FABRIC

Feasibility analysis and development of on-road charging solutions for future electric vehicles

# Assessment of traffic operations and management through combining ITS and dynamic charging

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| Authors | | Joram H.M. Langbroek (KTH), Jubin Jacob (TNO), Gerdien Klunder (TNO) & Joel P. Franklin (KTH) | |
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# LIST OF ABBREVIATIONS

| ABBREVIATION | DESCRIPTION |
|---|---|
| EV | Electric Vehicle |
| BEV | Battery Electric Vehicle |
| ICE | Internal Combustion Engine |
| ICEV | Internal Combustion Engine Vehicle |
| PHEV | Plug-in Hybrid Electric Vehicle |
| HEV | Hybrid Electric Vehicle |
| LD | Light Duty |
| HD | Heavy Duty |
| HGV | Heavy Goods Vehicle |
| GHG | Greenhouse Gas |
| SoC | State of Charge |
| HOV-lanes | High Occupancy Vehicle-lanes |

# EXECUTIVE SUMMARY

*The aim of this deliverable is to explore how traffic operations are affected by dynamic or dynamic charging. Based on different scenarios regarding development of dynamic charging facilities, deployment rates of EVs not compatible and compatible with dynamic charging and pricing of dynamic charging, the effects on traffic operations have been simulated, analysed and discussed. For this simulation exercise, motorways in a metropolitan area (The Hague-Rotterdam) in the Netherlands have been analysed as a case study.*

*Dynamic charging is likely to have a beneficial effect on $CO_2$ and $NO_x$-emissions, whereas $PM_{10}$-emissions are less affected. However, selectively providing dynamic charging on part of the network may come with the cost of deteriorating traffic operations. In this case study, the motorways already have a certain level of traffic congestion, and re-routing behaviour of part of the vehicles resulted in an increased pressure on the motorways equipped with dynamic charging. Moreover, this re-routing behaviour resulted in additional kilometres driven, implying a rebound effect.*

*An important notion to make is that the added value of dynamic charging is very much dependent on the deployment rate of electric vehicles in a situation where no dynamic charging will be provided. The added value of dynamic charging is limited in case of high deployment rates of electric vehicles not compatible with dynamic charging.*

*Another important aspect that is discussed in this deliverable is the choice of which lane(s) will be equipped with dynamic charging and whether mixed traffic is to be allowed. Several options are discussed from a traffic operations point-of-view. In this simulation exercise, it has been implicitly assumed that all lanes are available for dynamic charging and mixed operations. The reasons are high deployment rates of dynamic chargeable vehicles in some of the scenarios, as well as the detrimental effects of alternative approaches on traffic operations.*

*Lastly, in this deliverable the added value of infrastructure-based information systems is discussed. As dynamic charging is likely to be installed on a very limited part of the road network, traffic information systems based on dynamic charging lanes will provide very limited additional information compared to the already extensive information from wireless technologies. However, in case of specific lanes being equipped with dynamic charging, infrastructure based traffic information might be more precise than wireless systems, as traffic operations might differ tremendously between different lanes of a motorway, especially if there is a physical or regulatory separation between a charging lane and the other lanes of a motorway.*

# 1. INTRODUCTION

Large-scale dynamic charging systems might not only have a major influence on the use of fossil fuels and thereby connected air quality improvements, but there might also be a major influence on the operations of the road system. This depends largely on the ways in which electric roads are used and where they are provided. For planning purposes, it is important to anticipate on these issues in order to take the right decisions regarding future infrastructural development of chargeable roads. In this deliverable, a simulation exercise will be described, where different constellations will be evaluated in terms of travel time, emissions and air pollution as well as energy use.

The structure of this deliverable is as follows: In Section 2, the objectives of this deliverable are discussed. The case study for the simulation is discussed in Section 3. In Section 4, the technical details about the simulation study are discussed. The results are discussed in Section 5, followed by a Discussion section in Section 6, where also the connection between ICT-solutions and dynamic charging is discussed. The results of this deliverable are used for an estimation of the costs and benefits of dynamic charging.

# 2. OBJECTIVES

This study aims at investigating the physical operations of roadway systems under a staged deployment of dynamic charging infrastructure and partial market penetration of compatibly-equipped vehicles into the general fleet. The goal is to investigate traffic-operational as well as emission effects that are related to this staged deployment of dynamic charging infrastructure.

The study is based on a traffic simulation exercise using different scenarios that differ regarding level of infrastructure deployment, time, market share of dynamic chargeable vehicles as well as pricing scenarios of the dynamic charging infrastructure. The simulation is generic regarding the specific selection of charging infrastructure (inductive or conductive).

An important feature of this simulation study is that route choice is not considered to be fixed. This implies that some vehicles are either constrained to using charging-enabled roadways or have an incentive to do so; hence they may deviate from a time- or cost-minimizing route choice. The simulations assume information about location of charging infrastructure to be available in ITS route guidance systems.

The scenarios are based on assumptions regarding future infrastructure developments and the future deployment of dynamic chargeable vehicles with their characteristics. The analysis of five distinctive scenarios provides a basis to compare situations that are very different regarding market penetration of dynamic chargeable vehicles and infrastructural development of e-roads.

The outcome of this simulation study is a scenario analysis with an assessment of the resulting strain of a certain dynamic charging infrastructure deployment on the transport system in terms of congestion delays, energy consumption, and emissions; these can be significantly different from the standard case where all travellers choose routes based on the same criteria.

Based on the results of the simulation study, an assessment of the potential benefits of using charging infrastructure to carry traffic performance and traveller guidance information between individual vehicles and a traffic operations centre will be made. This assessment will be described in the Discussion section.

# 3. CASE STUDY

## 3.1 Case Study Area

In order to select an appropriate case study area, the following characteristics should be taken into consideration:

- There should be a parallel road structure in order to be able to simulate route choice.
- The parallel routes should not be too far apart in order to allow for realistic route choice changes connected to partial development of dynamic charging infrastructure.
- The case study area should be inside of a metropolitan area with at least some level of congestion in order to be able to observe effects of e-road deployment on traffic operations

The selected case study area for this simulation study is the motorway structure between the Dutch cities of Rotterdam and The Hague (see Figure 1). Rotterdam and The Hague are cities located in the western part of The Netherlands. The distance between these cities is approximately 30 kilometres. Between the cities, there are in the current situation two motorways, the A13 and the A4. The A13 was built from 1930 and is only 17 kilometres long. Most of the trajectory of the A4 between Rotterdam and The Hague was built in the 1960s, but the southern part opened only in the end of 2015 [1]. Since then, there is a parallel structure between the two cities. The two motorways are on average only 6 kilometres apart, which makes it an interesting case study because of the fact that route choice behaviour should be taken into account.

The A13 is a relatively congested motorway with 160,000 motor vehicles per day in 2014 [2] and can be considered as the busiest motorway of the Netherlands. The southern part of the A4 was opened in December 2015 and according to the first measurements, it is used by 60,000 motor vehicles per working day [3]. According to these measurements, the congestion on the A13 has decreased since the opening of the A4.

The A4 is the shortest path for traffic towards the Port of Rotterdam. This port is located at the southwestern side of Rotterdam and the A4 provides actually a shorter path to the port, coming from the north of The Hague, than in the previous situation where the A13 had to be used. Therefore, the A4 is and will be part of an important freight corridor [2].

Figure 2 gives an overview of the simulation network that consists of the A4 (western north-south corridor), A13 (eastern north-south corridor), A20 (west-east axis in Rotterdam, N470 providing a

west-east connection in the southern part of Delft and the Prinses Beatrixlaan (in blue) that is currently used as an alternative route in case of traffic congestion.


Figure 1: Case Study Area

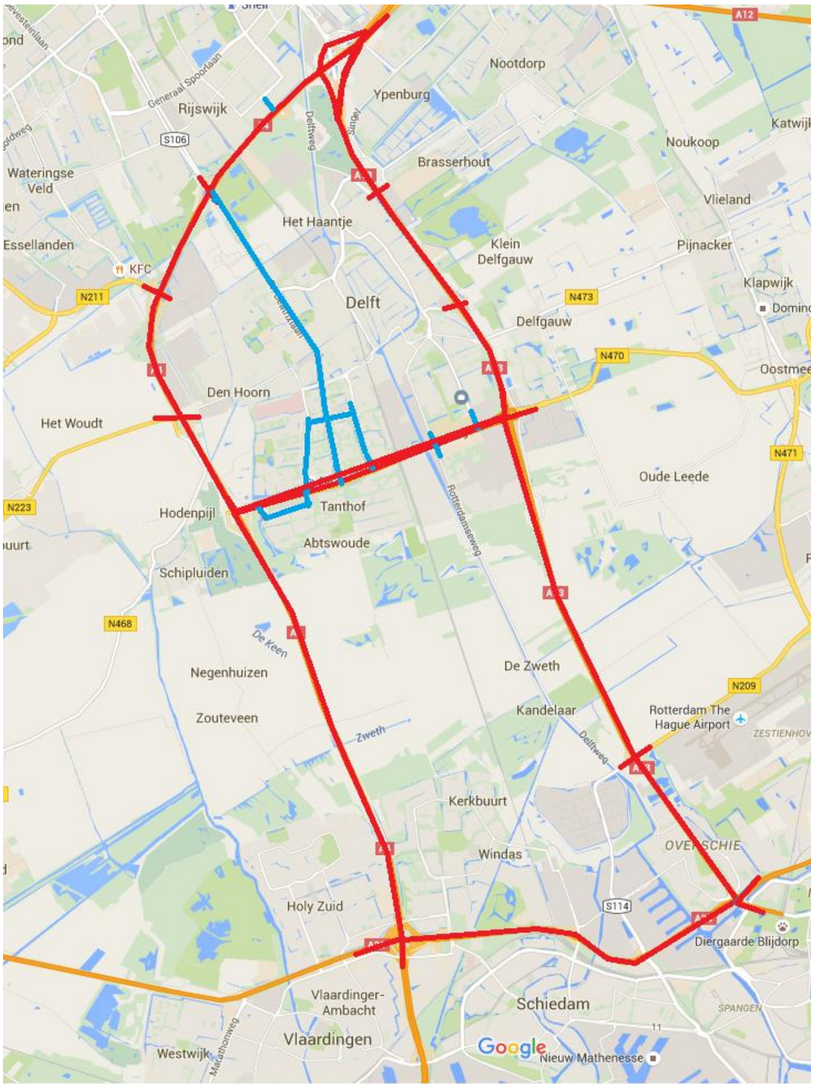


Figure 2: Simulation network

This case study is considered to be interesting for the investigation of electric road systems (ERS), because it enables studying route choice changes as a result of developing e-road on part of the network. Assuming a combination of dynamic chargeable hybrid heavy traffic, dynamic chargeable hybrid light vehicles and dynamic chargeable battery electric vehicles (BEVs), all with their specific range, this simulation study can give more insight in both energy consumption, local emissions and time spent in traffic.

## 3.2 Scenario development and conceptual model

Scenarios have been developed for both the infrastructural developments and the deployment of dynamic chargeable electric vehicles. For longer trips (such as Brussels-Amsterdam and back), e-roads might facilitate the use of electric vehicles. However, without more motorways being transformed to e-roads, the effects are assumed to be very limited, so the future network of e-roads is assumed to go beyond the simulation area and includes the staged deployment of an EU-wide network of e-roads. The market shares of dynamic chargeable vehicles are also assumed to increase over the years, as more and more of the fleet will be renewed in a time where dynamic chargeable vehicles are on the market. Another reason for expecting increasing market shares is the fact that over time, a larger and larger network of e-corridors within Europe is to be expected.

### 3.2.1 Number of dynamic chargeable vehicles → Pressure on the e-road

As the number of electric vehicles making use of e-roads increases, there will be a need for more e-road infrastructure. It might be decided to increase the number of roads to be equipped with dynamic charging. It should also be decided whether or not only one lane will be made chargeable or whether all lanes will be made chargeable. This is a decision that might also affect travel times: for example, if all on road chargeable EV-users are forced to take the slower right lane, the expected travel time is likely to increase. On the other hand, if an additional lane would be constructed dedicated to dynamic charging, this might decrease the pressure on the main road. The effect of the expected travel time for conventional vehicles and for –dynamic chargeable BEVs is unclear and depends on the way the dedicated lane is connected to the existing road network. In this deliverable, to simplify the assessment process, it is generally assumed that all lanes on selected stretches of motorway will be available for dynamic dynamic charging.

### 3.2.2 Pressure on the e-road → Infrastructure development

The more vehicles making use of e-roads, the higher the pressure on the infrastructure will be. In other deliverables within FABRIC there is discussion about whether or not there should be a system controlling the flow of chargeable vehicles, in order to avoid peaks of electricity demand. It has also been mentioned that vehicles should make a booking prior to enter the chargeable road. However, in order to make the simulation sufficiently simple (and understandable), those issues are not considered in this specific deliverable.

### 3.2.3 Infrastructure development – Number of dynamic chargeable vehicles

A more wide-spread network of dynamic charging facilitates the use of dynamic chargeable electric vehicles. Therefore, it is likely that the more infrastructure that will come available for

dynamic charging, the more attractive that it will become to purchase an EV. Many people only use some specific roads for their daily trips. However, sometimes they make use of some other routes for longer distance trips. Besides that, people might not use many roads, but the idea of being able to use these roads has a value as such. Therefore, a large part of the value of e-roads is about the option value: knowing that it is possible to make use of dynamic charging for a wide variety of destinations significantly increases the value of dynamic chargeable vehicles, besides characteristics of dynamic chargeable electric vehicles themselves such as price and range.

### 3.2.4 Infrastructure development – Route choice

As a subset of the total motorway network will be equipped with dynamic charging, this implies that there are some roads where dynamic charging is possible, while there are some other roads where dynamic charging is not possible. Dynamic charging serves as a substitute to static charging, meaning that part of the road users might prefer dynamic charging to static charging, even if this would imply that a detour has to be taken. Route choice might change due to this, altering the strains on the different parts of the transport system.

### 3.2.5 Pricing of dynamic charging – Use of e-roads

Dynamic charging implies an instalment cost that has to be paid for either by users of the system or by tax money. If users are to pay for the cost of dynamic charging, this cost should be included in the right to make use of e-roads or alternatively in the price of the electricity that is used. If this price premium is high, two effects are likely to happen: as dynamic charging is relatively expensive, consumers are likely to avoid dynamic charging. Firstly, there will be a perceived need to have larger batteries in order to be able to drive longer distances without the need to make use of dynamic charging. Secondly, static charging will become relatively more attractive. The consequence might be that the cost of dynamic charging infrastructure has to be borne by a smaller group of users.

The inclusion of dynamic pricing in dynamic route choice via ITS is not simulated. The effect of this is deemed to be much smaller than the effect of pricing between static and dynamic charging.

### 3.2.6 The effects of the deployment of non-compatible electric vehicles

Dynamic charging infrastructure is assumed to increase the number of electric vehicles being purchased, which has a beneficial effect on reducing Greenhouse Gas (GHG) emissions and improving air quality. However, even though a dense network of dynamic charging infrastructure facilitates the use of EVs as it becomes more convenient to use EVs, the main beneficial effects would arise if e-roads are “the reason why” electric vehicles become popular. This implies a strong behavioural component: if the future purchasing of electric vehicles is unaffected by whether or not dynamic charging infrastructure will be developed, the benefits are very limited.

## 3.3 Infrastructure

Which roads should be equipped with dynamic charging facilities first? In this analysis, providing e-roads on the A4 (Plaspoelpolder-Kethelplein), which is an important route for freight traffic towards the port of Rotterdam, is the start of this infrastructural development. After this, the rest of the A4 and part of the A13 (Plaspoelpolder-Kleinpolderplein) will be equipped with e-roads. This follows the reasoning of a staged and selective deployment of dynamic charging infrastructure.

The specific location of dynamic charging might be important in case of the presence of hybrid vehicles. When part of the road is equipped with dynamic dynamic charging facilities, the internal combustion engine may become activated after leaving the e-road and before entering the e-road. Therefore, it would be most beneficial from an air pollution point of view to provide dynamic charging on those parts of the motorways that are located close to concentrations of people being exposed to the air pollution from this road.

Infrastructure development in the simulations:

- Time period 1:
    - Only the northern part of A4 near residential areas is equipped with dynamic charging
    - Areas near the open fields will not be equipped with dynamic charging yet
- Time period 2:
    - A4 equipped with dynamic charging between The Hague and Rotterdam, northern and southernmost part of A13 near residential areas is electrified

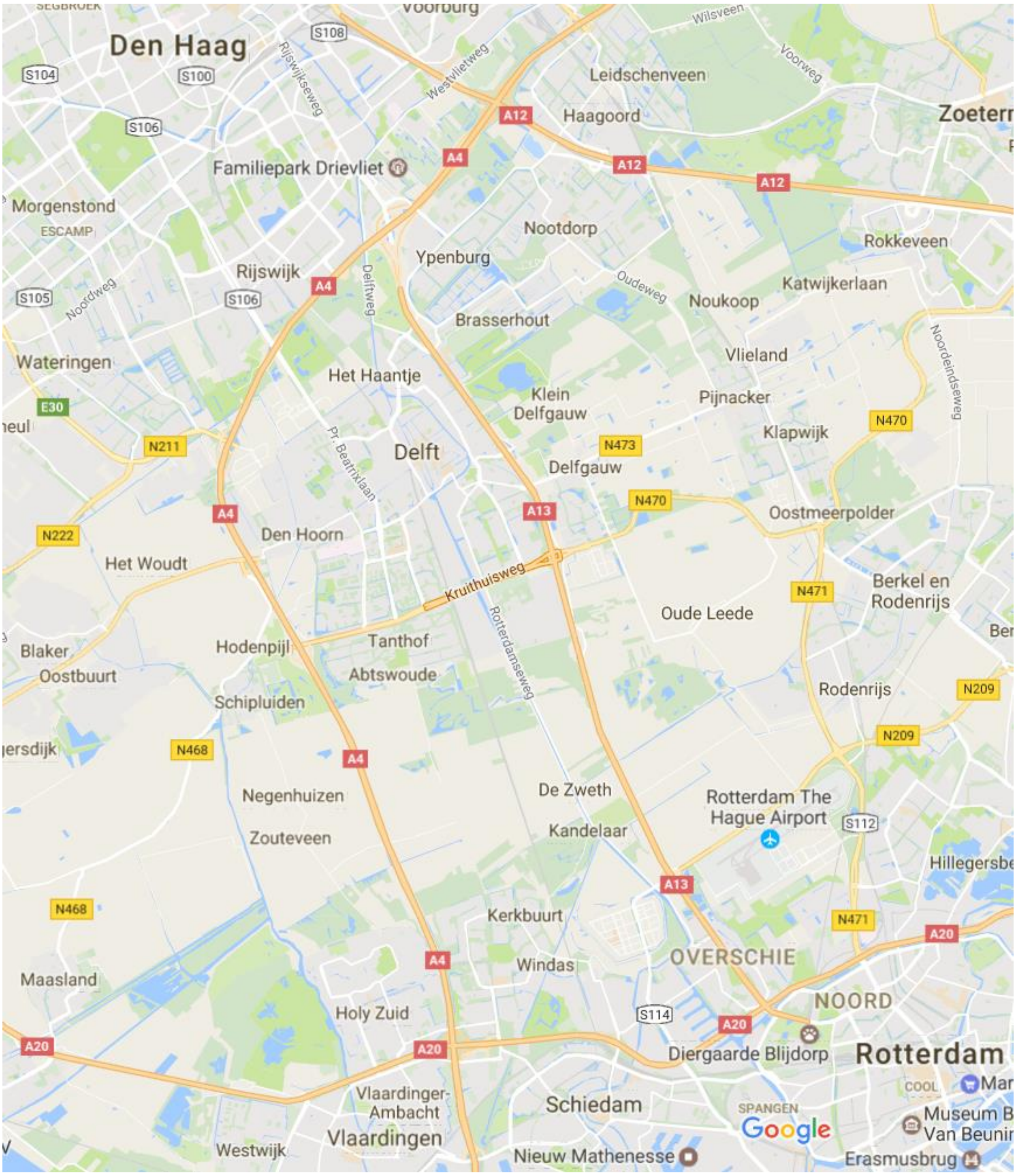


**Figure 3: Overview of the motorway network**

The location of the charging infrastructure has been chosen in such a way that charging infrastructure is preferably provided in the proximity of built-up areas. This is relevant because of the presence of hybrid electric vehicles (see 3.5). In Figure 4 and 5, a sketch of the development of e-roads in Time Period 1 and in Time Period 2 is given.

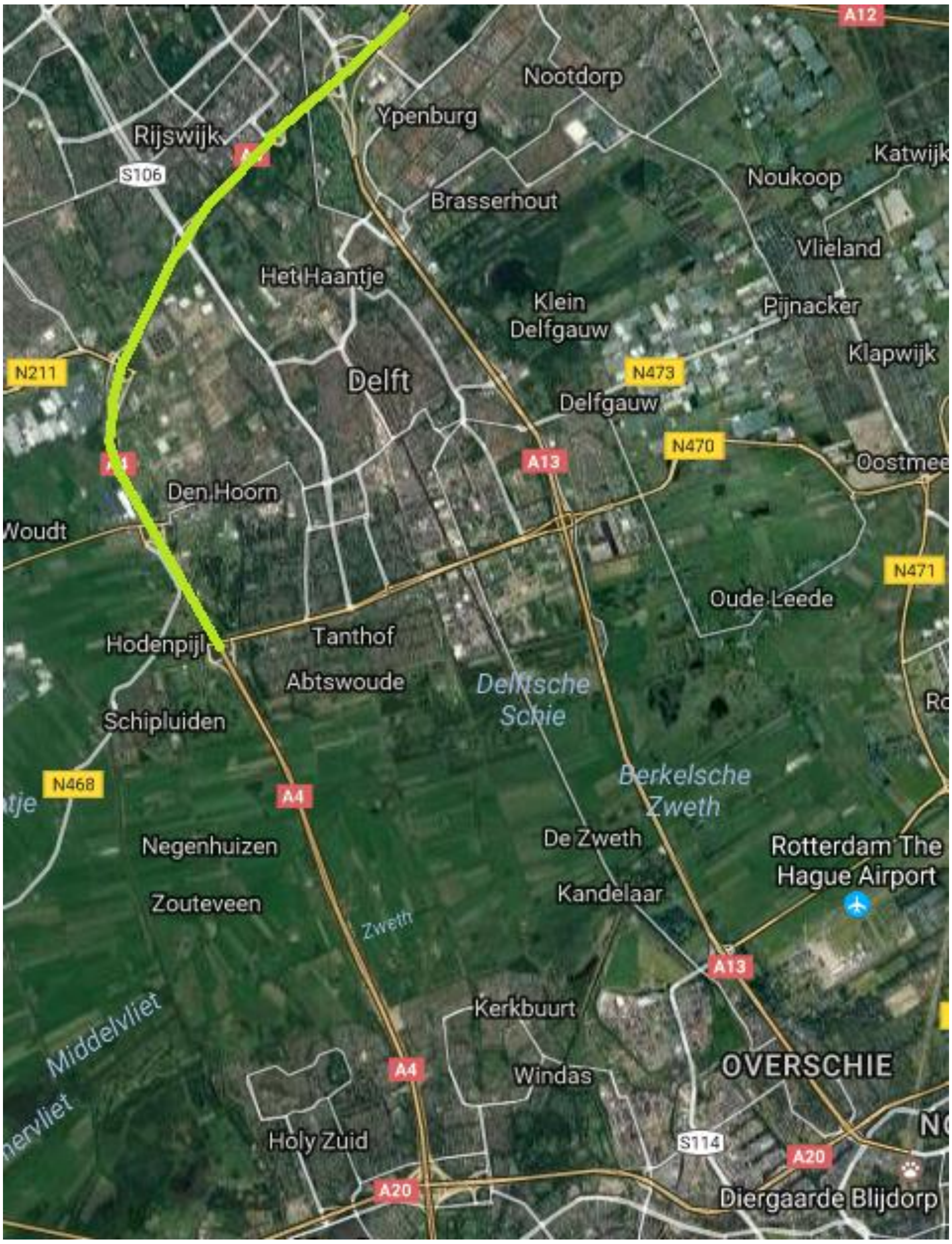


Figure 4: Development of dynamic charging (Time period 1)

In Figure 4, the provision of e-roads in the proximity of built-up areas is given. In the southern part of the A4, no charging pads are available. The built-up areas in the south (i.e. Holy Zuid) are less affected by air pollution from the A4, because the road goes through a tunnel there.

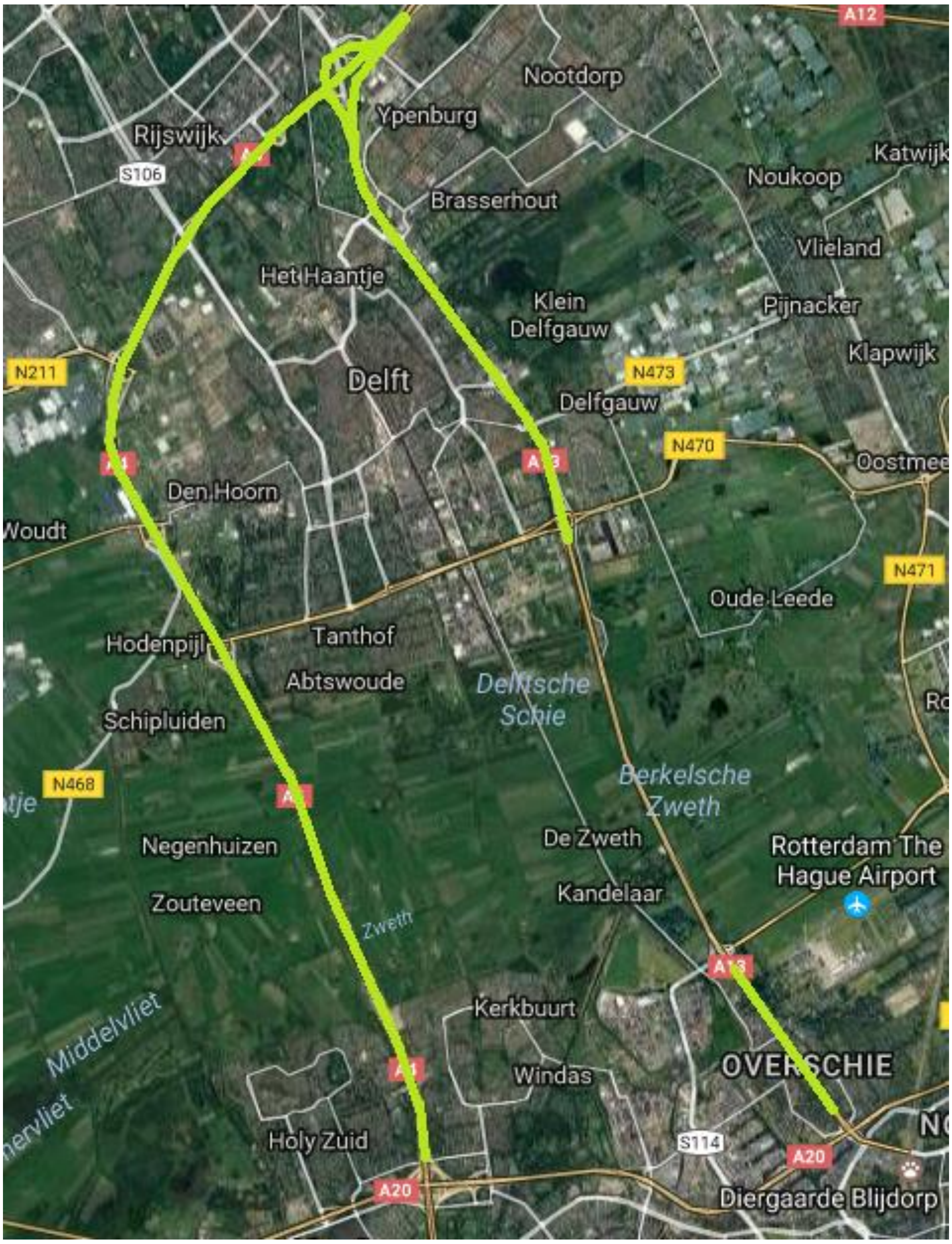


**Figure 5: Development of dynamic charging (Time period 2)**

In Figure 5, the location of dynamic charging in Time period 2 is shown. In this period, the A4 has been equipped with dynamic charging from the north to the south. Besides, dynamic charging on

the A13 is provided close to built-up areas (i.e. Overschie and Delft), whereas no dynamic charging is provided in rural areas such as Berkelsche Zweth, as these areas are relatively less sensitive to air pollution.

### 3.4 Market shares of dynamic chargeable vehicles

How much traffic will there be on the A4 and the A13 in the years of the simulation? Traffic prognoses have been used to estimate OD-matrices for 2030. These estimates are derived from the NRM model West [4,5,6]. The basis for these estimates is an OD-matrix from 2014, based on loop detector counts.

It is assumed that it is not feasible to retrofit cars with the equipment that makes it possible to make use of dynamic charging. Therefore, it will take several years before an existing fleet is replaced by a new fleet. According to figures from the Dutch central statistical agency [7], around 96 per cent of the passenger car fleet (containing more than 8 million cars) is less than 20 years old, and around 93 per cent is less than 15 years old. If on-road chargeable cars are considered to be superior to non-chargeable cars and all new vehicles purchased from a certain year will be dynamic chargeable vehicles, the proportion of the fleet consisting of chargeable cars will be likely to increase by around 6 per cent every year. If they are going to be considered as equal and half of the new vehicles purchased from a certain year will be dynamic chargeable vehicles, the proportion will be likely to increase by around 3 per cent every year and obtain a maximum of around 50%.

However, what type of electric vehicles will these chargeable vehicles be? Based on the current developments (purchases of BEVs and (P)HEVs) in the Netherlands [8], it will be likely that there is a group of car drivers owning a (P)HEV and a group of car drivers owning a BEV. Due to their flexibility, (P)HEVs are currently much more popular than BEVs, even though the increase of the number of BEVs is higher than the increase of the number of PHEVs. However, their popularity might change when more BEVs enter the market with a medium to high range. In this study, the market shares of (P)HEVs and BEVs are considered to be equal. According to forecasts of Rijkswaterstaat [2], A13 will have a 10% freight rate and the A4 around 15%. Because of potential re-routing, it is assumed that the freight rate on the whole network accounts for 10% of the total number of vehicles on the network.

It has been assumed that, in Time period 1 and Time period 2 (around 10 years after Time period 1), part of the vehicles making use of dynamic charging will be hybrid electric vehicles. When they

are charged on the road, they drive completely electrically. When not, they act like hybrid vehicles (re-generative braking) using both an internal combustion engine and an electric engine.

The first reason for this assumption is the fact that until now, heavy duty vehicles need so much energy that in order to provide a workable range, the batteries would be too heavy. For example, an e-truck with a range of around 200 km is currently 1,700 kg heavier than a comparable truck with an internal combustion engine [9]. The second reason is the fact that, in the Netherlands, plug-in hybrid electric vehicles have proven to be much more popular than BEVs [8].

The implication of this assumption is that the emissions reductions are lower than it would be the case if only BEVs would have been considered. Moreover, the use of PHEVs adds a dimension to the analysis, giving the possibility to analyse strategic locations for dynamic charging sections taking into account where exposure to local pollutants is the highest.

There are no public transport lines making use of the A13 or the A4. There are touring coaches, mostly chartered buses, but because of the scope of this analysis and the relatively low share of buses in the total number of vehicles on these motorways, buses have been disregarded in this study.

In the next section, the division of vehicles over the different defined vehicle classes is explained.

## 3.5 Vehicle classes

### 3.5.1 State-of-battery

Different vehicle classes need to be defined and vehicles need to have different states-of-charge in order to differentiate between EV-users that might need to deviate from their initial route choice and EV-users that do not need to deviate.

Each chargeable vehicle should be equipped with a specific state-of-battery. For heavy vehicles, the drive train is assumed to be plug-in hybrid, because of the fact that they should be charged almost continuously in order to be able to drive electrically. Assuming a high degree of home charging would imply that many vehicles on the road have a relatively high state-of-battery. Because of the fact that batteries are likely to decrease in price into the future, EVs could be equipped with large battery packs or the price of EVs could decrease while keeping the level of battery capacity equal to typical figures that are currently in use, which is assumed in this study.

Three different states-of-battery are considered: a high state-of-battery with an available range of approximately 160 kilometres when entering the simulation network, a medium state-of-battery with an available range of approximately 40 kilometres when entering the simulation network and a low state-of-battery with an available range of approximately 20 kilometres when entering the simulation network. Hybrid dynamic chargeable vehicles are assumed to always have a medium state-of-charge. The state-of-charge influences the mechanism for route selection, as described in the following subsection.

### 3.5.2 Mechanism for route selection

There needs to be a mechanism in the simulation that stimulates electric vehicle users to select an e-road if that would be necessary. For route selection, the concept of generalized cost has been used [10]. If the level of charge for a specific vehicle is so low that the destination cannot be reached, the generalized cost of the non-chargeable road should be so high that the EV-user with very high probability selects the route with the e-road. If the level of charge is rather low but well above what is needed (medium state-of-charge), the generalized cost of the non-chargeable road should be so high that there is a non-negligible chance that the EV-user selects a route equipped with dynamic charging facilities if that is not the road that was initially selected. The basic mechanism for route selection is equilibrium based route choice: people choose the route with the lowest generalized costs and the more people taking a specific route, the more congestion and longer travel times there will be. This longer travel time using this route might result in another route having the lowest generalized cost. This route choice process continues until equilibrium is reached where the generalized cost on all route alternatives is equal for each road user. This method is following Wardrop's first principle, stating that all users try to minimize their generalized cost [10].

### 3.5.3 Pricing

The costs of building up a network of e-roads are high. If these costs have to be paid by the users of the system, it would imply a high price of making use of e-roads. If charging on the e-road becomes more expensive, dynamic chargeable electric vehicles are likely to be less attractive. Besides this, there is an incentive for EV-users to make sure that their car is charged before driving, for example at home or using static charging stations in public spaces. Therefore, we should assume a different charge level for vehicles in case of a high price for dynamic charging.

Based on the assumptions of chargeable electric vehicle market shares, different vehicle classes have been defined for all scenarios (see Table 1)

| Vehicle type\ Scenario | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
|---|---|---|---|---|---|---|---|---|---|
| Cars (conventional and non-compatible BEV) | 90 % | 68.4 % | 73.9% | 79.2 % | 90 % | 14 % | 33.1% | 52.2 % | 52.2 % |
| HGVs (conventional and non-compatible BEV) | 10 % | 7.6 % | 8.2% | 8.8 % | 10 % | 1.6 % | 3.7% | 5.8 % | 5.8 % |
| Dynamic chargeable hybrid HGVs low state-of-battery | 0 % | 2.4 % | 1.8% | 1.2 % | 0 % | 8.4 % | 6.3% | 4.2 % | 4.2 % |
| Dynamic chargeable hybrid cars medium state-of-battery | 0 % | 10.8 % | 8.1% | 5.4 % | 0 % | 37.8 % | 28.4% | 18.9 % | 18.9 % |
| Dynamic chargeable BEVs low state-of-battery | 0 % | 3.6 % | 2.7% | 1.8 % | 0 % | 12.6 % | 9.5% | 6.3 % | 1.89 % |
| Dynamic chargeable BEVs medium state-of-battery | 0 % | 3.6 % | 2.7% | 1.8 % | 0 % | 12.6 % | 9.5% | 6.3 % | 3.78 % |
| Dynamic chargeable BEVs high state-of-battery | 0 % | 3.6 % | 2.7% | 1.8 % | 0 % | 12.6 % | 9.5% | 6.3 % | 13.23 % |
| **Total** | **100 %** | **100 %** | **100 %** | **100 %** | **100 %** | **100 %** | **100 %** | **100 %** | **100 %** |

**Table 1: Vehicle classes in the different scenarios**

The vehicle classes follow the reasoning explained above. The dynamic chargeable BEVs are equally distributed over three different states-of-battery in scenarios 2, 3, 4, 6, 7 and 8. Low state-of-battery does not allow to cover the distance between Rotterdam and The Hague. Medium state-of-battery does allow to cover this distance, but does not allow to return and a charging event has to take place if the car is not charged dynamic. High state-of-battery does allow to cover the distance between Rotterdam and The Hague, as well as the return trip. In this case, dynamic charging is not necessary and only beneficial in order to cover long distances far beyond the simulation area.

Scenarios 1 to 4 are for Time period 1 and the traffic counts will be based on the prognoses for Time period 1. Scenario 1 is a reference scenario, where there is no dynamic charging and where the traffic composition consists of 90 % cars and 10 % heavy goods vehicles. Scenario 2 accounts for a high adoption rate of dynamic chargeable vehicles of 6 % per year, assuming that dynamic chargeable vehicles are considered superior to conventional vehicles and that all new vehicles from a given year will be dynamic chargeable (either hybrid or battery electric). From this year (the assumed base year for the introduction of dynamic charging in Europe), the market share of

these vehicles increases by 6% per year for both cars and HGVs. This results in a situation in Period 1 where 2.4 % of the traffic consists of hybrid HGVs and 7.6 % of the traffic of conventional HGVs. 68.4 % of the cars is still conventional, and the remaining 21.2 % is dynamic chargeable. Half of this percentage consists of chargeable hybrid cars and half of it of dynamic chargeable BEVs. In scenario 3, it is assumed that dynamic chargeable vehicles are considered equal to conventional vehicles, which implies a lower adoption rate of 3 % per year. The percentages of all dynamic chargeable vehicle classes will be half of those in Scenario 2.

Scenarios 5 to 9 consider the situation in Time period 2, where Scenario 5 is the reference scenario without dynamic charging. Scenario 6 accounts for a high adoption rate of 6 % per year, resulting in 84 % of the vehicles being dynamic chargeable in Time period 2. Scenarios 8 and 9 consider a slower adoption rate of 3 % per year, resulting in 42% dynamic chargeable vehicles. Scenario 7 considers a medium rate of 4.5 % per year, resulting in 63% dynamic chargeable vehicles. The difference between Scenario 8 and Scenario 9 is due to different pricing scenarios. In Scenario 8, dynamic charging is assumed to have the same user cost as static charging whereas in Scenario 9, dynamic charging is assumed to cost twice as much as static charging at home or at static charging stations in public space. This results in another distribution of states-of-battery (assumed are 10% low state-of-battery, 20% medium state-of-battery and 70% high state-of-battery). Because of the higher price of dynamic charging, fewer vehicles are likely to make use of dynamic charging due to lower adoption rates and fewer dynamic chargeable vehicles actually that need to be charged.

### 3.5.4 Deployment of electric vehicles regardless of the development of e-roads

Many of the benefits of dynamic charging are assumed to depend on the underlying rate of deployment of electric vehicles: this means that benefits are higher if the charging infrastructure stimulates people to switch from conventional, internal combustion engine vehicles, to electric vehicles. In a situation where the number of electric vehicles is basically the same in a scenario with dynamic charging as in a scenario without dynamic charging, the decrease of emissions due to the dynamic charging system are assumed to be negligible. There is large uncertainty about the future market share of electric vehicles in general, and even more uncertainty about the future market share of electric vehicles in case of a Europe wide system of dynamic charging. However, there are several forecasts on different geographic levels. There are also ambitions of policy makers. For example, in the Netherlands, in the “Green Deal”, it has been stated that in 2025, 50% of newly sold vehicles should be electric, of which 30% should be BEVs [11]. Because of uncertainties regarding future EV deployment, the energy use and emission results are calculated using two different scenarios regarding dynamic charging.

In the Low EV growth scenario, the number of EVs will not increase dramatically due to constant price premiums over internal combustion engine vehicles (ICEVs) and no revolutionary improvements in travel range. In the High EV growth scenario, the number of EVs will increase dramatically due to improvements in travel range and decrease of cost premiums compared to similar ICEVs. This distinction has been made in order to investigate the effect of this autonomous deployment of EVs on traffic operations and emissions, both regarding travel behaviour and regarding the beneficial effect of e-roads on emissions. If more BEVs and PHEVs would be bought due to the provision of e-roads, the societal value is much higher.

In the traffic simulation, electric vehicles that are not compatible with dynamic charging infrastructure have been treated as conventional vehicles, as their travel behaviour is supposed to not be significantly different from the behaviour of conventional vehicles. However, in the emission model and the energy use model, a distinction has been made between conventional vehicles and EVs that cannot be charged dynamic, so called non-compatible EVs.

In the Low EV growth scenario (that is pessimistic in the sense that dynamic chargeable vehicles have a relatively lower share and effect), a high deployment rate of EVs is assumed, with 24% of the vehicles that are non-compatible with e-roads being EVs in Time period 1 and 84% of the vehicles that are non-compatible with e-roads being EVs in Time period 2. In the High EV growth scenario, no such a revolutionary change in the deployment of EVs is expected compared to the current situation, with a market share of 5% in Time period 1 and 20% in Time period 2.

In Table 2, the effects of a high level of deployment of EVs are visualized. This scenario implies a higher number of the non-compatible vehicles being electric vehicles (24% in Time period 1 and 84% in Time period 2). In Table 3, the effects of a much lower EV deployment are visualized, where 5% of the non-compatible vehicles being electric vehicles in Time period 1 and 20% in Time period 2.

High (detailed)

| Vehicle type\ Scenario | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
|---|---|---|---|---|---|---|---|---|---|
| Cars (conventional) | 68.4% | 52.0% | 56.1% | 60.2% | 14.4% | 2.2% | 5.3% | 8.4% | 8.4% |
| Cars EV PHEV not compatible | 10.8% | 8.2% | 8.9% | 9.5% | 37.8% | 5.9% | 13.9% | 21.9% | 21.9% |
| Cars EV BEV not compatible | 10.8% | 8.2% | 8.9% | 9.5% | 37.8% | 5.9% | 13.9% | 21.9% | 21.9% |
| Dynamic chargeable hybrid cars medium state-of-battery | 0.0% | 10.8% | 8.1% | 5.4% | 0.0% | 37.8% | 28.4% | 18.9% | 18.9% |
| Dynamic chargeable EVs low state-of-battery | 0.0% | 3.6% | 2.7% | 1.8% | 0.0% | 12.6% | 9.5% | 6.3% | 1.9% |
| Dynamic chargeable EVs medium state-of-battery | 0.0% | 3.6% | 2.7% | 1.8% | 0.0% | 12.6% | 9.5% | 6.3% | 3.8% |
| Dynamic chargeable EVs high state-of-battery | 0.0% | 3.6% | 2.7% | 1.8% | 0.0% | 12.6% | 9.5% | 6.3% | 13.2% |
| HGVs (conventional) | 7.6% | 5.8% | 6.2% | 6.7% | 1.6% | 0.3% | 0.6% | 0.9% | 0.9% |
| HGV's (hybrid not compatible) | 2.4% | 1.8% | 2.0% | 2.1% | 8.4% | 1.3% | 3.1% | 4.9% | 4.9% |
| Dynamic chargeable hybrid HGVs low state-of-battery | 0.0% | 2.4% | 1.8% | 1.2% | 0.0% | 8.4% | 6.3% | 4.2% | 4.2% |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

**Table 2: Vehicle classes including non-compatible PHEVs and BEVs (Low EV growth scenario)**

Low (detailed)

| Vehicle type\ Scenario | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
|---|---|---|---|---|---|---|---|---|---|
| Cars (conventional) | 85.5% | 65.0% | 70.1% | 75.2% | 72.0% | 11.2% | 26.5% | 41.8% | 41.8% |
| Cars EV PHEV not compatible | 2.3% | 1.7% | 1.85% | 2.0% | 9.0% | 1.4% | 3.3% | 5.2% | 5.2% |
| Cars EV BEV not compatible | 2.3% | 1.7% | 1.85% | 2.0% | 9.0% | 1.4% | 3.3% | 5.2% | 5.2% |
| Dynamic chargeable hybrid cars medium state-of-battery | 0.0% | 10.8% | 8.1% | 5.4% | 0.0% | 37.8% | 28.4% | 18.9% | 18.9% |
| Dynamic chargeable EVs low state-of-battery | 0.0% | 3.6% | 2.7% | 1.8% | 0.0% | 12.6% | 9.5% | 6.3% | 1.9% |
| Dynamic chargeable EVs medium state-of-battery | 0.0% | 3.6% | 2.7% | 1.8% | 0.0% | 12.6% | 9.5% | 6.3% | 3.8% |
| Dynamic chargeable EVs high state-of-battery | 0.0% | 3.6% | 2.7% | 1.8% | 0.0% | 12.6% | 9.5% | 6.3% | 13.2% |
| HGVs (conventional) | 9.5% | 7.2% | 7.8% | 8.4% | 8.0% | 1.3% | 3.0% | 4.6% | 4.6% |
| HGV's (hybrid not compatible) | 0.5% | 0.4% | 0.4% | 0.4% | 2.0% | 0.3% | 0.74% | 1.2% | 1.2% |
| Dynamic chargeable hybrid HGVs low state-of-battery | 0.0% | 2.4% | 1.8% | 1.2% | 0.0% | 8.4% | 6.3% | 4.2% | 4.2% |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

**Table 3: Vehicle classes including non-compatible PHEVs and BEVs (High EV growth scenario)**

### 3.5.5 Traffic growth

As this simulation exercise has been done for two time periods, an estimation has to be made of future traffic flows on the network. Use has been made of the traffic growth figures of the NRM model West [4]. According to this model, traffic levels are growing by between 2.8% and 12.2% between 2010 and 2030. The average between these two values (7.5% growth between 2010 and 2030) has been taken as a starting point for the traffic simulation. As the basis for the simulation is a traffic model from 2014, the traffic levels are assumed to grow by 5.9% during the period 2014-2030. Further into the future, no traffic growth estimations have been found. Because of the fact that some trends might imply a decrease in the number of kilometres travelled (an example being an increase of teleworking or car-sharing), whereas other trends might imply an increase of traffic, it has been assumed that the traffic levels of Time period 1 and Time period 2 will be equal.

## 3.6 Evaluation

The results of the simulation of the different scenarios will be evaluated regarding traffic operations and emission of exhaust gases. This evaluation will always be done compared to the base scenarios that simulate traffic operations in two distinctive time periods in a situation where there is no dynamic charging.

### 3.6.1 Travel times

Traffic operations are likely to be affected by the introduction of dynamic charging. As dynamic charging will be provided on only a part of the roads, changes in route choice are likely to happen. If the driver behaviour that results from the presence of dynamic charging infrastructure changes, then travel times on a system level may be affected. This effect would be negative if the road infrastructure is used less efficiently, and this effect would be positive if the road infrastructure is used more efficiently. The absolute travel time in a specific scenario is less important than the relative travel time in comparison with the travel time in the reference Scenarios 1 and 5.

Connected to travel times, the average speed in the network will be evaluated as well. The rationale is the same: if the transport system efficiency changes because of driving behaviour and route choice changes, then this reflects in changes of the average speed.

### 3.6.2 Emissions

Emissions of exhaust gases such as $CO_2$, $NO_x$ and PM are likely to be affected by the introduction of dynamic charging. A distinction should be made between global, aggregate measures of emissions on the one hand, and localized emissions on the other hand. For pollutants that affect local air quality, such as $NO_x$ and PM, it matters where emission takes place. Exposure to exhaust gas emissions increases with the amount of pollutants being emitted on a specific location, but also on the number of people that are exposed to these pollutants. As hybrid dynamic chargeable vehicles will be likely to drive electrically when using the e-road and use fossil fuels when not using the e-road, the location of e-roads should be chosen in a strategic way. The effects of exhaust gas emissions in sparsely populated areas are not equal to the effects of emissions in densely populated areas. For GHG such as $CO_2$, however, it does not matter where the emissions take place.

### 3.6.3 Energy use

The third aspect that will be evaluated in this deliverable is energy use. Energy use is closely related to exhaust gas emissions, but another reason for estimating energy use is to gain an insight into the need for electrical power on e-roads in the different scenarios.

## 3.7 List of assumptions

In order to make this simulation exercise as transparent as possible, the assumptions on which the simulations are based are explicitly mentioned in this Section.

3.7.1 Assumptions related to the infrastructure deployment:

1. From a certain year, an extensive network of e-roads will be built throughout the European Union, focusing on a Trans-European Network of e-corridors that connects major European cities and urban areas.
   - Even though the simulation only covers the motorways between The Hague and Rotterdam, the network does not stop there and also contains through traffic from and to areas outside the network.
2. E-roads are able to charge electric vehicles (both light and heavy vehicles) regardless of how many chargeable vehicles are making use of a specific e-road at a specific time
   - In other words: the system is not controlled for a maximum number of charging events and no booking is needed. Any dynamic chargeable vehicle entering the e-road can be charged if requested/activated by the driver
3. The level of energy transmission on an e-road equals maximum 50 kWh per charging vehicle
   - This implies that cars get more than enough electricity to drive and to charge their battery as well, whereas heavy duty vehicles do not always get enough energy for their propulsion. However, together with the energy in the batteries, full electric driving mode is possible on this e-road
   - The FABRIC prototypes are 20kW. After discussions with Renault and other experts, the passenger EV dimensions may allow for a system of up to 50kW in the future. Because of the long-term dimension of this exercise, it has been assumed that the technology will develop towards higher charging load. In addition to this, for HGVs it could theoretically be assumed that higher power could be achieved due to more available space under the vehicle and the activation of more pads on the road when a HGV is detected.

4. In Scenarios 2, 3, 4, 6, 7, 8 and 9, all lanes of the stretches of motorway where dynamic charging is available can be used for dynamic charging. This implies that these lanes can be used both for conventional vehicles, non-compatible electric vehicles and vehicles charging dynamic.

- Infrastructural developments (extensions of motorways etc.) will have a very large influence on the network performance, thereby disturbing to show the real mechanisms of interest for this study
    - e.g. providing a fourth lane on the A13 would, besides the fact that there is hardly place to build this lane, influence the capacity of the road, as well as the effects that route change behaviour of chargeable vehicle users have on travel times.

3.7.2 Assumptions related to the vehicle types:

1. In the base cases, the deployment of BEVs, PHEVs and hybrid trucks will increase
    - In other words, there will be more and more electric vehicles regardless of the development of e-roads
    - The volume of EVs as a percentage of non e-road compatible vehicles will be 5% in Time period 1 and 20% in Time period 2 in the low EV growth scenario, whereas it is assumed to be 24% in Time period 1 and 84% in Time period 2 in the high EV growth scenario.
2. From a certain year, there are dynamic chargeable vehicles on the market, which will be taken into service at a rate of 6%, 4.5% or 3% per year.
    - This assumes that of all new vehicles entering the market, 100%, 75% or 50% switches to the new technology. In case dynamic chargeable vehicles are considered superior to conventional cars, all new vehicles from the starting year will be dynamic chargeable. In case these vehicles are considered equal, half of the new vehicles from this starting year will be dynamic chargeable. This implies that after 15 years, 45-90% of the fleet is replaced by dynamic chargeable vehicles.
3. Half of the dynamic chargeable light vehicles will be hybrid electric and half of these vehicles will be battery electric.
    - This accounts for taste differentiation and for different needs for different road users
4. All electric heavy duty vehicles will be hybrid electric
    - This accounts for the fact that currently very heavy battery packages are required to provide an e-truck with enough range for its daily operations
5. BEVs have a range of up to 200 kilometres, PHEVs of up to 40 kilometres and e-trucks of up to a few kilometres
    - This implies that future developments of battery technologies will be used to make the vehicles lighter and cheaper rather than extending the available range.

6. The available range of dynamic chargeable BEVs when entering the network is distributed among a low, medium and high state-of-battery

   - If the user cost of dynamic charging equals the cost of static charging, this distribution is uniform (one third of the chargeable vehicles in each group)

   - If the user cost of dynamic charging equals two times the cost of static charging, this distribution is skewed (10% low state-of-battery, 20% medium state-of-battery and 70% high state-of-battery). This has implications on the attractiveness of dynamic chargeable vehicles and is tested in Scenario 7.

7. The available range of dynamic chargeable hybrid electric vehicles when entering the network equals the range of a medium state-of-battery

8. The route choice of dynamic chargeable vehicles depends on their state-of-charge. Drivers of vehicles with high state-of-charge do almost not take into consideration where e-roads are located. Drivers of vehicles with medium state-of-charge have a non-zero probability to make a detour in case the otherwise shortest path is not equipped with e-road infrastructure. Drivers of vehicles with low state-of-charge will make a detour in case the otherwise shortest path is not equipped with e-road infrastructure. This implicitly models a situation with perfect information on eRoad availability in ITS systems.

3.7.3 Assumptions related to the creation of motorized traffic in the simulation area:

1. In all scenarios, the traffic intensities are based on loop detector counts from 2014 and on prognoses from the Dutch national traffic model LMS/NRM 2030

2. It is assumed that the total number of trips in the network is not influenced by the introduction of dynamic charging. In other words, the origin-destination matrix does not change between the different Scenarios that are assessed. This implies no mode choice shifts, no shifts in origins and destinations and no changes in the number of trips made.

3.7.4 Assumptions related to driving and route choice behaviour:

1. Car drivers aim to minimize their generalized travel costs

   - This implies that car drivers might adapt their routes in order to decrease their travel times (or costs)

2. BEV users not able to reach their destination within the simulation network choose the chargeable road with a very high probability (almost 100%)

3. BEV users that have a medium state-of-battery are likely to select a route with an e-road

4. Dynamic chargeable PHEV-users have an economic incentive to make use of the chargeable road and weigh this against the time and cost of the detour

3.7.5 Assumptions related to traffic operations:

1. Vehicles can be charged without keeping to a specific speed.

2. The amount of traffic has an influence on the travel times on the network. This means that congestion effects are taken into account.
3. The location of dynamic charging infrastructure is available as perfect information to the users. Either by knowing their environment or perfect information in ITS trip advisory systems.

3.7.6 Assumptions related to exhaust gas emissions:

1. Emission factors of conventional cars will follow the trend of the last decades regarding $CO_2$, $NO_x$ and PM emissions
    - This implies that the (conventional) vehicles in the vehicle fleet in Time period 1 consists mainly of Euro 6 petrol cars/trucks, and a few diesel cars
    - The (conventional) vehicle fleet in Time period 2 consists only of Euro 6 petrol cars/trucks (if there are diesel cars/trucks, they are considered as clean as the petrol cars, which is a reasonable assumption according to the expected new regulations)

## 3.8 Summary

For this simulation exercise, nine different scenarios have been developed. These scenarios differ regarding time, infrastructure deployment, development of market shares of chargeable vehicles and initial states-of-battery. The scenarios are briefly described in Table 4.

For the evaluation of emissions and energy use, a distinction has been made between two possible scenarios: in the High EV growth scenario, the development of the number of electric vehicles accounts for 5% of the vehicle fleet in Time period 1 and 20% of the vehicle fleet in Time period 2. In the Low EV growth scenario (high level), the development of electric vehicles accounts for 24% of the vehicle fleet in Time period 1 and 84% of the vehicle fleet in Time period 2.

| Scenario | Time period | Infrastructure | Market share chargeable vehicles | Distribution State-of-Charge |
|---|---|---|---|---|
| Scenario 1 | 1 | No e-road | 0 % | Not applicable |
| Scenario 2 | 1 | A4 half e-road | 24 % | Low/medium/high: 33⅓ / 33⅓ / 33⅓ |
| Scenario 3 | 1 | A4 half e-road | 18 % | Low/medium/high: 33⅓ / 33⅓ / 33⅓ |
| Scenario 4 | 1 | A4 half e-road | 12 % | Low/medium/high: 33⅓ / 33⅓ / 33⅓ |
| Scenario 5 | 2 | No e-road | 0 % | Not applicable |
| Scenario 6 | 2 | A4 + half A13 e-road | 84 % | Low/medium/high: 33⅓ / 33⅓ / 33⅓ |
| Scenario 7 | 2 | A4 + half A13 e-road | 63 % | Low/medium/high: 33⅓ / 33⅓ / 33⅓ |
| Scenario 8 | 2 | A4 + half A13 e-road | 42 % | Low/medium/high: 33⅓ / 33⅓ / 33⅓ |
| Scenario 9 | 2 | A4 + half A13 e-road | 42 % | Low: 10%, Medium: 20%, High: 70% |

**Table 4: Short description scenarios**

# 4. SIMULATION

This section describes the simulation toolchain that was used to assess the transport network under study and obtain the relevant results pertaining to vehicle energy consumption, emissions and travel times.

## 4.1 Simulation toolchain

The goal of the transport network assessment task was to assess the effects of certain dynamic charging infrastructure deployments on the transport system in comparison with a reference scenario where all travellers choose routes based on the same criteria. The pressure on the transport network was to be assessed in terms of the following aspects:

- Travel times (average speed on the network)
- Emissions (CO2, NOx and $PM_{10}$)
- Energy consumption (litres of fossil fuel and kWh)

The simulation toolchain used within FABRIC consists of a combination of traffic simulation, vehicle modelling and emissions calculation tooling. Using this combination of tooling in investigating the physical operations of roadway systems, the assessment of the aforementioned aspects was performed. The flow of data between the various components of the simulation toolchain is illustrated in Figure 6: Simulation toolchain for transport network assessment

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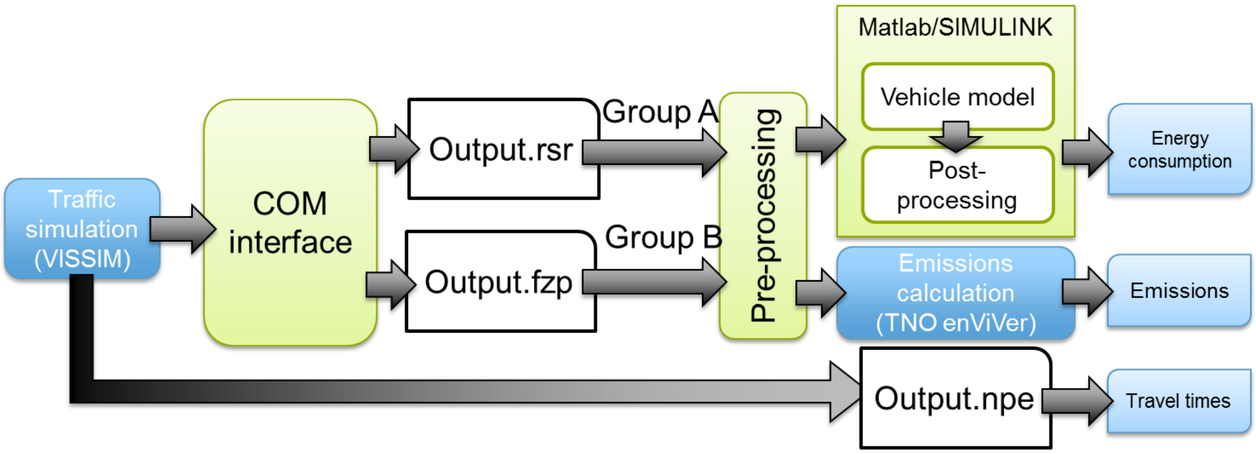


**Figure 6: Simulation toolchain for transport network assessment**

The various scenarios of the traffic network were simulated in the traffic simulation software VISSIM [12]. The travel time results are obtained directly from VISSIM. The emissions results are obtained by providing the traffic simulation results to TNO's emissions determination software

enViVer. The energy consumption calculations are done by supplying the speed profiles of the vehicles to a vehicle model after which the energy consumption calculation is performed. These simulation toolchain components are explained in the subsequent sections.

## 4.2 Traffic simulation (VISSIM)

PTV Vissim is a microscopic multi-modal traffic flow simulation software package. The traffic network was configured with the required percentage of vehicles belonging to each vehicle class according to Table 2 and Table 3. The software package is able to simulate the movement of the different vehicle classes through the network with their corresponding acceleration and deceleration levels [12].

A small part of the network was available (N470), however, it needed large extensions to include all relevant roads and a thorough revision for the traffic demand, parameters and route choice. It is a detailed representation of the current reality (2016), matching perfectly the number of lanes and speed limits (separated for passenger cars and trucks). The parts of the A4 and A13 that were chosen as chargeable e-roads, have the same number of lanes as currently (mostly 3) and vehicles can change lane everywhere (where this is allowed in reality). The demand has been derived from recent traffic counts, updated with a growth factor towards 2030 (derived from the Dutch national NRM traffic model), however, this growth factor appeared to be very small compared to the calibration corrections that were needed to represent a realistic amount of congestion during the peak hours. Also, the demand in Time period 2 was considered equal to that in Time period 1, since there are too many uncertainties for a prediction so far in the future to assume anything else. The demand was stored in 24 Origin-Demand matrices, for each hour of the day. Only the morning peak (7:30 – 8:30) was selected for this study.

An important requirement from the traffic simulation software was to assess the effect of selective routing of vehicles that want to utilize dynamic charging. This was achieved by dividing the traffic network into various sections, after which a penalty was imposed on dynamic charge-compatible vehicles, if they tried to use non-charging lanes. This penalty depends on the charging state of the battery: a lower charging level of the battery is connected to a higher penalty, since the incentive for using the charging lanes will be higher in this case. The general cost of a route is calculated as follows: $\alpha * tt + \beta * d + \gamma * c$, in which $\alpha, \beta, \gamma$ are the cost coefficients, *tt* is the travel time of the route in seconds, $d$ is the distance of the route and $c$ is the (vehicle type specific) cost parameter for the link costs. The cost coefficients $\alpha$ and $\beta$ were kept on the standard values of 1 and 0 respectively. Three states of charging of the battery were included in the simulations: low, medium and high. The corresponding penalties ($\gamma$) are 1000, 600 and 1. These were chosen based on several experiments, comparison of general route costs and inspection of the simulation results, such that vehicles with a low state of battery were indeed found to have chosen significantly often the chargeable road. This is necessary to simulate a realistic behaviour, where

car drivers with a low state-of-charge vehicle have a very high probability to adjust their route to be able to charge dynamic. Distribution over routes is calculated with a Kirchhoff distribution [12, 13], calculating the utility of a route using the general cost. Some parameters of the Kirchhoff distribution and the number of route alternatives were tuned in order to observe a realistic route choice, both for the conventional as for the compatibel vehicles for dynamic charging. Vehicles are distributed over the routes, after which a simulation is done, leading to new travel times. By repeating this several iterations, equilibrium can be reached in which no road user can improve its travel time by choosing another route. For each scenario, enough iterations (at least 5) were done in order to reach a state close or equal to equilibrium. The results of the traffic simulation are then post-processed to obtain the travel time, emissions and energy consumption values. Apart from the .npe file, which directly provide the total travel times, there are two groups of data (provided by the .rsr and .fzp files, containing respectively individual section travel times and individual vehicle trajectories) that need to be post-processed to give the emissions and energy consumption data. The .fzp files contains the vehicle identification numbers in the transport network and their corresponding speeds as a function of time (per second). The .rsr files contain the durations for which the dynamic chargeable vehicles are traversing an dynamic charging pad.

## 4.3 Simulation outputs

The simulation toolchain delivers the travel times, vehicle emissions and energy consumption as results. The methodology used in determining these results is discussed in the subsequent sections.

### 4.3.1 Travel time determination

The following parameters that pertain to the travel time in the transport network are reported in the .npe file as illustrated in Figure 6: Simulation toolchain for transport network assessment

4:

- Average speed per vehicle class: Average speed over the whole network and the whole simulation period per vehicle class
- Total distance travelled: Total distance (in kilometres) of all vehicles of the same vehicle class over the whole network and the whole simulation period
- Total travel time: Sum of all travel times of all vehicles of the same vehicle class over the whole network and the whole simulation period
- Total delay time: Difference between the realized travel time and the travel time when the vehicles could drive at their intended speed (connected to the speed limit), summed over

all vehicles of the same vehicle class over the whole network and the whole simulation period

- Average delay time per vehicle: Difference between the realized travel time and the travel time when the vehicles could drive at their intended speed (connected to the speed limit), average over all vehicles of the same vehicle class over the whole network and the whole simulation period

The parameters of the delay time and the average delay time are important results for the cost-benefit analysis of FABRIC task T.5.5.3. They are good indicators for the amount of congestion in the network connected to the introduction of different constellations of dynamic charging.

### 4.3.2 Emission calculation

The detailed results from VISSIM (trajectories with speeds and acceleration per second of each individual vehicle) are then supplied into TNO's enViVer software, which, after classification of the speed profiles of the various vehicle classes, will generate emissions values based on a pre-calibrated library of emissions models corresponding to the various vehicle classes being considered. The enViVer software calculates the emissions based on the speeds and accelerations of the individual vehicles on the transport network, after which a network level aggregate is calculated and reported.

The following components are considered in the emissions measurements:

- $CO_2$
- PM10
- $NO_x$

The PM emissions that originate from the tyres and brakes of all vehicles are also considered. The electric vehicles are modelled without tailpipe emissions; only $PM_{10}$ from the tyres is remaining. A new model is developed and added to EnViVer for this. The Hybrid Electric Vehicles (compatible for dynamic charging) are assumed to have an energy management by which they operate in zero emission mode when they are on the e-road. This energy management is implemented by a post-processing of the VISSIM results.

For the conventional vehicles, a vehicle fleet is considered which is assumed representative for 2030 or 2040, consisting of almost only Euro 6 vehicles, with 5 percent diesel vehicles in 2030 and 0 percent diesel vehicles in 2040.

### 4.3.3 Energy consumption modeling and analysis

***Road load model***

The road load model [14] calculates the force required to overcome the various road loads that the vehicle has to overcome to maintain the desired speed profile. The road loads and their corresponding equations are shown below.

1. Air drag

$$F_{air} = \frac{1}{2}\rho C_d A_{front} v_{vehicle}{}^2$$

where $\rho$ is the density of air, $C_d$ is the drag coefficient, $A_{front}$ is the frontal area and $v_{vehicle}$ is the speed of the vehicle.

2. Rolling resistance

$$F_{roll} = c_r(m_{vehicle})gsin(v_{vehicle})\cos\alpha$$

where $c_r$ is the rolling resistance coefficient, $m_{vehicle}$ is the mass of the vehicle, $g$ is the acceleration due to gravity and $\alpha$ is the road inclination. (Road inclination is assumed to be zero for the transport network under study). $\sin(v_{vehicle})$ is a term that assumes a value of zero when the vehicle is at standstill.

3. Slope resistance

$$F_{slope} = (m_{vehicle})g\sin\alpha$$

Finally, the total road load force is determined as

$$F_{roadload} = F_{air} + F_{roll} + F_{slope}$$

***Powertrain model***

The powertrain model [14] consists of two components, the first being the calculation of the vehicle inertia, and the second being the calculation of the power demand from the traction motors during motoring and the power regenerated during regenerative braking, using the results of road load calculation and the vehicle inertia.

The force required to overcome vehicle inertia is calculated as

$$F_{inertia} = (m_{vehicle}).\frac{dv_{vehicle}}{dt}$$

where $m_{vehicle}$ is the vehicle mass and $v_{vehicle}$ is the speed of the vehicle.

Thus the total tractive force is calculated as

$$F_{traction} = F_{inertia} + F_{roadload}$$

The calculated traction force is then used to determine the required traction (propulsion) power.

$$\boldsymbol{P_{traction}} = \boldsymbol{F_{traction}}.\,v_{vehicle}$$

Depending on the vehicle class, the power demand is calculated in different ways.

***BEVs***

The driveshaft power required during motoring ($F_{traction} > 0$) is given by

$$P_{electrical,mot} = \frac{P_{traction}}{\eta_{electrical}}$$

where $\eta_{electrical}$ is the powertrain electrical efficiency, $P_{traction}$ is the tractive power required to meet the road load and overcome vehicle inertia and $r_w$ is the wheel radius. The powertrain electrical efficiency is a lumped parameter combining the traction battery and motor efficiencies.

Similarly, during regeneration mode ($F_{traction} < 0$), the power regenerated is given by

$$P_{electrical,gen} = P_{traction}\eta_{electrical}$$

The electric power required during motoring mode ($F_{traction} > 0$) is given by

$$P_{electrical,mot,lim} = \max(P_{electrical,mot}, \quad P_{max,motoring})$$

where $P_{max,motoring}$ corresponds to the maximum motoring power.

Similarly, the electric power produced during generating mode ($F_{traction} < 0$) is given by

$$P_{electrical,gen,lim} = \max(P_{electrical,gen}, \quad P_{max,generating})$$

where $P_{max,generating}$ corresponds to the maximum regenerating power.

The total electrical power demand is calculated as

$$P_{electrical} = P_{electrical,mot,lim} + P_{electrical,gen,lim} + P_{aux}$$

where $P_{aux}$ is the power demand of the auxiliary systems.

The electrical energy demand from the battery is calculated as a time integral of the power demand $P_{electrical}$.

### ***Conventional (Internal Combustion Engine) vehicles***

The fuel consumption of conventional vehicles (vehicles with internal combustion engines) is calculated using a Willans line [15]. The Willans line assumes that the fuel consumption is a linear function of the engine losses and the internal losses in the powertrain. The instantaneous fuel consumption can thus be expressed as

$$\dot{m}_f = \alpha . P_{traction} + \beta$$

Where α is a measure for the efficiency of the powertrain and β is a measure of the internal losses in the powertrain.

The total fuel consumption is calculated as the time integral of the fuel consumption $\dot{m}_f$.

### ***PHEVs***

Since parallel hybrid electric vehicles use both the internal combustion engine and the battery, a simple rule-based energy management approach is implemented to determine how the required tractive power is split across the two energy sources. Depending on the required tractive power, the hybrid powertrain works in one of 3 modes, considering two traction power demand thresholds $P_{thresh1}$ and $P_{thresh2}$. The logic to determine the powertrain operating mode is tabulated below.

| **Mode** | **Criteria** |
|---|---|
| Mode 1: Electric engine only | If $P_{traction}$ <= $P_{thresh1}$ OR if the vehicle is travelling over an dynamic charging pad |
| Mode 2: Internal Combustion Engine (ICE) only | If $P_{traction}$ > $P_{thresh1}$ AND $P_{traction}$ <= $P_{thresh2}$ |
| Mode 3: Electric engine assisting ICE | If $P_{traction}$ > $P_{thresh2}$ |

**Table 5: Criteria for engine activation**

After determining the portion of drive power obtained electrically, and the portion obtained from the internal combustion engine, the energy consumption and fuel consumption is determined as described for the BEVs and conventional internal combustion engine vehicles.

### *Vehicle parameters*

The values used for the road load parameters used in the vehicle models as well as for the energy consumption computation are listed in the table below:

| **Vehicle parameter** | **Heavy-Duty Hybrid (HGV) [16]** | **Light-Duty Hybrid (Hybrid car) [17]** | **Light-Duty EV [17]** | **Conventional Heavy-Duty (HGV) [16]** | **Conventional Light Duty [16]** |
|---|---|---|---|---|---|
| Vehicle mass [kg] | 32806 | 1333 | 1230 | 32806 | 1200 |
| Vehicle frontal area [$m^2$] | 9.76 | 2.2 | 2.2 | 9.76 | 2.2 |
| Aerodynamic drag coefficient [-] | 0.6 | 0.24 | 0.24 | 0.6 | 0.24 |
| Rolling friction coefficient [-] | 0.006 | 0.005 | 0.005 | 0.006 | 0.005 |
| Electrical efficiency [%] | 83% | 86% | 83% | N/A | N/A |
| Maximum motoring power [kW] | 100 kW | 50kW | 90 kW | N/A | N/A |
| Maximum regenerative power [kW] | 40 kW | 30kW | 60 kW | N/A | N/A |
| Maximum engine power [kW] | 340 kW | 75 kW | Not applicable | 340 kW | 70 |
| Auxiliary power demand [kW] | 2.5 kW | 1.25 kW | 0.675 kW | 2.5 kW | 1.05 kW |
| Willans line coefficient α (motoring operation) [liter/kJ] | $6.102 \times 10^{-5}$ | $5.18 \times 10^{-5}$ | Not applicable | $6.029 \times 10^{-5}$ | $9.420 \times 10^{-5}$ |
| Willans line coefficient β (motoring operation) [liter/kJ] | $3.625 \times 10^{-4}$ | $1.395 \times 10^{-4}$ | Not applicable | $7.512 \times 10^{-4}$ | $1.395 \times 10^{-4}$ |

| | | | | | |
|---|---|---|---|---|---|
| Willans line coefficient α (regeneration operation) [liter/kW] | $5.303 \times 10^{-5}$ | Not applicable | Not applicable | Not applicable | Not applicable |
| Willans line coefficient β (regeneration operation) [liter/kW] | 0 | Not applicable | Not applicable | Not applicable | Not applicable |

**Table 6: Vehicle parameters per vehicle class**

Since the predicted performance of light duty vehicles beyond 2020 was available from the JRC report well-to-wheels analysis of future automotive fuels and powertrains in the European context, the energy consumption and fuel consumption results from the model were checked against the results reported in the JRC report for the NEDC cycle [16]. The results of the vehicle model are compared with the fuel consumption and energy consumption results reported in the JRC report for light duty vehicles and are tabulated below.

| | Fuel consumption [l/100km] | Energy consumption [kWh/km] | Fuel consumption [l/100km] | Energy consumption [kWh/km] | Fuel consumption calculation error [%] | Energy consumption error [%] |
|---|---|---|---|---|---|---|
| Conv LD | 4.430 | 0 | 4.347 | 0 | 1.853273 | 0 |
| PHEV LD | 2.110 | 2.700 | 2.146 | 2.580 | -1.72512 | 4.444 |
| BEV | - | 10.590 | - | 11.000 | - | -3.871 |

**Table 7: Energy use per vehicle class**

It can be seen from the table that the error margins are within 5%.

For the charging infrastructure, it has been assumed that 50kW of power is being supplied to the vehicles that are compatible with dynamic charging, as long as they are traveling over the charging pads.

### *Energy consumption simulation workflow*

The simulation workflow used to calculate the energy consumption is shown in the figure below

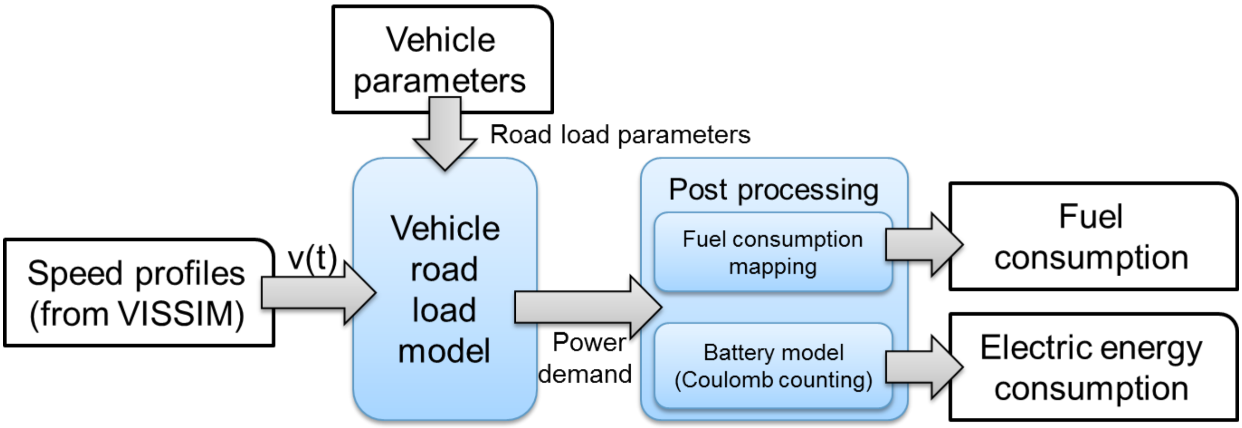


**Figure 7: Workflow energy consumption simulation**

The energy consumption workflow consists of two primary components, the vehicle model and the post-processing. The vehicle model calculates the road loads acting on the vehicle, based on which it calculates the power required by the vehicle for propulsion, auxiliary power demand and HVAC power demand as explained in the previous section. The power demand is then post-processed in two ways:

- Fuel consumption mapping: a mapping is made which transforms the power demand into an equivalent fuel consumption.
- Battery model: a simple power integration approach is used to determine the battery energy consumption/SoC change in the battery.

For the system level/transport network energy consumption, both the kWh electric energy consumption of the (PH)EVs and that of the charging pads are added together with the kWh equivalent of fuel consumption (assumed is a diesel equivalent, 1l = 11.1 kWh). A key assumption here is that the energy from the charging pads is being used to sustain the battery charge and prevent engine operation, and not to directly influence the electric energy consumption of the vehicle while in the network. In reality maybe the vehicles have a lower 'net' energy consumption while in the network, since they win back some energy from the charging pads. (In fact in most light duty (LD) cases they win back more energy than they need to drive, which would mean a negative energy consumption). But to accurately account for this, individual (initial) states of charge of each of the vehicles' batteries will have to be considered, along with an energy management strategy that determines how the dynamic charging pad energy is being used (direct consumption or just to top up the battery, also ceasing to accept energy when the battery is full or when regenerative braking is happening). However such an accounting of the individual SoC

and the energy managements of the individual vehicles was outside the scope of this work. For the system level energy consumption calculation, energy sources apart from the charging pads (for example charging before or after the journey, since this influences the energy content of the batteries) are not considered.

# 5. RESULTS

The results of this simulation exercise are reported in terms of travel times, emissions and energy consumption. These results give insight into the impact of dynamic charging infrastructure deployment on the transport system with respect to several use cases with different coverage of dynamic charging infrastructure and vehicle penetrations.

## 5.1 Introduction

The starting point of this simulation exercise is an origin-destination matrix that covers a small motorway network between the Dutch cities of The Hague and Rotterdam. The number of trips is assumed to be fixed and any differences in the total number of vehicles counted are due to random variations. This implies also that total traffic levels are assumed to be invariable between the nine simulated scenarios.

## 5.2 Travel times

The introduction of dynamic charging infrastructure is assumed to have an effect on traffic operations. Due to their investment costs, it is likely that e-roads will not be constructed everywhere but rather at a limited amount of locations. Some owners of dynamic chargeable EVs will thus be in a situation where they have to deviate from the route that they would have chosen if having a conventional vehicle. Due to this route choice behaviour, the pressure on the different roads in the simulation network is likely to change, which might have an influence on traffic congestion.

In this section, the scenarios are compared regarding the following traffic operations variables: average delay time, total delay time, average speed, total distance travelled and total travel time. After a general picture, some specific analyses for particular vehicle classes will be carried out. In Table 8 aggregate statistics related to travel times are presented for each Scenario.

As the number of vehicles having left the network depends on the traffic situation, there is a correlation between the number of vehicles having left the network and the traffic situation in each scenario. The delay time in Scenario 1 (which is the reference scenario for Time Period 1) is lower than that in Scenario 2, Scenario 3 and Scenario 4, which implies that a higher share of the vehicles from the OD-matrix has left the network, and a lower number of vehicles are still in the network. In Scenarios 2, 3 and 4, 24%, 18% and 12% of the vehicles is chargeable dynamic and a subset of this category has been marked with a low state-of-charge. This low state-of-charge has forced drivers to select another route than was selected following the user equilibrium. Therefore, certain roads got more congested, resulting in a higher average delay time and a higher total travel time on a system level. A similar pattern is visible comparing the scenarios of

Time Period 2. The delay times of the case scenarios are generally higher than that of the reference scenario in Time Period 2 (S5). An exception is scenario 9, where a different distribution of vehicles over the different states-of-charge is assumed. In that scenario, vehicles have a tendency to charge their vehicle at home, so that fewer vehicles are in need of charging while driving on the network. Therefore, the average probability of making a detour in order to be able to charge decreases, so that the traffic efficiency increases. When we zoom in to the dynamic chargeable vehicles with different states-of-charge, this pattern becomes clearer.

| High # autonomous EVs | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
|---|---|---|---|---|---|---|---|---|---|
| Average delay time (s) | 93.997 | 119 | 98.513 | 101.23 | 100.56 | 132.93 | 119.9 | 109.82 | 98.449 |
| Total delay time (h) | 624.51 | 789.32 | 654.78 | 673.96 | 665.37 | 887.36 | 797.71 | 732.23 | 652.1 |
| Average speed (km/h) | 72.674 | 68.59 | 72.081 | 71.683 | 71.887 | 67.305 | 69.206 | 70.785 | 72.732 |
| Total distance travelled (km) | 221410 | 215410 | 221010 | 222450 | 220920 | 219300 | 221870 | 224150 | 223510 |
| Total travel time (h) | 3,046.7 | 3,142.3 | 3,066.2 | 3,103.4 | 3,073.2 | 3,258.2 | 3,206.3 | 3,166.9 | 3,073 |
| Average travel time (h) | 0.127 | 0.132 | 0.128 | 0.129 | 0.129 | 0.136 | 0.134 | 0.132 | 0.129 |
| Number of vehicles having left the network | 17.693 | 17.024 | 17,447 | 17.520 | 17.323 | 16.876 | 17,160 | 17.355 | 17.341 |
| Number of vehicles in the network | 6,224 | 6,856 | 6,480.8 | 6,447 | 6,498 | 7,156 | 6,790,6 | 6,649 | 6,505 |

**Table 8: Travel times in each scenario**

| | S2 | S3 | S4 | S6 | S7 | S8 | S9 |
|---|---|---|---|---|---|---|---|
| Low state-of-charge (s) | 132.31 | 104.33 | 107.71 | 146.62 | 135.37 | 127.18 | 116.79 |
| Medium state-of-charge (s) | 119.39 | 111.33 | 115.62 | 144.25 | 133.01 | 120.77 | 107.4 |
| High state-of-charge (s) | 116.13 | 100.56 | 99.996 | 109.04 | 109.33 | 105.07 | 96.687 |

**Table 9: Average delay time per vehicle for different states-of-charge**

In each scenario, vehicles with a high state-of-charge have a lower average delay time than vehicles with a medium or a low state-of-charge. This is due to the fact that vehicles with a high state-of-charge only make use of e-roads if that would fit with their route with minimal generalized costs. However, drivers of vehicles with a high state-of-charge are not likely to take detours

because of the fact that some routes include (more) e-roads than the currently chosen route. In all case scenarios but Scenario 3 and Scenario 4, vehicles with a low state-of-charge have a higher average delay time than vehicles with a medium state-of-charge.

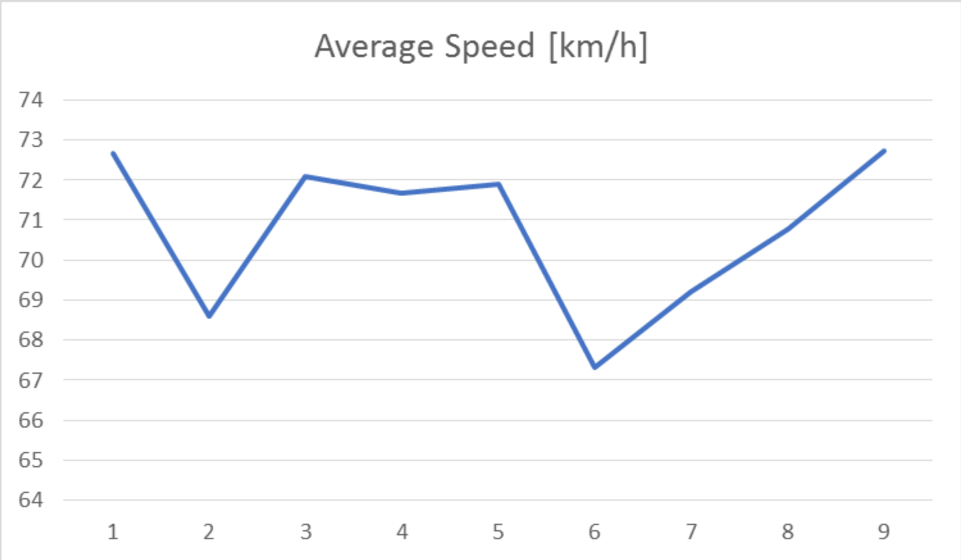


**Figure 8: Average speed (km/h) in each scenario**

Figure 8 gives a graphical representation of the average speed on the network. It is clearly visible that Scenario 2 and Scenario 6 give a much lower average speed in the network, which is an indication of less efficiency. In Scenario 2, this is due to the fact that the network of e-roads is very limited (in fact there is only one e-road stretch that can be used), so a high number of vehicles are forced to make a detour, thereby increasing the pressure on the road that is equipped with dynamic charging. In Scenario 6, the infrastructure has developed much, but also the number of dynamic chargeable EVs has increased tremendously, provoking a large number of detours increasing the strain on the transport system. Between Scenario 6 and Scenario 9, there is an almost linear increasing trend of average speeds: this is due to a lower number of dynamic chargeable vehicles (S6-S8) and another distribution of vehicles over the different states-of-charge (S9).

### 5.2.1 Relative increase of travel time

As this simulation exercise has a specific scope and time (one morning rush hour), it is useful also to consider relative travel time and delay time increase. Compared to the total delay time in the reference Scenario 1, the total delay time increases by 26% in Scenario 2, by 4% in Scenario

3 and by 7% in Scenario 4. This increase is due to the fact that a relatively large part of the dynamic chargeable vehicles has taken a different route that would not have been taken if these drivers had been able to minimize their generalized cost leading to user equilibrium. Compared to the total delay time in reference Scenario 5, there is an increase of total delay time by 33% in Scenario 6, 20% in Scenario 7 and 10% in Scenario 8. In Scenario 9, there is a small decrease of total delay time, mainly due to the fact that the composition of the traffic is different. As discussed above, in Scenario 9, a larger percentage of the dynamic chargeable vehicles have a high state-of-charge, meaning that they are not influenced by the location of the charging pads when choosing their route.

The total travel time is much less influenced: there is an increase of 3%, 1% and 1% in Scenario 2, 3 and 4, and there is an increase of total travel time by 6%, 4%, 3% and less than 1% in Scenarios 6, 7, 8 and 9. Effects on total delays are usually relatively larger than on travel times, because delays only take into account the extra travel time compared to the travel time at free flow speed, while travel times look at the complete travel times.

## 5.3 Emissions

Decreasing global and local emissions is among the most important rationales for the focus on electro-mobility, which can be facilitated by the development of dynamic charging throughout Europe. In this Section, the emission effects of different scenarios of dynamic charging have been explored based on the simulation exercise that has been described above. The structure of this Section is as follows: first, the global emissions of the investigated pollutants $CO_2$, $NO_x$ and $PM_{10}$ in each of the scenarios are investigated. Secondly, based on emission maps, the effects of the selected location of charging pads are explored. In case of dynamic chargeable PHEVs that still have an ICE internal combustion engine (ICE), it might matter where charging pads are located. If the ICE gets activated in (lesser populated) rural areas, less people are exposed to exhaust emissions than if the ICE gets activated in densely populated areas. As described above, in this simulation exercise the charging pads have been located in such a way that locations in the proximity of large population densities are prioritized.

### 5.3.1 $CO_2$-emissions

Although not normally having health implications, $CO_2$-emissions are considered to be important global emissions because $CO_2$ is considered to be a greenhouse gas (GHG), but it does not really matter where the emissions take place. In this sub-section, an overview will be given of the differences in global emissions of $CO_2$, but also of $NO_x$ and $PM_{10}$ that are important pollutants having significant health effects.

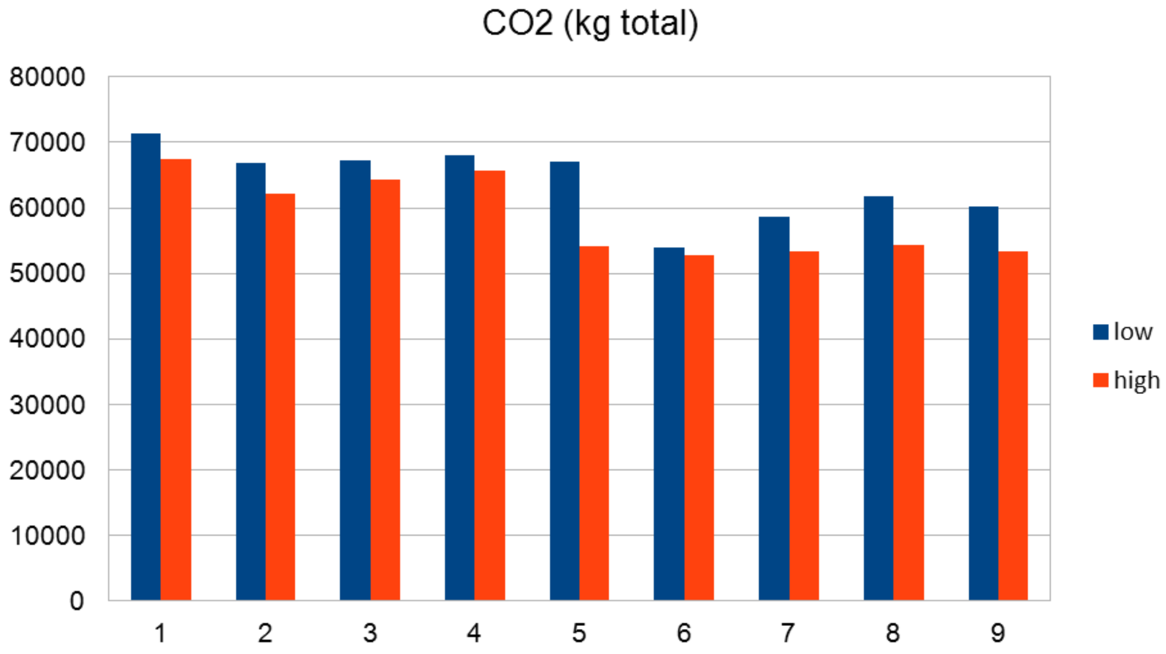


**Figure 9: Total $CO_2$-emissions in each scenario**

Figure 9 shows the evolution of $CO_2$ emissions for all of the scenarios, and both under the assumption of a high rate of non-compatible EV deployment and a low rate of non-compatible EV deployment. In the scenarios of Time period 1 (Scenario 1-4), there is a significant drop of $CO_2$-emissions for both the low and high non-compatible EV deployment assumptions. However, in the scenarios of Time period 2 (Scenario 5-9), the reduction of $CO_2$-emissions is much more pronounced under the assumption of a low deployment rate of non-compatible EVs (see Figure 7). There is no big difference in total $CO_2$-emissions between Scenarios 5, 6, 7, 8 and 9 under the assumption of a high deployment rate of EVs not compatible with dynamic charging. This implies that there is not a high $CO_2$-reduction because of the provision of dynamic charging.

Table 10 shows the relative reduction of $CO_2$-emissions comparing the case scenarios to the corresponding reference scenarios. It is visible that regarding $CO_2$-emissions, significant reductions are possible, but these reductions diminish tremendously in case of a high percentage of EVs not compatible to dynamic charging. This difference in effect size is most pronounced in the scenarios of timestamp 2 (Scenarios 4-7).

| Comparison | % reduction $CO_2$-emissions low | % reduction $CO_2$-emissions high |
|---|---|---|

| | | |
|---|---|---|
| S1-S2 | 6% | 5% |
| S1-S3 | 5% | 4% |
| S1-S4 | 0% | 3% |
| S5-S6 | 18% | 2% |
| S5-S7 | 13% | 3% |
| S5-S8 | 9% | 2% |
| S5-S9 | 10% | 3% |

**Table 10: Relative change of $CO_2$-emissions between case and reference scenarios**

| Scenario | CO2-emissions g per km (low) | CO2-emissions g per km (high) |
|---|---|---|
| S1 | 267.6 | 253.6 |
| S2 | 250.3 | 240.5 |
| S3 | 253.2 | 242.8 |
| S4 | 267.0 | 246.3 |
| S5 | 254.3 | 205.4 |
| S6 | 207.4 | 200.3 |
| S7 | 220.8 | 200.3 |
| S8 | 230.7 | 202.1 |
| S9 | 229.4 | 198.8 |

**Table 11: $CO_2$-emissions (g/km) in each scenario**

Table 11 shows the $CO_2$-emissions per kilometre in the different scenarios. Also here, it is visible that the $CO_2$-emissions are generally lower under the assumption of a high amount of BEVs not compatible with dynamic charging. Also, increase in number of vehicles that are compatible to charge on the e-road decreases the CO2-emissions per kilometre, as expected (remember from Table 2 and Table 3 that the order of scenarios with the highest number of electric (chargeable) vehicles to the lowest number of electric (chargeable) vehicles is S6 – S7 – S8 or S9 – S2 – S3 – S4). The other side of the coin is that dynamic charging does not decrease $CO_2$-emissions equally much compared to a situation with a low number of EVs (the low scenarios).

### 5.3.2 $NO_x$-emissions

Unlike $CO_2$-emissions, $NO_x$-emissions do have adverse health effects and therefore it matters where the emissions take place. Figure 10 shows the $NO_X$-emissions for all of the scenarios, and both under the assumption of a high rate of non-compatible EV deployment (high) and a low rate of non-compatible EV deployment (low).

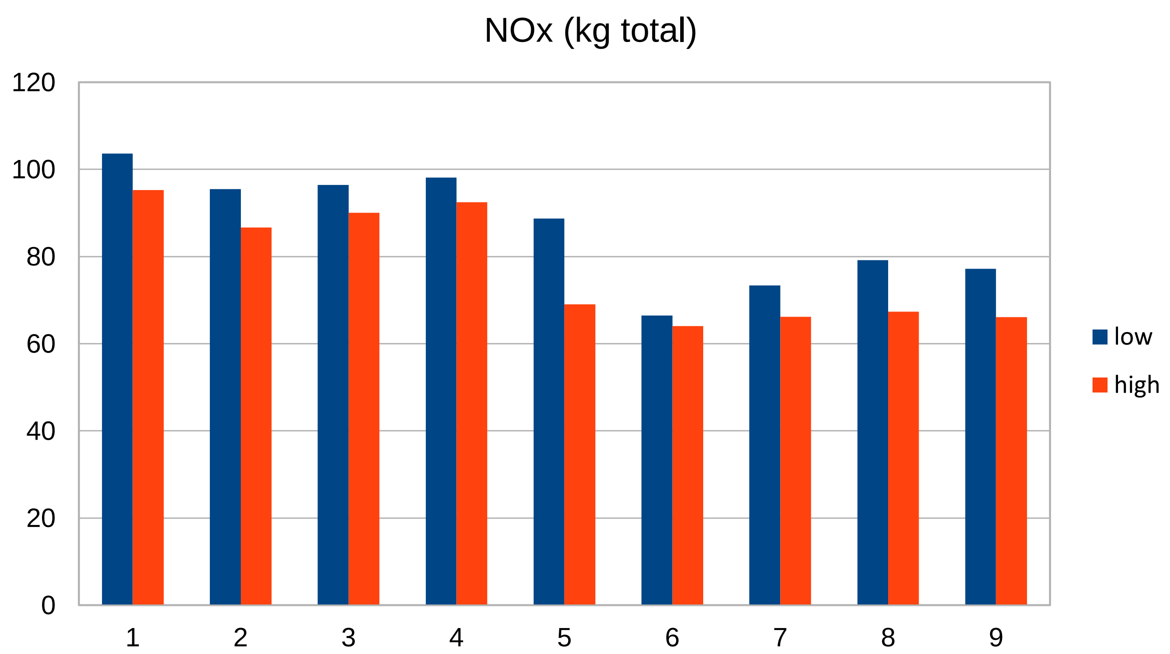


Figure 10: Total $NO_x$-emissions (in kg) in each scenario

| Comparison | % reduction NOx-emissions low | % reduction NOx-emissions high |
|---|---|---|
| S1-S2 | 8% | 7% |
| S1-S3 | 7% | 5% |
| S1-S4 | 1% | 3% |
| S5-S6 | 24% | 7% |
| S5-S7 | 18% | 5% |
| S5-S8 | 12% | 4% |
| S5-S9 | 13% | 6% |

Table 12: Relative change of $NO_x$-emissions between case and reference scenarios

Seen in percentage of reduction (Table 12), it is clear that in case of a low deployment rate of non-compatible EVs, some significant reductions of $NO_x$-emissions can be obtained, while in case of a high deployment rate, there is a significantly smaller beneficial effect of e-roads on $NO_x$-emissions.

Because of a higher total number of electric vehicles in case of a high deployment rate of BEVs that are not compatible with dynamic charging, the average $NO_x$-emissions per kilometre are lower (see Table 13). However, the additional beneficial effect of dynamic charging is much lower, especially for the Scenarios in Time period 2 (S4-S7). Considering the fact that dynamic charging

on a selection of the network has re-routing effects leading to higher distances, total emissions can even be reduced less.

| Scenario | NOx-emissions (gram per km) low | NOx-emissions (gram/km) high |
|---|---|---|
| 1 | 0.389 | 0.359 |
| 2 | 0.357 | 0.335 |
| 3 | 0.363 | 0.340 |
| 4 | 0.385 | 0.347 |
| 5 | 0.336 | 0.262 |
| 6 | 0.256 | 0.243 |
| 7 | 0.277 | 0.248 |
| 8 | 0.296 | 0.250 |
| 9 | 0.294 | 0.247 |

**Table 13: $NO_x$-emissions (g/km) in each scenario**

### 5.3.3 $PM_{10}$-emissions

The emission of $PM_{10}$ is less affected by dynamic charging than $NO_x$-emissions, because of the fact that electric vehicles still emit non-exhaust gas emissions, of which $PM_{10}$ is important. Because of the fact that EVs are usually heavier than comparable ICEVs, some contributing factors to $PM_{10}$-emissions count heavier as well, such as emissions related to the tyres.

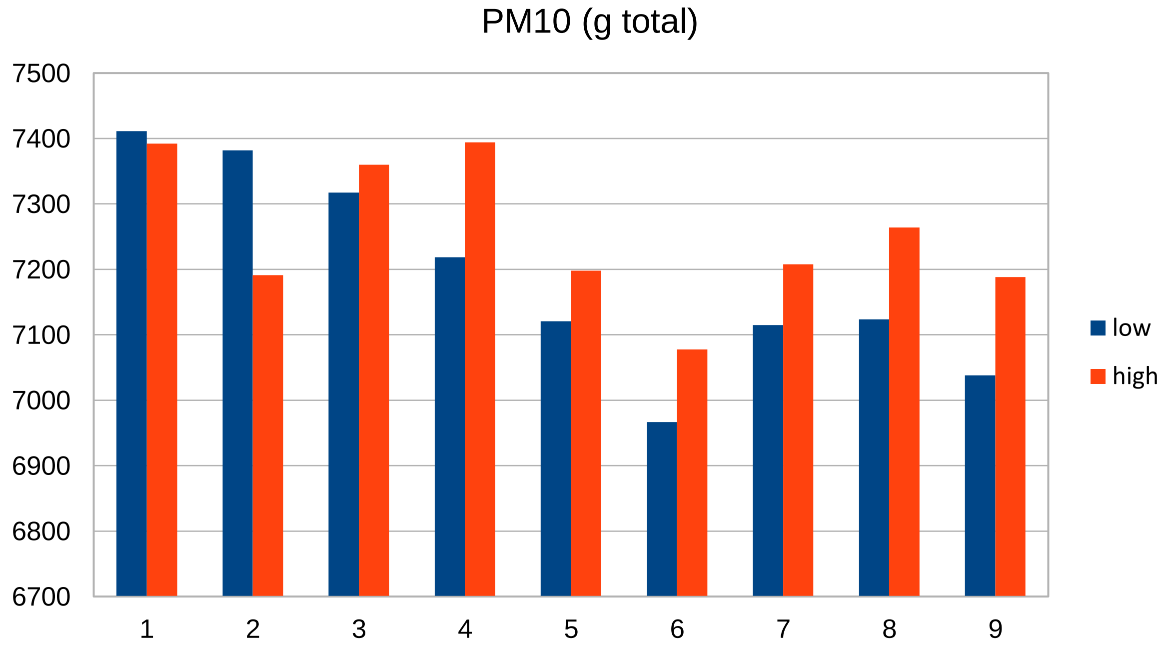


**Table 11: Total PM10-emissions (in g) in each scenario**

Figure 9 shows the emission of $PM_{10}$ in the different scenarios. In all scenarios, the emissions are between 4200 and 4650 gram, which is a difference of at most 10%. This is due to the fact that future ICEVs are assumed to be rather clean, so that even diesel vehicles will not emit much exhaust gas related $PM_{10}$ in the future. Most emissions are related to the tyres, which will not be solved by the introduction of electric vehicles. If EVs are heavier than comparable ICEVs, there might even be a higher $PM_{10}$-emission related to the tyres. This implies that electric vehicles are not the major solution to $PM_{10}$-emissions, and one should still be careful to plan new urban developments close to highly trafficked roads.

When considering the relative figures (see Table 14), there are hardly any differences between the case and the reference scenarios. In case of a high deployment rate of non-compatible EVs, there is even a small increase of $PM_{10}$-emissions expected (comparing Scenario 4 with Scenario 6).

| Comparison | % reduction $PM_{10}$-emissions low | % reduction $PM_{10}$-emissions high |
|---|---|---|
| S1-S2 | 1% | 0% |
| S1-S3 | 1% | 0% |
| S1-S4 | -2% | 0% |
| S5-S6 | 1% | 1% |
| S5-S7 | 1% | 1% |
| S5-S8 | 1% | 1% |
| S5-S9 | 1% | 2% |

**Table 14: Relative change of $PM_{10}$-emissions between case and reference scenarios**

| Scenario | $PM_{10}$-emissions (gram per km) low | $PM_{10}$-emissions (gram/km) high |
|---|---|---|
| S1 | 0.0278 | 0.0278 |
| S2 | 0.0276 | 0.0278 |
| S3 | 0.0275 | 0.0278 |
| S4 | 0.0283 | 0.0277 |
| S5 | 0.0270 | 0.0273 |
| S6 | 0.0268 | 0.0269 |
| S7 | 0.0268 | 0.0271 |
| S8 | 0.0267 | 0.0270 |
| S9 | 0.0268 | 0.0268 |

**Table 15: $PM_{10}$-emissions (g/km) in each scenario**

The emission figures per kilometre (see Figure 14) show that the $PM_{10}$-emissions per kilometre are very similar for all Scenarios, though a little bit smaller for the Time period 2 scenarios (4-7) and for the high scenarios, corresponding with a larger percentage of electrical vehicles.

### 5.3.4 Location of emissions

For emissions having health effects (in this case $NO_x$ and $PM_{10}$ have been investigated), it makes a difference where the emissions take place. Congestion effects related to re-routing behaviour might increase these emissions. Moreover, in case of hybrid electric vehicles that can charge dynamic, it makes a difference whether these vehicles are driving in electric mode or in non-electric mode. The charging pads have been placed in a strategic way, so that priority is given to provide dynamic charging in more built-up areas and along important freight routes.

In Figure 12-13, the concentrations of $NO_x$ have been plotted on a map in Scenario 1 and Scenario 2. No big differences are visible, and although the maximum concentration has decreased from 114 to 101 µg/m³, the concentrations are still too high on major parts of the network. This is probably due to the amount of congestion on these road parts, leading to higher emissions. The European yearly target is to not have concentrations of $NO_2$ higher than 40 µg/m³.

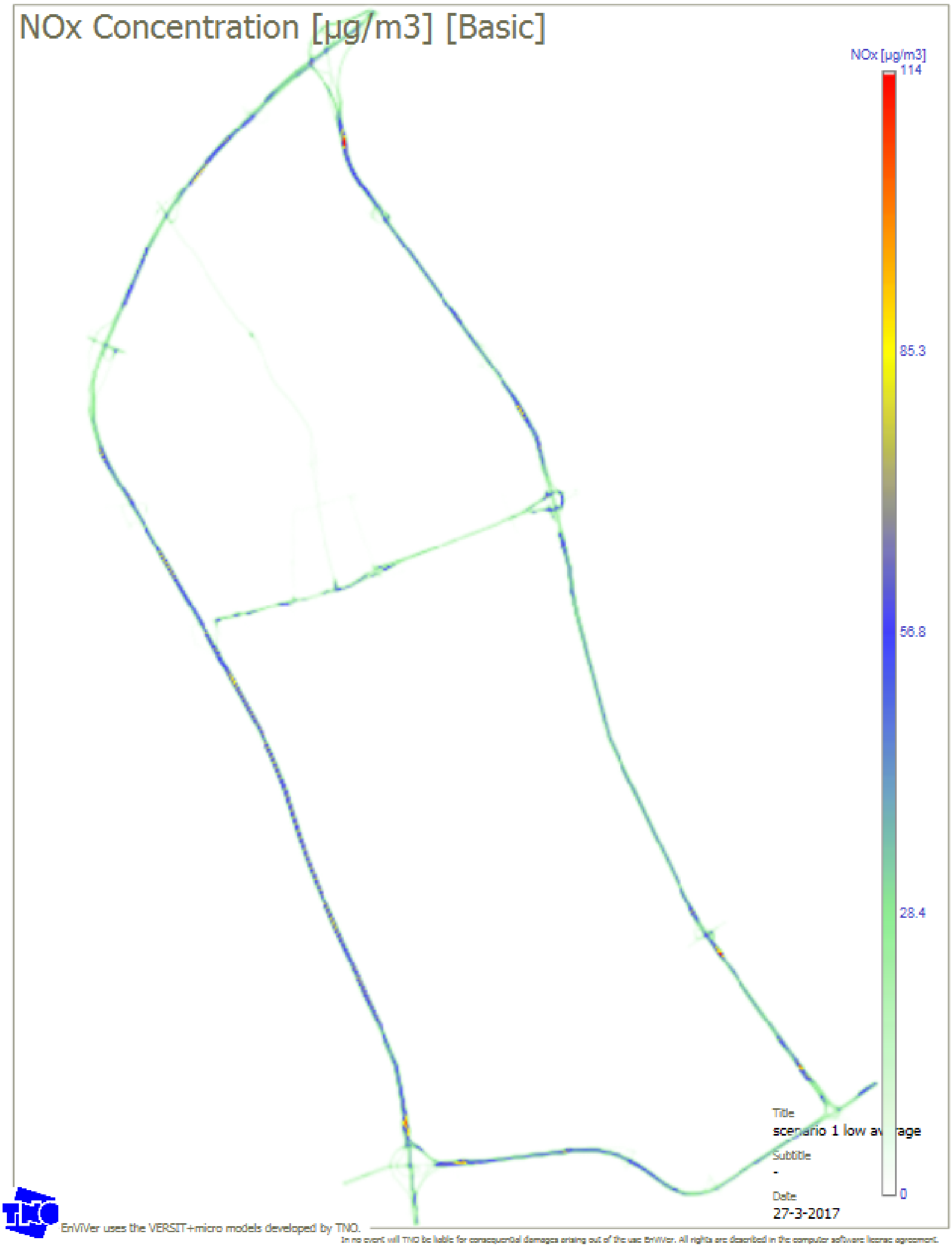


**Figure 12: Map $NO_x$-concentrations Scenario 1 low**

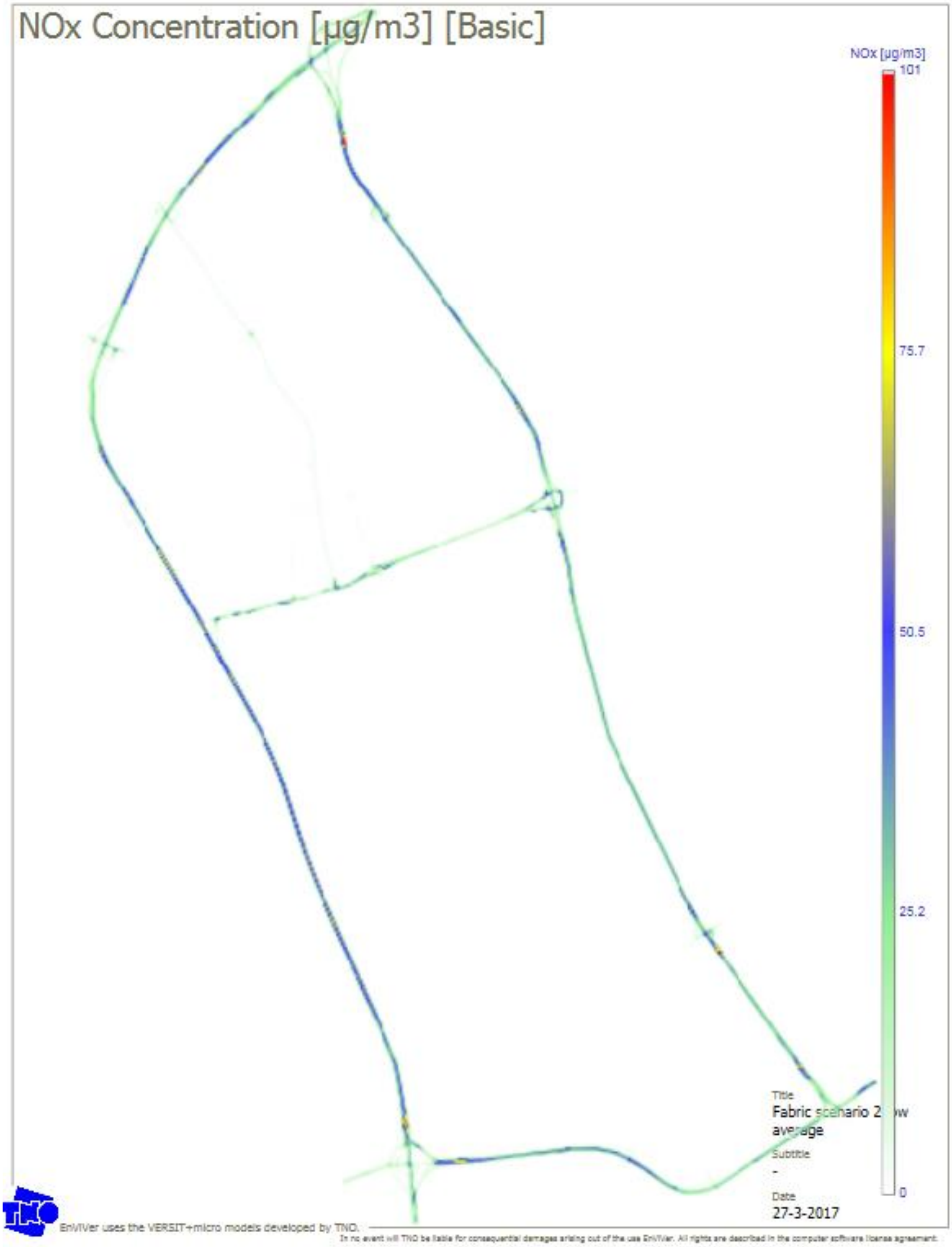


**Figure 13: Map $NO_x$-concentrations Scenario 2 low**

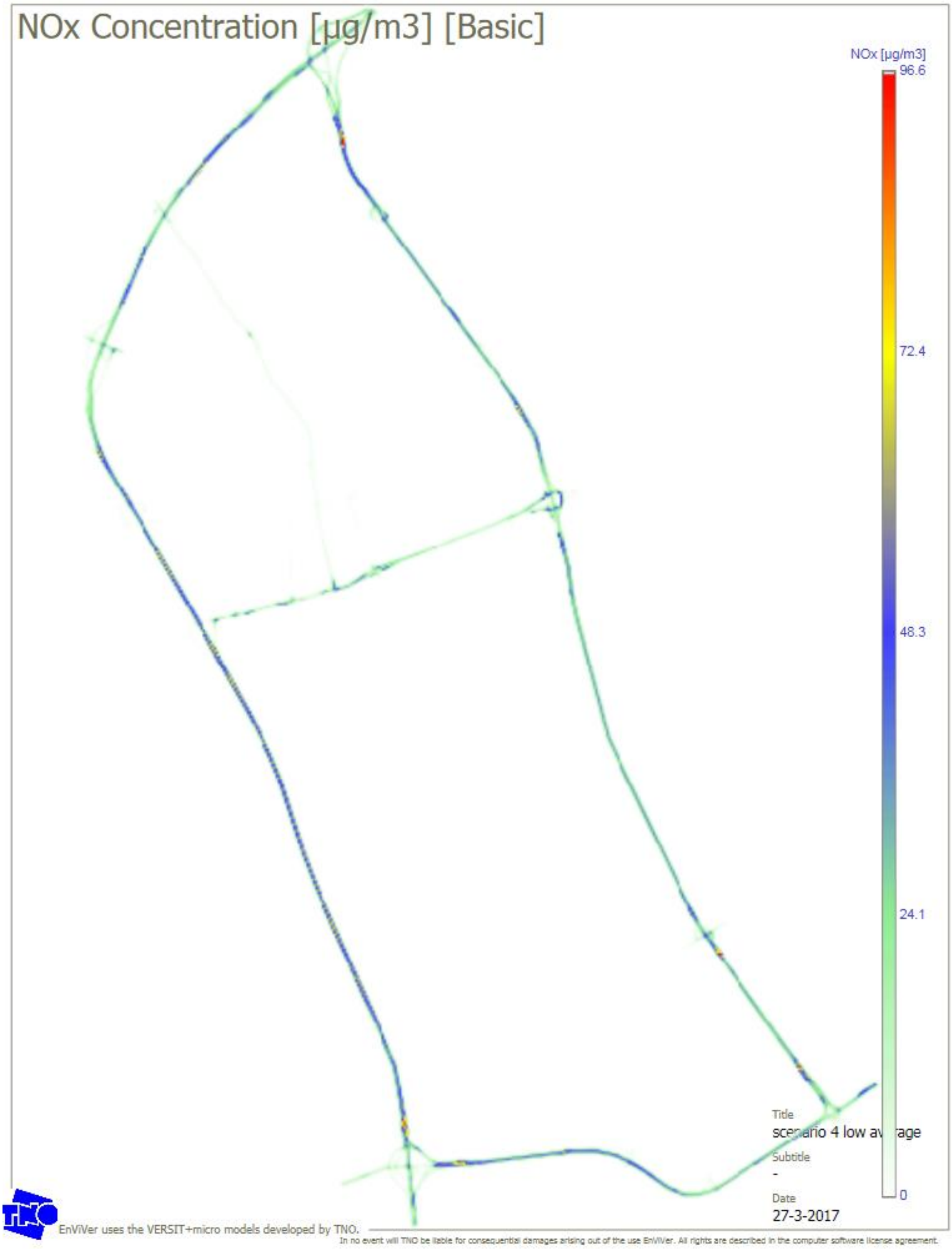


**Figure 14: Map $NO_x$-concentrations Scenario 5 low**

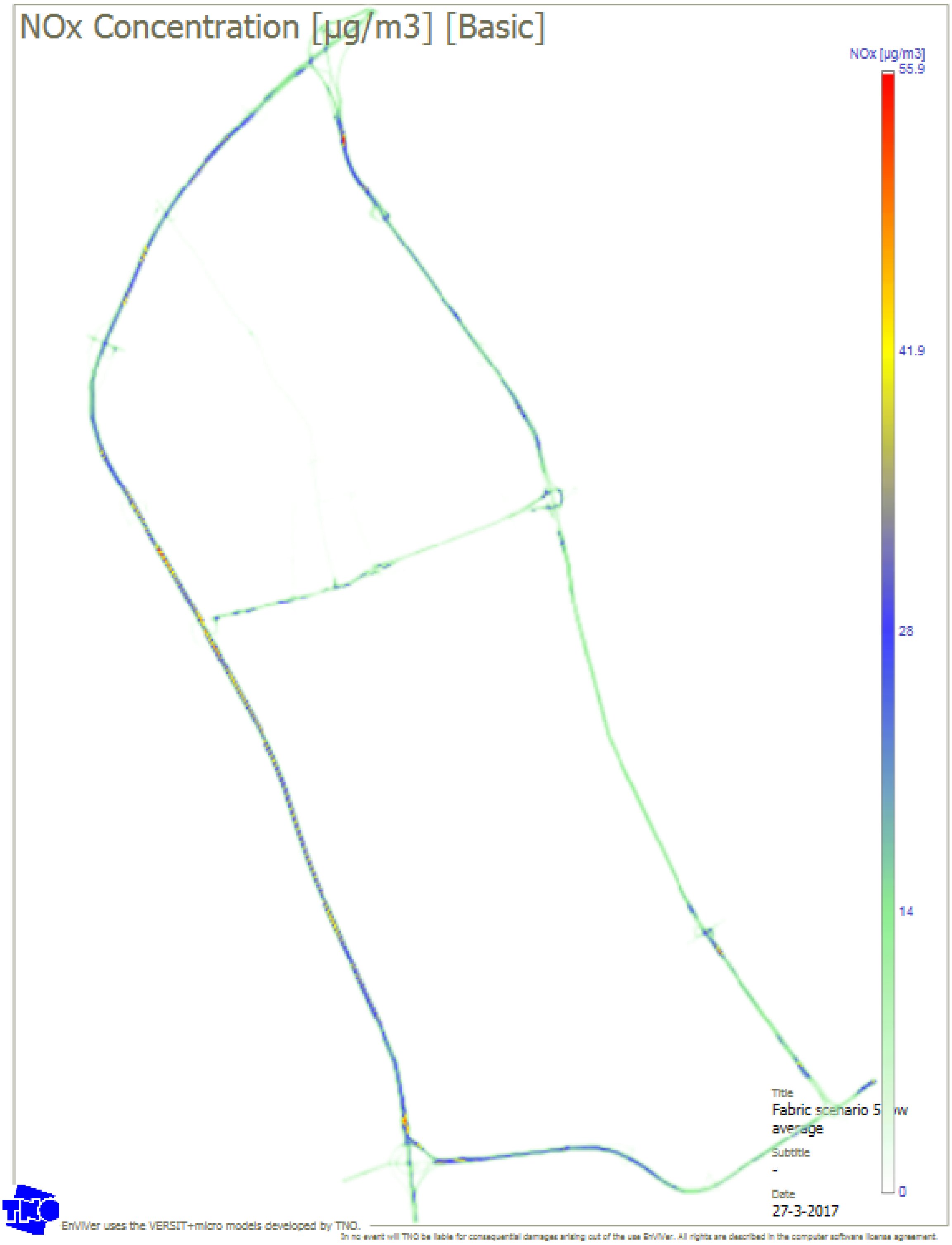


**Figure 15: Map $NO_x$-concentrations Scenario 6 low**

In Figure 14 and Figure 15, the $NO_x$-emissions for the Scenarios with the highest decrease (between reference Scenario 5 and case Scenario 6) are mapped. Here, especially at the east side of Delft and on the South part of the A4, improvements of air quality are noticeable. Also in the southeast side of the network (Rotterdam Overschie), problematic levels of $NO_x$ have been brought back to lower levels. In Scenario 4, there were concentrations of $NO_x$ up to 96 µg/m³. In Scenario 5, the maximum concentration of $NO_x$ was just below 56 µg/m³ and there are not many parts of the network where the concentration exceeds 40 µg/m³. However, the additional improvement of the air quality exactly where the e-roads are located is much less clear. Therefore, even with a relatively high percentage of hybrid vehicles, there are no indications for the exact location of charging pads to play a crucial role in improving air quality. However, the obvious result of having more electric vehicles in general is a decrease of transport-related $NO_x$-concentrations.

## 5.4 Energy consumption

### 5.4.1 Introduction

Electric roads have the possibility to decrease the energy consumption of a certain transport operation, as the use of electric vehicles implies a shift towards a more energy efficient propulsion method. However, this effect is not determined by the fact whether dynamic charging is possible, but rather on the indirect effects of providing dynamic charging on a large scale (increasing the attractiveness of electric vehicles). This implies that it plays a major role to which degree the deployment of electric vehicles depends on the provision of dynamic charging. This simulation exercise can give some insights in this issue.

**The role of the number of non-compatible EVs**

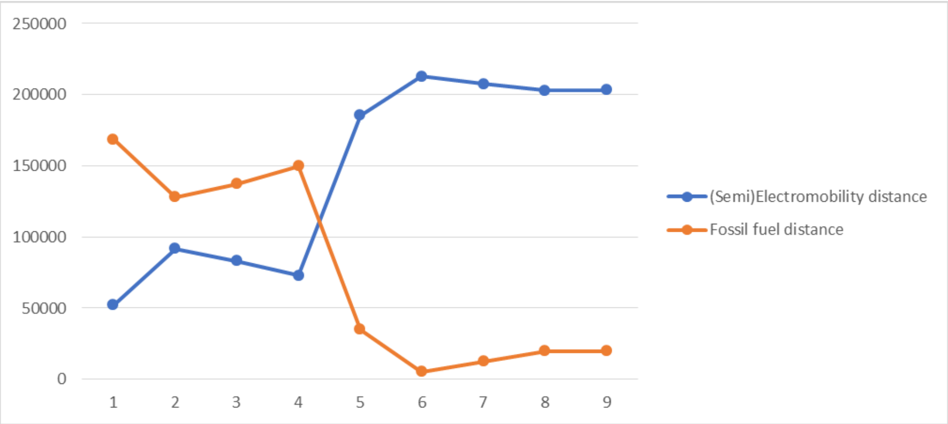


Figure 16: Distance by EVs and distance by ICEVs in each scenario (high)

Figure 16 depicts the division of distance driven by electric vehicles and the distance driven by fossil fuel vehicles. In the High Scenario, it is visible that there are not so many differences in the distance driven by EVs in Scenario 5, 6, 7, 8 and 9. The reason for this is the assumption that EVs will become popular anyway, regardless of whether electric road systems will be realized. From an efficiency perspective, this means that the added value of dynamic charging is low.

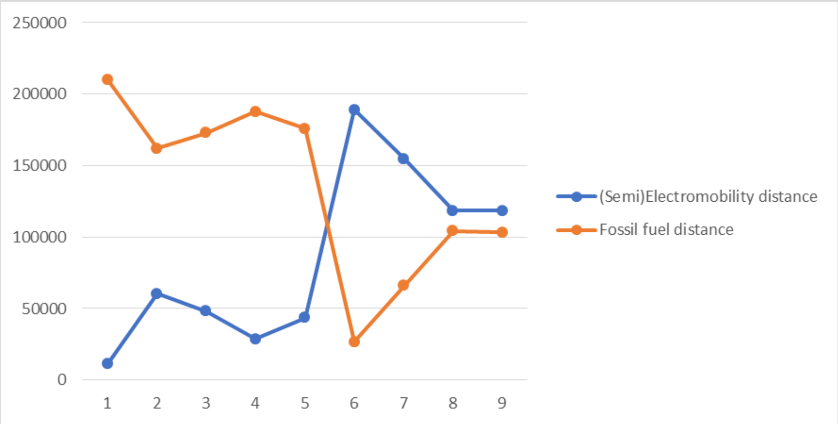


Figure 17: Distance by EVs and distance by ICEVs in each scenario (low)

The picture will look totally different in case the deployment of BEVs is low (Figure 17). In that case, it makes much more of a difference whether the motorways will be equipped with dynamic charging. In this way, there will be much more benefit of electric road equipment. In Scenario 6, much less fossil fuel will be used and more kilometres will be driven electrically.

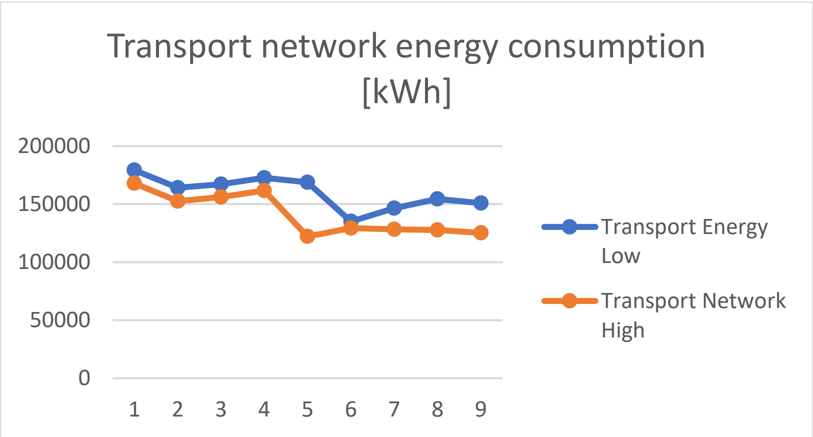


Figure 18: Total network energy consumption (kWh-equivalents) in each scenario (low and high)

Figure 18 shows the total amount of energy needed. In this figure, kWh-equivalents have been taken as a unit. These kWh-equivalents are a measure of the amount of energy that is needed to sustain the amount of traffic that is at the basis of this simulation exercise. In Figure 18, it is clear that the total amount of energy is always lower in case of a high deployment rate of BEVs that are not compatible to dynamic charging. However, in case of a high deployment rate, it takes actually more energy to provide dynamic charging to the absolute majority of the vehicles (according to Scenario 6) than in Scenario 5, where there is no dynamic charging. The modelling approach does not account for the impact of dynamic charging on the dynamic energy consumption of the vehicles, but assume dynamic charging as a means of battery top-up (range extension) and ICE deactivation. Seen from an energy efficiency point of view, equipping motorways with dynamic charging is only leading to the lowest possible energy use if the percentage of non-compatible BEVs does not exceed a certain number. As Figure 18 shows, in case of a low deployment rate, Scenario 6 will lead to minimal energy consumption, whereas in case of a high deployment rate, Scenario 5 (no e-roads) will lead to minimal energy consumption.

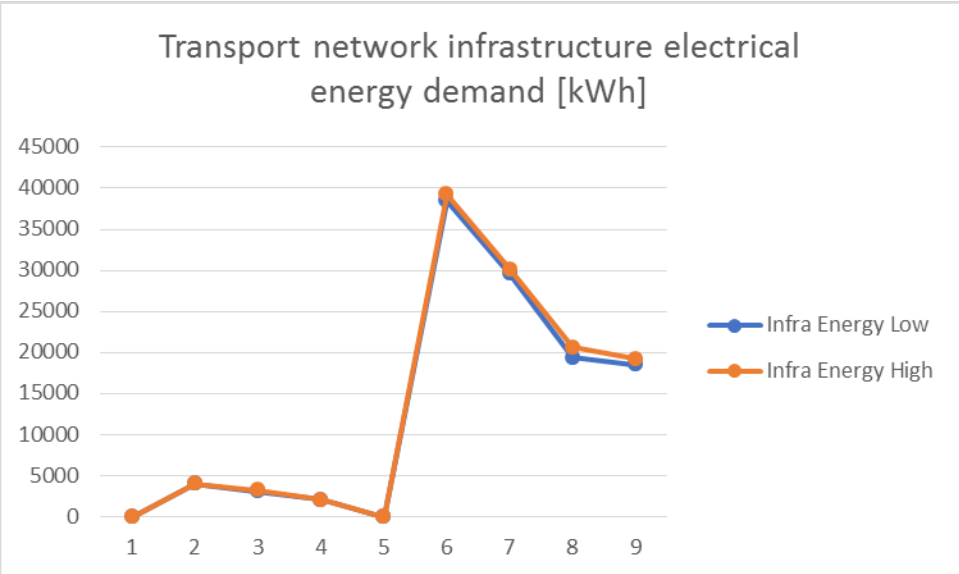


**Figure 19: Total electricity consumption (kWh) from e-roads in each scenario (low and high)**

There are large differences in the transport network infrastructure electrical energy demand between the different scenarios, as shown in Figure 19. In scenario 1 and 5, there are no e-roads, so there is no energy transmission. In Scenario 2, the energy transmission is almost 5,000 kWh, and in Scenario 6, almost 40,000 kWh needs to be supplied by e-roads, whereas in Scenarios 8 and 9, only 20,000 kWh needs to be supplied by e-roads (see Figure 19). There are two reasons for the large differences between Scenario 2/3/4 and Scenario 6/7/8/9: firstly, the number of

kilometres equipped with e-roads has heavily increased. Secondly, the number of dynamic chargeable vehicles has increased heavily as well. There are hardly any differences between the Infra Energy Low and Infra Energy High figures, but because they are based on different simulation runs involving the same number of dynamic chargeable vehicles only differing in the deployment of incompatible (PH)EVs, some small differences are visible for Scenarios 6, 7, 8 and 9.

## 5.5 The effect of pricing

In Scenario 9, the potential effect of price differentiation has been explored. This Scenario shares many aspects with Scenario 8 (in terms of the development of dynamic charging infrastructure and the assumed number of dynamic chargeable vehicles. However, a different distribution of state-of-charge has been assumed, a potential effect of price differentiation between static charging and dynamic charging. If electric vehicle users have to pay more for dynamic charging than for static charging, they are assumed to use less dynamic charging and to use more static charging, ceteris paribus. As e-road infrastructure is provided on a selection of the available motorways, electric vehicles with a low state-of-charge were stimulated to alter their route choice in order to be able to reach their destination. However, in case fewer vehicles are stimulated to alter their route choice, the system level efficiency of the network increases. Moreover, less energy is needed for the given traffic production (see Figure 16) and higher reductions of $CO_2$, $NO_x$ and $PM_{10}$-emissions can be obtained (See Tables 9, 11 and 13). This implies that, under the condition that a selection of a road network will be equipped with dynamic charging and under the condition that the price of dynamic charging has a significant influence on EV charging behaviour, there is a case to make for price differentiation between static charging (destination charging or fast charging) and dynamic, dynamic charging. However, another element that needs to be investigated in a later stage is the cross elasticity between the price of dynamic charging and the demand for dynamic chargeable vehicles.

# 6. DISCUSSION AND CONCLUSIONS

This simulation exercise has explored the effects of different combinations of infrastructure development and EV-deployment, under different assumptions of EVs non-compatible with dynamic charging. Because of re-routing behaviour, part of the energy gains of an increased use of electric vehicles gets lost. Also, it is apparent that the success of using dynamic charging is largely depending on whether there will be a fast or a slow uptake of electric vehicles irrespective of whether e-roads will be developed throughout the European Union. Under the assumption of a high uptake of EVs anyhow, the added value of providing e-roads is rather small. In some Scenarios, it has been shown that the energy consumption would even be smaller in case no e-roads are installed.

The simulation exercise has brought some questions/dilemmas to the surface that are worth exploring in order to inform decision makers in a later stage, for example when inductive charging could be installed at full scale.

## 6.1 Independent increase of the number of electric vehicles

The environmental gains of a system of dynamic charging heavily depend on the autonomous increase of the number of electric vehicles. Even though the current number of electric vehicles is comparatively low, this number is likely to increase into the future, as the range of new EVs entering the market increases while the price of these vehicles follows a decreasing trend. In different countries, very dissimilar forecasts have been made about the future deployment of EVs. Future policy plays a major role in this. For example, Sweden has the ambition to have a fossil fuel free vehicle fleet in 2030 [18], and in order to reach this goal, measures should be taken to heavily increase the uptake of electric vehicles regardless of whether e-roads are going to be installed.

The simulation analysis shows that in case of a high amount of electric vehicles not compatible with dynamic charging, the environmental gains of providing dynamic charging are rather limited. Only if dynamically charging EVs will replace ICEVs, a large environmental gain can be got. Another, more indirect effects, is that of behavioural adaptations of future EV-users. EVs that cannot be charged dynamic have some limitations in their potential use. These limitations might influence people's travel patterns in such a way, that they more often choose for the train rather than for the car when travelling over longer distances. However, the introduction of electric roads facilitates long-distance travelling by car. Generally, the biggest advantages of dynamic charging are to be expected if these infrastructural measures are the crucial factor in the development of electric vehicles. For light duty vehicles, there are already many options on the market, whereas

for heavy duty vehicles, there are also technical issues which remain to be solved and could be solved by the use of dynamic charging infrastructure.

In the current situation, dynamic charging throughout Europe is a rather abstract concept and it might not be very informative to study people's willingness to adopt electric vehicles in a far future under the condition that an extensive network of dynamic charging is available. However, as this simulation exercise illustrated, dynamic charging is most likely to be beneficial if it acts as a catalyst. After a period of larger scale tests and increased awareness about dynamic charging, future research could investigate exactly this aspect.

## 6.2 Capacity of chargeable lanes

In a staged deployment of electric roads, one way to go forward is to not provide roads that provide charging possibilities on every lane, but instead to provide charging on one of the lanes. As a lane on a multilane motorway has a capacity of around 2,100 person car equivalents per hour (Goemans et al., 2011), a relatively low number of dynamic charging vehicles per hour can be absorbed on one of the existing lanes. This would reduce the costs of e-road deployment and would enable to develop charging lanes on more different roads for a given budget.

There are several ways to develop charging lanes, each of them having different implications on traffic operations. In the following paragraphs, four different options will be discussed:

- Alteration of existing right lane
- Alteration of existing left lane
- Adding an additional chargeable lane
- Providing charging facilities on all lanes
- Dedicating one of the existing lanes for dynamic charging

### 6.2.1 Alteration of existing right lane

In most European countries, such as in the Netherlands, the right lane is the preferred lane to use and the other lanes should, under free flow conditions, only be used for overtaking. Another important rule is the fact that it is currently forbidden to overtake from the right. As congestion increases, the capacity of the remaining lanes will be used to a higher and higher extent, but the right lane will in many cases be the lane with the highest use rate. There are several reasons for this:

1. In most cases, on- and off ramps give access to the motorway's rightmost lane. This implies that this lane will be relatively busy, especially close to on- and off ramps.
2. Slow vehicles, e.g. freight traffic, should to a higher extent than passenger cars make use of the right lane because of the fact that their speed profiles might be lower than the regulated maximum speed on the motorway

Some vehicles that can be charged on-road will be added to the already existing group of conventional vehicles that preferably uses the right lane. This would probably not be a problem for low traffic intensities, but roads with low traffic intensities are less likely to be equipped with dynamic charging facilities due to the fact that usage rates will be insufficient. For roads with high traffic intensities, this might cause problems.

### 6.2.2 Alteration of existing left lane

What about providing charging facilities on the left lane? Regarding traffic operations, there are advantages of providing charging facilities on the left lane, as the traffic flow on this left lane is often lower. However, as HDVs will be among the vehicles to be charged on-road, the speed profile of this lane will change, which has implications for driving behaviour as well as traffic safety. Another regulatory problem of using the left lane for charging is the fact that the right lane will not be used as the preferred lane for all vehicles. Therefore, changes are needed of the regulations regarding overtaking from the right and the preferred lane used under free flow conditions. There might be a need to create a physical barrier between the charging lane and the remaining lanes, in order to make it more natural to overtake from the right. However, creating barriers would decrease the capacity of the road, as it gives fewer possibilities to flexibly use the available capacity of the motorway. Moreover, another problem which would be created with the alteration of the existing left lane into a charging lane is the fact that road users entering the road at some on-ramp will need to cross all lanes in order to be able to make use of the charging facilities. In situations with high traffic levels, this would be likely to create problems, especially for trucks that are relatively slow. Their weaving behaviour is likely to have a major influence on traffic operations. Another important factor is that lane changing behaviour on large motorways takes a lot of space. For example, vehicles having to move three lanes require some space to do so in free flow conditions, but in case of rather crowded roads, it might take a long stretch before the manoeuvre has been completed. This implies that some part of the e-road cannot be used by vehicles entering or exiting the road. Re-designing motorways with the provision of additional on- and off ramps directly giving access to the left lane of the motorway could be an option that solves the problem of weaving behaviour, but these infrastructural measures will require additional investments and physical space.

### 6.2.3 Adding a new lane dedicated to dynamic charging

The third option would be to add an additional lane to the existing lanes of the motorway. As this option would increase capacity, it would be likely to have less of an impact on traffic operations, unless the lane is of a limited length and the vehicles have to merge to the existing lanes afterwards. This lane should also have separate on- and off ramps in order to not interfere with traffic operations. However, providing another separate lane dedicated for dynamic charging would imply an additional cost. This cost is non-trivial, especially in case bridges and tunnels have to be adapted or even rebuilt.

### 6.2.4 Dedicating one of the existing lanes for dynamic charging

Closing one of the existing lanes of a motorway and only providing access for vehicles that are capable to dynamic charging has the most severe consequences for traffic operations. For motorways with excess capacity, the problems are limited. However, these motorways are not very beneficial for a successful development of dynamic charging, as there are fewer potential users of the system. For motorways which currently have capacity problems, however, this option has serious consequences on traffic operations, especially in case that a less-than-proportional part of the vehicles is capable to charge dynamic. For example, a motorway with a capacity of 6,300 motor vehicles per hour is transformed into a motorway with a capacity of 4,200 motor vehicles per hour + one lane of 2,100 dynamic chargeable vehicles per hour. With a traffic intensity of 4,500 motor vehicles per hour, out of which 200 EVs capable to dynamic charging, capacity problems will arise on the two lanes, whereas the lane equipped with dynamic charging will be heavily underused. This might stimulate car buyers to invest in dynamic chargeable vehicles, but this is a process that takes time.

### 6.2.5 Providing e-road lanes on all lanes

The last option implies that all lanes on e-roads will be available dynamic chargeable. This option is more expensive to implement, because of the fact that much more infrastructure has to be put into place. However, this option has advantages from a traffic operation point of view, as the current capacity of the road can be used just like before. Another advantage is that it allows for scenarios in which a large percentage of the vehicles can be charged dynamic, while this was not possible in case there was only one lane with dynamic charging.

### 6.2.6 Evaluation of the different configurations

In this subsection, the different configurations of e-roads are evaluated and policy implications are given. From an investment point of view, it might be most interesting to first provide one e-road lane on one of the existing lanes of a motorway. Regarding traffic operations, this would be a viable option in case the capacity of this lane has by far not been reached. For motorways that do not have a high travel demand, increased traffic flows on the rightmost lane are not likely to cause many problems. Because of weaving behaviour (especially waving behaviour by HDVs), the right lane has some advantages regarding traffic operations over the left lane. With increasing traffic flows, the left lane will be the first option to cause traffic operational problems, followed by the right lane. Above a certain traffic flow in combination with a certain market share of dynamic chargeable vehicles, different options have to be investigated. An additional lane can be added that is dedicated for dynamic chargeable vehicles. However, this option would imply major infrastructural investments, especially in case there are many bridges and tunnels. Another option (assuming current technical limitations are resolved) is to provide dynamic charging on more than one lane or to provide dynamic charging for all of the lanes. This option is vastly more expensive, but is most flexible from a traffic operations point of view.

In the simulations, it has been implicitly assumed that dynamic chargeable vehicles can be charged on all lanes of the e-roads that are part of the simulation exercise. Because of the fact that in some scenarios, the number of dynamic chargeable vehicles is relatively low, it might have been possible to only provide a single lane for dynamic charging. However, in another scenario for the Time period 1 and in all of the scenarios for Time period 2, the market share of dynamic chargeable vehicles is so high that providing one single lane for charging would have led to increased capacity problems. This is a political decision: how far into the future should this infrastructural development be planned for? The regulatory framework around e-mobility plays an important role as well: if all vehicles from a certain year have to be low emission or zero emission vehicles, there is more of a case to make for providing chargeable lanes that might have an overcapacity in the beginning. If, however, there is a lot of uncertainty surrounding the future deployment of electric vehicles in general and dynamic chargeable electric vehicles in particular, it might be wiser to first start providing one lane before equipping the entire road with chargeable lanes.

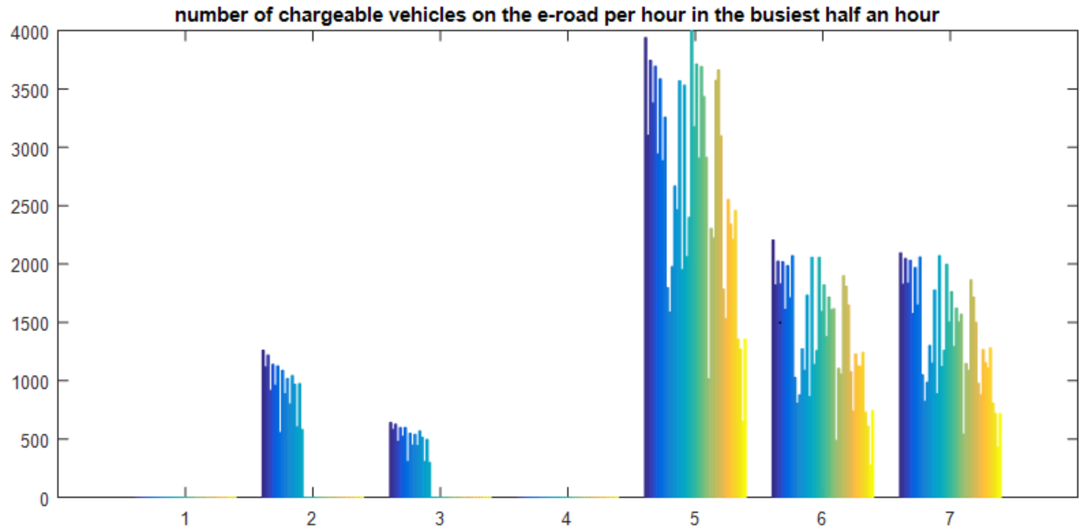


**Figure 20: Number of chargeable vehicles on e-roads per hour in the busiest half an hour**

In Figure 20, some insight is given in the number of chargeable vehicles on the e-roads. In Scenario 2, approximately 2,000 vehicles per hour will make use of the e-road stretch on the A4. This implies that, even with 24% of the vehicles of the network being dynamic chargeable, more than one lane should be equipped with dynamic charging in order to not create severe congestion.

In the scenarios 5-7, the amount of dynamic chargeable EVs would account for 7,000 or approximately 3,500 in Scenario 6 and 7. Even though there are now two e-roads, so the vehicles will be divided over two e-roads, there are so many vehicles that one lane would be too little and even two lanes would be too few in case of Scenario 5.

## 6.3 Intelligent transport systems and e-roads

There are possibilities to install traffic sensor and traveller guidance communication technology into the charging infrastructure. This technology would be able to provide high quality information of the state of the road, for example whether there is traffic congestion. This information could inform travellers and thus influence their route choice. However, the information that can be provided and can be collected is spatially limited to the future network of e-roads, which Is very likely to be concentrated on certain roads or even certain stretches of road. This implies that most of the road network will not be covered by this information system. At the same time, wireless information systems have the possibility to provide information throughout the network, including e-roads. These information systems have become more available and are widely used.

In the simulations for this task, the travel time of vehicles that had to charge increased. This effect would have been larger in case one of the other infrastructural options would have been chosen, especially in case the left lane would have been the lane equipped with dynamic charging technology. In case of a limited number of lanes to be equipped with dynamic charging, the distribution of traffic over the available lanes would change. Traffic information services physically attached to the e-road lanes have much better information about the e-road lane than about the other lanes. Therefore, the information is of limited value for a general overview about the traffic situation. Actually, it only tells whether it is faster to charge on e-road 1 or on e-road 2, because the rest of the motorway network is not covered by the same level of detail. However, current wireless technologies (say GPS-technology) might not be able to distinguish between the travel operations on different lanes going in the same direction. A combination of a GPS-system combined with very specific information about the state of traffic on the chargeable lane can provide additional information that may be interesting for a specific group of dynamic chargeable car users.

By being provided with specific information about the state of traffic on e-roads, collected on the e-road and then distributed using wireless technology, vehicles with a medium state-of-charge might be affected. These vehicles have enough range to make their trip, but not enough to also make the return trip. The decision whether or not to make any detour in order to make use of an e-road can be affected by specific information about the state of traffic on this e-road lane. This might have an influence on route choice and, indirectly, on traffic operations.

Example:

*A car driver with a medium state-of-charge level has to make a decision about taking a road that is longer, but equipped with an e-road lane, or another road that is shorter but without dynamic charging facilities. This road user makes use of a wireless in-vehicle information system (such as a GPS-system) that provides information about the state of the transport network. However, as one road can consist of both chargeable lanes and non-chargeable lanes, it is likely that travel time estimations are based on an averaged evaluation of the entire road. Because of the fact that the chargeable lanes have different purposes (they do not only provide transport but also provide charging for some of the vehicles), these lanes might become more crowded than the other lanes. On the other hand, given an early situation with only early adopters having dynamic chargeable vehicles, the lane with dynamic charging might be less crowded. Therefore, there might be differences in traffic flow and because of that, differences in travel times between the e-road lane and the non-chargeable lanes. As e-road lanes fulfil another purpose than conventional lanes of*

*the affected motorways, they are likely to attract more traffic and might have different travel times if mixed traffic is allowed. As the number of chargeable vehicles increases, these vehicles will push non-chargeable vehicles towards the other lanes. However, the information about traffic flows and travel times on e-road lanes is so place-specific that sensors on the e-road are likely to provide higher quality data than GPS-systems can do. This is comparable to the situation where part of motorways are tollroads or having High Occupancy Vehicle-lanes (HOV-lanes). Currently, the available wireless systems cannot distinguish the state of traffic on specific lanes. In case of HOV-lanes, it can only be assumed that the level of congestion on these HOV-lanes is lower than on the other lanes.*

In case all lanes of a motorway are equipped with e-road infrastructure, the added value of traffic sensor and traveller guidance communication technology is again limited, because of the fact that this difference between the different lanes has disappeared.

In every case, there are no benefits to only provide information systems using sensors that are connected to e-road lanes. The deployment of these lanes will simply be too sparse to create a comparative advantage above the well developed and wireless technologies that are currently available and cover a much larger part of the network. However, in some cases it makes sense to collect information about the state of the traffic flows, travel times and related issues specifically for the chargeable lane, if this information can be used by providers of wireless travel information in order to refine their travel time estimations in order to give a tailored travel advice to car drivers making use of dynamic chargeable vehicles. Cooperation between GPS-system providers and the provider of e-road information systems could in that way enhance traffic information and assist EV-users with making more informed decisions.

Also for vehicle-to-vehicle communication, there are currently wireless solutions available that will probably be further developed in the future, so also in that case, the beneficial effects of a communication system attached to the e-road are very limited. Finally, the predicted trend of a development of autonomous vehicles would also be unlikely to benefit from a communication system that is attached to the e-road, because of the scarcity of the network and because of the fact that currently, there are competing wireless technologies able to provide similar information.

| **Type of ITS** | **Potential for use on e-roads** |
|---|---|
| Traffic information | Limited due to sparsity of e-roads, only differences between different lanes on e-roads might be useful |

| | |
|---|---|
| Vehicle-to-vehicle | Limited due to sparsity of e-roads |

## 6.4 Policy implications

Based on this simulation exercise, the following issues for future policy measures should be reflected upon:

- For passenger cars, the ongoing development of electric vehicles will make electric roads less necessary into the future for daily trips. Therefore, it is doubtful to which degree e-roads will be the decisive factor for consumers to adopt an EV. The highest value of e-roads might be the option value: the possibility to make long-distance trips, without necessarily using e-roads on a daily basis. Therefore, the likely beneficial effects of a network of e-roads in Europe depend on the forecasts of the deployment of EVs in general
- While the implementation of e-roads does have a positive effect on reduction of pollutants such as $CO_2$ and $NO_x$, the relative benefit is heavily dependent on the number of non-compatible EVs. If a larger proportion of vehicle incompatible with charging are actually hybrid or full electric vehicles, the emission-reduction benefits of increasing penetration of dynamic charging vehicles for a given e-road coverage is less visible. For pollutants like PM10, non-exhaust related emissions of electric vehicles (from tyres and brakes) combined with increasingly less-polluting combustion engines lead to a marginal impact/benefit of implementing e-roads. Similarly, energy consumption reduction benefits of implementing e-roads depends heavily on the proportion of dynamic charging incompatible vehicles that are electric. In the case of a large adoption of incompatible electric vehicles, the energy consumption reduction benefit of implementing e-roads is only marginal.
- In case the development of e-roads will stimulate the downsizing of batteries in EVs, e-roads might increase the strains on the transport system, especially if dynamic charging is provided on a limited part of the network.
- Price differentiation of dynamic charging and static destination charging is assumed to decrease the need for dynamic charging for short distances. As expected, the fact that more vehicles have a high state-of-battery (decreasing the need to charge) leads to less detours and a better distribution over the road network, thereby decreasing travel times on a system level.
- When planning e-road lanes, the current traffic flows should be taken into consideration. Despite the fact that the need for dynamic charging is not very high in the beginning, traffic operations can be one of the arguments to decide providing all of the lanes of a congested

motorway with dynamic charging. If a constellation with only one lane is chosen, a careful assessment of the location of this lane should be made, accounting for the specific traffic situation at a particular stretch of road.

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