considering the costs of electrifying railway lines as well, that taking costs of 1.2 million per kilometer is suitable to use for our calculations at this moment.

# Appendix C: Energy usage

An important input factor of the optimization model is the energy a truck uses to drive and the costs that are related to this. Therefore we look at the energy usages per kilometer and the costs per unit of energy.

# **Energy usage**

Unfortunately, the energy usage of a truck differs among different trucks, therefore we differentiate the different trucks by type and weight (Romijn, Verstraten, Hilbers & Brouwers, 2016). This results in the following energy usage:

Category	Weight	Percentage	Energy usage	Energy usage
	In kg		in liter diesel / 100km	in liter diesel / km
Category 1	< 10.000	11%	17,3	0,173
Category 2	10.000 - 20.000	39%	28,1	0,281
Category 3	> 20.000	50%	39,1	0,391

The second thing we need to do is translating these energy usages to energy usages for an electric truck. At this moment the information available on the energy usage of trucks is limited. But we do have some examples available to us. As our main reference, we use the electric distribution truck case study of 2014. This study compared energy usages between diesel and electric trucks and compared their efficiency based on MegaJoules (Green Truck Partnership, 2014). It showed an increased energy efficiency of 73%. For our energy usages it means the following:

Category	Weight	Energy usage	Energy usage	Energy Usage
	In kg	in MJ / km	in MJ / km effecient	In kWh per km
Category 1	< 10.000	6,6778	1,7950	0,4986
Category 2	10.000 - 20.000	10,8466	2,9155	0,8099
Category 3	> 20.000	15,0926	4,0568	1,1269

We have validated this conversion with currently available cars that have an electric model and a comparable combustion engine model. These are the Mercedes B (diesel & electric), Volkswagen Golf (diesel & electric) and Volkswagen Up (gasoline & electric). For the two Volkswagen models, the calculated energy use is still higher than the actual use, for the Mercedes the difference is between 0,166 kWh per km actual usage and 0,164 calculated usage so the calculated usage is a bit too low, but the difference is minimal.

We can furthermore validate the numbers by looking at the scarcely available insights in electric truck energy usages. On of them is a test case in the Port of Los Angeles (2007). Here the energy usage was 2 kWh per mile or 1,25 kWh per kilometer, with a truck in category three. And this usage is a bit higher than the usage we are using, yet this specific example comes from 2007 while we are talking about 2020.

The difference in energy efficiency is expected to increase in the future as well. The report by Siemens & the TU Dresden (2014) also takes that into account. They state that electric trucks have an increased energy efficiency of 0,8% per year up until 2030 and for diesel trucks the increased energy efficiency is 1,2% per year up until 2030.

# **Energy costs**

The second thing we need to consider related to energy, are the costs. Since we consider diesel and electricity, we need to know the price of diesel per liter and electricity per kWh and how they develop.

For electricity, we could use electricity prices as they are for consumers. Yet, energy prices differ significantly for bulk consumption. Internally at Rijkswaterstaat, I have been suggested to use  $0,08 \in$  per kWh (Natuur & Milieu, 2016) For the development of the energy prices we use the report by Siemens and the TU Dresden (2014). They use two different scenarios, a 'basis' scenario with based on current development and expectations and a more conservative 'pro-diesel' scenario. In the pro-diesel scenario, they expect an electricity price decrease of -0,17% p.a. (2020-2030) and -0,80% p.a. (2030-2050). The basis scenario considers a price decrease of -0,15% p.a. (2020-2030) and -0,89% p.a. (2030-2050). The U.S.

Energy Information Administration (2016) considers four scenarios of which only one shows a significant decrease in electricity price. Interestingly, the U.S. Energy Information Administration connects the price of electricity to the level of oil and gas resources and technology. Because on the other end of the spectrum are those who see the development in solar and wind energy and expect that the costs decrease dramatically (RTLZ, 2016).

For diesel, we do not look at the price paid at the gas station, but we look at the price of production. Since the cost per kWh practically also is the production price per kWh. The diesel price is approximately  $1.254 \in$ , yet only 30% of that price are the production costs (United Consumers 2017). Once again we also look at the price development over the years. This results in the following prognoses. The pro-diesel scenario considers a price increase of 0,99% p.a. (2012-2030) and 0,75% p.a. (2030-2050) and the basis scenario considers a price increase of 1,54% p.a. (2012-2030) and 1,23% p.a. (2030-2050). The U.S. Energy Information Administration also compared 11 different oil-price projections. Between 2015 and 2040, the lowest annual increase was 1.9% and the highest was 2.4%.

# **Appendix D: Energy supply**

Calculating the energy supply is rather straightforward since the information available on the energy supply at this moment is limited to non-existed. We do have some numbers, in Belgium, tests on induction charging have taken place. Here energy supplies were generated of 3.6 kW and 22 kW. To be able to sufficiently charge a truck, with the least possible amount of infrastructure investment, these energy supplies are rather low, especially compared to the pantograph, the other technique we do have some numbers on. "The pantograph design allows for an energy transfer of 150 kW for traction and additionally up to 300 kW for onboard energy charging." (Siemens, 2017).

This makes the second point, our calculations are rather straightforward since we also only focus on the pantograph for the optimization at this moment. Partly since the energy transfer is much bigger and therefore more suitable and partly since we only have reasonable insides in the costs of this technology, making it impossible to make the calculations for other technologies.

The energy supply for the three different truck categories is as follows. The supply is 300 kW, considering a truck driving 85 km per hour, the amount of energy supplied per kilometer is 3,529 kWh. Depending on the energy usage per category, the amount of range that is added during a kilometer of dynamic charging is:

Category	Weight	Energy supply	Added range
	In kg	kWh per km	Km per km of infra
Category 1	< 10.000	3,529	7,0786
Category 2	10.000 - 20.000	3,529	4,3580
Category 3	> 20.000	3,529	3,1320

# Appendix E: Driving on non-national roads and static charging infrastructure

Routes, as has been defined, only drive on the national roads and as such are included in the calculations. Yet trucks also drive a considerable amount of time on non-national roads, therefore we have to consider the energy used during those kilometers.

Unfortunately little is known of the specific behavior of trucks that can be used to answer the question concerning the energy use on non-national roads. Therefore we use more generalized data that is available. In 2015, the total amount of kilometers driven in the Netherlands was 6,802,200,000 km, (CBS, 2016) the total amount of kilometers driven on the national roads was 4,280,836,938 (Rijkswaterstaat, 2015). On average a trip is 76 km (TLN, 2016) of which, if we take the same ratio, 48 km takes place on the national roads and 28 km takes place on non-national roads per trip. This means that at the beginning of each trip, already 14 km of energy is used from the battery and that at the end at least 14 km of energy should be left over.

The second part is the static charging infrastructure. Ideally, all the energy delivered to the vehicle should be delivered in a dynamic way. In this case, the truck can always drive and create value. Unfortunately this is not possible, for shorter trips, it is practically impossible to capture enough energy in the short time it is present on a national road, furthermore, it might not even be desirable to charge all the energy dynamically from an economic standpoint. To make it practically usable we use minimal energy levels at the start and endpoints of a route used in the flow refueling model. This minimal energy level is based on the kilometers that are driven on non-national roads and what we consider to be acceptable for static charging.

At this point, we consider one full battery per day as acceptable for static charging. Furthermore, we consider a truck to be able to charge for 10 minutes after each trip. The end of the trip means that a destination is reached and that some form of handling must take place, giving a moment to recharge. According to 'Warehouse Totaal' (2017), unloading a full truck could be done in 30 minutes, yet practically it takes much longer, loading and unloading can take up to more than an hour. This is underlined by Hoekstra logistics (2017), they state that loading and unloading takes between 15 minutes 60 minutes. Since a truck is not able to statically charge during the process and we take a conservative standpoint, we consider a moment of opportunity for static charging of 10 minutes.

To understand the impact of static charging we need to understand the daily energy need. To calculate the total energy need for one day, we could use the average amount of kilometers driven per day, yet this gives quite a wrong view since a truck is able to drive much further than approximately a 100 km per day. According to the Hindu Business Line (2009), a truck in Europe or the US is able to cover a distance of 700 to 800 km per day, which the system of dynamic charging infrastructure should at least be able to deliver.

Practically this means that a truck has already used some of its energy stored in the battery before entering the national road and so entering our calculations. To make these calculations we use the first trip of the day. At the beginning of the trip the energy level is:

## battery capacity range -14000 meter

At the end of the trip, a minimum energy level should be left. This energy should be able to cover the final 14 kilometers and the future use of the battery if more than one trip is possible on a day. Practically this means that the energy at the end of the trip must be at least:

Battery capacity range – (trip length / 800 x battery capacity range) –14000 meter

# **Appendix F: Network & Routes**

Our optimization is a flow optimization model. This means that for a flow, or route, the refueling points are optimized. Since each route makes use of a network the refueling points can be used by multiple routes and so the number of refueling points can be optimized. To do so we need two things, a network and routes that make use of that network.

The network consists of the Dutch national roads, with the exception of the N62 since this road is not connected to the rest of the network. Since our mathematical optimization model allows a stretch to be either equipped with the infrastructure or not equipped with the infrastructure, we divided the network of parts which we call edges. These edges correspond with the so-called 'baanvakken'. This does not make an exact optimal solution but provides a close optimal solution. Figure 10 shows the network that is used. The points between edges are called junctions.



## Figure 10, Route network

The second part is the creation of routes, it is impossible to select every single possible route, therefore we selected a set of points across the Network. The first set of points are the border crossings between the Netherlands and Germany and between the Netherlands and Belgium. Second, we included start and endpoints of national roads, such as the start of the N33 in the Eemshaven and the start of the A15 in Rotterdam Harbour. Finally, we included locations that were not sufficiently covered yet such as Harlingen and Serooskerke, etc.

Figure 11, shows the locations on the network map. The points we selected, correspond with the junctions of the network described in the previous section.



Figure 11, Start and End points for all routes.

Every possible combination of points is a route that is used for the optimization of the network dataset. A route is nothing more than the numbers of the edges it uses to get from A to B, and the order of which the route uses those edges. Yet retrieving this information for a large number of routes is less straightforward. Retrieving all of those routes and the

corresponding edge information manually is practically impossible. Therefore we wrote a model in ArcGIS that does the work for us.

The model is actually a layered combination of three different models. The first two models create the input for the model that actually does the work. Figure 12 shows schematically how the models are related. First, we iterate over all of the start positions and give that information to model 2, there, for each individual start position, and iteration is made for all possible finish positions. Then the start and finish position is given to model 3 that uses the start and finish position to make a route between those positions and create the data we actually need.





Yet this is not yet an ArcGIS model. Translating model 1 and model 2 to ArcGIS follows almost the same structure. First, we have a table containing the start positions (model 1) or the finish positions (model 2), next we have an iterator that loops through all of the values and selects one for each iteration. Finally, we insert the selected values in the following model (model 1 to model 2 and model 3 to model 4). Figure 13 and Figure 14 show what these models look like in ArcGIS.



Figure 13, Model 1



In model 3 the actual work starts. The input of model 3 are two numbers, a number referring to the start of the route and a number referring to the end of a route. Yet these numbers are not yet connected to the network of edges as presented before. Therefore we use a script that connects the numbers with the correct junctions. At the same time, we create a

route layer in which we can build the route. We then first at the start position with the tool 'add location' and we then add the finish position also with the tool 'add location'. We then use 'solve' so a route is created between the start and the finish. Since we need the number of the used edges, we use the 'copy traversed source features' to show us what edges are used. Finally, we export the table edges to excel for further configuration. At the end, the unnecessary data is deleted to minimize the impact on the speed of the model. Model 3 is shown in figure 15.

## **Appendix G: Emissions**

Emissions, or more specifically the reduction of emissions are an important factor for electrifying heavy duty transportation. We differentiate in two forms of emissions, one being emissions irrelevant of the location and two being the benefits that differ depending on the location of the emissions are emitted.

#### Location independent emissions

First, is putting a price on CO2 emissions that affect climate change and second is putting a price on emissions affecting the air quality. Keeping global warming at no more than 2 degrees means that each ton of CO2 has a price tag. What this price tag should be is difficult to predict. Between 2015 and 2050, the price differs substantially. In 2015, the price is set between 60 and 300 euro per ton CO2, in 2050, this is between 200 and 1000 euro per ton CO2 (Rijkswaterstaat, 2017). These ranges are rather broad, to give us more insight in what end to use, we look at a recent study on the price of CO2 at this moment, not the actual price, but the price it should be to cover the social costs of climate change. They calculated a price of 220 dollars per ton CO2, approximately 200 euro (Moore, Diaz, Than & Stober, 2015), which is at the lower end, but just in 2050. We still decided to calculate with the lower end of the numbers, first because it is a more conservative standpoint and in the end comes close to the actual social costs of CO2 and secondly because it is already significantly higher than the actual expected ETS-price which is between 40 to 160 euro per ton in 2050 ((Rijkswaterstaat, 2017).

For CO2 and NOx affecting the air quality we only have average costs across the nation, so not specific to the location, this is 11 euro per kg for NOx and 26 euro per ton CO2 (Schroten et al. 2014). The emission of CO2 is directly related to the energy use, for diesel, this means that the CO2 (WTW) is 3,230 per liter and TTW 2,606 per liter. Considering electricity, the CO2 emission is 0,526 kg per kWh (WTW) for standard (gray) electricity.

Electricity generated by the wind, is 0 (WTW) and 0,012 kg per kWh (LCA) (CO2emissiefactoren, 2017).

The current emission of NOx per kilometer differs strongly by the type of truck one considers. Euro V diesel trucks emit on average 4,75 gram per kilometer while Euro VI diesel trucks emit only 0,5 gram per kilometer (Kadijk et al. 2015). Since we want to understand the benefit of trucks driving electric, and those trucks are new as well, we should consider the results of the most recent truck. So 0,5 gram per kilometer.

## Location dependent emissions

Besides CO2 and NOx, Pm is an important factor affecting the air quality as a result of road traffic. Putting a price tag on the effects of Pm2,5 and Pm10 emissions is heavily influenced by the location where the Pm2,5 is being emitted. Highly urbanized areas have costs of 585 euro per kg, urbanized areas have a cost of 189 euro per kg and rural areas have a cost of 114 euro per kg for Pm2,5 and 234, 78 and 48 euro respectively (Schroten et al. 2014). To determine which road interval should be connected to which set of costs, we used the network as discussed in appendix F and a map with all population centers (CBS, 2011). We calculated the minimum distance of each interval to such a population center. We furthermore have a categorization of the different population centers, based on the density of activity, from one to five with one being the most urbanized. Since we only have costs for three categories, we combine category 2 & 3 and category 4 & 5. Yet this does not give a proper connection to the intervals, only intervals with a distance to a population center smaller than 250 meter get the same price category, intervals with a distance to a population center between 250 and 1000 meter drop one category, so from highly urbanized to urbanized and from urbanized to rural. If the distance to the closest population center is more than a 1000 meter, we consider it as rural area independent of the category of the population center.

The emissions for trucks, once again looking at Euro VI norm trucks is 0,02 gram per kilometer in total so both PM 10 and PM2,5.The reduction for electric trucks is difficult due to the limited information available. Therefore we make the comparison with electric cars and use the report of TNO (Kadijk et al. 2015). They state that for PM2,5 is zero for electric engines and PM10 (excluding PM2,5) has a 25% reduction. Furthermore, PM2,5 represents 25%.