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TOWARDS ZERO CO₂-, NO_x- AND PM₁₀-EMISSIONS BY PASSENGER CARS: TECHNOLOGY & BEHAVIOUR

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ABSTRACT

Modern societies rely on mass mobility, in particular by private car. Car numbers are growing worldwide due to economic and other factors. Nearly, all have engines that run on fossil fuels. Use of fossil fuels contributes to climate change (via CO₂-emissions) and local air pollution (primary NO_x- and PM₁₀-emissions). Both have profound environmental and health implications. The paper explores the technical and behavioural feasibility of zero-emission private car use in The Netherlands in 2030. Base year is 2010. The following research questions are addressed:

1. How much CO₂, NO_x and PM₁₀ did passenger cars emit in 2010?
2. How much will this be in 2030?
3. What would these figures be if electric cars become mainstream in 2030?
4. What would the impact be of sustained urbanization on these emissions?
5. How would a greener power mix in electric power plants affect the emissions of CO₂, NO_x and PM₁₀ by electric cars?

A simulation model was used to quantify a rich set of scenarios. Many car manufacturers aim to produce more (fully) electric vehicles (FEVs) in the coming years. More FEV translates into less (growth in) consumption of fossil fuels and emissions. The remaining emissions are still on the high side. Urbanization may support a further reduction. It reduces car ownership and use and thereby the growth in car kilometres, fossil fuel consumption and emissions. Growing production of renewable energy gradually makes the power mix greener. The most extreme combination of scenarios enables society to reduce CO₂-emissions far beyond the –50% target in 2030 for the assumed car mobility scenario. The feasibility of this outcome is rather uncertain. An extension of decades of neoliberal, market-first transport policy would very likely slow down the pace of the transition.

Keywords: air pollution, behaviour, car technology, car use, climate change, simulation, 2030.

1 INTRODUCTION

1.1 Transport and climate change

Climate change is a complex biophysical/biochemical process, which is still not fully understood. Most researchers acknowledge that the natural balance between sources and sinks of greenhouse gases is increasingly out of tune due to steadily increasing emissions of the various greenhouse gases by human activities [1]. The paper will deal with a major source of greenhouse gas emissions: The emissions are from combustion of fossil fuels in internal combustion engines (ICEs) of passenger cars. Hence, it deals with exhaust emissions and not with emissions of particles from wear of car brakes or tyres, which are frequently overlooked.

Road transport has a share of well over 25% in the final energy consumption in countries belonging to the Organisation for Economic Co-operation and Development

(OECD) [2]. Passenger cars (Table 1) dominate road transport in terms of vehicles and kilometre (km).

Currently nearly all cars have engines that run on fossil fuels. This is a rather inefficient way of converting energy into motion because only 12–30% of the combusted fuel is available as kinetic energy [3]. The remainder is wasted as heat and gaseous pollutants, in particular CO_2 , NO_x and PM_{10} . CO_2 -emissions are directly linked to climate change [4]. NO_x and PM_{10} are key air pollutants that have a negative impact on human health [5] and nature [6].

There is a relation between climate change and air pollution via fuel consumption [7]. This explains why regulators require car manufacturers to reduce both [8]. It also explains our interest in ways to reduce these pollutants simultaneously.

The relation between fuel consumption (reduction) and CO_2 -emissions is linear, but that is not the case for NO_x and PM_{10} . A reduction of $x\%$ in fuel consumption may then lead to $x\%$ reduction in CO_2 -, $y\%$ in NO_x - and $z\%$ in PM_{10} -emissions. This of course complicates (technical) emission reduction strategies.

1.2 Climate change mitigation and zero emissions

Climate change mitigation means reducing CO_2 and other greenhouse gases. Options to achieve this are in particular [see e.g., [9]]:

- (1) Reduce the total number of car km in a year by reducing the number and/or length of car trips. Typical options are
 - (a) Reduce the need to travel: Work from home and use electronic means to stay connected;
 - (b) Travel together by car (share a car);
 - (c) Travel differently: Use public transport or active modes (walking, cycling).
- (2) Increase the fuel efficiency of cars;
- (3) Increase the use of low-carbon fuels;
- (4) (Partial) replacement of carbon-based fuels by electricity (from renewable sources);

Changes in behaviour may be voluntary or mandatory. Technical progress, business mobility policies (no leased cars, business travel cards) and integrated government policies (spatial planning, investments in infrastructure and public transport, traffic management and mobility management) may support such behavioural changes.

The purpose of the paper is to discuss a series of options to reduce emissions of passenger cars to zero in The Netherlands by 2030 (reference year) compared to the base year 2010. The paper explores many of the recommendations for further research of our earlier paper [10].

1.3 Research questions

The following questions were addressed:

1. How much CO_2 , NO_x and PM_{10} did passenger cars emit in 2010?
2. How much will this be in 2030?
3. What would these figures be if electric cars become mainstream in 2030?

4. What would the impact be of sustained urbanization on these emissions?
5. How would a greener power mix in electric power plants affect the emissions of CO₂, NO_x and PM₁₀ by electric cars?

2 DEFINING THE PROBLEM

2.1 Population and car use; business as usual

The Netherlands is a densely populated small country; in 2010, it had 16.6 million inhabitants and an average population density of around 500 inhabitants per km². Many large cities have 5,000 or more inhabitants per km² [11]. Car mobility approached 98 billion km driven with 7.6 million cars in 2010 (driver only, add 40% for passenger km). In comparison, there were 17.13 million inhabitants and 8.2 million cars in 2017 [12]. The number of car km was the basis for the fuel and emission calculations in this paper. Relevant estimations can be found in Table 1.

To estimate car km in the year 2030, a set of assumptions was applied. There is a direct relation between individual wealth, car ownership and car use. The first assumption is therefore related to the average individual household income. We assume that there is no net economic growth plus a decrease in purchasing power of an average consumer household in the period 2010–2020. The arguments are that the economic downturn of 2008–2014 and recovery since 2014 balance each other out, while an economic cool-down should also not be ruled out around 2019–2020. The number of households also continues to increase and hence less income per household. These factors stabilize car use in 2010–2020. Second, an annual growth in car km of 2% is expected for 2020–2030. Third, the division of engine types stays the same. Fourth, cars with ICEs still dominate in 2030. This scenario was input to our simulation model (see Section 3), which has shown in Table 2. The lack of electric cars in this table seems strange given the values in Table 3. The explanation for this outcome can be found in Section 2.1.1.

Assumptions regarding urbanization will be added in Section 4.

Table 1: Estimated car use in The Netherlands in 2010 [13].

Ownership	Yearly car (driver) use in million km by fuel type				
	Petrol	Diesel	LPG	Electric	All
Private	55,143	18,404	3,251	–	76,798
Business	8,367	12,075	429	–	20,871
Total	63,510	30,479	3,680	–	97,669

Table 2: Car use in The Netherlands in 2030 (own estimations).

Ownership	Yearly car (driver) use in million km by fuel type				
	Petrol	Diesel	LPG	Electric	All
Private	67,219	22,434	3,963	–	93,616
Business	10,199	14,719	523	–	25,441
Total	77,418	37,153	4,486	–	119,057

2.1.1 Electric vehicle fleet by 2016

There were no electric vehicles (EVs) in The Netherlands in 2010. This changed after a new national tax regime and public and private initiatives to provide (a growing number of) charging facilities. By 2016, 86,200 EVs were in use. This small number can be explained by three factors: Price, low-density charging network and limited range.

The normal purchase price of an EV is way above the price of a similar non-electric (conventional) car. For private owners, this is too expensive, while the tax regime in The Netherlands favours business owners; they own 99% of all EVs. Business users tend to drive (much) more km than private users. The range of an average fully electric vehicle (FEV) (50–100 km per full charge) is very small compared to an average car with a conventional engine (700+ per full tank of fuel). This creates range anxiety: will the car battery last until the next charging point? Those who buy an EV favour a dual engine design (diesel–electric or petrol–electric). This is usually a plug-in hybrid electric vehicle (PHEV) (Table 3).

PHEV have lower CO₂- but higher NO_x- and PM₁₀-emissions than very fuel-efficient petrol cars [15]. The subsidy for PHEV could be regarded as ineffective.

2.2 Car use and emissions in The Netherlands

To estimate the corresponding tail pipe emissions, car km given in Table 1 were multiplied by the average fuel consumption and emission factors per fuel type. Table 4 provides the emissions on a tank-to-wheel (TTW) basis.

2.3 Technical progress compensated by more and older cars on the road

Policymakers like to have economic growth and lower emissions. Such a decoupling of economic growth and emissions has taken place as technical progress allowed a reduction in energy intensity of many products and increase of energy efficiency of (industrial) activities in advanced economies. The decoupling had a *relative impact* because the consumption of fossil fuels still grew, but at a lower pace than the economy. There is also a major caveat, as part of the lower growth in fuel consumption can be explained by outsourcing of production

Table 3: EV cars and ownership, NL 1 January 2016 [14].

Ownership	PHEV	FEV	Total
Business	75,270	9,347	84,617
Private	980	603	1,583
Total	76,250	9,950	86,200

Table 4: Car emissions in The Netherlands in 2010 and 2030 (own estimations).

Metric	Yearly emissions of all cars (in kiloton (kt))		
	CO ₂	NO _x	PM ₁₀
2010	12,257	20.2	9.2
2030	14,941	24.7	11.2

to low-wage countries, which are among the countries with the fastest growing economies and growing users of fossil fuels and emissions. A relative reduction still means an increase in greenhouse gases. For climate change, an *absolute* reduction is vital [16].

In the above estimations, we assumed no decoupling for car use; km and emissions grow with the same 21.9%. This seems conservative given that the latest model-based estimations indicate that CO₂-emissions of an average new car have been reduced from 181 to 106 g/km between 1998 and 2016 [17], while EU regulators aim to reduce these even further. Technical progress seems to work then or does it not? An important caveat is that fuel consumption and emission models cannot replace real measurements. What further complicates the situation is that there are many other interacting factors and developments:

- Higher safety standards lead to larger and heavier cars, which is not compensated by the use of lighter car parts [18];
- A demand for more luxury accessories leads to more on-board consumers of electricity, in particular air-conditioning, entertainment and navigation systems [18];
- Ageing of the car fleet extends replacement intervals: 80% of the cars sold yearly in The Netherlands are used [19];
- EU standards for fuel consumption and emissions and measurement procedures were developed in co-production with major car manufacturers. Tests could be manipulated. This explains a gap of 35% between test cycle data and data from real driving tests; hence, published fuel efficiency and emission data are too low [17].

The earlier estimates for 2030 can be explained by the growth of the car fleet plus these factors. The future is of course uncertain. As various examples have shown, technically fuel use and emissions of an average car can be much lower than the actual values, but will this also happen given these counteracting developments?

With this analysis, questions 1 and 2 have been addressed.

2.4 Policymaking

2.4.1 Urgency of the problem and policy targets

The urgency of CO₂-emission reduction becomes clear from the UN conference in Paris in 2016. A total of 195 countries signed the Paris Agreement. It sets targets for national CO₂-reduction policies in order to prevent the threat of a prolonged rise of the global average yearly temperature of 2% above pre-industrial levels, an out-of-control scenario. A reduction to 1.5% is advised to prevent islands from being taken by the oceans [20]. The world is now approaching the (short term) 1% average growth [21]. It may reach 2.7% in a business as usual scenario [22].

2.4.2 Multiple pollution sources

CO₂-emissions from transport are not the only source of climate change (Table 5). There are also methane emissions from agriculture and production and consumption of natural gas. The Netherlands is also a major trader in oil derivatives.

It becomes apparent that the growth of the population, the economy and international trade lead to higher CO₂-emissions of human activities until 2010. Around that year, the earlier mentioned decoupling of economic growth and emissions must have started.

Table 5: CO₂-emissions in The Netherlands in megaton CO₂-equivalents 1990–2016¹⁾ [23].

Activity/sector	Years			
	1990	2000	2010	2016
Industry and energy	94	98	101	101
Agriculture	8	7	10	7
Traffic and transport	32	37	39	35
Built environment	29	29	33	24
Total	163	172	183	167

Note: ¹⁾ Preliminary data for 2016.

2.4.3 Unfavourable policies

Since the 1980s of the past century, the political landscape has changed considerably in many countries in Europe, including The Netherlands. Before this period, the political majority and most people were in favour of a substantial role for government in Dutch society. Both the national and the provincial governments were involved with spatial planning and care for the environment. Then, a shift to the right took place, which led to a smaller role for government and a larger role for free market competition. This political wave has been labelled neoliberalism, to distinguish it from the classic liberalism movement, which happened more than a century ago in this and other European countries, when many monarchs lost their position and the national states were constituted in Europe [24]. This ‘business first’ policymaking has had profound implications for the environment. Major cuts were made in budgets for nature and environment, including research and protection [25]. Subsequent ministers of the Ministry of Transport (& Environment called officially) expanded the highway network and increased maximum speed from 100 to 120–130 km on many highways. This Ministry tried to remove environmental zones and 80-km speed limits on main roads crossing cities, arguing that these zones were limiting business and led to more congestion and air pollution. This argument was proven to be incorrect by research [26]. The local measures remained after it lost the legal battle with local governments and citizens living alongside these roads.

Air quality in The Netherlands has improved in the past decades due to de-industrialization and cleaner technology in many sectors. Yet, the country still scores average on air quality in Europe. The wind transports pollution from other countries, the North Sea and sea shipping. This background level cannot explain the rather poor air quality along many streets in major cities, however [27]. Cars and other motorized transport are its most likely source.

2.4.4 The Paris Agreement and The Netherlands

The Agreement [28] means that The Netherlands has to reduce its CO₂-emissions by 50% by the year 2030 and even 85–95% by 2050 in a 2% scenario. In a 1.5% scenario, even a 100% cut is needed; all values compared to the 1990 situation. CO₂-emission reduction targets influence all economic activities, but the implications per economic activity may vary, depending on the actual share in emissions, the way public and private decision-makers deem it necessary to set a lower or higher target for specific activities and the time frame in which such transformation should take place. Politics is a matter of balancing interests and taking responsibility. Who do politicians actually represent in what future analysts looking back probably would call ‘Climate Gate’?

The climate problem has a long history. Table 5 shows that it took many years to substantially reduce or stabilize CO₂-emissions by human activities.

The Paris Agreement asks for a (complete) decarbonization of the economy. This means heating and cooling without natural gas, differential pricing for energy and electric road transport [29]. Such a transition is very complex and expensive considering the short time span and until now very modest and fluctuating financial incentives by the national government, which creates uncertainty for long-term investors [30].

3 METHODOLOGY

3.1 Overview

The following research tools were used: desk research, a dedicated simulation model, scenarios (Section 4) and (quantitative) evaluation (Section 5). The scope of the article by Vleugel and Bal [10] was broadened to allow a more complex and larger scenario experiment. That experiment was the basis for the simulation model. These changes had profound implications. The research scope and questions were expanded. Some new input data were needed. The structure and functionality of the simulation model were adapted. Finally, the evaluation section and conclusions changed.

3.2 A simulation model

An MS® Excel® model was built to estimate the energy consumption and emissions of a fleet of passenger cars with different engine-fuel types. The model calculates total fuel consumption and emissions based on the estimated number of km driven per year, emission factors and average fuel consumption per km. It consists of the following items:

- A data entry and calibration module. This allows changes in user data (e.g., composition of car fleet, fuels used) and technical data (see Table 6 for a subset, vehicle brands and types);

Table 6: Input parameters (own estimations).

¹⁾	Fuel use (litre/100 km)	Electricity use (kWh/100 km)	Emission factors (CO ₂)
Petrol	5.6		2,269
Diesel	4.7		2,606
LPG	6.6		1,610
Hybrid ²⁾	4.45		2,269
PHEV ³⁾	1.8	11.6	2,269 + 464
FEV ⁴⁾	–	15.3	464
Hydrogen ⁵⁾	–	–	–

Notes: ¹⁾ All values are averages for a representative car fleet and based on the New European Driving Cycle (NEDC);

²⁾ Hybrid = two engines (diesel or petrol plus electric engine) in one car, which cannot be charged from a wall socket;

³⁾ PHEV = plug-in hybrid electric vehicle, a car which can be charged by the internal combustion engine or by a wall socket;

⁴⁾ FEV = fully electric vehicle, a car with an electric engine, which is charged externally;

⁵⁾ Hydrogen cars will not be considered because of the uncertainties regarding H₂ [31].

- In the solver module policy, scenarios are entered as constraints in a linear programming exercise;
- Matrices with data about fuel consumption, emission factors (EF) and TTW-wheel-to-wheel (WTW) conversion;
- A choice box to allow estimation of the impact of different degrees of urbanization on the number of car km driven;
- A choice box to estimate the impact of a different power mix to charge EV batteries;
- A choice box which adds dynamism in terms of growth of the car fleet and structural change in the power mix ('greener mix').

3.3 Data

Numerous academic and professional data sources were combined as in the earlier papers. This prevents reliance on biased data from car manufacturers or governments.

The averages given in Table 6 are key data to estimate the impact of scenarios on emissions (Section 4). For a complete picture, from here on, these emissions will be expressed on a WTW basis. TTW values were multiplied with a 'WTW-factor' [32]. No such multiplier was found for NO_x - and PM_{10} -emissions in the literature. CO_2 -multipliers were used to adapt all TTW values.

4 SCENARIOS AND APPLICATION

4.1 Introduction

The value of scenario experiments is that policy packages of different composition can be tested without the complexity and costs of in vivo experiments. Scenarios with substantially more FEV, urbanization and a greener power mix are fed into the model to estimate changes in car km, fuel consumption and emissions.

4.2 Fleet composition in 2030

Question 3 is about the impact of substantially more EV on CO_2 -emissions against the background of a -50% CO_2 target for 2030 (Section 2.4.4). To answer this question, scenarios with following assumptions were tested in the model:

- A uniform reduction % in CO_2 -emissions for all activities;
- A substantial share of FEV in 2030. They replace petrol, diesel and LPG in each scenario, but to a different extent. In all scenarios, FEV are powered by electricity from a mix of fossil and renewable sources (hence the term 'grey power mix');
- No PHEV because of their emission profile (see Section 2.1.1);
- (Partial) phasing out of ICE in 2030;
- Phasing out of fossil fuels in 2030;
- Continuation of growth in car km (21.9% between 2010 and 2030);
- No significant improvement of fuel efficiency at car fleet level between 2010 and 2030. Fleet replacement is a slow process, and it is unclear what the next technology cycle might bring, when it is road-worthy and what its impact will be by 2030.

4.2.1 Policy targets and emissions

Five scenarios were developed to allow an extensive sensitivity analysis (Tables 7 and 8): how does a change in fleet composition affect emissions of CO₂, NO_x and PM₁₀?

Partial replacement of ICE (Scenarios A and B)

In Scenario A, policymakers aim to replace 25% of all cars with ICE by FEV. If realized, then CO₂- and NO_x-emissions will rise. This contrary effect can largely be explained by the growth of the car fleet, the grey power mix and the assumption that cars will not become more fuel-efficient. If 87% of the petrol cars were used privately (Table 1), then the business-oriented subsidy for the purchase of an EV would hardly impact the petrol car market. It might affect the diesel car market because 39.6% of these are owned by a business. Hence, expanding the current tax regime to private car owners would make FEV much more affordable for the general public; hence, the changes in fleet composition would become more feasible, provided that the current limitations of using an FEV (see Section 2.1.1) are resolved. Scenario B contains a faster replacement of petrol ICE by FEV. Its main impact is a reduction in PM₁₀-emissions.

Double A (Scenario D)

Scenario D is more rigorous than Scenario A, but the reduction in CO₂-emissions is limited. It is more beneficial to focus on a vast and rapid reduction of petrol ICE in favour of FEV (Scenarios B and C). Table 8 presents the results.

Table 7: Policy targets and emissions in Scenarios A–C (source: the model).

	Scenario A	Scenario B	Scenario C
<i>Change in km by fuel type (compared to the 2010 values)</i>			
Petrol E95	–25%	–75%	–100%
Diesel	–25%	–25%	–25%
LPG	–25%	–25%	–25%
FEV # (grey mix) ¹⁾	Proportional	Proportional	Proportional
<i>Emissions in metric kiloton (kt)/year</i>			
CO ₂	13,261 (8%)	11,090 (–10%)	10,005 (–18%)
NO _x	20.8 (3%)	21 (4%)	21.1 (5%)
PM ₁₀	84 (–8%)	51.7 (–43%)	35.6 (–61%)

Note: ¹⁾ Electricity generation with fossil fuels only.

Table 8: Policy targets and emissions in kiloton in Scenarios D–E (source: the model).

	Scenario D	Scenario E
Petrol E95	–50%	–100%
Diesel	–50%	–100%
LPG	–50%	–100%
FEV # (grey mix)	Proportional	100%
CO ₂	11,658 (–5%)	8,452 (–36%)
NO _x	16.9 (–16%)	9 (–55%)
PM ₁₀	5.7 (–38%)	0.2 (–98%)

Full throttle (Scenario E)

Scenario E (Table 8) shows that it is possible to reduce CO₂-emissions by more than 35% when only FEVs are in use on Dutch roads. Local emissions are also substantially reduced.

4.2.2 About NO_x - and PM₁₀-emissions

The results reflect the earlier mentioned non-linear relation between CO₂- and NO_x- and PM₁₀-emissions (see Section 1.1). Especially, the NO_x values are hardly reduced when many ICEs remain on the road and FEVs remain powered by grey electricity. Scenario E scores best in regard to the target for 2030.

This discussion addressed question 3.

4.3 Scenario E + urbanization (Scenario F)

Use of transport modes is a function of spatial density. In The Netherlands, people living in urban areas own less cars and drive less km than people living in rural areas [33]. Distances between activities are smaller in cities than in rural areas. Public transport services, cycling and pedestrian routes are also more prolific, at least in a country like The Netherlands. In urban areas, use of public transport or active modes does not take as much additional time compared to cars, as it would do in rural areas. Car use is also restricted in urban areas by traffic measures, fees and limited space for parking.

Scenario F is used to address question 4. It contains the following assumptions:

- The same car fleet as in Scenario E (Table 8);
- Urbanization reduces the growth in (driver-only) car km. Hence, in scenario 2030 F1 and 2030 F2, car use will be lower than in scenario 2030E but still higher than in 2010..

Demographic studies mention a continuation of urbanization due to migration from rural areas and immigration. The urbanization rate (the % of people living cities) for 2010 is an estimate based on reference NKWK [34]. This leads to the values given in Table 9.

As expected, urbanization helps to reduce emissions even further. This impact could be enhanced if the number of cars is reduced by shared car ownership [35]. This answers question 4.

4.4 Scenario G (CO₂ only): Scenario F + power mix variants

The power mix (the actual mix of fuel sources [coal, gas, biofuel, wind and solar] used to produce electricity in power plants) is a complex topic. In the previous scenarios, a power mix corresponding to a CO₂ emission of 464 g/kWh was used as estimate, but this

Table 9: Scenario urbanization (source: the model).

	Situation 2010	Scenario 2030 E	Scenario 2030F1	Scenario 2030 F2
Urbanization rate	~50%	50%	55%	60%
Car (million km)	97.7	119	113	107.2
CO ₂ -emissions (in kiloton)	12,257	8,452	8,030	7,607
NO _x -emissions (in kiloton)	20.2	9.1	8.7	8.2
PM ₁₀ -emissions (in kiloton)	9.2	0.2	0.2	0.2

value may be too optimistic. The energy market is very dynamic, which leads to volatility in the power mix. Growing imports of cheap coal have replaced cleaner natural gas as fuel source in electric power plants. At the same time, there is more electricity from renewable sources, produced locally and imported. Renewable sources are not very well manageable due to the natural fluctuations in these resources. This explains why the power mix may change year by year. The following alternatives were explored (Table 10):

- Scenario G1: Scenario F1 (urbanization 55%) + 25% greener power mix;
- Scenario G2: Scenario F2 (urbanization 60%) + 25% greener power mix;
- Scenario G3: Scenario F1 (urbanization 55%) + 50% greener power mix;
- Scenario G4: Scenario F2 (urbanization 60%) + 50% greener power mix.

To reduce the earlier mentioned non-linear complexity, only the impact on CO₂-emissions was estimated. A greener power mix is already in the pipeline due to public and private investments in wind and solar power in The Netherlands and abroad. A key issue is the stability of the grid. Renewable energy sources, like sun, wind and water, have a fluctuating production. They also cannot be stored in large quantities, yet. Energy management becomes key to its success [36]. This issue is outside the scope of this paper. A dependency on fossil fuels remains. Nonetheless, a greener power mix helps to reduce emissions further along the line of the previous scenarios.

Taking all previous measures to the extreme leads to a major reduction in CO₂-emissions by passenger cars of –69% (2010 base) and 75% (2030 base) respectively. This answers question 5.

The ambitious CO₂ mitigation target requires a complete replacement of the Dutch car fleet by FEV.

By considering the WTW impact of cars, in essence, the entire chain must be addressed. This indicates that a much higher effort is needed to reduce the total level of car emissions.

Finally, it is important to realize that emissions of other road users such as vans, trucks, buses and coaches should also be included in the analysis to understand the full scale of the climate change mitigation challenge as far as road transport is concerned.

5 CONCLUSIONS AND OUTLOOK

A simulation model was used to quantify a rich set of scenarios. To achieve the –50% target for CO₂-emissions for passenger cars, all cars should become fully electric, urbanization should continue as expected and the power mix should become substantially greener. This would require mass production of electric cars instead of the current small series. Still, it may

Table 10: Scenarios power mix G (source: the model).

	2010 base	2030 base	2030 E	2030 G1	2030 G2	2030 G3	2030 G4
Urban.	50%	50%	50%	55%	60%	55%	60%
Mix (g/kWh)	464	464	464	348 (–25%)	348 (–25%)	232 (–50%)	232 (–50%)
Car km (billion)	97,669	119,057	119,057	113,105	107,152	113,105	107,152
CO ₂ -emissions (kiloton)	12,257	14,941	8,452	6,022	5,705	4,015	3,803

take about two decades with the current average car life cycle of 18 years before full electrification could be achieved. Another issue that has not been mentioned is the impact on the electricity grid and the need to develop a large-scale charging network. The scenarios regarding urbanization are in line with expectations. But, local policymakers have small budgets for alternatives like public transport. Bicycle use is growing so fast that cities start to experience congested cycling lanes and lack of bicycle parking facilities. Hence, it remains to be seen if car km can be reduced and in what manner in and around cities. The fast greying of the population (not considered) is also a factor that will have its impact on passenger car km. A greener power mix is likely with current investments. National transport policy should become more environment oriented. An extension of decades of 'neoliberal' transport policy would mean more roads and more car km, voluntary transition to EV and lower budgets for alternative modes of transport. The feasibility of the extreme scenario is, therefore, rather uncertain, but less extreme scenarios also lead to a significant reduction in CO₂-emissions.

REFERENCES

- [1] IPCC, *Understanding and attributing climate change*, www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter9.pdf, 2007.
- [2] IIASA, *Energy End-Use: Transport*, www.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/GEA_Chapter9.pdf.
- [3] Where the energy goes: Gasoline vehicles, www.fueleconomy.gov/feg/atv.shtml.
- [4] IPCC, *Climate change 2014, Mitigation of climate change, Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, USA, 2014.
- [5] Chu, J., Air pollution causes 200,000 early deaths each year in the U.S., MIT News Office. Rossman, R.E., 2009, The effect of vehicular emissions on human health, teachers.yale.edu/curriculum/viewer/initiative_08.07.09_u, 2013.
- [6] National Park Service, *Ecological Effects of Air Pollution*, www.nature.nps.gov/air/AQBasics/ecologic.cfm.
- [7] US EPA, *Air quality and climate change research*, www.epa.gov/air-research/air-quality-and-climate-change-research.
- [8] E.g., Dieselnets, EU: *Cars and light trucks*, www.dieselnets.com/standards/eu/ld.php.
- [9] Sims R., R. Schaeffer, F. Creutzig, X. Cruz-Núñez et al., Transport. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2014.
- [10] Vleugel, J., & Bal, F., The impact of a CO₂ reduction target on the private car fleet in The Netherlands, *WIT Transactions on Ecology and the Environment*, vol. 215, WIT Press: Southampton and Boston, pp. 109–120, 2018.
- [11] CLO, Bevolkingsdichtheid Nederland, www.clo.nl/indicatoren/nl210101-bevolkingsdichtheid-nederland, 11-08-2010., 11-08-2010.
- [12] CBS, www.statista.com/statistics/263749/total-population-of-the-netherlands/.opendata.cbs.nl/#/CBS/en/dataset/82044ENG/table?ts=1517220682507. Waard, J. van der, Jorritsma, P. & Immers, B., New drivers in mobility; What moves the Dutch in 2012 and beyond, discussion paper presented at *OECD International Transport Forum*, October 2012.
- [13] CBS, *StatLine: Verkeersprestaties motorvoertuigen; kilometers, voertuigsoort, grondgebied* Den Haag/Heerlen, 2016.

- [14] Ewalds, D. & Kampert, A., *Electrische personenauto's van particulieren*, CBS, The Hague/Heerlen, 23 Nov. 2017.
- [15] Vleugel, J.M. & Bal, F., Electric cars as buffers in an electricity network? *WIT Transactions on Ecology and the Environment*, vol. 203, WIT Press: Southampton and Boston, pp. 1–12, 2016.
- [16] Burton, M., *The decoupling debate: can economic growth really continue without emission increases?* www.degrowth.info/en/2015/10/the-decoupling-debate-can-economic-growth-really-continue-without-emission-increases/, 12-10-2015.
- [17] CBS, PBL, RIVM, WUR, *CO₂-emissie per voertuigkilometer van nieuwe personenauto's, 1998-2016* (indicator 0134, version 14, 28 April 2017), The Hague, Bilthoven, Wageningen, 2017.
- [18] Mol, J. de, Allaert, G. & Vlassenroot, S., *Autoconstructeurs moeten dringend op diet: Stijgend gewicht auto's nefast voor verbruik en emissies*, hdl.handle.net/1854/LU-333852, 2006.
- [19] NOS, Nederlands wagenpark wordt steeds bejaarder, nos.nl/artikel/2106283-nederlands-wagenpark-steeds-bejaarder.html?, 21 May 2016. CBS, Verkoop nieuwe personenauto's loopt terug, www.cbs.nl/nl-nl/nieuws/2016/41/verkoop-nieuwe-personenauto-s-loopt-terug, 2016.
- [20] United Nations, *The Paris Agreement*, unfccc.int/paris_agreement/items/9485.php.
- [21] Rice, D., Global temperatures could pass limit set by Paris Climate deal within 5 years, www.usatoday.com/story/weather/2018/02/01/global-temperatures-could-pass-limit-set-paris-climate-deal-within-5-years/1087326001, 1 Feb. 2018.
- [22] What you need to know about the Paris agreement, www.climaterealityproject.org/sites/clinaterealityproject.org/files/Paris_Agreement_Toolkit-Edit.pdf.
- [23] RIVM, Nationale broeikasgassen volgens IPCC, www.emissieregistratie.nl/erpubliek/erpub/international/broeikasgassen.aspx, Bilthoven, 2017.
- [24] Smith, N., Encyclopedia Britannica, Neoliberalism, www.britannica.com/topic/neoliberalism.
- [25] CBS Statline, *Kosten en financiering; natuur- en landschapsbeheer*, retrieved 31-01-2018. Between 2000 and 2015 gross costs (expenditures) fluctuated around 915 million Euros. This equals a nett reduction after inflation.
- [26] Wilmink, I., 80 kilometer zones and dynamic speed limits in the Netherlands, TNO, www.polisnetwork.eu/uploads/Modules/PublicDocuments/80_Km...
- [27] RIVM, *Luchtkwaliteit*, www.rivm.nl/Onderwerpen/F/Fijn_stof/Luchtkwaliteit, Bilthoven, 2013.
- [28] PBL, *Parijs-akkoord betekent halvering Nederlandse CO₂ uitstoot in 2030*, The Hague, 2016.
- [29] Duurzaamheidsoverleg Politieke Partijen (Dopp), Duurzaam is de toekomst, legacy.gscdn.nl/archives/images/Dopp-Def170425.pdf, 20 Apr. 2017.
- [30] Editorial Board, We hebben een Minister van Klimaat en Energie nodig, www.duurzaamnieuws.nl/we-hebben-een-minister-van-klimaat-en-energie-nodig/, 14 Mar. 2017.
- [31] Hench, S., Why are car manufacturers ignoring hydrogen engines? www.forbes.com/sites/quora/2017/06/27/why-are-car-manufacturers-ignoring-hydrogen-engines/#44bdb0d4027d: No fuel stations, no green sources, non-competitive price per unit.
- [32] Verbeek, R., Zyl, S. van, Grinsven, A. van, Essen, H. van, Brandstoffen voor het wegverkeer: kenmerken en perspectief v.2, TNO & CE Delft, Delft, June 2014.

- [33] Litman, T., Land use impacts on transport, how land use factors affect travel behavior, Victoria Transport Policy Institute, Canada, April 2007.
- [34] NKWK, Klimaatbestendige stad, waterenklimaat.nl/onderzoekslijnen/klimaatbestendige-stad/, 21-09-2018.
- [35] Vleugel, J.M. and Bal, F. 2017, More space and improved living conditions in cities with autonomous vehicles, *Int. J. of Design & Nature and Ecodynamics*, **12**(4), pp. 505–515, 2017.
- [36] Sandia National Laboratories, Renewable energy and distributed systems integration, addressing the challenges, energy.sandia.gov/energy/ssrei/gridmod/renewable-energy-integration/, 21-09-2018.