MASTER'S THESIS ENERGY SCIENCE (SYSTEM ANALYSIS)

THE POTENTIAL EFFECTS OF PASSENGER CAR ELECTRIFICATION ON CO_2 AND POLLUTANT EMISSIONS

A MODEL-BASED APPROACH

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ABSTRACT -By policymakers, the increasing amount of electric vehicles in the transport sector is regarded to be a pathway to decrease greenhouse gas emissions, improve air quality and decrease fossil fuel dependence. In this thesis, a model is used to quantitatively analyse and forecast the potential effects of passenger car electrification on the CO_2 emissions (greenhouse gases) and pollutant emissions (air quality) in the Netherlands in 2030. The model incorporates the total amounts, mileages, and (fuel) efficiencies of all cars to model CO_2 and pollutant emissions from (internal combustion engine) conventional cars and (full) electric cars. It was found that in the business-as-usual scenario, the effects of electrification on CO_2 emissions are small compared to the other modelled changes in the transport sector. The effect of electrification on air pollution emissions is larger, especially urban air quality improves from electrification. The effects of electrification could be further improved by increasing certain electrification components. Decreasing the fossil share in the electricity mix and increasing the amount of electric vehicles have the largest effects. Another, presumably less drastic measure could be to increase the average mileage of electric vehicles along with focusing this mileage on urban roads. The combined potential of improving all these electrification features are a 41-55% CO_2 and a 53-78% pollutant emission reduction in the passenger car transport sector compared to emissions.

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1. INTRODUCTION

1.1 BACKGROUND AND PROBLEM DEFINITION

Vehicles with electric drivetrains are becoming a more common phenomenon among Dutch passenger cars. (“Electromobility in the,” 2014) The growing presence of electric vehicles (EV) is the result of more stringent regulation and stimulation by subsidies. (Bakker et al., 2014) Policymakers generally believe that electrification of the transport sector is a pathway to decarbonize the transport system, reduce reliance on fossil fuels and improve air quality. (ibid.)

The transport sector contributes to 24,3% of the total EU greenhouse gas emissions. (European Commission, n.d.). To reduce these emissions, the EU has issued a directive in 2012 that poses a maximum emission of 95 grams of CO_2 per car per kilometre in 2020 (European Commission, 2012; 2011). The EU also has set urban air quality standards for its countries, which are linked to the pollutant emissions of internal combustion engines (ICE) of conventional cars. Because a growing number of electric vehicles contributes to attaining these goals, stimulation programmes have been set up by national governments to encourage private and corporate use of these cars. (Zhang et al., 2014; Mansour et al., 2011, Bakker et al., 2014; European Commission, 2011).

In the Netherlands, the stimulation consists of subsidy schemes and tax benefits for full electric vehicles (EV’s) and plug-in hybrid electric vehicles (PHEV). In major cities like Amsterdam and Utrecht, purchasing subsidies are provided for companies to invest in electric driving. (“Plan van Aanpak,” 2011) The infrastructure for battery charging is also supported: parking spots have been specifically assigned to electric vehicles so they have more charging facilities. Especially full electric vehicles are partly exempted from tax schemes that are usual for car owners. (ANWB, 2015)

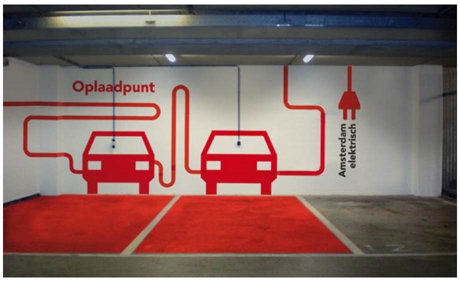


Figure 1.1: (groenparkeren.nl, n.d.). Designated parking spot for electric vehicles in Amsterdam.

For a large part, these encouragement policies are in place to reduce CO_2 emissions from the transport sector and to improve overall and regional air quality (pollutant emissions). (“Plan van Aanpak,” 2011; Bakker et al., 2014) However, how much electrification could contribute to less CO_2 and pollutant emissions in the transport sector and in what specific time frame is not exactly clear. The calculation method to estimate annual emissions of *all* cars, and thereby the relative effect of EV implementation, is complex. It depends on many features that differ in conventional (cars with an internal combustion engine) and in electric vehicles. Such are the total amount of electric vehicles in the car park, the emission factor of the electricity mix or how both car types are used.

In this master’s thesis, a model-based approach is used to quantitatively analyse the effects of electrifying the transport sector on future CO_2 and pollutant emissions. In the next subsection, scientific context and a policy overview are provided to further delineate and define the research area. The research question follows in section 1.3.

1.2 LITERATURE OVERVIEW

1.2.1: Electrification and CO_2 and air quality

CO_2 EMISSIONS

If research boundaries are placed around the vehicles only, the environmental effect of (full) electric vehicles as opposed to conventional cars is clear: EV's have *zero* emissions (which is how they are often advertised) because the propulsion technology does not require any fuels to burn. (Wu et al., 2012) Conventional internal combustion engines do consume fuels and thereby emit greenhouse gases and pollutants that affect air quality. (Klein et al., 2014) However, if electrification is examined in more detail, approximating the emissions is a lot more complex: Electric power used by electric vehicles also causes emissions, because it is generated by different energy carriers that each have their own emission factors. (Tarroja et al., 2014; Sorrentino et al., 2014) Also, the variety of car features and the number of cars that are used complicate the scale in which electric vehicles can offset emissions more complicated.

In literature, the positive effects of electrification on greenhouse gas emissions are subscribed. (Sorrentino et al, 2014; Smith, 2010) The magnitude of this effect however depends largely on the type and source of electricity generation sources. (Tarroja et al., 2014; Muneer et al. 2015) For instance, in parts of the US the electric vehicle's carbon emissions are still considerable because coal-fired plants take up a major part of the electricity production. (Kim & Rahimi, 2014) In the event that electric vehicles are charged with renewable energy sources, in which case cars are charged purely (and presumably in a decentralised way), the highest amount of avoided emissions can be achieved. (Tarroja et al., 2014; Sorrentino et al., 2014) Going in more detail, the exact time on which charging occurs is critical. The electricity mix varies with the time of day because it depends on the electricity demand profile. Some power sources generate the base load while other sources provide peak load demand. The supply of intermittent (renewable) electricity varies with how much energy (solar or wind in the case of the Netherlands) is available at a point of day. (Kim & Rahimi, 2014; Zhang et al., 2011)

The effects of electric vehicles on the transport sector are also tied to the performance of the cars they displace. If cars with a low fuel efficiency (and associated high emission output) are replaced by electric vehicles, the impact of EV's grows. Two types of this efficiency can be defined: A general efficiency, fixed for each car, is dependent on a variety of car features, including fuel type, weight and engine characteristics. (Faria et al., 2012) A use-based efficiency can also be defined, and is determined by how the car is used. The use-based efficiency is dependent on driver behaviour (gear selection and acceleration patterns) and traffic components, like the amount of start/stops, speed limits or road types. (Nijland et al., 2012) (Birrell et al., 2014)

POLLUTANTS

Other exhaust gases associated with (conventional) road traffic are air pollutants. Epidemiological studies have indicated that the internal combustion engines of conventional cars emit a number of airborne pollutants that are directly harmful to human health as well as to the environment. (Maynard et al., 2009; Masiol et al., 2014) Five of the most emitted harmful direct emissions associated with road transport are CO, NOx, volatile organic compounds (VOC), SO2, and particulate matter smaller than 10 micrometer (PM_{10}) (Sorin et al., 2014; Masio et al., 2014; Klein et al., 2012) In urban areas, the on-road transport forms the largest health effect of atmospheric pollutants, due to the high concentration of cars and the high population density (Soret et al., 2014).

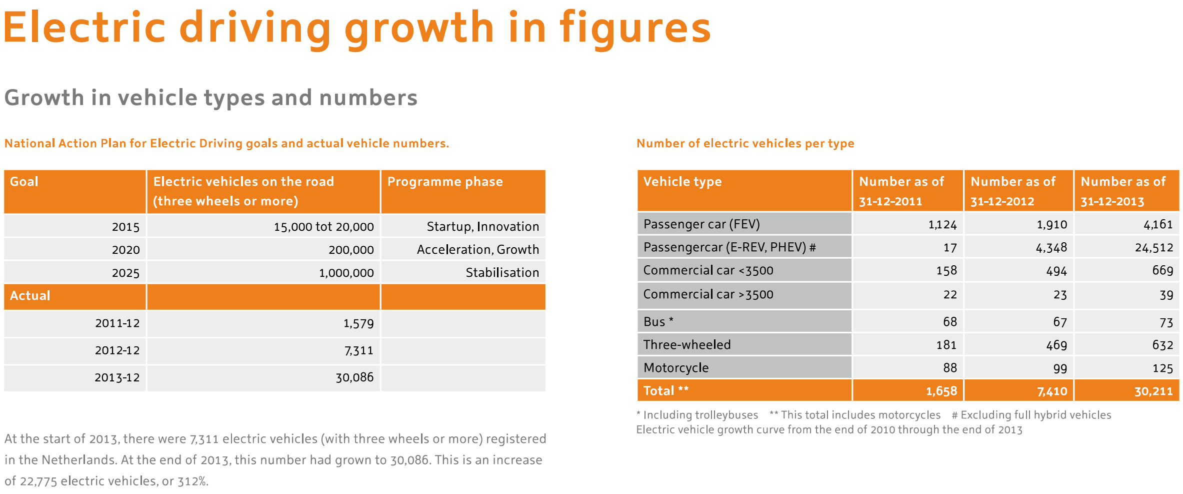
The replacement of conventional cars by electric vehicles could reduce emissions of these pollutants, because electric vehicles have no exhaust emissions at all. However, indirect pollutant emissions from electricity generated by fossil power plants could offset these effects, comparable to the case with CO_2. Lindly & Haskew (2002) found a slight increase of SO_x emissions and a slight decrease in NO_x as a result of EV implementation.

1.2.2: Overview on Dutch EV-policy

According to EU directives and international climate agreements, the Dutch government has set the goal to decrease CO_2 emissions and improve air quality in its major cities. (Bakker et al., 2014) Concretely, the emissions from the transport sector should be reduced by 17% compared to 1990-levels, which amounts to a maximum emission level of 25 megaton. (Sociaal-Economische Raad [SER], 2013) Increased electric driving has an important stake in these goals; the evaded emissions from 200.000 electric cars are expected to be 0,5 megaton in 2020 (“Plan van Aanpak,” 2011). The ministry has set financial incentives (tax exemption schemes) to encourage electric driving (both PHEV and FEV), and enabled additional fostering policy in urban areas. (ANWB, 2015; Bakker et al., 2014) The number of all electric vehicles (especially PHEV) has grown by a factor 20 over two years. Another interesting fact is that only passenger cars and light duty transportation vehicles are proposed to be fit for electrical power. (Nijland et al., 2012; “Electromobility in the,” 2014)

CURRENT GROWTH FIGURES: LARGE GROWTH IN EV’S

On behalf of the ministry of Economic Affairs, the Dutch Enterprise Agency has reported on the current and historic amounts of electric cars. This growth is the result from the governmental stimulation programmes as well as the increased availability of the vehicles. In the most recent report (2014), it is stated that the number of electric vehicles has grown from 1.579 at the end of 2011 to 30.086 at the end of 2013 (see table). It should be noted that the majority of those vehicles are plug-in hybrids or electric vehicles with range extenders, which run for the largest on gasoline. PHEV vehicles take up 80% of the total electric car park. The amount of full electric vehicles has so doubled between the end of 2012 and the end of 2013. (“Electromobility in the,” 2014)



Electric driving growth in figures

Growth in vehicle types and numbers

National Action Plan for Electric Driving goals and actual vehicle numbers.

Goal	Electric vehicles on the road (three wheels or more)	Programme phase
2015	15,000 tot 20,000	Startup, Innovation
2020	200,000	Acceleration, Growth
2025	1,000,000	Stabilisation
Actual		
2011-12	1,579	
2012-12	7,311	
2013-12	30,086	

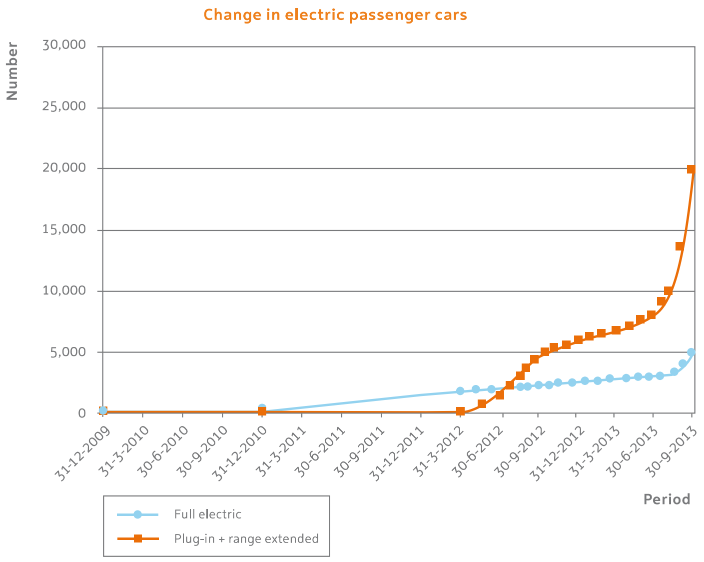
At the start of 2013, there were 7,311 electric vehicles (with three wheels or more) registered in the Netherlands. At the end of 2013, this number had grown to 30,086. This is an increase of 22,775 electric vehicles, or 312%.

Number of electric vehicles per type

Vehicle type	Number as of 31-12-2011	Number as of 31-12-2012	Number as of 31-12-2013
Passenger car (FEV)	1,124	1,910	4,161
Passengercar (E-REV, PHEV) #	17	4,348	24,512
Commercial car <3500	158	494	669
Commercial car >3500	22	23	39
Bus *	68	67	73
Three-wheeled	181	469	632
Motorcycle	88	99	125
Total **	**1,658**	**7,410**	**30,211**

* Including trolleybuses ** This total includes motorcycles # Excluding full hybrid vehicles
Electric vehicle growth curve from the end of 2010 through the end of 2013

Figure 1.2 (“Electric mobility in,” 2014): The left table shows the planned amounts of electric vehicles on the road. The right table shows figures and numbers of the current EV amounts in the Netherlands.



Source: RDW, edited by RVO.nl

Figure 1.3 ("Electric mobility in," 2014): Growth of electric vehicles in the Netherlands. Especially electric vehicles with internal combustion engines included have grown in the last three years.

POLICY VISION ON ELECTRIC DRIVING

The main goals of stimulating EV's are the reduction of greenhouse gas emissions and the fossil-fuel dependence (thereby enhancing energy security), improvement of air quality in cities and the achievement of green economic growth. ("Plan van Aanpak," 2011) The basic mechanism of how electric cars could affect greenhouse gas emissions and air quality has already been explained earlier. The economic argument that the Dutch government makes is based on the pioneer role that the Netherlands could play. Economic growth could be achieved by improving the Dutch competitive position as a testing ground for innovative solutions for transport and for all associated industries surrounding EV's like manufacturing, battery development and the services industry. ("Plan van Aanpak," 2011) The Dutch government also highlights important conditions that reinforce the *testing ground* characteristic for electric driving: especially the *Randstad* (Dutch metropolitan area including the four major cities) with its relatively short commuting distances and flat landscape.

Stimulation is necessary to overcome disadvantages that electric driving has compared to conventional driving:

- The purchasing (investment) costs are high compared to conventional cars. This is exemplified by figure 1.2, which shows the price difference between a gasoline and an electric car of the same type. The expensive battery that an electric vehicle uses drives up costs. (Nijland et al., 2012; Giessen-Gondelach & Faaij, 2012).
- Practically, an electric vehicle has a limited driving range. Charging infrastructure is also not as omnipresent as gas stations. This limits the freedom of movement compared to conventional cars. (Nijland et al., 2012; Neubauer & Wood, 2014a)

EV STIMULATION: LOCAL FOCUS

As they are the most direct link to citizens and traffic, local governments also play an important part in EV stimulation. Especially the major cities in the Randstad have been designated as focus areas of electric driving. (Nijland et al., 2012; "Plan van Aanpak," 2011) This means that the municipal administrations are allowed to spend extra budget to stimulate electric driving within their areas. Apart from the national agenda, air quality is of extra importance for city municipalities, as they are to meet with EU standards. (Bakker et al., 2014) Stimulation on this level consists of public tenders for charging infrastructure and creating designated parking spots to charge electric vehicles (both plug-in and full electric). It must also be noted that the policy varies across municipalities. (Bakker et al., 2014) Larger cities often have a more developed EV-related (and EV-friendly) strategy as opposed to smaller ones. Also important to note is that the current policy stimulates both full electric cars as well as plug-in hybrid cars, although the latter category is not studied in this thesis. Although the environmental effect is limited, hybrid cars do a have (much) larger driving range and have smaller purchasing costs, which does make hybrid cars a more attractive way to electrify the fleet (Bakker et al., 2014).

EV STIMULATION: TAX EXEMPTION AND SUBSIDY SCHEMES

Stimulation exists mainly of exempting users of electric vehicles (both full as well as plug-in hybrid) from road and vehicle taxes (Bakker et al. 2014). Full electric vehicles have been exempted from BPM (vehicle purchase tax) until 2018 and MRB (vehicle circulation tax) until 2015. ("Electric mobility in," 2014) Moreover, the tax addition percentage of leasing a company car ("bijtelling" in Dutch) is in the lowest scale (4%). Interestingly, a recent tax reform actually made a difference between electric cars and hybrid cars on this particular point, moving plug-in hybrids from the lowest scale to a 15% scale from 2016. (ANWB, 2015)

There are also various subsidy schemes. On national level, businesses can have their investment in electric vehicles rebated by up to 36% of a maximum of 50.000 euros. (Rijksdienst voor ondernemen [RVO], 2014) Also, the ministry of Economic Affairs supports the logistics and taxi firms with €3.000 subsidy per electric taxi or delivery van. Locally, the major Dutch cities (presumably part of the designated focus areas for stimulating electric vehicles) also grant an extra €5.000 subsidy per vehicle within their region. These schemes show that corporate car users can benefit the most if EV's were used.

1.3: RESEARCH AREA, DELINEATION AND RESEARCH QUESTIONS

The short overview of the literature in the previous chapter points out many causal relationships between emissions, electrification and the transport sector. The impact of transport electrification on the emissions or air quality is studied in a number of different case studies. What lacks in scientific literature is a more complete model that involves a quantitative analysis of the effect of electrification on CO_2 emissions and air quality of passenger car transport. This is a relevant topic because the transport sector has a large effect on these emissions and because there is public money involved in electrification as a solution.

This thesis therefore utilizes a model that calculates annual emissions from all Dutch passenger cars, which incorporates all relative characteristics. This model calculates emissions for the current situation (assumed to have no electrification) and for a future situation with a significant amount of electric vehicles (2030, see delineation).

Four clear delineations have been made to avoid complexity and provide borders.

1. The model will focus on the Netherlands. To be precise, only the kilometres travelled by *Dutch* cars on *Dutch* roads will be considered.
2. Only passenger cars will be considered in the model. This is because the energy consumption within the transport sector is for the most part accounted for by passenger cars and light duty transportation (Tarroja et al., 2014; Lindly & Haskew, 2002). Passenger cars account for about 73% of the road traffic of the total transport sector (CBS, PBL, Wageningen UR, 2014). Moreover, Nijland et al. (2012) have stipulated in their outlook on the future role of electric driving that the electrification development is mostly aimed at passenger cars and light duty transportation.
3. The time frame has been set to 2030. This is an important year as both the Netherlands (conditionally) and the European Union have defined goals to achieve 40% reduction of CO_2 emissions compared to 1990 levels, together with 30% energy efficiency (Renzenbrink, 2014; "Nederland onder voorwaarden…", 2011). Moreover, a goal was set to reduce CO_2 emissions by

17% compared to 1990 levels. (SER, 2013) This year can therefore be used as a checkpoint for the different aspects of electrification.

4. Although plug-in hybrids are also part of the policy definition of electric vehicles, **only full electric** vehicles are considered. This is because hybrid cars, which use both an electric engine as well as an internal combustion engine, are assumed to be a transition technology of conventional cars towards electric vehicles. As the potential of electric driving is addressed in this thesis, the mature technology (of full electric driving) is considered.

With the research area defined, the following research questions have been proposed for this thesis:

WHAT IS THE POTENTIAL ROLE OF PASSENGER CAR ELECTRIFICATION IN REDUCING CO_2 AND POLLUTANT EMISSIONS IN THE NETHERLANDS IN 2030?

1. What are modelled CO_2 and pollutant emissions in 2030 according to business-as-usual scenario's compared to modelled 2013 emissions?

In the first results section, the emission figures from Dutch passenger cars are presented for a business-as-usual scenario in 2030. In this case, the amount of electric cars and the electricity mix are set to a figure as expected by Dutch policy outlooks. The same applies to the general transport characteristics and conventional car park features, for which input is found from literature.

2. What are the effects of varying electrification features on CO_2 and pollutant emissions in 2030?

As seen in the literature, the effects of electrification are dependent on its different features. In this sub question, these variables are varied in different scenarios to observe their potential in further reducing emissions by electrification. Four factors have been chosen and are stated below, along with the source on which the variable is based on.

1. Degree of electrification: This is the amount of electric vehicles as percentage of the total passenger car park. This is a basic variable that shows the effects of the penetration of electric vehicles within the car park.
2. Electricity mix: The performance of electric vehicles is for a great deal dependant on the fuel mix used for the generation of the electricity that it runs on. As the traditional countrywide electricity is mostly generated by fossil fuels, electric vehicles still emit CO_2 or airborne chemicals through power plants. The mix of different fuels used is an important factor in the CO_2 emissions of electricity consumption. (Harmsen & Graus, 2013) Natural gas, which dominates the Dutch power mix, has a lower CO_2 factor (CO_2 emissions per energy unit) than coal, which is the second most used fuel. Wind power has no emissions and is expected to grow according to the policy to achieve 16% renewable electricity by 2023. (SER, 2013)
3. EV mileage: The total of travelled miles that electric vehicles make on average. Naturally, increasing the mileage travelled by electric vehicles could have positive effects on emissions as does increasing the amount of EV's does (1). Furthermore, this variable is brought to attention by the high investment costs for electric vehicles (Autozine, n.d.; Bakker et al., 2014). To let cheaper fuel prices compensate for these high initial costs, a higher-than-average mileage could be a result.
4. Urban EV mileage: Dutch policy seems to aim concentrate EV stimulation on urban areas. The reasons given are mostly the short distances (which match the limited range that they currently have) and the high economic activity within (large) cities. (Nijland et al., 2012) Within this

electrification variable, the percentage of the annual mileage of EV's spent in urban areas is varied.

2. METHODOLOGY

In this research, the emissions from all passenger cars are considered. Because transport emissions are dependent on many elements of the transport sector, a model is used in this thesis to account for most of these elements, as well as with several electrification aspects. In the next subsection, the operationalization of the research elements is explained. This is followed by the schematic overview of the model that is used. In the next subsection, it is shown what the differences are in the transport system between 2013 and 2030 and how they are accounted for. In the final subsection, the input values for the model are given.

1.1 OPERATIONALIZATION AND MODEL BASICS

Input: conventional cars and electric cars

In this model, it is assumed that the passenger car transport sector consists of two car types that cause emissions.

- Conventional cars, powered by (only) an internal combustion engine. Gasoline and diesel cars are selected to represent this group (this is explained in 1.2)
- Electric vehicles, fully powered by an electric drivetrain.

Both car groups are discerned because they both have a different calculation scheme to their corresponding approach emissions. Also, the distinction is necessary to determine the (relative) effect of electric vehicles on the emissions of the total sector.

Output: emissions

- CO_2 emissions: In the model, purely the CO_2 emissions that come from the use of the car are considered. For cars with internal combustion engines, this means that only the emissions from the fuel consumption are considered. The fuel consumption is calculated by multiplying the use of each times its efficiency. For electric vehicles, the CO_2 emissions of the electricity consumption are considered. This is computed by the CO_2 intensity of the electricity mix, which is given by the share that each energy carrier has in the electricity production. This factor is also multiplied by the total energy consumption of each car, which is given by its use times efficiency. Within both vehicle groups, the CO_2 emissions figures comprise other greenhouse gases (N_2O and CH_4) as well. The usual unit in which it is given is CO_2 equivalent (CO_2-eq), which converts the effects of the other GHG's in terms of CO_2 effects.
- Pollutant emissions: In this model, the most important pollutants from the transport sector that have an effect on air quality are chosen: NO_x, SO_x, CO, Volatile Organic Compounds (VOC) and Particulate Matter of less than 10 micrometer (PM10) (based on Maynard et al., 2009). For conventional cars, the emissions of these pollutants are given by Klein et al. (2012), and are not dependant on fuel consumption (except for SOx) but purely on the distance travelled. For electric vehicles, the emissions are given by the emission factor of each pollutant per generated kilowatt-hour. This depends on the emission factors of each carrier and its share in the electricity mix. In the results a clear distinction is made between **total** pollutant emissions and **urban** pollutant emissions. Because literature has indicated that the effects in urban areas are the largest, urban pollutants are regarded separately.

Definition of electrification

As effects of electrification are scrutinized in this thesis, the definition of this electrification is given at this point. In this thesis, electrification means a one-on-one replacement of a conventional car in the system. This means that an EV is never an extra vehicle in the transport system and always offsets the use of another car, taking over its annual mileage.

An alternative definition of electrification is one purely focused on the travelled kilometres. This means that a specific amount of kilometres is driven with electric vehicles instead of conventional cars. This could simplify the calculations and displace assumptions about how electric vehicles are introduced in the system, as the amounts of cars do not have to be found. In the methodology of this thesis however, the first (amounts) definition is chosen over the second one for the following reasons:

1. As found in the policy research, the subsidy schemes are for a large part focused on stimulating the cars rather than the actual miles that are driven.
2. When vehicles are considered instead of the kilometres, a more accurate approximation can be given of the emissions of the transport sector. This is because the specific vehicle features are important determinants for emissions.
3. Via this methodology, the actual kilometres that the vehicles travel are still dealt with, because the annual average mileage is considered. The mileage that electric vehicles travel (on average) is one of the variables of which the effects are researched.

Model basics: approximating annual emissions from passenger cars

The model is built in Microsoft Excel. It calculates CO_2 and pollutant emissions for two situations: the current situation (“2013”) and the future situation (“2030”). 2013 has been chosen because it is the latest (full) year in which certain details of the transport sector were administrated. The choice for 2030 is explained in section 1.3. The general output is given in total annual emissions per year, which is usually in the order of megatons in the case of CO_2 and tons in the case of pollutants. The effect of the studied variables can then be given in a reduction of these emissions between 2030 and 2013. For $CO_{2,}$ this is given in absolute terms, for pollutants, this is given in overall average percentage (because a range of compounds is assessed).

To keep the explanation of the calculation schemes clear, only CO_2 emissions are addressed in this model outlook. Calculation of air pollution emissions will be the same apart from a few details. These details are shown when every compartment is discussed.

As was established in the theory section (1.2), emissions from transport are directly related to fuel (or energy) consumption. The model shows emissions on an annual level, which means that the fuel consumption on an annual level is calculated. The total emissions are then given by multiplying three different factors for each car group (figure 2.1).

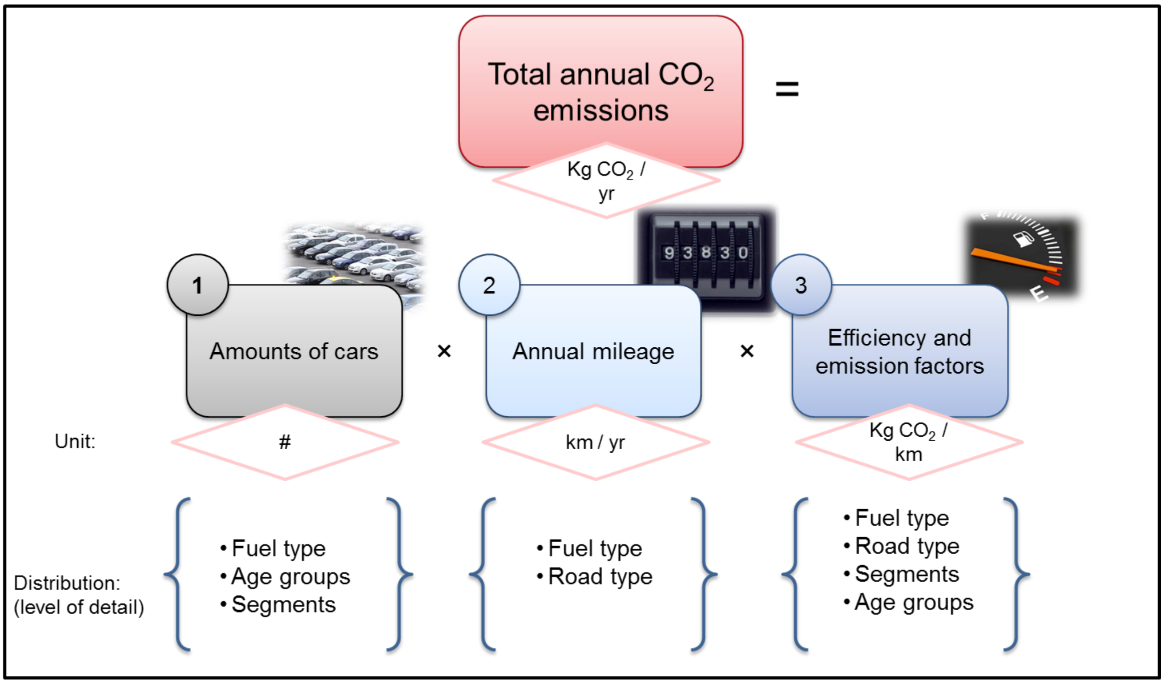


Figure 2.1: Basic calculation scheme of emission calculation

This specific method is chosen because it provides the ability to differentiate the emissions across different transport features. These transport features are given by the *level of detail*, which is depicted in the lower part of the figure. The total car park can then be divided in categories that are given by these levels of detail. For each category, input can be found to a level of detail that is relevant for the efficiency of cars. In table 2.1 it is shown how relevant factors of efficiency (as found in literature) are operationalized in the model.

Type of efficiency	**Operationalization in model**	**Categories within factor**	**Associated factor in fuel efficiency / emissions**
General efficiency	Fuel type	Gasoline, Diesel, Electric	Differed emission factors and efficiencies of different fuel types
	Segmentation (car classes)	A, B, C, D, E, J, L	Weight of car / aerodynamic resistance
	Age groups	Defined age groups of manufacturing years	Development in efficiency over the years
	Engine type **Not operationalized**	N/A	Further engine characteristics (like cylinder volume)
Variable efficiency	Road types	Urban, Provincial and Motorway	Average speed and amount of starts/stops
	Other use factors **Not operationalized**	N/A	Driver behaviour, weather effects

It is important to note that, as shown in table 2.1, not every efficiency factor can be properly modelled. The engine type variance would make the model a lot more complex, because a lot of car types have a large number of different engine types. Coping with this complexity would require a lot more time and effort than is provided for this thesis. Another important neglected variable are the driver/climate effects on efficiency. As there is no global average found for the whole car park or for how they vary across the given categories, this differentiation cannot be considered within the model.

FIXED CHANGES IN 2030 COMPARED TO 2013

As mentioned earlier, emissions will be calculated for a current case and a future case. In the model, it is assumed the following factors are decisive for emissions:

- Volume of (total) cars: the total amount of cars and of course how this amount is distributed over segments and age groups.
- Efficiency development: newer cars tend to be more fuel efficient due to more stringent regulations. Input is found how this efficiency develops for both car types.
- Fleet renewal: it is assumed that the total car park in 2030 is different from the car park in 2013. If the average age of cars is the same, it means a large part of the car park consists of cars that are to be built in the future. Regarding the efficiency development, this could have a large effect.
- Annual mileage: the mileage could vary in the future as result of gas prices and other mobility options.
- Electrification: this variable is the research object of this thesis and discussed in the next subsection.

These factors affect the 2030 values of the amounts, mileages and efficiency factors (figure 2.1). A (single) base case will be established for the above standing factors, to calculate the new emissions in 2030. The electrification variables, scrutinized in this research, are modeled more extensively and explained in the next subsection,

Varied features in the model

STUDIED VARIABLES

The objective of this thesis is to find the potential of electrification of the transport sector. This means that certain electrification variables and its effects are scrutinized in this thesis. The exact impact of these *studied* variables on emissions is assessed and discussed in the second sub question.

The studied variables are the following:

- V1: Degree of electrification. This is the percentage of electric cars in the total passenger car park. Increasing this percentage increases the amount of passenger cars, but also reduces the amount of conventional cars (as was explained by this model's definition of electrification.
- V2: Electricity mix. This is the distribution of each share of the energy carriers in the total annual electricity production, accounting for the CO_2 and pollutant emissions per kilowatt-hour. In the variant scenarios the fossil fuel share decreases at the expense of the renewable share.
- V3: EV mileage. The total electric mileage will be varied to assess what the impact is of increasing the electrified kilometres on emissions. This increase happens at the expense of the mileage of conventional cars, which will decrease accordingly. Increasing this variable could represent a stimulation for people who make more than average miles per year are encouraged to buy and use electric cars
- V4: Electric Urban mileage: Because EV's are most efficient and conventional cars are least efficient in urban areas (Wu et al., 2015), electrification is the most effective when it is applied in these areas. With this variable, the road type distribution of electric vehicles is altered towards a more urban focus, which increases the kilometres made in urban areas and decreases the kilometres driven on the other road types. As with V3, increasing this urban focus causes the opposite to occur for conventional cars so the same amount of kilometres are still covered overall. Increasing this variable could represent a stimulation of EV's travelling over urban roads rather than other roads, not only because of the efficiency difference but also because the city trips fit better with the limited range that EV's might

have. Another argument was found in the policy outlook (section 1.2), which states that the major cities are *focus areas* for reasons of urban air quality and economic activity.

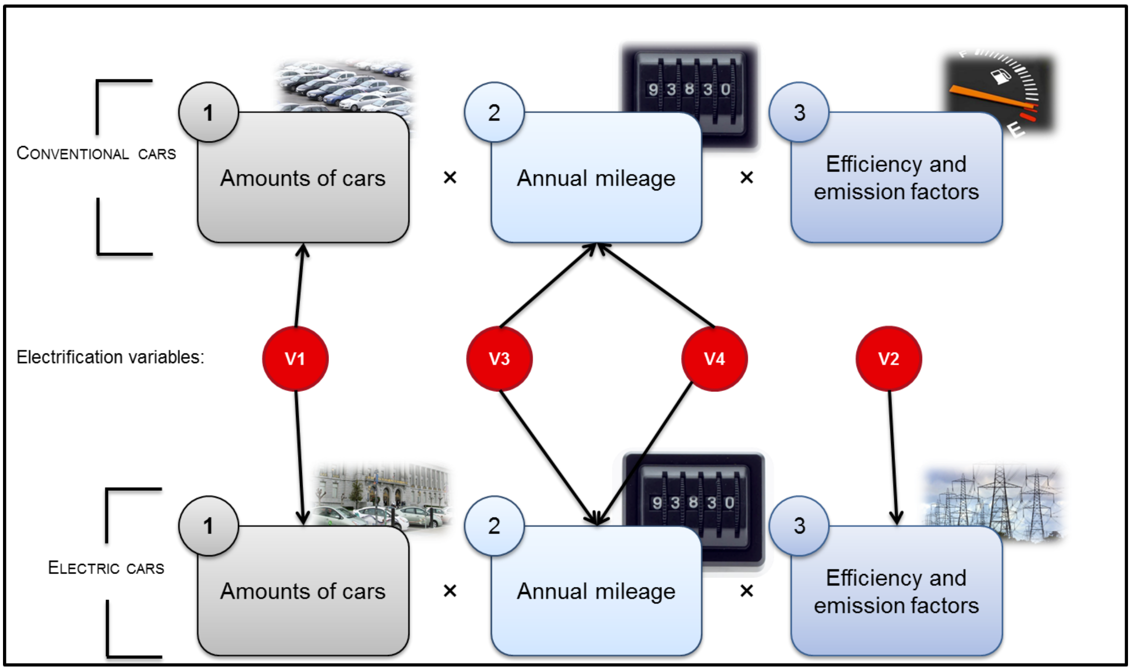


Figure 2.2: Effects of the studied variables on the emission calculation schemes of conventional cars and electric cars

2030 SCENARIO'S AND ACCORDING SETTINGS OF STUDIED VARIABLES

In this thesis, the studied variables have to do with the amount of electric vehicles, the electricity mix and how electrification is applied. To be able to compare each variable effect, the amount of settings is limited to the five cases given. This leads to four different scenarios in which the emissions vary.

- Frozen implementation case: This scenario shows the emissions without any electrification applied.
- Base case: This scenario shows the effects of basic electrification figure for the amount of electric vehicles and basic electricity mix development. No specific electrification (EV mileage and urban mileage) is introduced yet.
- Advanced case: the amount of electric cars and the electricity mix are conservatively improved. The two electrification focus variables (V3 and V4) are now also introduced.
- Extreme case: The amount of electric cars double, fossil share in electricity mix decreases a lot. EV mileage is increased by 50% and the electric vehicles are fully focused on urban roads.

To provide another perspective on the electrification effect, the frozen technology case is also shown. This is mentioned apart from the others, because it implies that also the other technological transportation features are different from the base case: they are changed back to the 2013 case (implying that the technology is frozen).

2.2: DETERMINING INPUT OF MODEL COMPARTMENTS

Pars-pro-toto method

The passenger car park has a variety of different features. These features can also be seen as a *level of detail* to regard the passenger car park (see figure 2.1). To cope with the large number of features, the method only incorporates the *most occurring* features of the car park to generate a decent overview of the car park, without making the research overly complicated. Within car park features, the most occurring parts are selected to represent the full car park. This is called the *pars-pro-toto* (part for total) method. Each level of detail is specified below, including by what parts it is represented.

1. Amounts and distribution

In this model, a few characteristics have been chosen that are important factors in emissions of cars and can also be used to classify the car park in to: fuel type, age group and segments. To cope with the large number of features within these characteristics, the method only incorporates the *most occurring* features of the car park to represent the full car park, without making the research overly complicated.

1A: CONVENTIONAL CAR AMOUNT DISTRIBUTION

- Fuel type: There are many other fuel types in the Netherlands besides gasoline and diesel. (CBS, 2014a) For the sake of simplicity, only gasoline and diesel cars are taken into account to represent all conventional cars. This means that no other fuel and associated usage and amount are taken up in the analysis. This thesis also assumes a fixed ratio between gasoline and diesel cars
- Age groups: Generally, partly thanks to more stringent international regulations, conventional cars have better engine efficiency, using less fuel and accordingly emitting less CO_2 per driven kilometre. The EU has implemented a system that puts emission limits on new passenger cars to improve air quality and reduce CO_2 emission, each limit called Euro-x. Euro-1 has been of effect since 1993, and Euro-6, which is the most recent one since 2014. For the model, a 5-year interval has been chosen to distinguish different age groups with each their own usage factors and air pollution emissions, loosely based on the publication of the discussed limits and also on the occurrence of cars across ages. This results in 5 different age groups for each modelled year, as shown in table 2.1. These age groups correspond to a 5-year period in history in which the car is produced.

Group numbers	Manufacturing year 2013	Manufacturing year 2030
1 (less than 6 years old)	>2009	>2024
2 (6-10 years old)	2005-2009	2020-2024
3 (11-15 years old)	2000-2004	2015-2019
4 (16-20 years old)	1995-1999	2010-2014
5 Older than 20 years	<1996	<2010

Table 2.1: Age groups and the associated generation in the two years in which emissions are modelled.

- Segmentation: Segmentation of cars is a classic categorizing method for the passenger car retail sector. (Segments, n.d.) This is a useful way to determine the fuel efficiency of cars. (Autoweek, n.d.; Autozine, n.d.) and also categorize the passenger car park in the Netherlands ("Mobiliteit in Cijfers," 2014), because the statistical report that is used shows exactly in what percentage every segment occurs in the Netherlands. The distribution among the most occurring segments (over 80% of the car park) is used in this thesis.

1B. AMOUNTS AND DISTRIBUTION FOR EV'S: ELECTRIFICATION

Electrification is a very important concept in this thesis. As explained before, it means that one conventional car is exchanged for one electric vehicle. Of course in practice this does not always work this way (see discussion, section 5), but for the model this method can simplify the case enough to return a good representation of the impact of electrification. In the model, a percentage is used as input for electrification for the total amount of electric vehicles. How they are distributed over age groups and segments and how they displace conventional cars is explained below:

- Growing EV percentage over new age groups: Within every age group, a certain percentage is electric. This percentage increases with the newer age groups as it is assumed the inflow of electric vehicles grows with the years. The sum of these numbers amount to the number associated with the pre-defined degree of electrification (V1). The distribution over age groups is shown in figure 2.3.

- Constant EV-percentage over segments: It is assumed that electric vehicles will have the same occurrence over segments as the conventional cars. This means, within every age group, a percentage of each cars within segment is exchanged for an electric “counterpart”. This is shown in table 2.2. Another important assumption is that the larger class conventional cars will be exchanged by electric vehicles that have an efficiency similar to the D/E segment. This assumption is made because within the passenger car range, the D/E segments are the largest EV’s available.

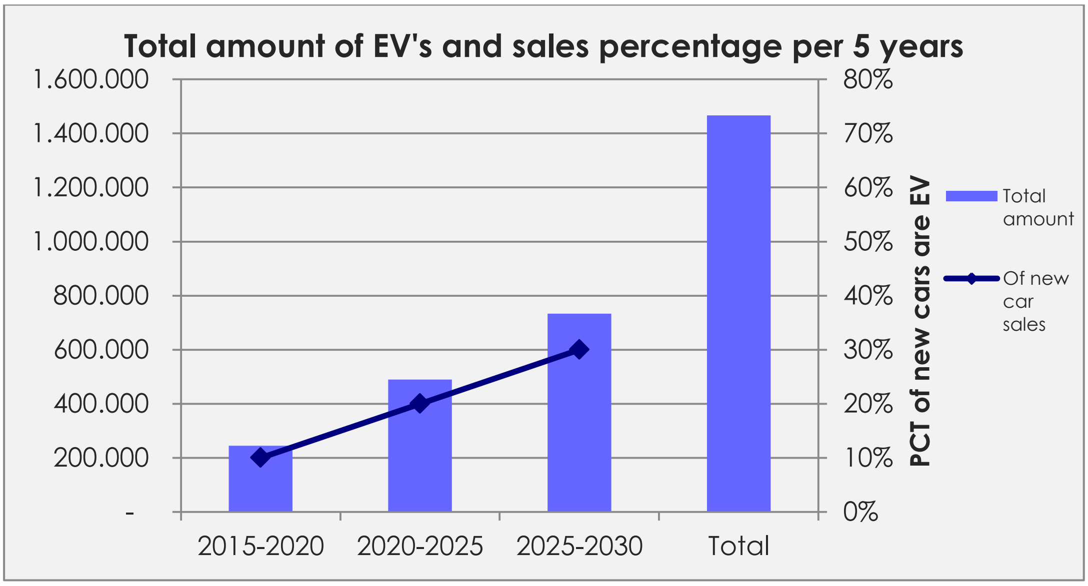


Figure 2.3: Distribution of EV amounts over age groups. The total bar shows all electric vehicles in 2030.

EV-segment	Typical manufacturer and type	Displaced conventional car segment
A	Volkswagen e-UP!	A (gasoline only)
B	Nissan Leaf	B
C	Volkswagen Golf electric	C
D/E	Tesla Model S	D, E, J, L

Table 2.2: Electric vehicles segments and their conventional counterparts

Studied variable (V1): Electrification is one of the studied variables and will be varied to assess its effect on the transport output. How the variable affects the different compartments in the model is shown in figure 2.3.

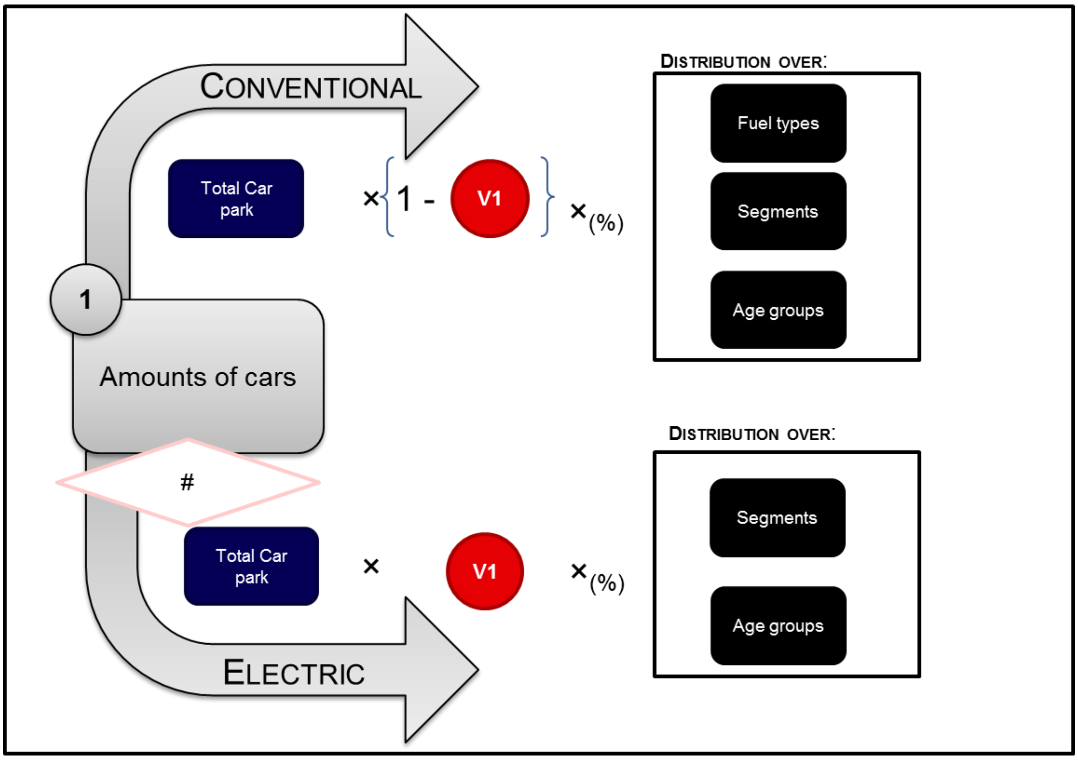


Figure 2.4: How the degree of electrification variable (V1) affects the car amounts in model.

2. Determining annual mileage and its distribution among road types

2A: CONVENTIONAL CAR MILEAGE

The annual travel distance ("mileage") of cars is an important factor for the annual CO_2 emissions from passenger cars. In the model, the average mileage of each car is assumed to be constant over segments and ages, as no clear data were found on a variation complexity regarding those features. Fuel type and road type are however important distribution factors.

- Based on if it is a gasoline or diesel car, each car is assigned a certain annual mileage yearly. The ratio between the mileages of these fuel types is kept constant.
- The annual mileages of all cars are distributed over different road types: urban, provincial and highway. This is relevant for the different fuel efficiencies on those particular road types.

2B: ELECTRIC VEHICLE MILEAGE

The annual mileage of electric vehicles is calculated conservatively at first. The electric vehicles will have an average annual mileage, which is based on the (weighted) average of gasoline and diesel cars. The distribution of this mileage over road types is also the same as the conventional cars. In variant cases, this mileage and road type distribution will be varied for electric cars.

Studied variables (V3 and V4)

- V3: EV mileage. The total electric mileage will be varied to assess what the impact is of increasing the electrified kilometres on emissions. This increase happens at the expense of the mileage of conventional cars, which will decrease accordingly.
- V4: Electric Urban mileage: With this variable, the road type distribution of electric vehicles is altered towards a more urban focus, which increases the kilometres made in urban areas and decreases the kilometres driven on the other road types. As with V3, the opposite occurs for conventional cars so all cars still cover the same amount of kilometres.

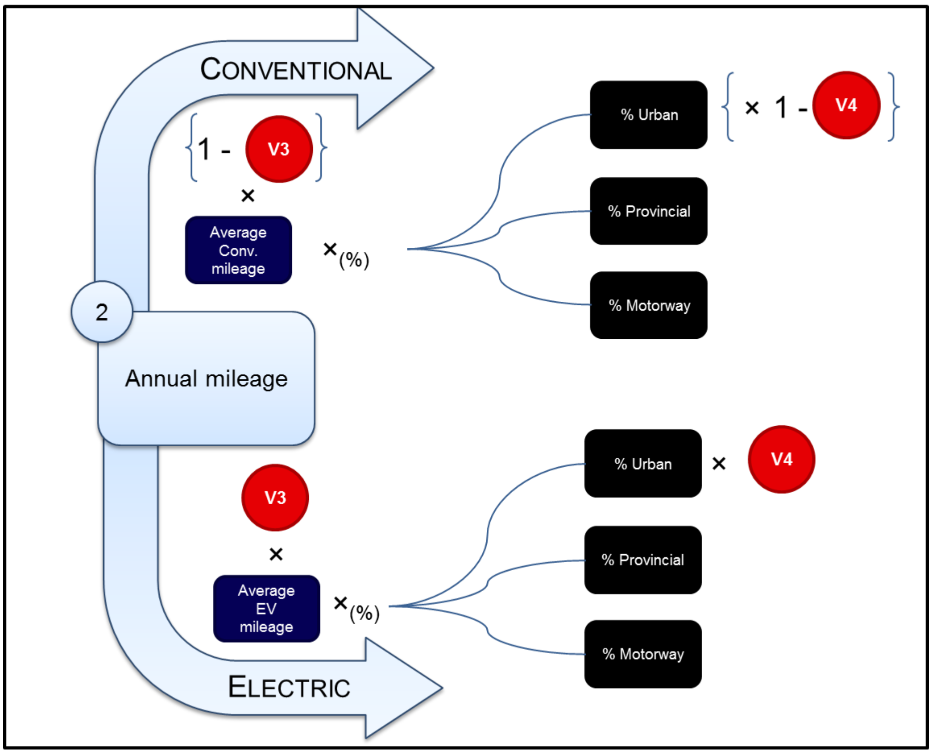


Figure 2.5: How electric vehicle mileage variables affect the calculation schemes of emissions from conventional and electric vehicles

3. Determining efficiency and emission factors

3A: CONVENTIONAL CAR FUEL EFFICIENCY AND EMISSION FACTORS

The emission factors of CO_2 and pollutants are differently calculated. For CO_2 (and SO_x), the emissions are directly linked to the fuel consumption of each car (which varies with segment, age and fuel type). This means that they are based on emission factors per amount of fuel used. (Vreuls & Zijlema, 2013; Klein et al., 2014)

For pollutant emissions (except for SO_x), the emissions are given as a factor per kilometre (varying with fuel type and age group), meaning that it varies with the annual mileage especially. (Klein et al., 2014)

- Consumption data: For every car in a specific fuel type, age group and segment, fuel consumption figures are found for the three different road types. (km/L)
- For each fuel type, a specific CO_2 consumption is found (kg CO_2-eq/L; SO_x/L)
- Pollutant emission data: Within each fuel type and age groups, emission factors are found for the three different road types.

3B: ELECTRIC VEHICLES: ELECTRIC EFFICIENCY AND EMISSION FACTORS

The emissions (both CO_2 and pollutants) are the product of this energy consumption with the electricity mix emission factors. In the model, the energy use is determined by the electric efficiency of the EV's and their use and presence. The overall emission factors are given by the product of the share of each carrier in the total electricity production and the emission factor of each carrier. The share of each carrier in total electricity production is the electricity mix, which is also a studied variable in this research (V2).

- Like for conventional cars, electric efficiencies (in km/kWh) will be found for all EV-segments on three different road types.
- The electricity mix will be retrieved and also varied as it is part of the studied variables (V2). The variation will go towards a decreased share of fossil energy carriers, as they contribute to the CO_2 and pollutant emissions for the most part.
- The CO_2 emission factor is the sum of the energy carrier's CO_2 emission factors times their share in the annual production.
- The pollutant emission factor of the electricity mix is also calculated by adding up the individual pollution factors of each energy carrier times its share in the mix.

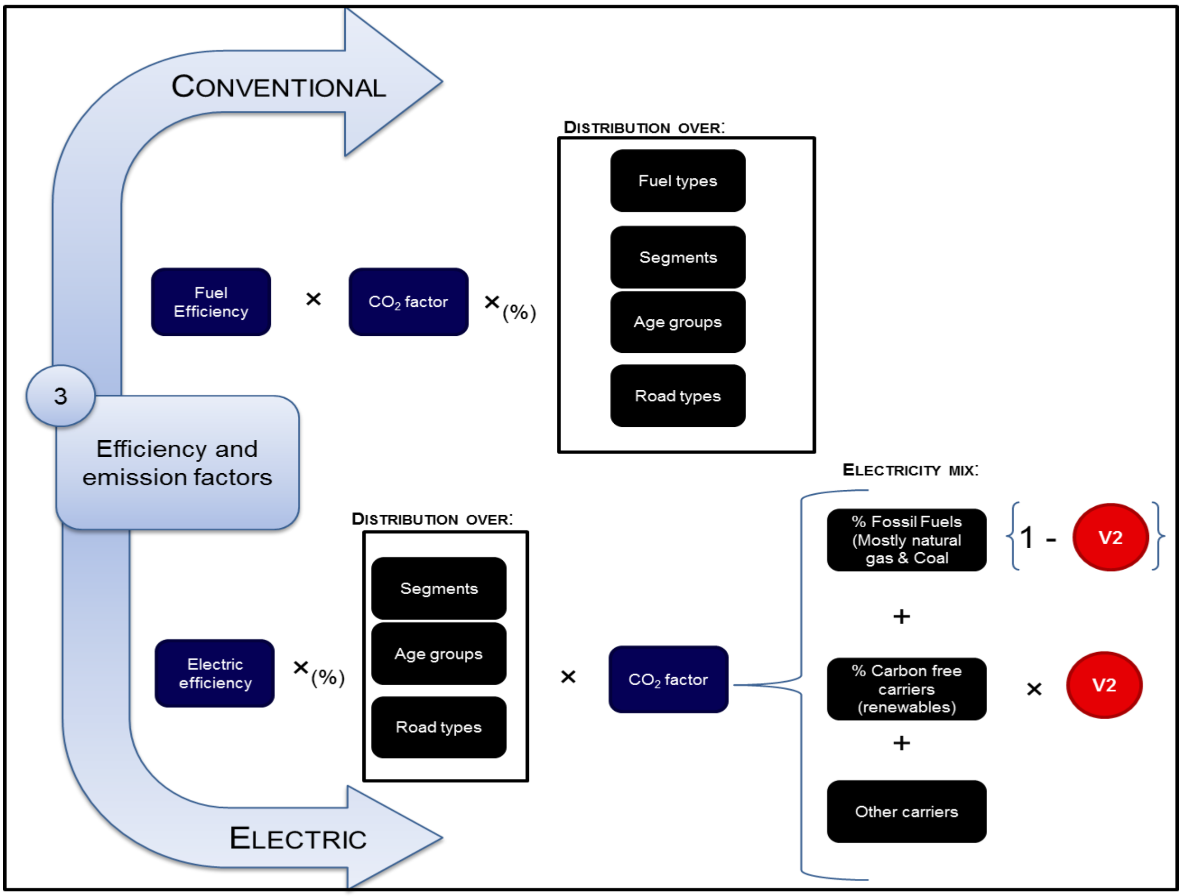


Figure 2.6: Calculation scheme for efficiency and emission factors. The electricity mix variable (V2) affects the CO_2 factor of electric vehicles only.

2.3: INPUT VALUES OF MODEL

In this subsection, the values of each input variable are given, including their sources. They are given for both researched situations: 2013 (current) and 2030. For the studied (electrification) variables, the values are given for the four different cases in which they are varied.

This model requires a lot of data input from a variety of different sources. To keep the overview in this section clear, the explanation on how sources are interpreted to gain certain figures are minimized. Each research compartment has a few tables in which the basic figures are given, including the literature used. When the explanation of the figures is too long, an appendix table is referenced to.

1: Amounts, segment and age group distribution of the car park in 2013 and 2030

Total car park magnitude

	2013	2030	Source
Total amount of cars (all kinds)	8,15 million	Constant	“Mobiliteit in Cijfers,” (2014); Shell, 2013; Rabobank, 2013

1a: Distribution of conventional car amounts

	2013		2030		Source
	Gasoline	Diesel	Gasoline	Diesel	
Total percentage of full car park (%)	100%		82%		“Mobiliteit in Cijfers,” (2014); assumption
Fuel type (% of conventional cars)	82%	18%	Constant	Constant	“Mobiliteit in Cijfers,” (2014); CBS, 2014a
Age groups (%) (1;2;3;4;5)	25;27;27;15;6	25;27;27;15;6	30;30;30;5;5	30;30;30;5;5	“Mobiliteit in Cijfers,” (2014)
Segmentation (%) (A;B;C;D;E;J;L)	(21;29;22;11;3;10;4)	(0;21;30;27;11;7;4)	Constant	Constant	“Mobiliteit in Cijfers,” (2014); BOVAG-RAI (2014)

1b: Distribution of electric vehicle amounts

Electric 2030	Base case 2030	Advanced case	Extreme case	Source
Degree of electrification (% of total cars)	18%	25%;	40%	“Plan van Aanpak,” (2011); Assumptions
Distribution over age groups (% of all cars)* (1;2;3;4;5)	30;20;10;0;0	42;28;14;0;0	67;44;22;0;0	Assumptions
Distribution over segments (% within each segment)*	18%	25%	40%	Assumptions

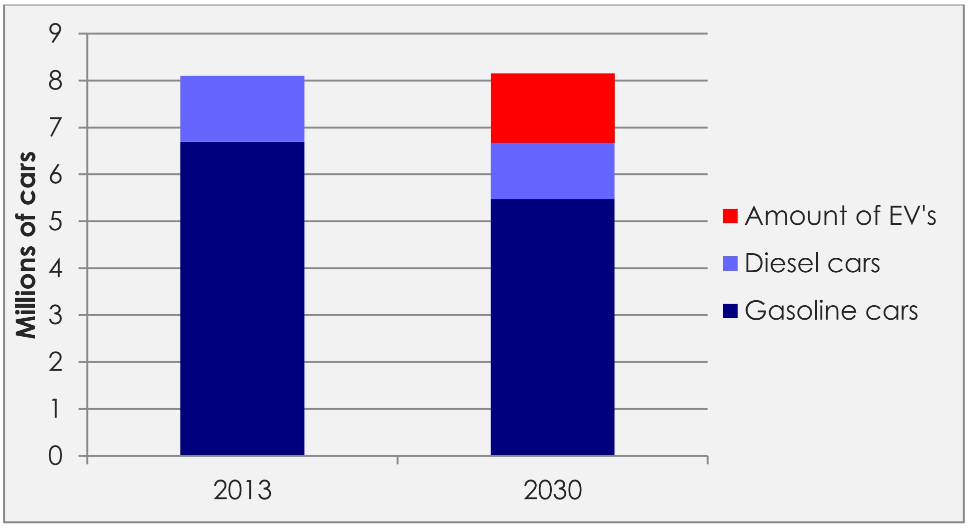


Figure 2.7:Distribution of cars with different fuel types. Note that the total amount is maintained, but 18% of the conventional cars are displaced for electric vehicles

2. Mileage and road type distribution

2a: Total annual mileage of conventional cars

	2013		2030		Source
	Gasoline	Diesel	Gasoline	Diesel	
Average annual mileage* (km)	10.554	23.283	10.026	22.119	CBS (2014b, 2014g); Mobiliteitsbalans 2012 (2012)
Road type distribution* (%) [urban, provincial, motoway]	22;36;42				Van den Brink et al. (2010)

2b: Total annual mileage of electric vehicles

2030	**Base case**	**Advanced case**	**Extreme Case**	**Source**
V3: Annual mileage (km)	11.928	14.911	17.893	Assumptions
V4: Road type distribution	22;36;42	**44**;14;42	**57**;1;42	

CURRENT – The current mileage figures only apply to conventional cars. The exact annual average mileage is based on statistical research done by CBS (2014b). The road type distribution is based on a research done by Van den Brink et al., (2010), who have extensively done research on the distribution across all road types by passenger cars and have found this average. As no outlook was presented, it has been kept constant for the future.

FUTURE – The annual mileages of conventional cars are both expected to decrease by 5% (Mobiliteitsbalans 2012, 2012) along with the total decrease in demand transport.

EV CASES – In the model it is assumed that electrification occurs by displacing conventional cars, the annual mileage that the displaced conventional car drives is also taken up fully by the electric car. This means that the annual mileage of electric vehicles is actually the weighted average of the mileages of gasoline and diesel cars. In an advanced case and extreme the mileage increases by 25% and 50% respectively.

The road type distribution of electric vehicles also varies with the increasing urban focus (V4). The percentage of kilometres spent in urban areas doubles in the advanced case. In the extreme case, the electric vehicles spend all their provincial (least efficient) mileage in urban areas, which in the standard case then amounts to 57%. This percentage could grow if the EV mileage (V3) increases as well.

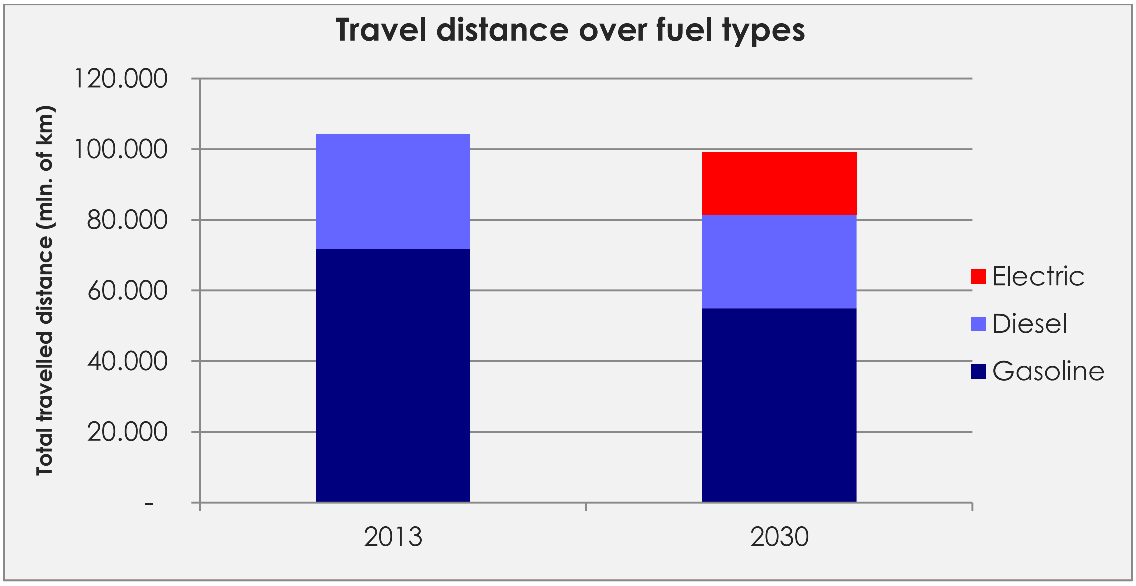


Figure 2.8: Total travel distance in two modelled years. Note that the total travelled kilometres of cars is expected to reduce, while electric cars will take up a substantial amount of all the travelled kilometres.

3a: Efficiency and emission factors of conventional cars

There is a variety of different car groups and associated efficiency due to the segments, age groups and different efficiency trends are considered. This is why in the table, only indicative figures are shown of a segment B car. To put it in perspective, also an older generation segment B car is used (age group 2) and another segment of the same age group is shown (segment C). The same goes for pollutant emissions, for which NOx emissions are taken as representative figure to show the differences.

Appendix B shows how all values for this compartment are retrieved.

3a: Conventional car fuel efficiency and emission factors

Selected segments (Indicative)		2013		2030		Sources
		Gasoline	Diesel	Gasoline	Diesel	
Segment B Age group **1** **Km/L**	Urban	18.0	24.2	20.8	28.0	Autoweek (n.d.); Autozine, (n.d.); "Fuel Economy of," (2012); Additional Assumptions
	Provincial	24.0	31.6	27.8	36.6	
	Motorway	19.2	25.7	22.2	29.7	
Segment B Age group **2** Km/L	Urban	13.3	17.9	19.8	26.7	
	Provincial	19.9	24.6	26.5	34.8	
	Motorway	14.6	19.2	21.2	28.3	
Segment **C** Age group 1	Urban	14.7	21.7	17.0	25.2	
	Provincial	21.8	28.1	25.2	32.5	
	Motorway	16.1	23.0	18.7	26.6	
CO_2 emission factor (kg CO_2-eq/L fuel)		2,338	2,685	Constant		
NOx emissions Age group 1 kg/km	Urban	0.042	0.632	0.031	0.461	Klein et al., (2014)
	Provincial	0.019	0.344	0.014	0.251	
	Motorway	0.011	0.566	0.0081	0.413	

3b: EV electric efficiency and emission factors

		2013	2030 (base case	2030 Advanced case	2030 Extreme case	Sources
Segment B Age group **1** **km/kWh**	Urban (rated)	6,4	7,41	N/A		Autozine (n.d.); Autoweek (n.d.); Wu et al., (2015);
	Provincial	5,12	6,67			
	Motorway	3,84	5,92			
Segment B Age group **2** Km/kWh	Urban	N/A	7,1			
	Provincial	N/A	6,01			
	Motorway	N/A	4,95			
Segment **C** Age group 1 **km/kWh**	Urban	6,72	6,0			
	Provincial	4,16	5,42			
	Motorway	3,9	4,82			
V2: Electricity mix (% fossil)		82%	67%	50%	40%	CBS, (2014c, 2014d, 2014e, 2014f); Rooijers et al., 2014
CO_2 emission factor (CO_2-eq/kWh)*		0,49	0,38	0,287	0,232	Grütter Consulting AG (2012)
NOx emissions Age group 1		0,19	0,17	0,12	0,10	Emissies bedrijven (n.d.)

g/kWh*					

*Emission factors of electricity mix are directly affected by the changing electricity mix changes.

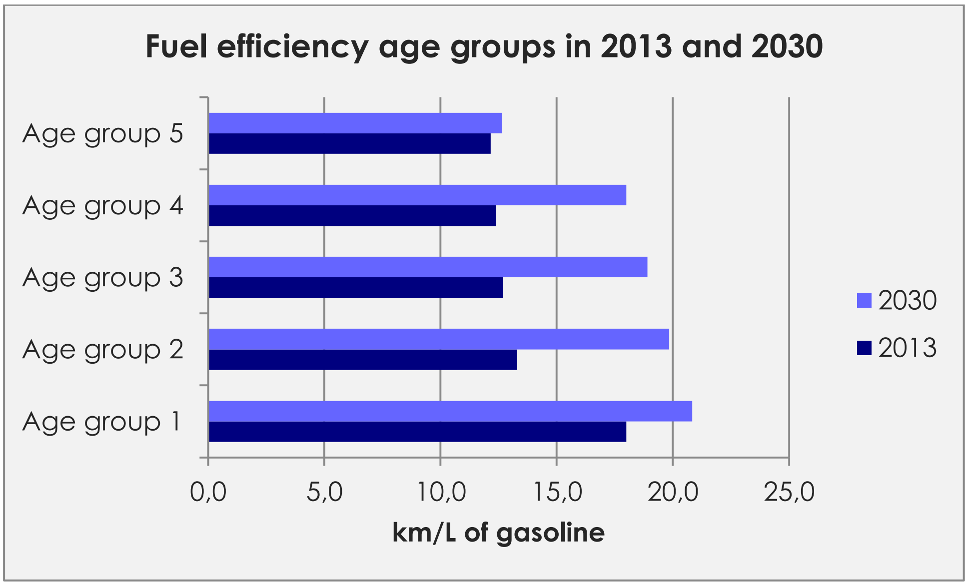


Figure 2.9: Example of fuel efficiency in urban areas of a segment B car in the two modelled years. Note that the age groups correspond to the age of the car within that year. Age group 1 is the most recent generation, 5 the oldest.

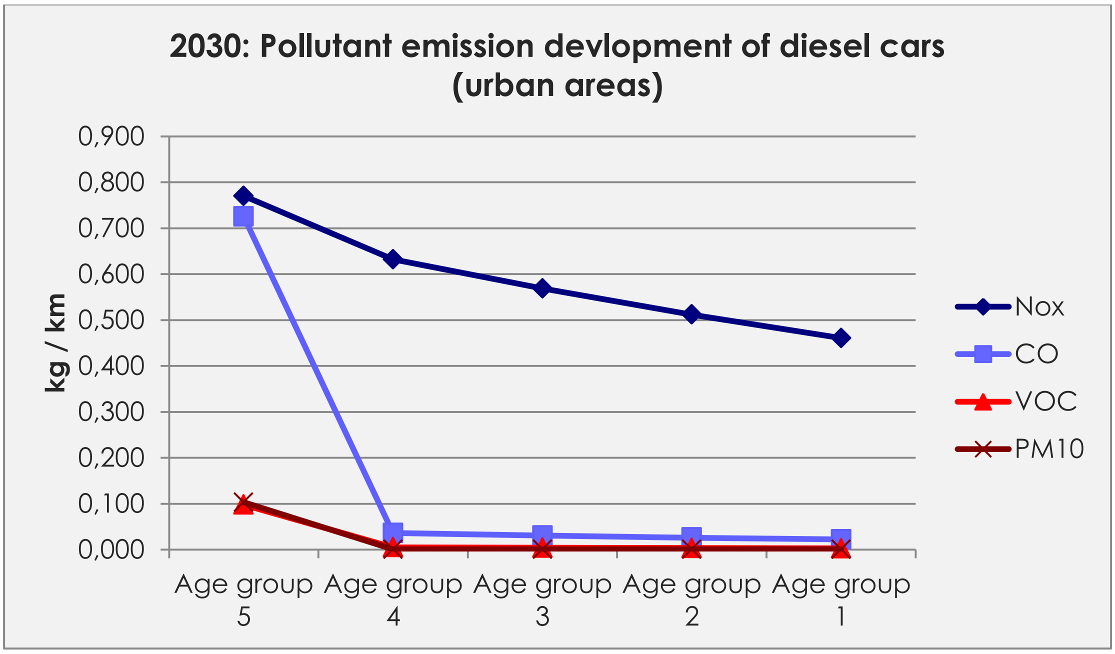


Figure 2.10: Example of fuel efficiency in urban areas of a segment B car in the two modelled years. Note that the age groups correspond to the age of the car within that year. Age group 1 is the most recent generation, 5 the oldest.

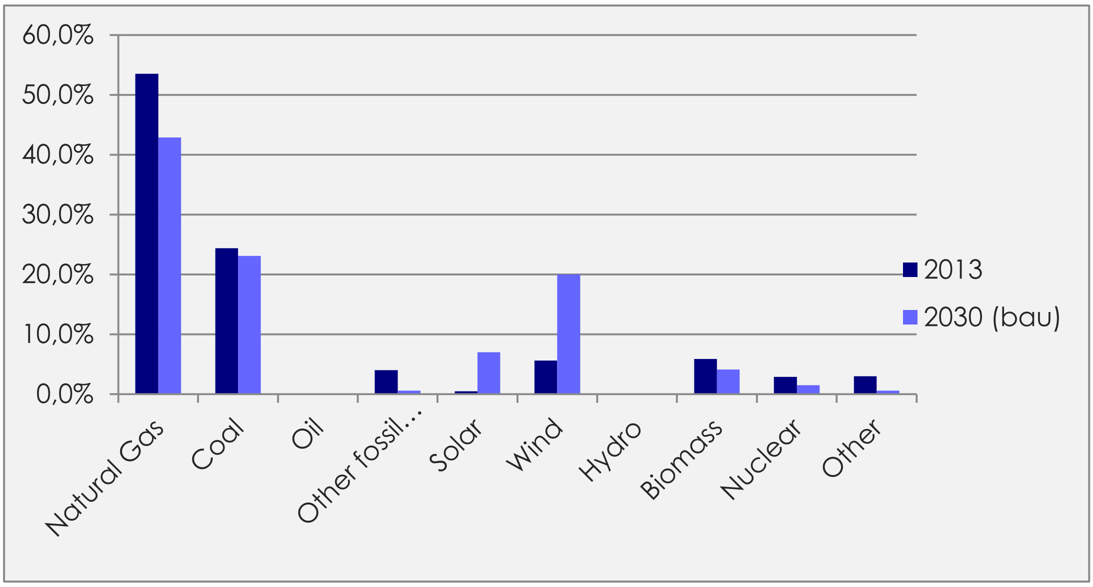


Figure 2.11: Electricity mix in 2013 (CBS, 2014c) and 2030 (Rooijers et al., 2014). N

3. RESULTS

3.1: PROJECTED CO_2 AND POLLUTANT EMISSIONS IN 2030 ACCORDING TO BUSINESS-AS-USUAL SCENARIO'S

In the proposed passenger car model, electrification is introduced in the passenger car transport sector. As explained in chapter 2, electrification implies that a conventional car is replaced by an electric vehicle of a similar segment. For 2030, this means that there are electric vehicles of different ages on the road, distributed over the occurring segments. The overall CO_2, total pollution and urban pollution figures are given for the base year (2013) and 2030, together with the specific effect of electrification on these emissions.

Synopsis of model outcomes

In short, the outcomes of the base case model simply that the impact of electrification is limited on CO_2 emissions, slightly larger for total air pollution figures and the largest for urban air pollution. This can be explained by the large efficiency development that the average conventional cars undergoes between 2013 and 2030, making the difference in CO_2 emissions per driven kilometre less large. Concerning pollutants, it is observed that electrification incurs a decrease in its emissions, because the modelled emissions from power plants are very low compared to conventional cars and because EV's have no urban emissions at all.

CO_2 emissions

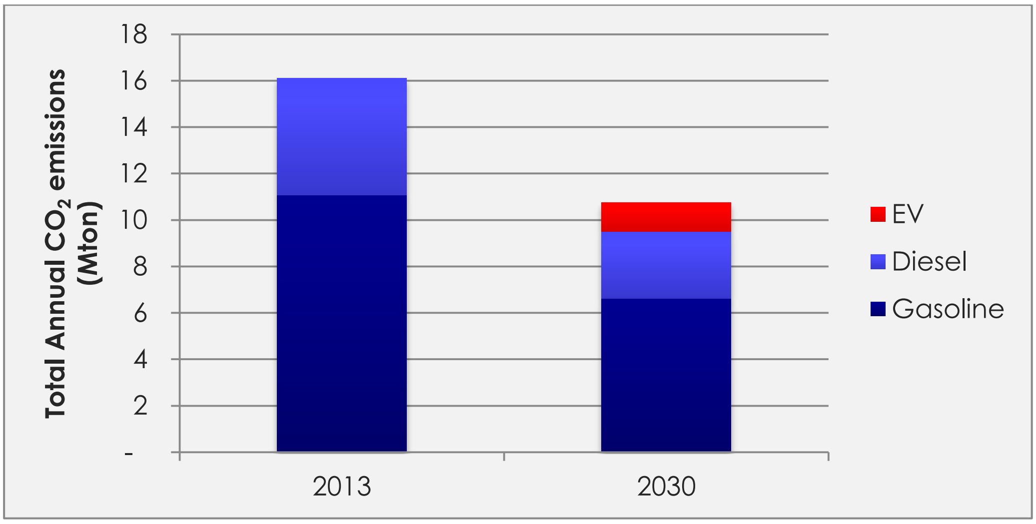


Figure 3.1.1– Modelled CO_2 emissions in 2013 and in 2030 from passenger cars. Emissions from passenger cars are expected to decrease by over 30% according to the model

The base case scenario shows great change in CO_2 emissions 2030 by the transport sector; a reduction of about 33% (figure 3.1.1). This reduction however is only partly accounted for by electrification, as other factors that were modelled (like fleet renewal) seem to play a larger part in the overall CO_2 emission reduction in 2030 (see figure 3.1.5).

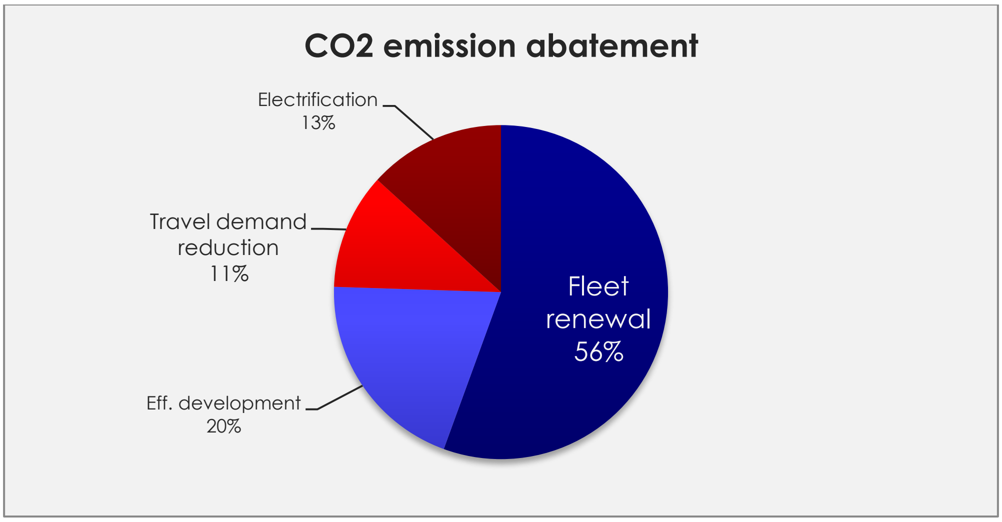


Figure 3.1.2: Share in CO_2 emission reductions effects from transport sector from 2013 to 2030

The contribution of electrification to CO_2 emission reduction is only limited to 13%. Fleet renewal (people owning and using newer cars than the current cars) and efficiency development (the general efficiency improvement every 5 years) are more important than the contribution of electric vehicles. This puts the CO_2 emission abatement argument to implement and stimulate electric vehicles in perspective.

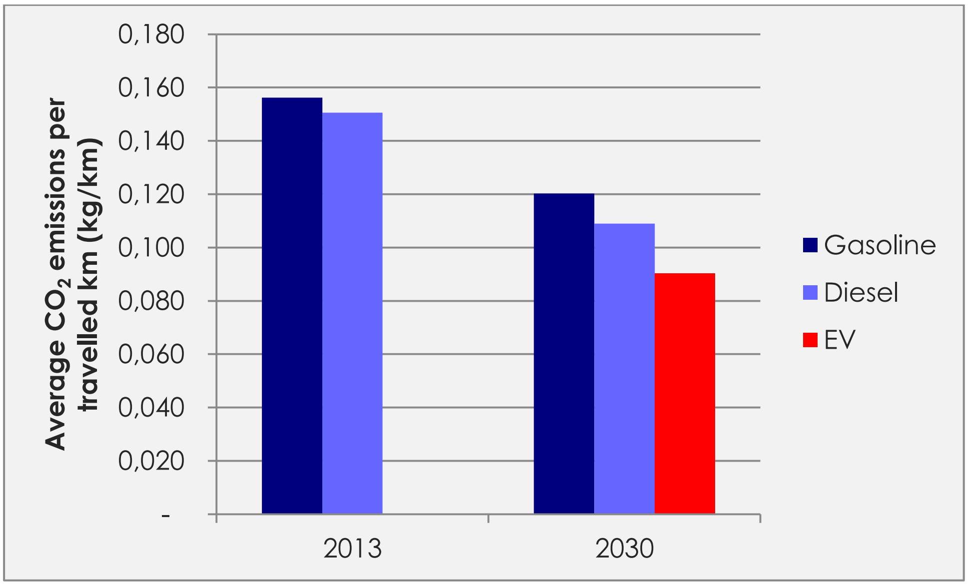


Figure 3.1.3: Average CO_2 emissions of cars per kilometre in two modelled years

	CO₂ avoided per electrified kilometer (kg)		
	Urban	**Provincial**	**Motorway**
EV for gasoline car	0,08	0,03	0,06
EV for diesel car	0,06	0,02	0,04

Table 3.1.1: Avoided CO_2 emissions per kilometre in 2030 over different road types. It depicts the figures of an average electric vehicle replacing an gasoline car (first row) and a diesel car (second row)

The limited CO_2 effects can also be observed on the average emissions per car (figure 3.1.3). This figure depicts a large difference in CO_2 emissions per car for conventional cars between the two periods modelled periods. The difference with electric vehicles in 2030, especially for diesel cars is not very as large (20 grams per kilometer on average). This is also reflected in the avoided CO_2 per electrified kilometer (table 3.1.1). This table represents the abated CO_2 if an EV were used on a certain road type instead of its conventional counterpart. It shows that electrification is especially useful for gasoline cars in urban areas.

Total air pollution

Pollutant	Year	Gasoline	Diesel	EV
SO_x (ton)	**2013**	0,19	0,037	-
	2030	0,11	0,021	0,20
NO_x ('000 ton)	**2013**	5.252	18.602	-
	2030	1.376	11.383	0,554
CO ('000 ton)	**2013**	217.830	5.375	-
	2030	96.923	742	0,1717
VOC ('000 ton)	**2013**	13.764	639	-
	2030	13.783	266	0,2467
PM10 ('000 ton)	**2013**	527	1.238	-
	2030	947	127	0,0100

Table 3.1.2: Pollutant emissions from the transport sector over the three different fuel types

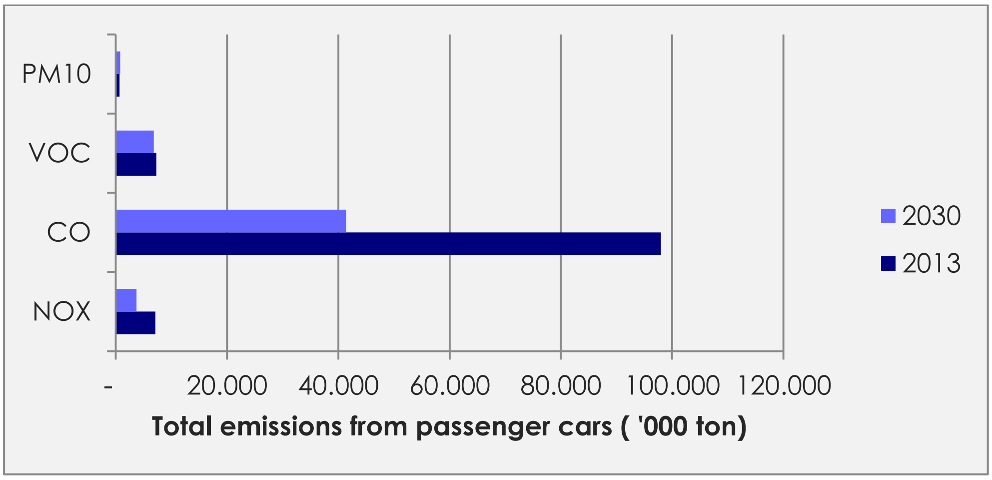


Figure 3.1.4: Comparison of pollutant emissions in millions of kg in two researched years. SOx is not regarded as it is too small compared to the other pollutants.

Table 3.1.2 and figure 3.1.4 show the annual emissions of the pollutants compared over the two researched years. It can be observed that pollutant emissions from conventional have decreased from conventional cars, which his partly due to the estimated reduction explained in the methodology. Also, the pollutant emissions from electric vehicles are a lot lower compared to the conventional emissions. Pollutant emissions are derived from fossil power plants only, which generate only part of the total electricity that EV's consume.. The emissions from power plants are a lot lower than emissions from conventional cars.

Figure 3.1.4 shows that CO is emitted the most in the transport sector together (also showing a large cut of over 50%). PM10, VOC and NOx are polluted on a smaller scale. This does probably not return a fair perspective on the effects of the different pollutants, for instance, PM10 can be a lot more harmful in low concentration than CO according to air quality guidelines (European Commission, 2015). Figure 3.1.4 shows the 2030 pollutant emissions as percentage of the emissions in the base year. The average of this percentage is used to return a figure for the effects on air pollution.

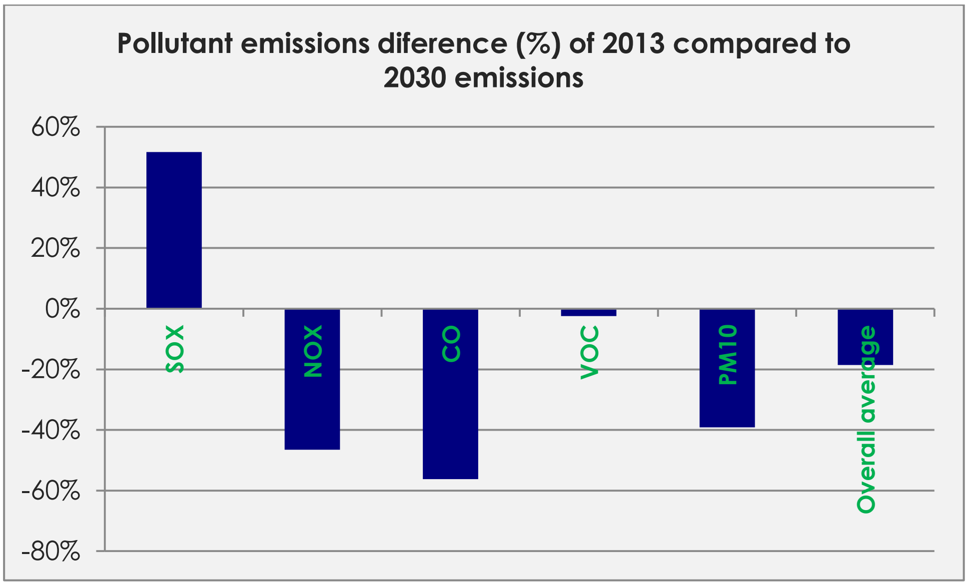


Figure 3.1.4: Emissions of each pollutant as percentage difference of their emissions in 2013

SO$_x$ EMISSIONS

The SO$_x$ emissions are a special case. The emissions from conventional cars are calculated differently from the other pollutants, as they are dependent on the fuel consumption of each car (like CO$_2$), as opposed to only the distance travelled by the cars in general (which is used for the other pollutants, as given by Klein et al., 2014). The modelled SO$_x$ emission amounts are therefore a lot lower than the other pollutants, a total in the order of kg's instead of kilotons. The SO$_x$ emissions from electricity production are in the same order of magnitude as the others. This in turn leads to an increase of Sox emissions due to electrification. However, this amount is so low (in comparison to the other pollutants) that it probably is not significant. Therefore, SO$_x$ emissions are not regarded anymore from this point, and suggested future research for this pollutant is taken up in the discussion section.

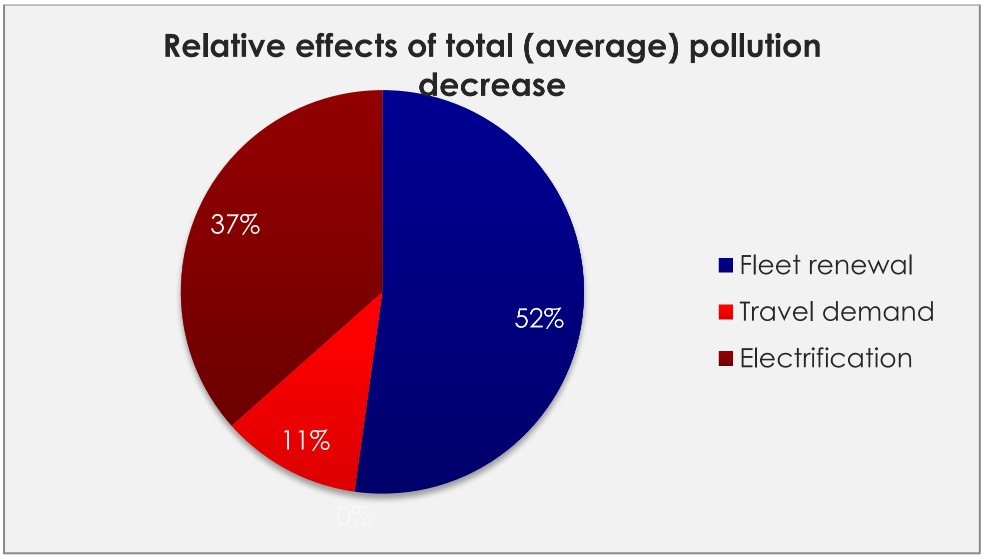


Figure 3.1.5: Relative effects of each individual change from 2013 to 2030 in total air pollution effects. Note that efficiency development does not play a role here

Figure 3.1.5 shows the effects of the altered variables in 2030. Effects of electrification are a lot larger (37%), though not as large as the effects of fleet renewal (52%). Also, efficiency development has no more stake in the pollution reduction. This can be declared: the model purely treats fuel efficiency as CO_2 related and pollutants do not depend on fuel use, but on car age and travel distance.

Urban air pollution

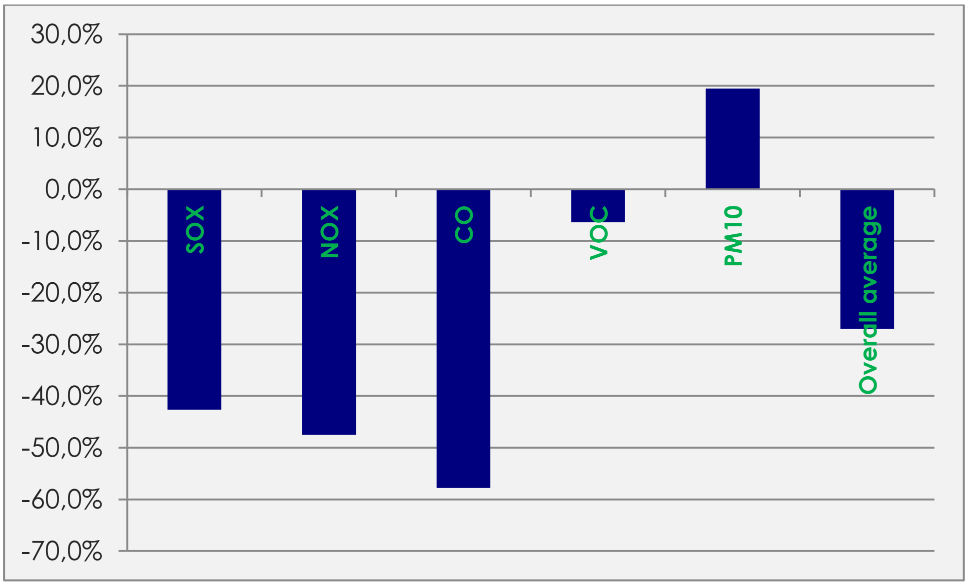


Figure 3.1.6: Pollutants emitted in urban areas in 2030 (as percentage of their emissions in 2013). Note the increase of PM10.

For simplicity, the urban air pollution emissions have already been shown in percentage change compared to the emissions in 2013. As figure 3.1.6 shows, the relative emissions in urban areas will decrease a lot in 2030, with a 25 percent decrease on average. This means that air quality in urban areas could be a lot better than in 2013. Interestingly, this effect is dampened by the increase of PM10 emissions in 2030 by almost 20%. The cause of this increase is the *negative* effect of fleet renewal concerning this pollutant. According to Klein et al., (2014), which has been the basis of the pollutant emissions in the road type areas, newer models emit more PM10 in urban areas than older generation cars. It was assumed that these figures would not decrease or increase in the next coming years, so taking up new (conventional) cars in the car park (fleet renewal) leads to increased PM10 emissions according to the model.

In spite of the increased PM10 emissions, the effect of electrification in the increasing air quality is now the highest compared to the others (71%). Urban air quality benefits the most from electrification of the transport sector as opposed to CO_2 emissions and total air pollution figures (figure 3.1.7). Fleet renewal is in this case the least important factor in these figures.

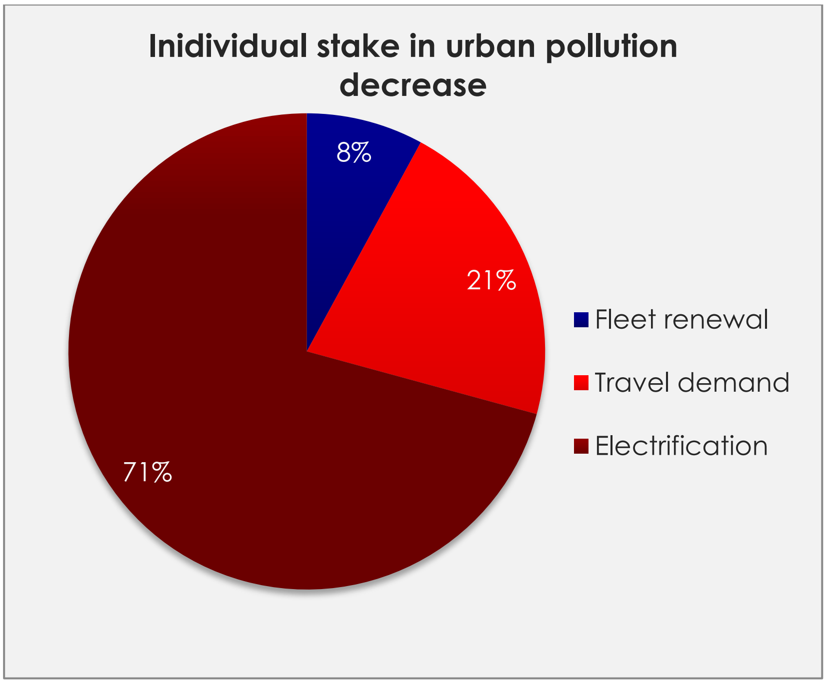


Figure 3.27: Individual effects of each variable case in the base case. Considering urban emissions, electrification has a very large impact in improving the urban air quality in 2030.

Overall outlook on base case electrification

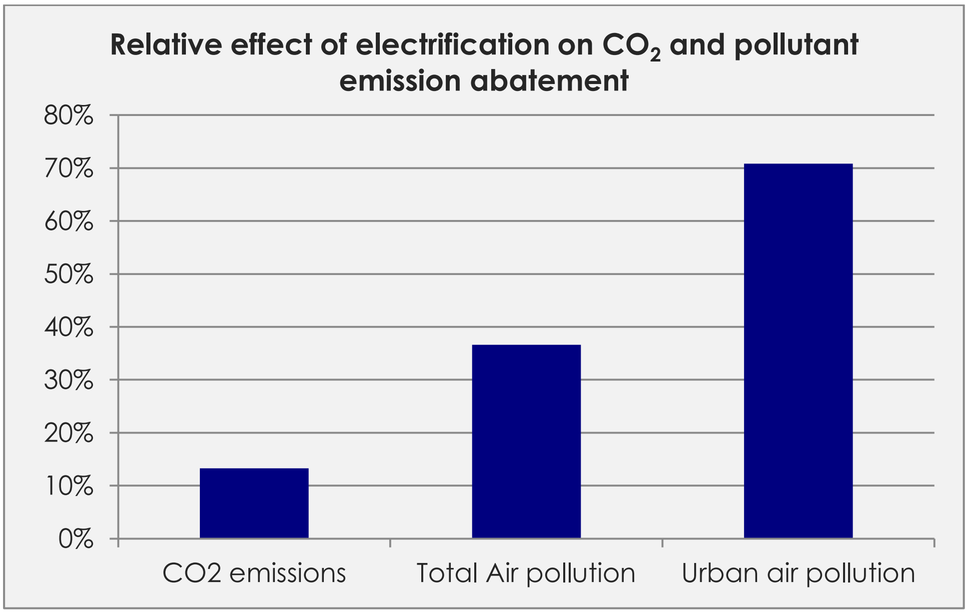


Figure 3.1.8: The relative effects of base case electrification in 2030 on the different studied emission groups.

As can be seen in figure 3.1.8, the considerable increase of electric vehicles towards 18% has a large stake in urban air quality improvement (71%), an intermediate effect on total air pollution (35%) and only a small effect in the CO_2 emission reductions (13%) from the transport sector. One could conclude from this figure that air quality, especially in urban areas, is a more important argument for electrification of the transport sector than CO_2 emissions. For the CO_2 case and total air pollution amounts, fleet renewal is more important factor in abatement of these emissions. In spite of the positive effect on urban air quality, one could question the arguments of electrification being important to reduce CO_2 emissions when a business-as-usual scenario is assumed.

3.2: POTENTIAL EFFECTS OF VARYING ELECTRIFICATION FEATURES

The effects of 4 different electrification features on CO_2 emissions and air quality are modelled. To provide a perspective of their relative impacts, the amount of settings of these variables is reduced to three or four. Each setting corresponds to one scenario type. Given underneath are 5 scenarios of which the first two are two scenario's that do not involve electrification (frozen tech and frozen implementation) and the other three depict three levels of electrification implementation.

- *Frozen technology case:* This scenario setting holds all technology variables the same as the 2013 case except for the volumes. This means only the ratio between conventional cars and electric cars change, but efficiency levels and emission factors are still constant.
- *Frozen implementation case*: electrification variables are the same as in the 2013 situation, meaning no electrification takes place at all. All other variables (car park, efficiency) do change according to the modelled base case.
- *Base case:* Variables are set to the business-as-usual case as established in section 3.1. This means only V1 (electrification) and V2 (electricity mix) come into play, set to the base case level. As it is assumed that the EV mileage and urban focus (V4) are not manipulated in business-as-usual conditions, these variables remain 0.
- *Advanced case:* Every studied variable is slightly shifted to a new situation. Also V3 (increased EV mileage) and V4 (relative urban EV-mileage increase) are introduced.
- *Extreme case:* All variables are taken to a larger level to the most extreme case, in which the variable changes the most compared to the original case. In table 3.2.1, the values of each variable within each case are given.

The settings of these cases for the studied variables are given in table 3.2.1

Studied variable	Unit	Frozen tech/ imp.	Base	Advanced	Extreme
V1: Degree of electrification	% EV's	0%	18%	25%	40%
V2: Electricity Mix	%fossil (% NG / % coal	82% (54/24)	66% (43/23)	50% (32.5/ 17.5)	40% (26 /14)
V3: EV mileage	% change from average mileage	N/A	0%	+25%	+50%
V4Urban electrification	% change in average urban mileage	N/A	0	+100%	Full urban focus

Table 3.2.3: Values of the different studied variables under different scenario's (cases)

In this paragraph, the following setup is used: First the total potential is given, by varying all variables together under the four cases. This returns an idea of the potential extra CO_2 and pollutant abatement potential. In the following subsection, the *individual* effects of each variable are illustrated, together with the effect of *paired* electrification variable changes (combinations).

SYNOPSIS OF OUTCOMES

It was found that further varying the electrification features has a positive effect on CO_2 and pollutant emissions. The most extreme setting, which depicts a potential of the electrification effects, could cut CO_2 emissions over 50% percent compared to 2013, while the total and urban pollution figures reduce by 80 and 100% respectively. When the variables are analyzed individually, it comes forward that the amount of electric vehicles (V1) and the fossil share in the electricity mix have the greatest effect on CO_2 emissions. The combination of increasing EV mileage (V3) and focusing no urban areas

(V4) could be a good alternative for an individual improvement in V1 and V2, as it shows comparable results considering CO_2 emissions and better results in air quality. Another important outcome is that combining the variables has a much larger effect on emissions than increasing individual variables.

Total potential effects of variables

CO_2 EMISSIONS

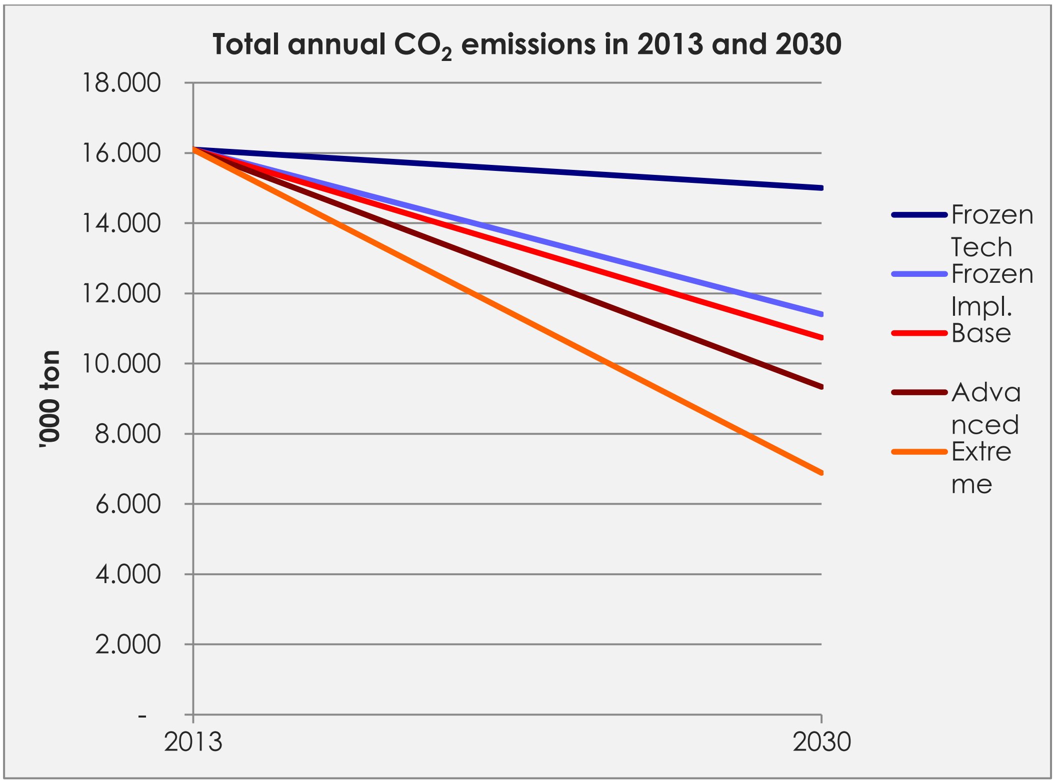


Figure 3.2.1: Four different electrification scenario's and the effects on the modelled CO_2 emissions from the transport sector. Note that the model *does not* predict annual CO_2 emissions in the years between 2013 and 2030

According to the model, CO_2 emissions from the transport sector can potentially be reduced by over 50% compared to 2030 (given by the *extreme* case). However, the share of the contribution of electric cars in this potential is limited, as a large part is already accounted for by other variables (fleet renewal, efficiency development, decreased automobile transportation). This is depicted in the *Frozen impl.* curve, which shows great improvement in CO_2 emissions already without any interference by electric cars.

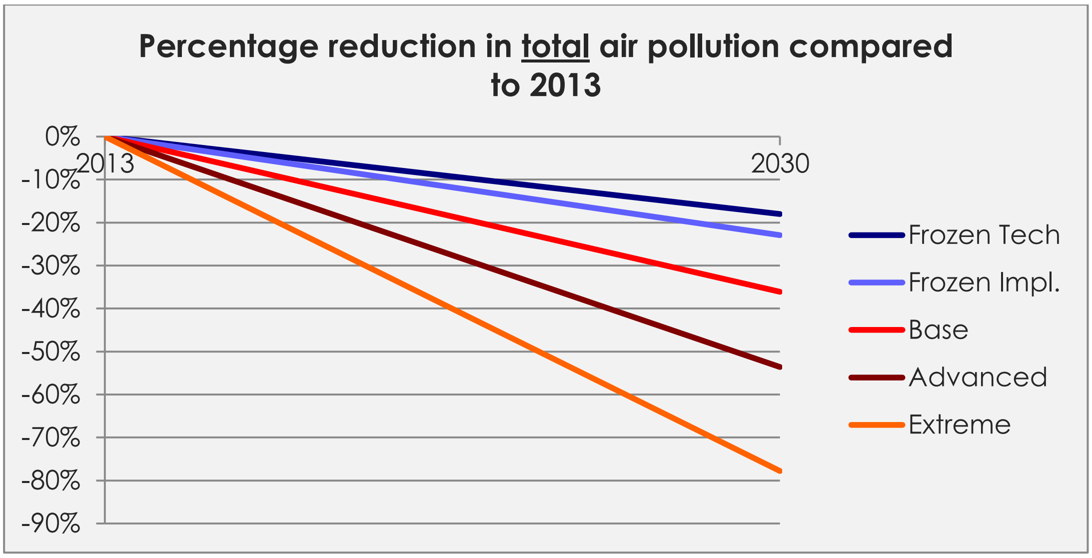
The base case, which accounts for a business-as-usual improvement of the electricity mix and a EV-penetration of 18%, shows only a very small deflection from the case without any electrification, together accounting for an extra 700 kton of avoided CO_2 emissions (this was also pointed out in paragraph 3.1).

The *advanced* case, accounting for more EV's, a more fossil-free electricity mix and improved focused electrification gives a nice first potential of CO_2 emission abatement. Understandably, the increased electrification and improved electricity mix has positive effects for CO_2 emissions. However, combined with increased EV mileage and focus on the urban areas, the difference with the base case is larger than the difference of the base case with the frozen implementation case: An extra 1.000 kton of emissions is avoided on an annual bases. The effect of the combined variables taken to an extreme level shows an even larger decrease to just under 7 Mton of annual CO_2 emissions.

The outcomes of the model imply that electrification could have a potential large effect on overall CO_2, cutting emissions by over 50% compared to 2013. In relative sense, a lot of steps can be taken within the bandwidth to optimize CO_2 emission abatement by electrification.

TOTAL AIR POLLUTION AND URBAN AIR POLLUTION

In terms of air pollution, the model shows that the effects electrification are a lot more pronounced. This can be explained by the very low pollutant emissions per km of electric vehicles compared to conventional cars. Moreover, the electric vehicles have no exhaust emissions, which means that electrification in urban areas positively affects urban air quality immediately.



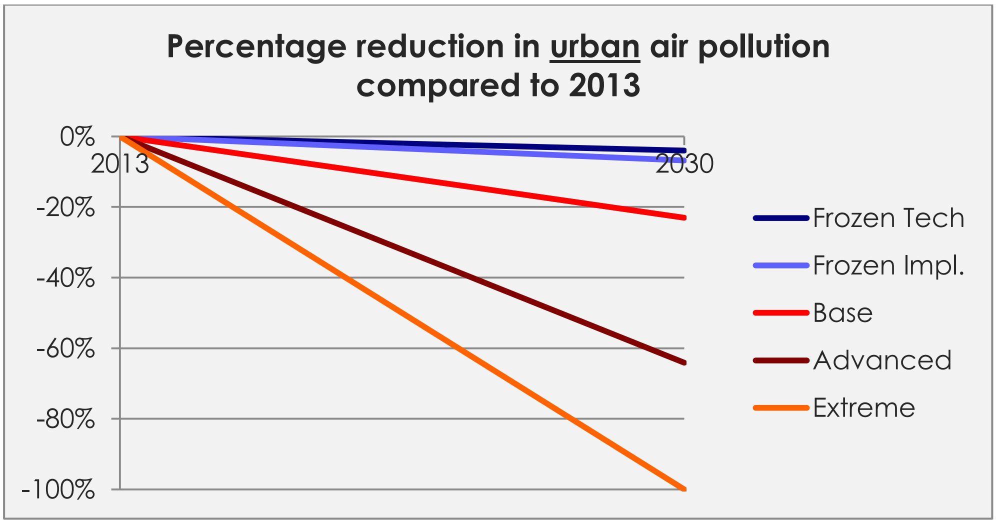


Figure 3.2.2ab: Effects of four different scenario's on pollutant emissions in transport sector, in total (a) and in urban areas (b). Average emissions of 2013 are used the reference year for both emission types.

For the total air pollution, increased presence of the electric car (both its penetration within the car park as well as increased mileage) lead to a considerable decrease of the emissions of the researched pollutants. The total effects of more EV's, their increased mileage and their increased presence on urban roads are large. Total air pollution from passenger cars could be cut in half by a slight increase in the variables (advanced case) and removed for 80% by the extreme case. This is even more pronounced in the urban air quality case, where the advanced case leads to an over 60% decrease in urban air pollution. In the most extreme case, all urban emissions are eliminated. This is caused by the fact that all miles in urban areas are travelled by electric vehicles.

Individual effects of single variables

In this subsection, the effects of every individual input variable and three combinations are examined. The individual inputs are mentioned in table 3.2.2. They are compared to the 2013 case and the modelled base case. The results and discussion about the differing effects are firstly given in an overview. Then, the effects of paired combinations are shown.

The effects of each variable on the total emissions are depicted in Appendix C.

GENERAL OVERVIEW OF VARIABLE EFFECTS

An overview of all the different effects has been given in table 3.2.2ab. To showcase the (difference in) effects, the reduced CO_2 emissions as effect of the measure have been given as a percentage reduction compared to the 2013 base-year. The values of each variable effect should be compared to the base case effects to put the effect in perspective. This is why the base case reduction of emissions is mentioned in each table. Also note that electricity mix has no (extra) effect on air pollution figures because the EV emissions are already a lot lower than conventional car pollutant emissions. This is why its effect on air pollution is not regarded in the table.

Studied variables		Changes in input factor			Effects on CO_2 emissions (pct change compared to 2013)		
Variable name	Unit	Base case	Advanced case	Extreme case	Base case	**Advanced case**	**Extreme case**
Degree of electrification	% EV's	18%	25%	40%	-32,9%	-34,6%	-38,3%
Electricity Mix	%fossil (% NG / % coal	66 (43/23)	62 (40,3 / 21,7)	40 (26 /14)		-34,8%	-35,9%
EV mileage	% change from average mileage	0%	+25%	+50%		-34,2%	-35,4%
Urban electrification	% change in average urban mileage	0	+100%	Full urban focus		-34,1%	-34,8%

Studied variables	Effects on **Total** air pollution (pct change compared to 2013)			Effects on **urban** emissions (pct change compared to 2013)		
	Base case	**Advanced case**	**Extreme case**	Base case	**Advanced case**	**Extreme case**
Degree of electrification	-36,1%	-41,2%	-52,21%	-23,1%	-29,4%	-43,0%
Electricity Mix			N/A		N/A	N/A
EV mileage		-39,51%	-42,94%		-27,2%	-31,3%
Urban electrification		-40,4%	-43,0%		-39,6%	-49,5%

Table 3.2.2ab: Overall effects of each variable on CO_2 emissions, total air pollution and urban air pollution

Considering the CO_2 emissions (table 3.2.2a) it can be observed that the individual effects of shifting each variable do not vary a lot. It can be seen that relatively the amount of electrification has the largest effect. Another interesting finding is that when the advanced case is considered, the CO_2 emissions decrease by about the same percentage for all four variables. It should also be noted that these values do not say everything, because not all variable changes are equally easy to achieve. Regarding that, EV mileage and urban electrification (the latter two factors) could be interesting.

Although the input factor changes appear to be radical when compared to the base case (as depicted in the left, blue side of table 3.2.3a), stimulating EV mileage in urban areas (at the expense of conventional cars) might perhaps demand less (financial) effort than the first two factors.

In all more advanced cases of electrification the air quality (table 3.2.2b) benefits to a certain degree. In terms of total air pollution, the amount of electric cars is the strongest factor compared to the effects of the other two mileage factors. The urban electrification factor is however the largest when it comes to urban air quality, showing that with the same limited amount of electric vehicles (18%), it still reduces urban air pollution emissions by a larger factor than just the mere increase of electric vehicles.

EFFECTS OF VARIABLE COMBINATIONS

In table 3.2.2, the three combinations of electrification variables are shown.

Combination code	Involved variables
C1	EV mileage x Urban focus (V3 x V4)
C2	Degree of electrification x Electricity mix (V1 x V2)
C3	All studied variables (V1 x V2 x V3 x V4)

Table 3.2.4: Different combinations of variables that have been examined. Note that C3 is the same as the potential discussed in the last subsection, as all variables combined have been assessed to return a potential

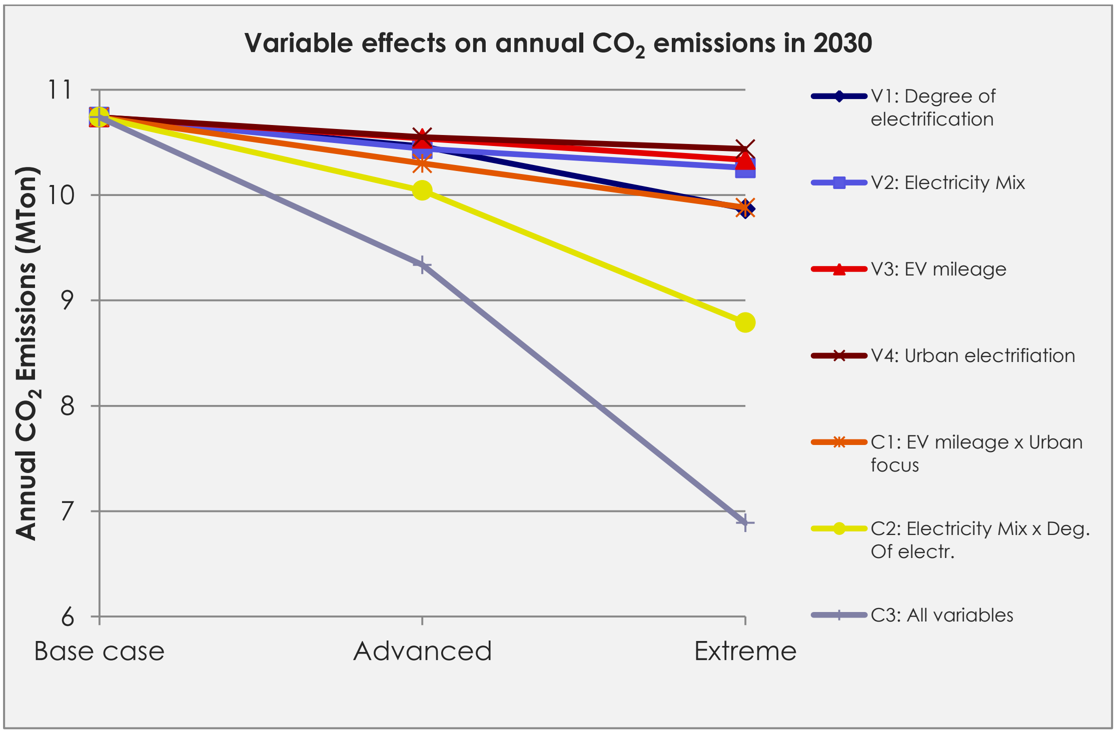
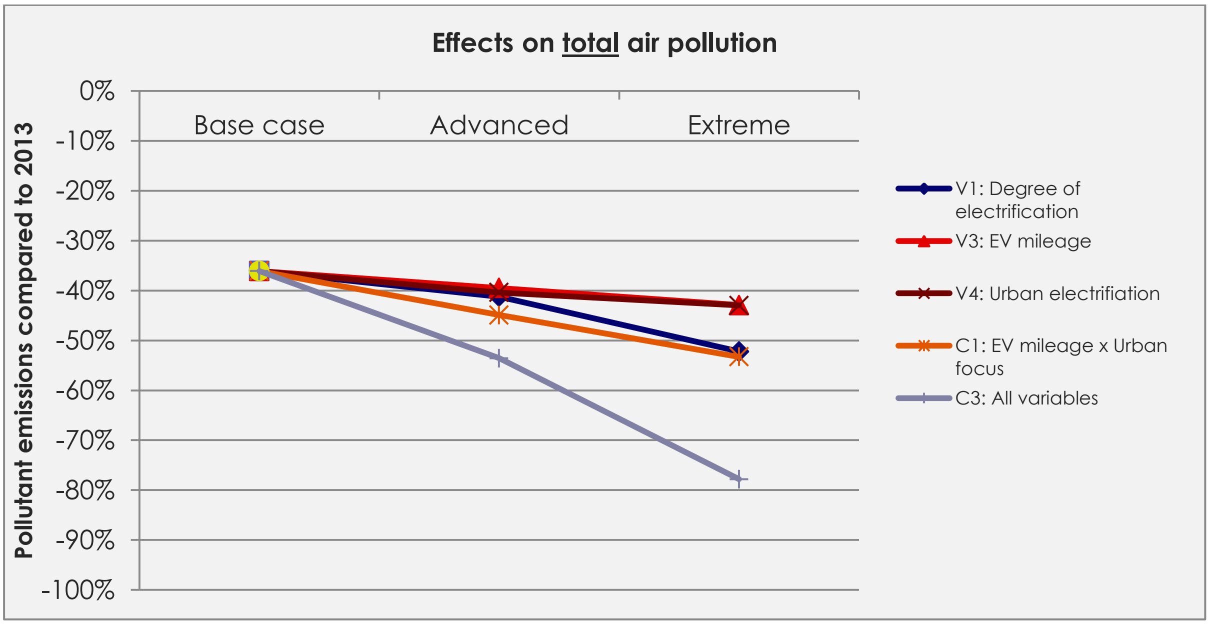


Figure .3.2.3: Effects of different variables on CO_2 emissions. Note the scale for CO_2 emissions starts at 6 Mton to showcase the differences better.

Figure 3.2.3 shows the effects of the different variables on CO_2 emissions. What strikes at first is how close together the individual variable effects are together (this could also be observed in table 3.2.3. This could imply that single improving one of these variables in 2030 does not have any large effect on the CO_2 emissions. A combination of variables has larger effects, as exemplified by C2 (electricity mix and degree of electrification) and especially C3. Another interesting point is the C1, which combines 'simple' variables of simulating higher annual EV mileage and focuses electric vehicles in urban locations. Doing this with the business-as-usual electricity mix and the base case amount of electric vehicles delivers an output similar to the single increase of electric vehicles (V1).



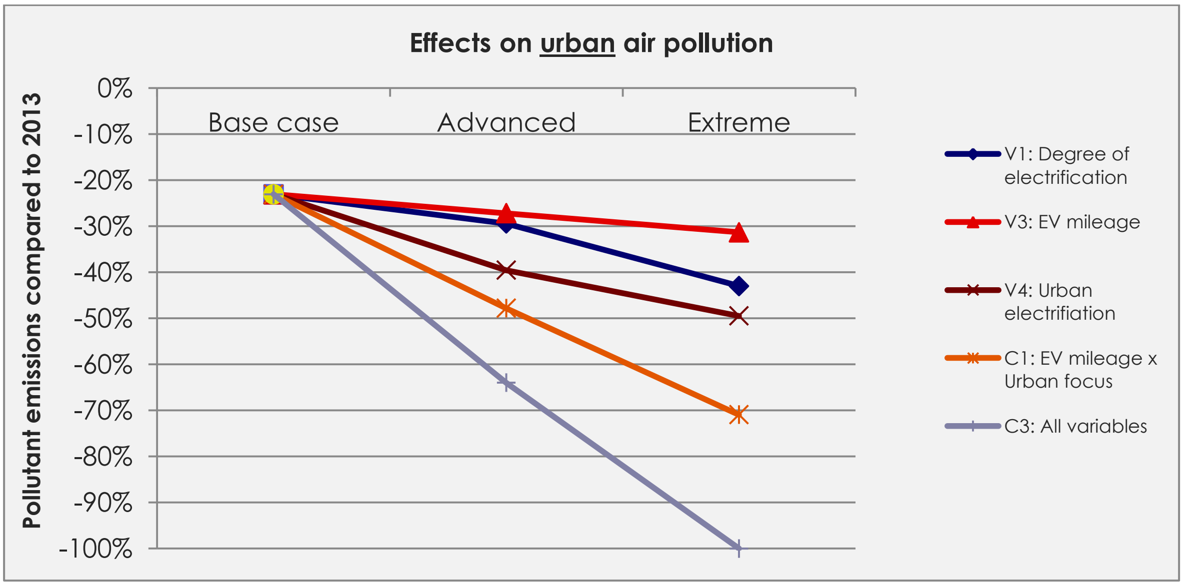


Figure 3.2.1ab: Effects of single variables and variable combinations on pollutant emissions. Note that electricity mix variables (V2 and C2) have been excluded as they have no extra effect

The effects on the total and urban air pollution are given in figure 3.2.3 (a and b). Electricity mix (V2) and the combination with electricity mix (C2) have been excluded because improving electricity mix has no effect on pollution results. In terms of total air pollution, it can be observed that single variable changes do not have large effects, and the higher emissions reductions are achieved through. Similarly to the CO_2 emissions case, C1 has slightly better results than V1. Effects on urban air pollution again are a lot more pronounced. Especially C1 has a large effect on urban air quality, as the urban focus of electric vehicles (V4) is augmented by the increased amount of miles that EV's can travel (V3).

Combination variable analysis: Electric mileage and urban electrification (C1)

CO_2 EMISSIONS

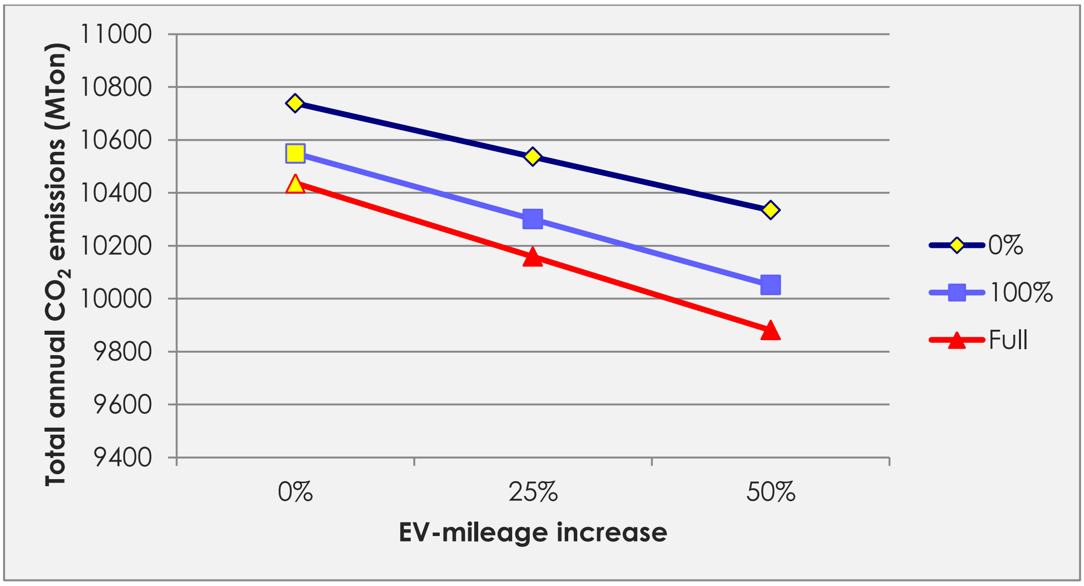


Figure 3.2.2 Effects of combining increase of electric mileage with an urban focus.

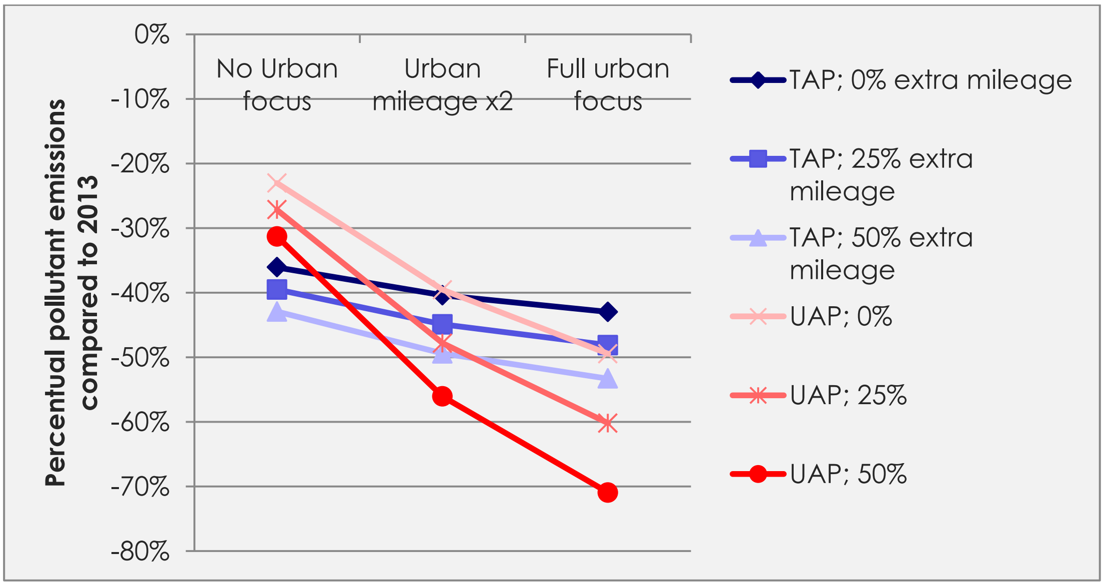


Figure 3.2.3: Effects of the combination of EV-mileage with urban electrification on total (blue variant lines) and urban (red variant lines) air pollution. Note that TAP stands for total air pollution and UAP stands for Urban Air Pollution

In the case of CO_2 emissions, again the relationships are quite linear. Possibly interesting is the more extreme case of full urban electrification and large mileage increase (by 1.5). This causes emissions to fall under 10 megaton.

In the case of total air pollution, the variables strengthen each other linearly in the same way, figure 3.2x shows a gradual decrease of total air pollution. Urban air pollution could however be greatly reduced by this combination measure, as the increased electric mileage from variable 3 is more deployed in urban areas (variable 4), displacing the pollution of conventional cars in those areas. A potential of 70% reduction was modeled in the extreme case.

Combination variable analysis: Electricity mix and electrification (C2)

Note that this combination has no increasing effect on pollutant emissions other than the individual effect of V1, as it has been determined earlier that electricity mix has no effect on pollutants.

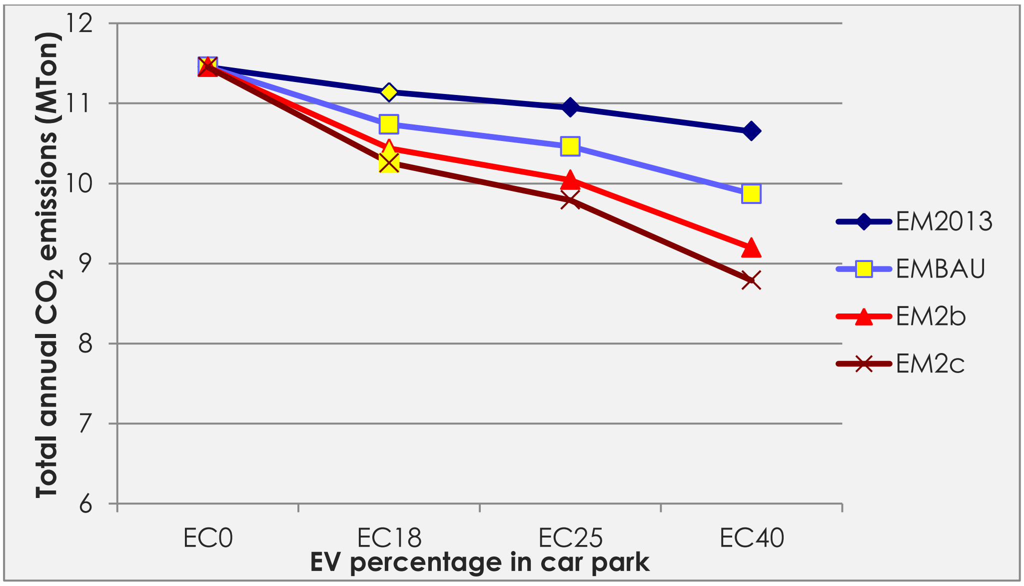


Figure 3.2.4: Combinatory effects of increasing electrification (EV-presence) with different electricity mix scenario's. Yellow points show the base case of both variables.

Figure 3.2.7 shows the effects of electrification are magnified by increasing electricity mix. What is interesting is that the extreme case of reducing the fossil share in the electricity mix does not seem to make a large difference compared to a more advanced case. Also, it can be seen that a 25% electrification and an advanced electricity mix has a similar effect on CO_2 emissions as a 40% electrification with the base case electricity mix.

4. DISCUSSION

Outcomes and conclusions rely for a large part on the data input. The magnitude of the analysis, carried out on the full Dutch passenger car sector, caused inevitable methodological errors, as simplification is often used to circumvent any complexity. In building up the model and calculating effects, assumptions are implied that probably affect the outcome in all parts. In this section, the most important assumptions and their effect on the outcomes are briefly stipulated. Note: to prevent too many graphs in this section, only impacts on CO_2 emissions are given in this section when sensitivity tests are given.

Reliability of data input

Fuel efficiency conventional cars: probably overestimated

The fuel efficiency of different cars has been taken from websites Autozine (n.d.) and Autoweek (n.d.). In these websites, fuel usage is posted, which is taken from the standardized tests. This test returns an urban and an extra-urban value, which have been used as a basis for the efficiency of passenger cars on the three different road types. However, there has been criticism on these tests. Ligterink & Smokers (2013), claim that the values that the manufacturers give with their new cars are usually largely overestimated, meaning their actual fuel consumption is a lot larger in normal circumstances. Sometimes efficiency differences over 20% were found. It is therefore probable that the used efficiency factors the maximum possible efficiency of cars. Because the efficiency is for a large part dependant on how one uses the car (acceleration patterns, climate control, payload), the *average* efficiency is probably a lot lower. No correction factor has been used in this thesis, because this factor probably differs a lot with the different segments and age groups that were defined. However, this does mean that emissions from conventional cars are probably higher.

Electric efficiency of electric vehicles

It is not easy to find accurate data on the energy efficiency of electric vehicles. According to many in which manufacturers post the ranges rather than how efficient the electric engine consumes electricity. This also applies to how efficiencies differ on road types: the relationship is certainly present but how large this definite figure is lacks. Factors have been assumed based on different researches to calculate the efficiency difference. This may give an unreliable figure on how much electricity is used (and how much CO_2 is emitted) by electric vehicles.

Figures 4.1 and 4.2 show the effects of a decreased efficiency. To simplify, all efficiencies (gasoline, diesel and electric) have been reduced by 20%. What is interesting is that the CO_2 emissions increase as expected, but also the differences between the two years increase (although both efficiencies decrease by the same factor). As is also shown in figure 4.2, the effect of electrification seems to be larger, which supports argument of abating CO_2 via electrification. This effect is interesting to research in a follow-up study.

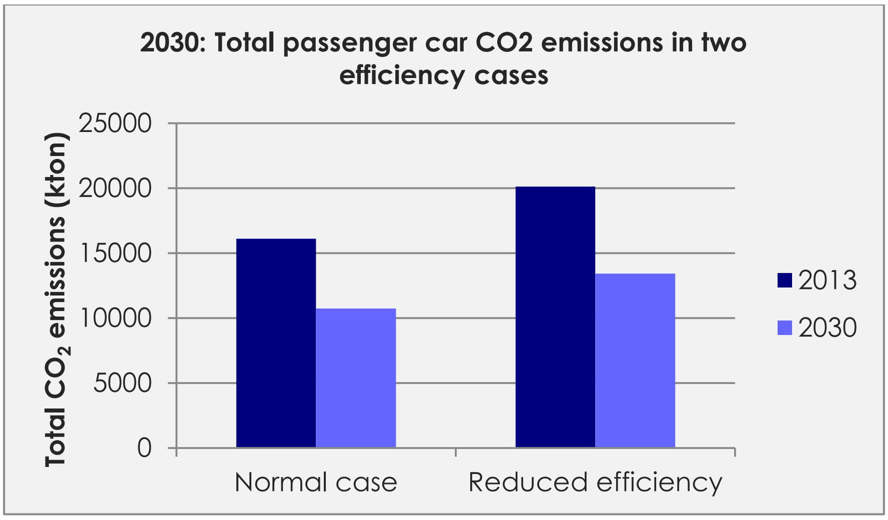


Figure 4.1: Effects of differed efficiency on total emissions. Note that emissions are higher with a reduced efficiency, as is the decrease in emissions

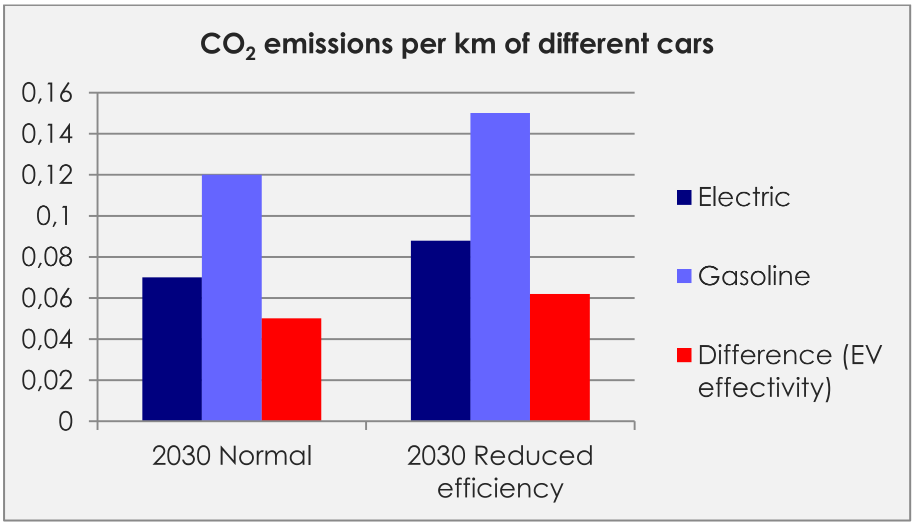


Figure 4.2: Effects of efficiency on total emissions. If all cars are 20% less efficient (shown in right case), the avoided emissions of electrification per km is higher.

Validity of research

Simplifications: mileage distribution across the car park and pars-pro-toto

The methodology in this thesis had to take emissions of the full passenger car park and all the kilometers travelled into account. To keep the research viable, simplifications had to be made to find adequate number that represent the total numbers and how they are distributed. Only gasoline and diesel powered cars were appointed to represent the conventional car fleet, while only full electric cars were to represent all the EV's. This is an effective method as these car types cover 96% of the current car park, but it does however exclude other possible trends in transport. This is an important limitation of the research, because it does not take any other scenario of other car technologies into account.

Another important assumption is that the annual kilometers travelled were only specified for the fuel types, and kept constant for all different segments and age groups. The same goes for the distribution over urban, provincial and motorway roads of the mileage, this is constant for all cars in the model. This means that all types of conventional cars travel the same distance on the same roads according to the model, which is not likely. A research on travel behavior done by a Dutch transport research institute suggests (Mobiliteitsbalans 2012, 2012) that small segment A cars are used more in city areas and shorter distances, while there are more large cars on average on provincial legs. This simplification might also return an incorrect approximation of the emissions from conventional cars.

Underdeveloped variables: Amount distribution: segments, age groups, and fuel types

Regarding the limited time and material of this research, it is difficult to develop an accurate forecast on what the transport sector looks like in 2030. For some variables, indications could be found of the future, like efficiency development or car amounts. For a lot of other variables, (certain) future values could not be found and applied into the model, and were therefore kept constant. The distribution of different features in the car park is probably one of the more important ones, because this has a large impact on the emissions from the transport sector. For instance, it might be the case that people use smaller cars more than currently in 2030, or that people buy less new cars, or start buying diesel cars more. This could have a great impact on emissions and presumably on the electrification strategy as well. It would be interesting to research the influence of these variables in a follow-up research.

The sensibility of the impact on distribution among segments is shown in the figures underneath. For segments, two situations are taken in which smaller cars dominate and large cars dominate (see figure 4.3). For age groups, because the normal case already has relatively young cars (90% is 15 years or younger), two extra states are taken with slightly older cars and much older cars. Interestingly, the same effects seem to take place as with reduced efficiency: Total CO_2 emissions grow in less 'positive' scenario's (with larger or older, more consuming cars), but the relative effect on electric vehicles (reflected by emissions per km) does not seem to be as great. Therefore, in the case of more old cars or less small cars, electrification could be more effective. This could be an interesting follow-up research subject.

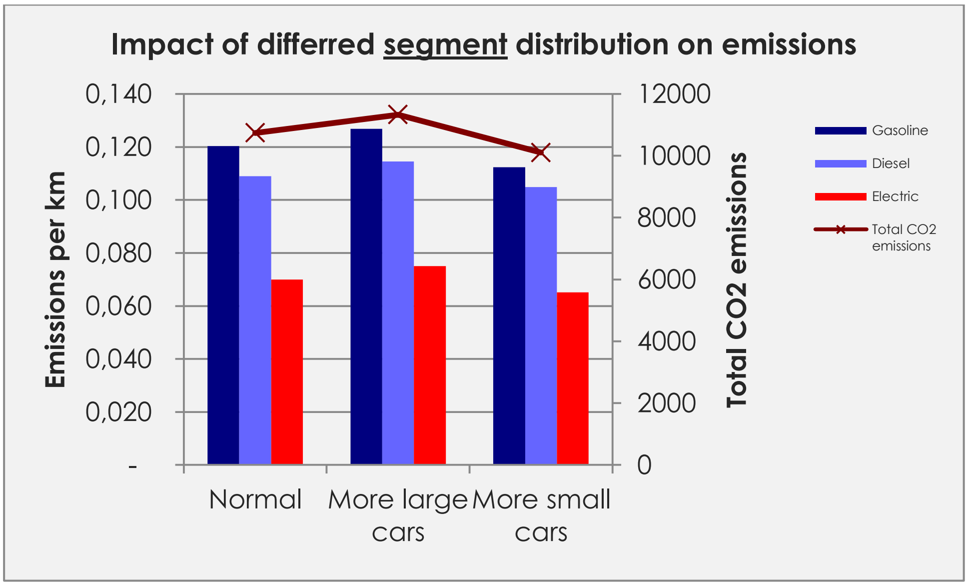


Figure 4.3: Differed segment distribution compared to the base case. In the middle group, the percentage of large cars has been induced compared to the normal case. In the right group, the percentage of small cars has been induced.

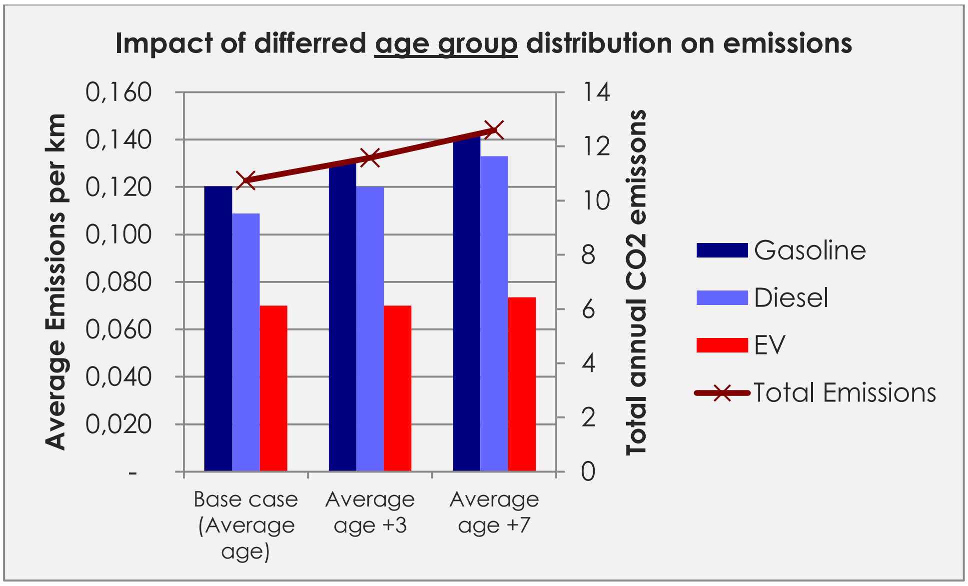


Figure 4.3: Differed age group distribution compared to the base case. In the cases, average age of the car park has been induced by 3 years (middle group of columns) and 7 years (last group of columns).

Electrification systemic errors: electrification and partial electrification and interdependence

In this thesis, important variables that are used are electrification and partial electrification. The challenge of introducing this into the model was to translate the variables in the right way to acquire a valid representation. three major problems came forward in modelling with these variables:

1. The variables are probably partly interrelated but however are treated as if they are separate. For instance, increasing the urban focus variable probably already implies that the EV mileage will increase, within in the model, they are treated as variables that are independent from each other.
2. It has not been the focus of the thesis to assess the costs of changing electrification features. However, this would be useful as it shows the effectivity of each variable change, together with measures to achieve such change. This would allow policymakers to balance the modelled variable effects against each other.
3. In the model, electrification always occurs according to one constant pathway for the sake of simplicity. It is assumed that every extra electric vehicle displaces a conventional car of the same segment, and that electrification is constant over all segments (every extra percent is divided over all segments, corrected by how much they occur). In reality, EV's are probably not taken in use to displace a car of the exact same segment, or used in the same fashion as a conventional car would be used. This undermines the validity of the model on how electric vehicles will be used and in what amount (distribution) they will be. Ultimately, this could have effects on how emissions are calculated from electric vehicles and from conventional cars.

Scale of energy (emissions) assessment

It has been made clear in the problem structure that only the emissions of energy consumption from the use of cars themselves are regarded. However, the energy consumption (and environmental effects) of the production and decomposition of cars, the so-called Life Cycle Analysis, could also be an important factor. Especially because it could contrast the view of the importance of *fleet renewal*: in the model this is in all respects a positive effect on CO_2 and pollutant emissions, but if one would consider the extra emissions from producing these new cars and demolishing the old ones. It could also put the positive effects of electrification into perspective: in some studies it is found that production of electric vehicles (especially the large batteries) a lot more energetic and environmental impacts than production of conventional cars.

Another important scale that was not examined is the local or time-dependant effects of electricity consumption. In the model, it is assumed that all electricity is derived from all energy carriers, each with a certain percentage dependant on how much they contribute to the total electricity production over a year. In reality, the allocation is different: the energy carriers used to generate a specific amount of electricity depend on the time (and load patterns) of day or the location. One could research the effects on the (day-to-day) electricity mix if the increased amount of electric vehicles were all charged at the same time (like when people get home from work); probably there will not be enough renewable capacity (and share in the electricity mix) as the general electricity mix would imply. This also gives ideas of an interesting follow-up research: what the effects are of an increasing amount of electric vehicles on the actual electricity mix used for EV electricity.

Impact of other transport variables

Because the results of electrification on CO_2 emissions small, one could also find a solution within a more integral perspective on the transport sector. This research suggests that the renewal of the passenger car fleet and efficiency development may have a large positive effect on CO_2 emissions from the transport sector. Maybe shifting these variables could be the basis for more (cost-)effective pathways to achieve a less CO_2 emitting transport sector. The supported changes could be (for instance) more stringent (per km) emission caps on gasoline cars (increasing their efficiency) or a tax cap on total annual mileage (reducing travel demand). A cost-benefit analysis of a transport sector with these measures (focused on conventional cars) compared to a transport sector with the supported implementation of EV's could provide interesting context to electrification as main decarbonisation option.

6. CONCLUSION

The goal of this research is to assess the effects of electrification of Dutch passenger cars on CO_2 and pollutant emissions in 2030. A model was used to forecast the CO_2 and pollutant emissions from passenger cars in 2030 and in 2013, based on different changing transport features (fixed variables) and electrification features (studied variables). The basic effects of business-as-usual electrification with a forecasted electricity mix were modelled, which established the base case for 2030 (section 3.1). The effects of shifting and combining the electrification components (4 variables in total) are given to show what the full potential of passenger car electrification is (section 3.2).

Results show that CO_2 and pollutant emissions from passenger cars will be reduced by 33% and 36% respectively in 2030 compared to 2013 in the business-as-usual (base) case. The actual effects of electrification in this case however are only limited for CO_2 emissions. Only 13% of the CO_2 reduction in 2030 compared to 2013 is accounted for by the implementation of electric vehicles. For air pollution emissions, the relative effects of electrification are larger: 37% for total air pollution and 71% for urban air pollution. The model shows that the renewal of the conventional passenger car fleet and the developing fuel efficiency are trends that play a more important role than electrification. Therefore, it is concluded that under business-as-usual conditions, (urban) air quality is a more important reason for passenger car electrification than CO_2 emission abatement.

Varying the electrification components has mixed results on emission abatement. It was found that increasing the amount of electric vehicles (V1) potentially has the highest potential effect on CO_2 emissions (extra 6% reduction) and air pollution figures (extra 10% reduction). Decreasing the fossil share in the electricity mix (V2) also has a high effect on CO_2 emissions, but no extra effect on pollutant emissions. The individual effects of the electrification mileage variables, increasing the EV mileage (V3) and focusing the mileage of EV's in urban areas (V4) are not as large, although V4 does have the highest potential for urban air pollution. The combination of these electrification mileage variables does show an extra effect on total and urban pollution, and a considerable extra reduction effect on CO_2 emissions. This combination may be an interesting alternative to increasing the amount of electric vehicles or that are probably more expensive or more debated.

Based on the outcomes of this model, the answer to the research question is dependent on the perspective of what emissions are examined (CO_2 or airborne pollutants) and to what scale electrification features can be changed. If the business-as-usual case of electrification is maintained, the effect on reducing CO_2 emissions from the transport sector is limited to a small 13% in 2030 and 40% on total air pollution reduction. In terms of air pollution this is a considerable effect, especially urban air quality could greatly improve by replacing conventional cars by electric vehicles, so the potential is large in that respect. For CO_2 emissions, the base case results show only a small potential, especially when compared to the effect of efficiency development and fleet renewal within conventional cars.

If however certain features of electrification were to change in 2030, the CO_2 and pollutant emission reduction potential could be higher, which is of course especially relevant for the CO_2 emissions because of the small part it has in the base case. Further decrease of the fossil share in the electricity mix (which involves many other stakeholders and economic interests) or increased stimulation of electric vehicles in the car park (which could lead to a large increase of government expenditures) could be seen as drastic measures. An interesting alternative policy, presumably less drastic, could be aimed at replacing conventional cars with high annual mileage with electric vehicles (V3), together with focusing implementation of electric vehicles on urban areas (V4). This could offset total CO_2 emissions in a similar way as improving the electricity mix and EV-amount. Another important effect is that these variables improve the effectiveness of each single electric vehicle, because more CO_2 and pollutants are avoided per kilometre and per vehicle. This could make the electric vehicle more relevant in reducing CO_2 emissions and improving air quality, adding to the reason for consumers or businesses to invest in electric driving.

7. LITERATURE

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APPENDIX A: AMOUNTS AND DISTRIBUTION WITHIN THE DUTCH CAR PARK

FUEL TYPE DISTRIBUTION

CURRENT – As explained in the methodology, all conventional cars exist of gasoline and diesel cars. The exact ratio between gasoline and diesel cars is used to produce the distribution of gasoline and diesel cars within the model. According to "Mobility in Cijfers," (2014) gasoline then takes up (79/96) 82,2% of the car park and diesel takes up 17,6%. This means for every diesel car there are 4,67 gasoline cars.

FUTURE - For the future situation, it is still assumed that conventional cars exist only of gasoline and diesel cars, implying that no other propulsion technology will significantly emerge (besides electric). It is assumed that, within the conventional cars, the ratio of gasoline and diesel cars, both in amounts as well as distance travelled, remains constant too. This is because historically, the improvements in efficiency of both car types have been more or less constant, which could imply that the ratio of taking a gasoline/diesel could be constant. Moreover, the relative production means of both fuel types will be the same in the future. Produced from the same basic fuel (mineral oil), diesel oil is of a lower grade and therefore always easier to produce than gasoline oil. ("Differences between diesel," 2013) A large change in engine technology could change the environmental impact of diesel, maybe incurring a change in tax regimes, but there is no indication of that to be found yet.

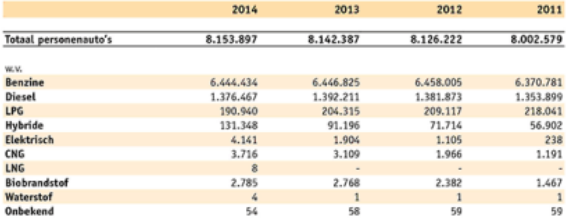
AGE GROUPS

CURRENT - Every year, cars are manufactured and sold on the market. Generally, partly thanks to more stringent international regulations, conventional cars have better engine efficiency, using less gas and emitting less CO_2 per driven kilometre. (European Commission, 2014) The EU has implemented a system that puts emission limits on new passenger cars to improve air quality and reduce CO_2 emission, each limit called Euro-x. Euro-1 has been of effect since 1993, and Euro-6, which is the most recent one since 2014. For the model, a 5-year interval has been chosen to distinguish different usage factors and air pollution emissions, loosely based on the publication of the limits and also on the occurrence of cars across ages. This results in 5 different age groups.

Group numbers	Manufacturing year 2013	Manufacturing year 2030
1	>2009	>2024
2	2005-2009	2020-2024
3	2000-2004	2015-2019
4	1995-1999	2010-2014
5	<1995	<2010

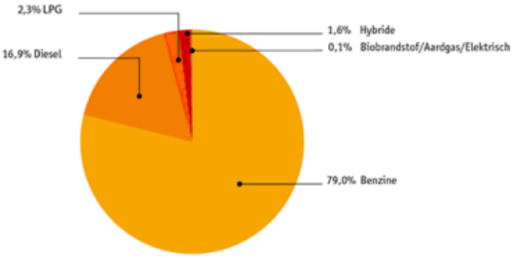
FUTURE – It is possible that a whole different car park has probably arisen in 2030. As people take new cars and old cars are replaced with new ones, the distribution over age groups might be the same, just with the age groups updated to the years that are applicable. The new groups for the 2030 scenario are shown.

The distribution across these age groups could be held constant (for simplicity), as no clear data could be found on a shift in this distribution.



	2014	2013	2012	2011
Totaal personenauto's	8.153.897	8.142.387	8.126.222	8.002.579
w.v.				
Benzine	6.444.434	6.446.825	6.458.005	6.370.781
Diesel	1.376.467	1.392.211	1.381.873	1.353.899
LPG	190.940	204.315	209.117	218.041
Hybride	131.348	91.196	71.714	56.902
Elektrisch	4.141	1.904	1.105	238
CNG	3.716	3.109	1.966	1.191
LNG	8	-	-	-
Biobrandstof	2.785	2.768	2.382	1.467
Waterstof	4	1	1	1
Onbekend	54	58	59	59

Personenautopark naar brandstof in %



Bron: RDC|CBMI, RAI Vereniging

SEGMENTATION

CURRENT - According to BOVAG-RAI (2014), the most occurring car segments are A, B, C, D, E, J and L (together over 86% of the total car park). These segments have been assumed to represent the total car park.

FUTURE - For the 2030 outlook, the percentages are held constant. This is because no relevant studies have been found about how the distribution in segments will shift in the future.

EV amounts and their distribution

CURRENT Currently, the amount of full electric cars is negligible: under 0,1%. ("Electric Mobility in," 2014) As stated before, it is therefore assumed that the full car park exists of conventional cars.

FUTURE As the amount of (full) electric vehicles is an important factor in the projected possible CO_2 and pollutant emissions, the electrification is an important variable that will be varied. According to "Plan van Aanpak," (2011), the amount of electric vehicles is projected to be around 1 million in 2025. A conservative estimation based on this figure is made in this thesis of around 1,5 million. Expressing it as a rounded-off percentage of the total car park has left a electrification factor of **18%.** A conservative growth in the advanced case is assumed to be 25%, the extreme case (over a doubling) is held at 40%.

In terms of amounts of electric cars, electrification is a percentage of the total amount of cars. As the amount of cars vary across fuel type, age groups and segments, every subgroup gets its own electrification percentage. As said before, it is assumed that electrification will be constant over all studied segments (meaning every segment is electrified over an equal percentage). The same goes for both fuel groups, both gasoline and diesel cars have the same degree of electrification.

Concerning the age groups, it is believed that electric vehicle sales will increase in the future ("Plan van Aanpak," 2011) leading to an increasing degree of electric vehicles in the younger age groups. The percentages for the age groups will be set accordingly that they increase with younger age groups and that the total amount of electric vehicles is equal to a realistic number found in policy outlooks.

APPENDIX B: EFFICIENCY AND EMISSION FACTORS OF CONVENTIONAL CARS

CO_2 EMISSIONS

The CO_2 emission factors for gasoline and diesel are used to calculate CO_2 emissions from the fuel consumption of conventional cars. They are based on a figure used by the IPCC, retrieved from dsd. These emissions are assumed to remain constant, as it is directly related to the amount of energy content of the fuel.

CURRENT - The most frequent passenger car manufacturers and types have been selected from a raw data file of the BOVAG (umbrella organisation for the automotive sector). Of all these car types, the most recent usage data have been taken from Autozine (n.d.), which posts usage facts based on standardized tests (NEDC). Three factors are returned: urban driving, extra-urban driving and a combined usage factor. All these car types have been arranged according to their segment, which lead to an average usage factors for every segment. These average usage factors have been taken as representative usage factors for the 2010-2014 age group.

Distribution over road types

As part of the NEDC test, the databases with usage facts of cars do not post a usage factor for highway use (which is different from extra-urban use). Therefore, for every car the highway usage has been computed based on the other two urban and extra-urban usage factors of the cars. As the efficiency drops with higher speeds than extra-urban driving, but is still higher than the urban, the efficiency is a an average between urban and extra-urban driving, only with more weight given to the urban factor, to account for the energy consumption at high speed.

Urban consumption (η_{urb})	Urban usage facor given by Autoweek (n.d.) & Autozine (n.d.)
Provincial efficiency (η_{prov})	Extra-urban usage factor given by Autoweek (n.d.) & autozine (n.d.)
Motorway efficiency (η_{hw})	$20\% * \eta_{prov} + 80\% * (\eta_{urb})$

Distribution over age groups

For the cars with manufacturing years before 2010, of which a large part of the car park exists, a calculation method is used. For every segment, a number of *guide car types* are selected, which were car types that have existed for 20 years and have updated the model regularly (Volkswagen Golf is a well-known example). For every age group (every five years until 1995) a model of these guide cars was selected and its fuel efficiencies registered at Autoweek (n.d.). The average efficiency development per age group within each segment was calculated from these guide cars. This efficiency development has then been used to calculate the average usage numbers of all cars in each segment over the different age groups, with the most recent age group (EU-5) as baseline.

FUTURE – Throughout the years, conventional cars have faced great efficiency development. According to an IEA study (, 2012), there still lies a lot of potential in the fuel usage of internal combustion cars. The report proposes that a 50% reduction in fuel consumption per kilometre compared to the 2010 efficiency might be possible in 2035 with new turbocharged gasoline and diesel engines. In a North-American study cited within the same report, a 15% reduction could be achieved compared to 2006 in 2020, implying a change of 5% per 5 years. Based on this report and on the historical efficiency development, a 5% efficiency development over every 5 years is assumed. This means that for every new generation, the usage amounts decrease by 5%.

CONVENTIONAL CAR AIR POLLUTION FIGURES

CURRENT - An extensive research on air pollution chemical emissions by cars has been carried out by Klein et al. (2014). This model has defined emission values (in kg/KM) for all basic air pollution chemicals for all types of transport. The degree of detail does not vary over different usage factors or over segments, but does vary over age groups corresponding to the emission limits set by the European Union. This could apply well, because many of these air pollution chemicals (like NOx) are not dependant on how the engine is used, but on engine heat for instance.

SOx-emissions are usage dependent. Klein et al. (2014) have stated the current S-content in both gasoline and diesel. In the model it is assumed that the full S-content in fuel oxidises upon consumption to atmospheric SO_2. This will also stay constant in the future

FUTURE - In the future case, it is assumed that the historical trend of declining emission factors according to Klein et al. (2014) continues. The reduction of pollutant emissions of both fuel types every five years is stated in the table underneath.

	Future kg/km emission reduction every 5 years (%)	
Pollutant	Gasoline	Diesel
NO_x	10%	10%
CO	15%	15%
VOC	0%	20%
PM10	0%	10%

APPENDIX C: EFFICIENCY AND EMISSION FACTORS OF ELECTRIC CARS

ELECTRIC EFFICIENCY

CURRENT – For conventional cars, there are a lot of numbers available given the great variety of cars. Unfortunately, for electric vehicles this is not the case. No databases were found with different usage factors of full electric vehicles. Even the car manufacturers themselves are vague on the actual usage of the EV. This probably has to do with the great variance in the actual electricity consumption. To cope with this variance in the model, factors have been chosen that affect the efficiency of electric vehicles: road type and climate control (HVAC). Another calculation method has been used to approach the actual usage of every EV in each road type.

ABSOLUTE EFFICIENCY

As full electric cars are currently not common, only a few models are available in the Netherlands. Common manufacturers usually have one electric model. The usage factor on different road types is not clear, but they do have the battery capacity (in kWh) and a maximum range (in km) documented in brochures. This maximum range is when ideal circumstances occur, usually highly overestimated compared to the actual range. Driver behaviour, vehicle speed and climate control effect play an important role. By dividing the range by the battery capacity, an *absolute efficiency* for every electric vehicle can be obtained. The variation of this absolute efficiency among the available electric cars shows the relative difference between car types. This returns a variation across electric vehicle segments.

ROAD TYPE VARIANCE

The model used in this thesis simplifies the usage factors of electric vehicles, based on empirical research done on cars. In the model, two different factors are discerned that affect the actual energy consumption of electric vehicles. Like for conventional cars, the road types are discerned, each (urban, extra-urban, motorway) are assigned a different factor. A climate factor is also introduced, because the control of the internal climate of the car can greatly affect the efficiency of cars. As it is the only official number available, the efficiency as calculated according the maximum range and battery capacity) is used as the basic varied number.

Electric cars are the most efficient when used within urban areas. The great advantage lies in the regenerative braking, where the energy ‘lost’ when the vehicle brakes is used to charge the electromotor again (Wu et al., 2015; Golembiewki et al., 2014; Giessen-Gondelach & Faaij, 2013). Therefore, it is assumed in this model that the maximum efficiency as computed according to equation x is equal to the urban efficiency.

According to Wu et al. (2015), the efficiency of electric vehicles drops when they are used on highways, which is equal to 47%. The speed limit on motorways is set the speed limit on 70 miles per hour, equivalent to 112 kilometres per hours, which could well apply to Dutch highways. Based on these data, a efficiency drop of **40%** is assumed.

No actual efficiency (or range) factors could be found in scientific literature about provincial roads. It could be assumed that, because of the lower speed limits, the efficiency is generally higher than on motorways. Because of the higher speed and the lower amount of starts and stops, the efficiency is probably lower than on urban roads. Wu et al. (2015) have posted the power that the engine uses versus the velocity of their test car. Although the (air) resistance of cars increases exponentially with speed, the test shows that the power increases linearly. This is why in this thesis, it is assumed that the efficiency drop is **20%,** which is halfway between the efficiency decrease of highway versus urban roads.

A summary of the assumed efficiency factors per road type can be found in the table underneath.

Road type	Efficiency decrease factor compared to highest efficiency	Assumption based on source
Urban	1,0	Highest possible efficiency
Provincial	0,8	Interpolation between urban and provincial
Motorway	0,6	Wu et al. (2015),

Calculation scheme for usage prediction

CLIMATE CONTROL VARIANCE

As climate control is one of the other important factors that affect the car efficiency, it is introduced as a separate factor applied at all times. On average, it is believed that the effect of heating or cooling a car could reach up to 33% efficiency loss (Lee et al., 2013). In a more detailed research, Neubauer & Wood (2014) found climate demand difference between different climates. In the Los Angeles climate (which is warmer than the Dutch one), a difference of 8% was found on average. In Minneapolis, with comparable summers but much colder winters, an efficiency effect of 20% was found as a direct effect of HVAC. As is exemplified in this data, scholars believe that the effect of heating (in case of cold climates) is higher than cooling. For this reason, a climate effect of **17%** has been used to model the actual efficiency affected by climate control in electric vehicles.

FUTURE – Three factors need to be considered for future change. The general usage factor (which is computed from the battery capacity and range), the efficiency factors on different road types and the climate efficiency factor. It is assumed that the relative differences across

Giessen-Gondelach & Faaij (2012) presented an outlook on the development of EV-battery technologies. They posed that there are multiple battery standards that could potentially power vehicles in the future, and the current standard (Lithium ion) fulfils most requirements (especially in efficiency standard) in the long term. However, no clear conclusions were made yet about the specific efficiency development in the future, apart from a well-to-wheel energy consumption of 314-374 Wh/km. As the charge/discharge energy efficiency within the car already is at a high rate (90-92%) (Gondelach & Faaij, 2012), it is believed that this number might not improve a lot. It is therefore assumed that the range might improve, but only with the associated increase of battery capacity, leading to the same efficiency.

The climate effect might improve, although it is hard to find literature on that point. An interesting way may be a more passive pathway to apply climate control in the car. Neubauer & Wood (2014) suggest the use of heat pumps, which may reduce the overall energy demand from the battery, or perhaps the use of a separate engine. Within the technology given, it is assumed that the climate effect might reduce to **10%** in 2030. Over each 5 years, it improves by 3,333%

For usage factors on different roads, it might be the case that the efficiency factors converge, perhaps due to more aerodynamic design of the car, or perhaps more automated use of the car at high speeds (less aggressive accelerating and decelerating). It is therefore assumed that the motorway efficiency factor decreases from 40% to 20%, with the provincial efficiency kept in between at 10%. This means an average development of 6,66% improvement over every 5 years

Emission factors

Electric vehicles have no exhaust emissions when only the vehicle is considered. The direct effects of EV-use are therefore derived from generation of the electricity that is used. In this model, it is assumed that the electricity that the EV's use comes directly from the Dutch grid, without being directly linked to a specific source. This means that every fuel has a share in the average amount produced. The total overview is called the electricity mix.

ELECTRICITY MIX

CURRENT - The electricity mix for the current situation is taken from the 2013 situation according to CBS (2014c). This shows how large the share of every fuel is in the generated electricity in the Netherlands.

FUTURE - The future electricity mix is based on a research report from CE Delft with a few assumptions added. Electricity mix is also a studied variable. The non-renewable sources with a low share have been kept constant for simplification (oil, 'other fossil sources', nuclear).

Renewable sources as well as coal and natural gas have been forecast in more detail. According to scenario's carried out by Rooijers et al. (2014) both coal and gas still are important fuels in the future electricity mix in the business as usual scenario, respectively accounting for 23.1% and 42.9% of the electricity production.

A CO_2 factor is calculated for every energy carrier in the energy mix. Of the entire energy mix, coal, natural gas, other fossil fuels and other energy sources are assigned a factor. The rest is assumed to be 0 (which is largely accurate for renewables and nuclear), the others are too small to have a significant impact on the overall emissions.

This is based on the emissions that the IPCC reports per kg of every material, specified by Vreuls & Zijlema (2013). For coal and natural gas, an overall efficiency has been calculated based on the total input (in kg or m^3) in the electricity sector and the output (in MWh) that came out of it. For "other fossil fuels", (amounting to 4% of the current electricity mix) the emission factors of the described fuels have been taken from Zijlema & Vreuls (2013). They have been assumed to have an equal share in the production by other fossil fuels, with the same efficiency as well (assumed to be 20%). The same line of methodology has been used for *other* energy sources.

EMISSION FACTORS: AIR POLLUTION EMISSIONS

Unfortunately, no emission factors of the studied air pollution chemicals are given for fossil fuels that generate electricity. Therefore, It started with the important assumption that only coal and natural gas account for emissions. As they take up the largest part of the non-renewable fleet, this could be a good indication of the emissions from the electricity sector. This line of methodology is chosen because the possibilities for collecting data on these emission factors are limited. From Emissieregistratie (n.d.), emissions of chemicals can be retrieved from individual power plants over 2012. The electricity production in that same year of these power plants can be obtained from the energy company. For natural gas plants and coal plants, an average has been computed for every chemical per produced MWh.

FUTURE – It has been assumed that both emission factors remain constant over the years, as there is no literature found of (great) improvements on that front.