Fuel and drivetrain options for road transport

Impact on air pollution and external costs

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Content

List of abbreviations

AQGs	World Health Organization’s Global Air Quality Guidelines
BEV	Battery-Electric Vehicle
CNG	Compressed Natural Gas
E85	Ethanol with 85 vol% bioethanol and 15 vol% fossil petrol
Euro 6	European emission standard for light-duty vehicles (cars and vans)
Euro VI	European emission standard for heavy-duty vehicles
FAME	Fatty Acid Methyl Ester
FCEV	Fuel Cell Electric Vehicle
GTL	Gas to Liquid
HDV	Heavy-Duty Vehicle (includes lorries and trucks but also buses)
HGV	Heavy Goods Vehicle
HVO	Hydrotreated Vegetable Oil, a diesel substitute
ICEV	Internal Combustion Engine Vehicle, conventional vehicle
LNG	Liquid Natural Gas
LPG	Liquid Petroleum Gas
LCV	Light Commercial Vehicle (van)
PM	Particulate Matter
TTW	Tank-to-wheel
WTT	Well-to-tank
WTW	Well-to-wheel

Summary

Background

Air pollution is a major environmental contributor to public health problems worldwide. The World Health Organization (WHO) estimates that every year, exposure to air pollution causes seven million premature deaths and results in the loss of millions more healthy years of life. Road transport is one of the major sources contributing to air pollution.

In a previous study for the EPHA, CE Delft calculated the total costs of road traffic-related air pollution in the EU28. In this study, we continue the search for health and social benefits by examining additional options to reduce diesel-related emissions from road transport.

Goal of this study

This study is an extension of a previous study and focuses on two main elements:

1. **Fuel and/or drivetrain scenarios**: We analyse what the impact on emission levels would be if fuels/energy carriers such as electricity, CNG (compressed natural gas), LPG (liquefied petroleum gas), biofuels and drivetrains such as plug-in hybrids and flex-fuel vehicles (which can run on high blends of fossil fuel substitutes) would replace diesel vehicles or diesel use.

2. **Broadened range of external costs**: In addition to external costs from NO_x and PM we also assess other external costs such as from CO_2 emissions, noise, road safety, and congestion.

There are many different fuel and drivetrain combinations which potentially could replace diesel vehicles. We are particularly interested in examining the impacts of substitutes for diesel which may be promoted from the viewpoint of minimising air pollution and climate change. The scenarios aim to look at the impacts on air pollution and in particular on health when replacing diesel with alternatives.

It is important to realise the scenarios are hypothetical and constructed to reveal the maximum potential of diesel substitution: they do not reflect realistic fleet developments. Numbers in the tables may not add up due to rounding.

Impacts on air pollution emissions

The scenarios reveal the following impacts on NO_x and PM emissions:

- Replacing diesel vehicles with zero-emission (full-electric) vehicles is by far the most effective scenario to reduce NO_x and PM emissions (both tank-to-wheel and well-to-wheel).
- To a lesser extent, tank-to-wheel NO_x emissions can be reduced by replacing diesel vehicles with plug-in hybrid vehicles or vehicles running on natural gas (either CNG or LNG). Tank-to-wheel PM emissions on the other hand are reduced far less with CNG and LNG. Apart from the most effective option, which is replacing them with zero-emission vehicles, PM emissions would also be reduced by replacing older diesel vehicles with the newest Euro 6 and Euro VI standard vehicles or plug-in hybrid vehicles.
- The potential of liquid petroleum gas (LPG), ethanol (E85) and hydrotreated vegetable oil (HVO) to reduce well-to-tank NO_x and PM emissions is limited and even leads to increased well-to-wheel emissions for the latter two.

Impacts on external costs

We estimate that in 2030 for EU27 countries the costs that result from these emissions will amount to 14 billion euros, compared to 63.8 billion euros in 2016. This means that existing policies to reduce or modify diesel use will reduce the financial impact of diesel emissions but will not eliminate them (see Table 1). Over 90% of these costs are health costs.

External cost reductions are possible by replacing diesel use with alternative fuels and drivetrains. Replacing diesel vehicles with zero-emission (full-electric) vehicles would result in costs from air pollution of 10.1 billion euros in 2030, which is a reduction of more than 70% compared to the baseline.

Replacing diesel use with compressed or liquid natural gas (CNG or LNG), plug-in hybrid vehicles or new diesel vehicles (Euro 6 and Euro VI) reduces external costs from air pollution by roughly 30 to 45% compared to the baseline. Diesel and petrol substitutes (hydrotreated vegetable oil and ethanol) do not result in a decrease in external costs.

Table 1 - Main results: costs for direct air pollution (TTW) from road transport in EU27 in 2016 and 2030 for various scenarios (costs in billion euros)

	Total costs	Reduction compared to 2030 baseline	Health costs	Health costs (% of total)
2016				
	63.8		58.5	91,7%
2030				
Baseline	14.0		12.8	91.4%
1. CNG/LNG	9.1	-35%	8.5	93.5%
2. LPG	12.2	-13%	11.3	92.2%
3. HVO	14.0	0%	12.8	91.4%
4. Plug-in hybrid	8.0	-43%	7.4	92.7%
5. E85 (bioethanol)	10.7	-23%	9.9	92.1%
6. Euro6/VI diesel	9.5	-32%	8.7	91.8%
7. Electricity	3.9	-72%	3.7	94.4%

The total level of external costs in 2016 increases from 64 billion to 721 billion euros when additional external impacts such as well-to-tank emissions, CO_2 emissions, congestion, noise, and traffic safety are also taken into account (see Table 2). Consequently, the fuel and drivetrain scenarios reveal larger external cost reductions ranging from 5 billion to 45 billion euro, whereas external costs from solely air pollution can be reduced by 0 to 10 billion euro.

Table 2 - External costs of petrol and diesel transport in 2016 and 2030 for different scenarios (costs in billion euros)

	Tank-to-wheel air pollution	Well-to-tank air pollution	Well-to-tank CO_2	Tank-to-wheel CO_2	Accidents	Noise	Congestion 2016*	Total external costs	Reduction compared to 2030
2016									
	64	6	22	72	261	56	241	721	
2030									
Baseline	14	4	17	54	236	54	221	600	
1. CNG/LNG	9	2	10	46		54		578	3.6%
2. LPG	12	4	13	51		54		592	1.3%
3. HVO	14	6	10	18		54		559	6.8%
4. Plug-in hybrid	8	4	19	45		54		588	2.0%
5. E85 (bioethanol)	11	8	18	41		54		589	1.8%
6. Euro 6/VI diesel	9	4	17	53		54		595	0.9%
7. ZE vehicles	4	3	27	17		46		555	7.4%

Main conclusions

Substituting diesel road vehicles with full-electric vehicles is by far the most effective way to reduce tank-to-wheel emissions and associated external costs. It is roughly twice as effective as replacing diesel vehicles with plug-in hybrid vehicles, new (Euro 6/VI) diesel vehicles and CNG/LNG. This conclusion is still valid when we include well-to-tank emissions, i.e. the air pollution associated with the production of fuels/energy carriers.

Both hydrotreated vegetable oil (HVO) and ethanol (E85) have limited benefits in terms of replacing diesel use from a health perspective. For HVO this is because it can be used in the current vehicle fleet and the exhaust emissions remain practically the same whether regular diesel or HVO is used. Provided HVO is produced from truly renewable sources, it has substantial benefits in terms of reducing well-to-wheel emissions. We should note that in the more distant future when electricity production is expected to shift to higher shares of renewable production, the relative advantage of HVO will decrease.

Including additional external impacts in the external cost calculations such as noise pollution, congestion, and traffic safety, reveals a larger potential to reduce these costs when replacing diesel with alternative fuels and drivetrains. Broadening the scope of external costs can therefore provide an argument and justification to the public for policymakers to introduce additional measures to curb road transport emissions and allocate a greater budget for these measures.

1 Introduction

Air pollution and air quality guidelines

Air pollution is a major environmental contributor to public health problems worldwide. The World Health Organization (WHO) estimates that every year, exposure to air pollution causes seven million premature deaths and results in the loss of millions more healthy years of life (WHO, 2021). In September 2021 the WHO published its new Global Air Quality Guidelines (AQGs) in which stricter recommendations are set for a number of air pollutants.

While not legally binding, AQGs are an evidence-informed tool for policymakers to guide legislation and policies, in order to reduce levels of air pollutants and decrease the burden of disease that results from exposure to air pollution worldwide (WHO, 2021). It is expected that the upcoming revision of the Ambient Air Quality Directives will be adopted by the European Union, with a more closely alignment of the EU's air quality standards with the 2021 WHO Global Air Quality Guidelines.

In Europe, air pollution is still a major cause of premature death and disease. According to the European Environment Agency (EEA), in 2019, around 307,000 premature deaths were attributable to $PM_{2.5}$ in the 27 EU Member States. Nitrogen dioxide (NO_2) was linked to 40,400 premature deaths, and ground-level ozone (O_3) was linked to 16,800 premature deaths (EEA, 2021).

Road transport is one of the major sources contributing to air pollution

In a previous study for the EPHA, CE Delft found that the total costs of road traffic-related air pollution in the EU28 in 2016 were between 67 and 80 billion euros (CE Delft, 2018). The share of diesel vehicles in these costs amounts to more than 80%. NO_x emissions have the largest share in the total costs (both health and non-health related) of air pollutants (65%), followed by $PM_{2.5}$ (32%). Although these costs are expected to drop, due to the future emission standard called Euro 7 and VII[1], currently under development and expected to be implemented from 2025, the projected external costs in 2030 still amount to 20 to 26 billion euros.

Different fuel and vehicle technologies available to curb emissions

The EU proposes a ban on the sale of new petrol and diesel cars from 2035, aiming to speed up the switch to zero-emission vehicles. In the 2018 study, a full phasing out of diesel road vehicles was assumed to assess the overall impact of diesel emissions on external (health) costs. Road vehicles can however have a number of different drivetrains and fuel types, which all differ in their environmental 'performance'. Also, transport causes external costs which are not related to air pollution but stem from traffic safety, noise pollution and congestion.

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[1] Euro 7 (Arabic numeral) is the seventh European vehicle emission standards for exhaust emissions of new passenger cars and light commercial vehicles. Euro VII (Roman numeral) is the seventh emission standards for trucks and buses.

In this study, we aim to extend the 2018 study by looking at these two elements.
To elaborate:

1. We analyse what the impact on emission levels would be if fuels such as CNG, LPG, biofuels, and drivetrains such as plug-in hybrids and flex-fuel vehicles would replace diesel vehicles or diesel use.

2. The second addition to the 2018 study is broadening the range of external effects. The 2018 study was limited to the external costs from NO_x and PM emissions. In this addition, we also assess other external costs such as from CO_2 emissions, noise, road safety, and congestion.

Scope of the study

This study is in part an update of the 2018 study, *Health impacts and costs of diesel emissions in the EU* (CE Delft, 2018). There are a number of differences and extensions as well. Table 3 summarises some of the main differences between this study and the previous one.

Table 3 - Differences in scope between this study and the 2018 study

Topic	This study	2018 study
Geographical scope	EU27	EU28
Included Member States	Bulgaria, Estonia, **France**, Germany, Hungary, Poland, Romania, Slovenia, Spain	**Austria**, Bulgaria, Estonia, Germany, Hungary, Poland, Romania, Slovenia, Spain
Tank-to-wheel emissions	Included	Included
Well-to-tank emissions	Included	Not included
Health costs	Included	Included
Other external costs (congestion, noise, safety, CO_2)	Included	Not included
Second baseline scenario (TRUE)	Not included	Included

France was added and Austria is no longer one of the Member States examined.

Overview of the study

In Chapter 2, we describe the methodology used for this study. In Chapter 3, we describe the technology scenarios and the characteristics of the different fuel types and vehicle technologies we focus on. In Chapter 4, we focus on the impact of emissions (NO_x and PM) in 2030 of the scenarios. In Chapter 5, information on the external costs in the baseline and the scenarios is given. In Chapter 6, we conclude with the main findings.

2 Methodology

In this chapter, we highlight the methodological steps taken to arrive at the external costs. We distinguish five steps that we will describe further in the following sections:
- Step 1: Construct baseline scenario.
- Step 2: Draw up the technology scenarios.
- Step 3: Define approach for valuating emissions.
- Step 4: Determine external cost factors per type of air pollutant.
- Step 5: Determine other external cost factors.

All external costs are calculated for the baseline scenario as well as for seven distinct scenarios in which the current diesel transport is replaced by other technologies in 2030.

2.1 Step 1: Baseline scenario

The first step in the analysis was to construct the baseline scenario. This consists of the emissions in the base year, which is 2016, and the emissions in the year 2030. For the most part, the emissions for the year 2016 are in line with the 'COPERT' baseline scenario of the previous study. This is one of the two baseline scenarios that was constructed. In the following text box, we provide some more information about the two baseline scenarios from the previous study and why the COPERT baseline was chosen now. A more detailed methodological description of the baseline scenario is included in Section 2.1.1.

The emissions and activity data for the year 2030 were calculated with the use of yearly growth rates based on the 'NAPCP' scenario[2] of the GAINS database (IIASA, ongoing). Some more information on the GAINS model and baseline used can be found in Section 2.1.2.

COPERT baseline versus TRUE baseline

In the 2018 study two baseline scenarios were used, one based on COPERT and the other based on TRUE.
In this update of the 2018 study, we use only one baseline, which is an updated version of the COPERT baseline. Adding the TRUE baseline would not add any additional information since the relative difference between TRUE and COPERT remains the same. Another reason not to use the TRUE baseline is that it would double the number of outcomes and since the information density with the additions made in this study is already quite high, the readability of the report would be harmed.

The downside of not using TRUE is that we do not present a bandwidth in outcomes. We can add however that the bandwidth between the TRUE and COPERT outcomes from the 2018 study also applies to the outcomes in this study. Roughly/on average the TRUE outcomes were 20% higher, which would mean that the outcomes of this study would also become 20% higher if the TRUE baseline would have been used.

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[2] NAPCP is the acronym for National Air Pollution Control Programme. EU Member States are required to prepare and report their NAPCP according to the minimum content and common format (Commission Implementing Decision (EU) 2018/1522)2 stipulated by Article 6 of the Directive (EU) 2016/2284 on the reduction of national emissions of certain atmospheric pollutants, hereafter referred to as the Directive or the NECD4. The NAPCP should demonstrate compliance with the Member States' respective emission reduction commitments and set out how compliance will be achieved.

2.1.1 Base year emissions and activity data

The 2016 base year emissions of NO_x, PM_{10} (abrasion), $PM_{2.5}$ (combustion), SO_2 and NMVOC are based on COPERT 5. The emissions are available for motorways, urban roads, and other roads. These are the same values as in the previous study, with the exception that the list of countries is now slightly altered.[3] The energy use per vehicle category, which was not reported explicitly in the previous study, is based on the CO_2 emissions from COPERT 5 as well as STREAM (CE Delft, 2021)[4]. The CO_2 emissions are calculated from the energy use with the emission factors as presented in Annex A.
The vehicle kilometres are based on the *Handbook on the external costs of transport* (CE Delft et al., 2019a). The vehicle kilometres in (CE Delft et al., 2019a) study are based on COPERT 5 and Eurostat. The vehicle kilometres are available for motorways, urban roads, and other roads.

2.1.2 Emission reductions in 2020 and 2030

The emission reductions in 2020 and 2030, as well as the trend in vehicle kilometres and energy use, in the baseline scenario, are based on the National Air Pollution Control Program (NAPCP) scenario of the GAINS database (IIASA, ongoing).

GAINS was launched in 2006 as an extension to the RAINS model, which is used to assess cost-effective response strategies for combating air pollution, such as fine particles and ground-level ozone. GAINS is used as part of the standard modelling framework for negotiations under the Convention on Long-range Transboundary Air Pollution and the European Union (IIASA, 2021). GAINS estimates historic emissions of ten air pollutants and six GHGs for each country, based on data from international energy and industrial statistics, emission inventories and data supplied by countries themselves.

The allocation to different road types for 2030 was assumed to be the same as in the base year.

2.2 Step 2: Technology scenarios

The next step in the analysis was to define seven technology scenarios in which diesel vehicles are replaced by alternatives. These scenarios reflect the range of different technologies that can in theory replace diesel vehicles. However, it must be noted that the scenarios are hypothetical and constructed to reveal the maximum potential of diesel substitution: they do not reflect realistic fleet developments. In general, it is very unlikely that any technology will replace all diesel vehicles on the road by 2030. These scenarios should therefore be interpreted as an indication of the positive (or negative) effects that different alternatives for the current diesel fleet could have.

The technologies considered are zero-emission (full electric), plug-in hybrid, CNG, LNG, LPG, biodiesel (HVO), ethanol (E85) and new Euro 6/VI diesel vehicles (see also Chapter 3). For each scenario, only the vehicle categories for which models with the specific fuel type are on the market are included.

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[3] France was added and Austria is no longer one of the Member States examined.

[4] STREAM is a periodically updated study with key emission figures for different modes of transport.
A wide range of international literature on real-world emission data is consulted for STREAM, making it a state-of-the art document on tank-to-wheel and well-to-wheel emission factors for the transport sector.

Also, whenever a change of vehicles is required, it was assumed that these vehicles are new[5]. This last assumption was included to show that the scenarios have two effects:

1. The impact of an alternative fuel.
2. The effect of a new vehicle versus an old vehicle.

A more elaborate description of the technology scenarios is included in Chapter 1.

2.3 Step 3: Approach for valuating air pollutant emissions

The approach for valuating emissions of air pollution has been discussed in detail in the previous study (CE Delft, 2018). This section provides a short recap of the approach, which follows the approach of the previous study.

The damage costs have been estimated following the Impact Pathway Approach. The Impact Pathway starts by focusing on the moment pollutants are released. These pollutants are subsequently transported through the atmosphere to other regions where they are added to existing emission concentrations. This concentration then leads to changes in 'endpoints' relevant to human welfare. An example of such an endpoint — and the most important endpoint in this study — is human health. The changes can be monetarily valued by quantifying the amount of damage caused at the endpoints.

The damage costs used in this study consider three main endpoints of air pollution:

1. Human health (morbidity, i.e. sickness and disease, and premature mortality modelled as a reduction in life expectancy).
2. Ecosystem services (biodiversity and crops).
3. Buildings and materials (man-made capital).

The damage costs are differentiated towards countries, based on differences in population density, income levels, and valuation of human health (VOLY). This ensures that specific values are constructed for road transport and electricity production. In Annex A the country-specific emission factors for electricity production used are given. Differences stem from the differences in energy mixes for electricity production.

For each of the following components external costs are quantified in this study:

- NO_x emissions (tank-to-wheel and well-to-tank);
- PM_{10} emissions of abrasion (tank-to-wheel and well-to-tank);
- $PM_{2.5}$ emissions of combustion (tank-to-wheel and well-to-tank)[6];
- SO_2 emissions (tank-to-wheel);
- NMVOC (tank-to-wheel).

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[5] For the scenario with use of biodiesel, no change of vehicle is required. The assumption that these are new vehicles was made to ensure comparability between the scenarios.

[6] Implicitly, the health costs of ultrafine particulates are part of the external costs of $PM_{2.5}$. This entails that a general health cost valuation for each vehicle type for ultrafine particles is assumed. This means that if certain vehicle/fuel types have a relatively higher share of ultrafine particles within $PM_{2.5}$, this is not taken into account.

2.4 Step 4: Determine external cost factors per type of air pollutant

The Handbook on external costs (CE Delft et al., 2019a) provides official damage costs for all European countries constructed following the route as explained in Section 2.3.
We have taken the damage costs of different air pollutants for the EU27 on average and for the countries that are under investigation in this study. Table 4 gives the specific values for $PM_{2.5}$ and NO_x that are recommended for use in transport, as well as the overall damage costs for PM_{10}. The damage costs of PM_{10} are related to emissions caused by the wear and tear of tires and breaks.

Table 4 - Total costs damage factors in 2020 (€ per kg)

	$PM_{2.5}$ transport metropole*	$PM_{2.5}$ transport city	$PM_{2.5}$ transport rural	NO_x cities	NO_x rural	$PM_{2.5}$ electricity generation	NO_x electricity generation	PM_{10} wear & tear	SO_2	NMVOC
EU27	€ 402	€ 130	€ 74	€ 22	€ 13	€ 20	€ 12	€ 24	€ 12	€ 1
AT	€ 496	€ 161	€ 93	€ 44	€ 26	€ 29	€ 23	€ 33	€ 17	€ 2
BG	€ 211	€ 67	€ 33	€ 11	€ 7	€ 8	€ 6	€ 6	€ 5	€ 0
EE	n/a*	€ 103	€ 35	€ 5	€ 3	€ 6	€ 3	€ 5	€ 5	€ 0
FR	€ 428	€ 138	€ 92	€ 29	€ 17	€ 26	€ 18	€ 26	€ 15	€ 2
DE	€ 465	€ 149	€ 96	€ 38	€ 22	€ 39	€ 21	€ 41	€ 17	€ 2
HU	€ 320	€ 103	€ 60	€ 27	€ 16	€ 21	€ 15	€ 19	€ 10	€ 1
PL	€ 307	€ 99	€ 57	€ 16	€ 10	€ 18	€ 9	€ 18	€ 9	€ 1
RO	€ 304	€ 98	€ 47	€ 22	€ 13	€ 14	€ 10	€ 13	€ 8	€ 1
SI	n/a*	€ 101	€ 57	€ 24	€ 15	€ 18	€ 14	€ 17	€ 10	€ 1
ES	€ 360	€ 116	€ 48	€ 9	€ 5	€ 10	€ 5	€ 12	€ 7	€ 1

* Metropole only applies to cities larger than 0.5 million inhabitants. Some countries do not have such cities hence these damage values are not being reported. This is the case for Slovenia and Estonia.

Most of the damage costs for traffic air pollution are related to health costs (90-100%). Table 5 gives the specific values for health-related costs in these national totals.
For transport, health damage costs account for almost the entire costs of air pollution.

Table 5 - Health costs damage factors (€ per kg)

	$PM_{2.5}$ transport metropole*	$PM_{2.5}$ transport city	$PM_{2.5}$ transport rural	NO_x cities	NO_x rural	$PM_{2.5}$ electricity generation	NO_x electricity generation	PM_{10} wear & tear	SO_2	NMVOC
EU27	€ 402	€ 130	€ 74	€ 20	€ 11	€ 20	€ 10	€ 24	€ 11	€ 1
AT	€ 495	€ 161	€ 93	€ 41	€ 23	€ 29	€ 20	€ 32	€ 17	€ 2
BG	€ 211	€ 67	€ 33	€ 10	€ 6	€ 8	€ 6	€ 6	€ 5	€ 0
EE	n/a*	€ 103	€ 35	€ 4	€ 3	€ 6	€ 2	€ 5	€ 5	€ 0
FR	€ 427	€ 138	€ 92	€ 26	€ 15	€ 26	€ 16	€ 26	€ 14	€ 1
DE	€ 464	€ 149	€ 96	€ 36	€ 20	€ 39	€ 18	€ 41	€ 17	€ 2
HU	€ 320	€ 103	€ 60	€ 25	€ 14	€ 20	€ 13	€ 19	€ 10	€ 1
PL	€ 307	€ 98	€ 57	€ 14	€ 8	€ 18	€ 7	€ 17	€ 9	€ 1
RO	€ 304	€ 98	€ 47	€ 21	€ 12	€ 14	€ 9	€ 13	€ 8	€ 0
SI	n/a*	€ 101	€ 57	€ 21	€ 12	€ 17	€ 11	€ 16	€ 9	€ 1
ES	€ 360	€ 116	€ 48	€ 8	€ 4	€ 10	€ 4	€ 12	€ 7	€ 1

* Metropole only applies to cities larger than 0.5 million inhabitants. Some countries do not have such cities hence these damage values are not being reported. This is the case for Slovenia and Estonia.

2.5 Step 5: Determine other external effects

In this study, external effects besides air pollution are also valuated in order to relate the damage of air pollution to damage from other external effects. The effects are valuated according to *European Handbook for external costs of transport* (CE Delft et al., 2019b). The other external effects included in this study are climate change, noise pollution, congestion, and accidents. The damage costs presented below are updated to the price levels for 2020.

Table 6 shows the damage costs of climate change. The carbon price is not differentiated towards countries as climate change is a global phenomenon and therefore emissions are valued equally regardless of location.
Unlike air pollution, the damage costs for climate change or not based on actual damage. Due to the uncertainty in the future effects of climate change, it is not possible to estimate the damage of climate emissions through this method. Emissions of climate change are estimated using the avoidance costs approach which bases the damage costs on the average costs of policy measures required to mitigate climate emissions. A more detailed discussion about the valuation of climate emissions can be found in CE Delft et al., (2019b).

Table 6 - Damage costs for climate change (€/ton CO_2-eq.)

CO_2 price 2030
€ 100

Source: CE Delft et al., (2019b).

Table 7 and Table 8 show the external costs of noise and accidents per vehicle kilometre. These costs are based on noise pollution and accidents levels in 2016 from CE Delft et al., (2019b). For the current study, the costs are updated to the price levels of 2020.

Table 7 - Noise costs (€ per vehicle km)

Noise	Passenger car - petrol	Passenger car - diesel	Bus/coach	MC	LCV	HGV
EU Aggregate	0.009	0.010	0.062	0.102	0.013	0.067
Austria	0.009	0.010	0.049	0.052	0.012	0.085
Bulgaria	0.011	0.012	0.072	0.109	0.014	0.012
Estonia	0.009	0.010	0.050	0.076	0.012	0.013
France	0.006	0.007	0.037	0.044	0.008	0.083
Germany	0.005	0.006	0.028	0.037	0.007	0.009
Hungary	0.009	0.010	0.050	0.062	0.012	0.024
Poland	0.011	0.011	0.069	0.075	0.014	0.011
Romania	0.025	0.027	0.169	0.248	0.032	0.064
Slovenia	0.005	0.005	0.024	0.025	0.006	0.012
Spain	0.016	0.017	0.081	0.121	0.022	0.028

Source: CE Delft et al., (2019b).

Table 8 - Accidents costs (€ per vehicle km)

Accidents	Passenger car	Bus/coach	MC	LCV	HGV
EU Aggregate	0.077	0.178	0.135	0.045	0.167
Austria	0.147	0.305	0.675	0.048	0.356
Bulgaria	0.046	0.103	0.372	0.000	0.134
Estonia	0.037	0.341	0.054	0.001	0.037
France	0.051	0.125	0.153	0.024	0.240
Germany	0.106	0.315	0.362	0.091	0.228
Hungary	0.131	0.125	0.133	0.083	0.133
Poland	0.094	0.189	0.165	0.001	0.141
Romania	0.197	0.300	0.632	0.279	0.119
Slovenia	0.044	0.082	0.268	0.001	0.112
Spain	0.070	0.169	0.100	0.100	0.095

Source: CE Delft et al., (2019b).

Table 9 shows the results for congestion. The values are taken from the *European Handbook of external costs* CE Delft et al., (2019b). Congestion levels do not scale linearly with the amount of traffic. At the same time, the valuation of congestion also differs significantly depending on the economic conjuncture. In a booming economy, congestion levels are higher, and the valuation of travel time is also higher. As a result, there is large uncertainty in the development of congestion costs for 2030. Therefore, no congestion costs are estimated for 2030 specifically. Rather, we have included the 2016 congestion level and valuation as a proxy for congestion costs in 2030.

Table 9 - Total congestion costs[7] for 2016 level (euro per vehicle km)**

Delay cost	Passenger car	Bus/coach	MC	LCV	HGV
EU Aggregate	0.068	0.161	n/a*	0.123	0.103
Bulgaria	0.042	0.095	n/a*	0.051	0.061
Estonia	0.033	0.065	n/a*	0.048	0.048
France	0.063	0.145	n/a*	0.090	0.100
Germany	0.064	0.147	n/a*	0.139	0.115
Hungary	0.060	0.113	n/a*	0.098	0.089
Poland	0.086	0.203	n/a*	0.133	0.150
Romania	0.142	0.331	n/a*	0.171	0.234
Slovenia	0.023	0.044	n/a*	0.036	0.038
Spain	0.085	0.128	n/a*	0.203	0.066

Source: CE Delft et al., (2019b).

* No congestion costs for motorcycles are calculated as they are often able to filter through traffic jams.

** Due to the nature of congestion costs, it is not possible to estimate 2030 cost levels without detailed research. The 2016 level is included as a proxy.

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[7] Congestion costs in the *Handbook on external costs* are presented as total delay costs and as deadweight loss costs. Total delay costs exist out of internal and external costs of congestion, whereas the deadweight loss approach shows the social optimal level of congestion. Due to technical difficulties, it is not possible to provide just the part of congestion costs that are external. For this study we have opted for total delay costs as this is based on actual congestion levels.

3 Fuel technology scenarios

In this chapter, we describe the fuel technology scenarios that form the core of our analysis. We explain the differences between the different fuel types and drivetrains which we distinguish. We also map the difference in ‘environmental performance’ between the fuel types and drivetrains per vehicle type, looking at both the well-to-tank (WTT) and tank-to-wheel (TTW) emissions.

3.1 Aim of the scenarios

There are many different fuel and drivetrain combinations which potentially could replace diesel vehicles. We are particularly interested in examining the impacts of substitutes for diesel which may be promoted from the viewpoint of minimising air pollution and climate change. The scenarios aim to look at the impacts on air pollution, and in particular on health when replacing diesel with alternatives. In each scenario, *only* diesel use is replaced with an alternative, and petrol use is assumed equal to baseline levels.

It is important to realise the scenarios are hypothetical and constructed to reveal the maximum potential of diesel substitution: they do not reflect realistic fleet developments.

3.2 Description of fuel types and drivetrains

The six different fuel types (or energy carriers) which we examine in this study will be described shortly in this section. A general remark before we go into detail is that most alternative fuels which can be used in internal combustion engines can be either fossil-based or in the form of bio or synthetic (e-) fuels[8]. In terms of air pollution, biofuels and e-fuels differ very little from their fossil counterpart since the level of NO_x and PM emissions are determined largely by end-of-pipe control measures.

A second general remark should be made on biofuels. Sustainable production of biofuels can be challenging from the perspective of available feedstocks and biodiversity. Biofuel production should ideally not compete with food production and minimise the impact on ecology and biodiversity. These potential adverse effects of biofuel production are beyond the scope of this study and external impacts from biodiversity losses and food competition have not been quantified.

3.2.1 Compressed natural gas (CNG) and liquid natural gas (LNG)

Both CNG and LNG are forms of natural gas (methane). The difference is the way they are transported in the vehicle, either in a compressed gas form (CNG) or as a liquid (LNG). LNG is not used in passenger cars and LCV’s, but mostly in HGV’s and long-distance buses. CNG on the other hand is mostly used in cars and LCV’s as well as in city buses.

Both CNG and LNG also come in the form of a biobased fuel, bio-CNG and bio-LNG. The chemical make-up of these fuels is identical to the fossil variant and does not impact

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[8] Synthetic or e-fuels are liquid or sometimes gaseous fuels derived from gasification of solid feedstocks such as coal or biomass or by reforming of natural gas.

the emissions of NO_x and PM. They do however have the potential to reduce CO_2 emissions. In this study, we limit the scope to fossil-based CNG and LNG.

Although in terms of mass, CNG and LNG vehicles produce limited amounts of PM emissions, there are concerns about ultrafine particle emissions. CNG cars and vans, unlike their diesel and petrol counterparts, are not subject to a particle number emission limit (and are not fitted with particle filters).
CNG and LNG vehicles emit especially large numbers of ultrafine particles as small as 2.5 nm. These ultrafine particles could potentially be the most harmful to human health, as they have been shown to penetrate deep into the body (T&E, 2020).

3.2.2 Liquid Petroleum Gas

In the EU, LPG is a regulated fuel composed of a mixture of propane (C3H8) and butane (C4H10). It is also referred to as 'autogas' when applied in motor vehicles. LPG is prepared by refining petroleum or 'wet' natural gas and is derived from fossil fuel sources, being manufactured during the refining of petroleum (crude oil) or extracted from petroleum or natural gas streams as they emerge from the ground.

LPG has a lower energy density per litre than either petrol or fuel oil, so the equivalent fuel consumption is higher. It is used in petrol cars and most vehicles are retrofitted with an additional LPG tank, rather than purchased as a new LPG vehicle. The fuel is stored in liquid form, which requires it to be stored under pressure.

3.2.3 HVO100

Hydrotreated vegetable oil (HVO) is a so-called diesel substitute or biodiesel. HVO100 and other diesel substitutes are sometimes referred to as 'drop-in' fuels. HVO100, in which the number 100 stands for 100%, is produced fully from biomass, which can consist of either plant-based materials or animal fats (or a combination of both). More specially, the production of HVO needs to consist primarily (95%) of residual flows of biomaterials which are needed to have low well-to-tank CO_2 emissions. However, it should be noted that the availability of 'advanced' (as defined in the REDII) bio feedstocks is not sufficient to cover the energy demands of the road transport sector. This would instead imply a significant use of feedstocks with high indirect land-use change risk and associated CO_2 emissions. Moreover, when HVO is produced from food feedstocks, it affects the global food prices, something which has become a prominent concern with the war in Ukraine (NewScientist, 2022[9]). In addition, advanced feedstocks serve competing uses outside the transport sector which further reduces its potential.

3.2.4 Ethanol 85

Biobased petrol substitutes are often accompanied by a number that depicts the percentage of plant-based fuel which regular fossil petrol is mixed with. E85 stands for 85% ethanol from plant-based materials.
Ethanol-based petrol substitutes are suitable only for Otto engines[10]. Moreover, ethanol is more corrosive than fossil petrol, which requires modification to the fuel system in the

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[9] www.newscientist.com/article/2312151-cutting-biofuels-can-help-avoid-global-food-shock-from-ukraine-war/#ixzz7NY1Y47On

[10] In 1876, a German engineer, Nikolaus August Otto advanced the study of heat engines by building of the first working four-stroke engine. The cycle of the Otto engine is called the Otto cycle. It is the one of most common thermodynamic cycles that can be found in automobile engines and describes the functioning of a typical spark ignition piston engine (Thermal Engineering, 2019).

vehicle. This is why for older vehicles (before 2010) blends higher than 10 to 20% are not feasible. For blends as high as E85, specific ‘flex-fuel’ cars are required in which these modifications are custom-made by car manufacturers.

3.2.5 Electricity

One of the drivetrain/energy carrier combinations we look at in this study is plug-in hybrids (PHEV’s). PHEV’s have both an electric motor powered by electricity from an onboard battery pack, and an internal combustion engine running on either petrol or diesel. Most PHEV’s have an otto engine running on petrol rather than a diesel engine. Currently, PHEV’s are available on a reasonable scale for passenger cars, although the technique in principle is also applicable in LCV’s. Typically, a PHEV can run between 20 to 50 kilometres on the battery pack and then needs to switch to (fossil) fuel consumption. In our scenario, we assume 30% of vehicle kilometres of PHEV’s are driven in full-electric mode.

Full-electric vehicles (FEV’s), also referred to as battery-electric vehicles (BEV’s), do not have a combustion engine but rely fully on the electric motor powered by electricity from the onboard battery pack. Similar to PHEV’s the battery pack of FEV’s needs to be charged by plugging them into a charging point which, depending on the power output of the charge point, can fully charge a vehicle between several hours (regular charging) or less than 30 minutes (fast charging). On a fully charged battery pack, most modern FEV’s can run somewhere between 250 and 450 kilometres.

3.2.6 Euro 6/VI diesel

Although not an alternative drivetrain or fuel, the newest Euro 6 emissions standards for light-duty diesel vehicles and Euro VI emission standards for heavy-duty diesel vehicles also have the potential to reduce NO_x and PM emissions compared to older vehicles. In order to provide a comprehensive comparison of different fuel and drivetrain options, we also added the Euro 6/VI diesel scenario (in which we adopt emission limits stages Euro 6-d and Euro VI-D).

3.2.7 Comparison of the environmental impact

Figure 1 and Figure 2 show the performance of different technologies concerning NO_x and PM_{10} emissions (combustion). Since particle size of PM combustion emission is below 2.5 μm, Figure 2 effectively also shows $PM_{2.5}$ emission factors. Only those technologies that are included in the scenarios as defined in Table 10 are included in these figures. For electricity, the well-to-tank emissions as presented in this figure are calculated with the EU27 average emission factors for electricity production in the year 2030. HVO is omitted from this figure because in the HVO scenario the vehicles are not replaced. Therefore, the emissions per kilometre are largely dependent on the fleet composition per country.

Apart from the tank-to-wheel and well-to-tank emissions of pollutants, the effects of abrasion are quantified in this study as well. However, because these emission factors per kilometre are equal for all technology types, these emission factors are omitted from Figure 1 and Figure 2.

All emission factors are averages based on a multitude of international literature on (real-world) emissions from different transport modes. Much of this work can be found in CE Delft’s periodically updated STREAM study gathers state-of-the-art data on well-to-tank and tank-to-wheel emission factors (CE Delft, 2021). Since the STREAM emission actors are averages from multiple studies, it is possible that individual studies may give values that deviate from the figures shown in Figure 1 and Figure 2.

Figure 1 - Emission factors of NO_x (tank-to-wheel and well-to-tank) for different vehicle technologies

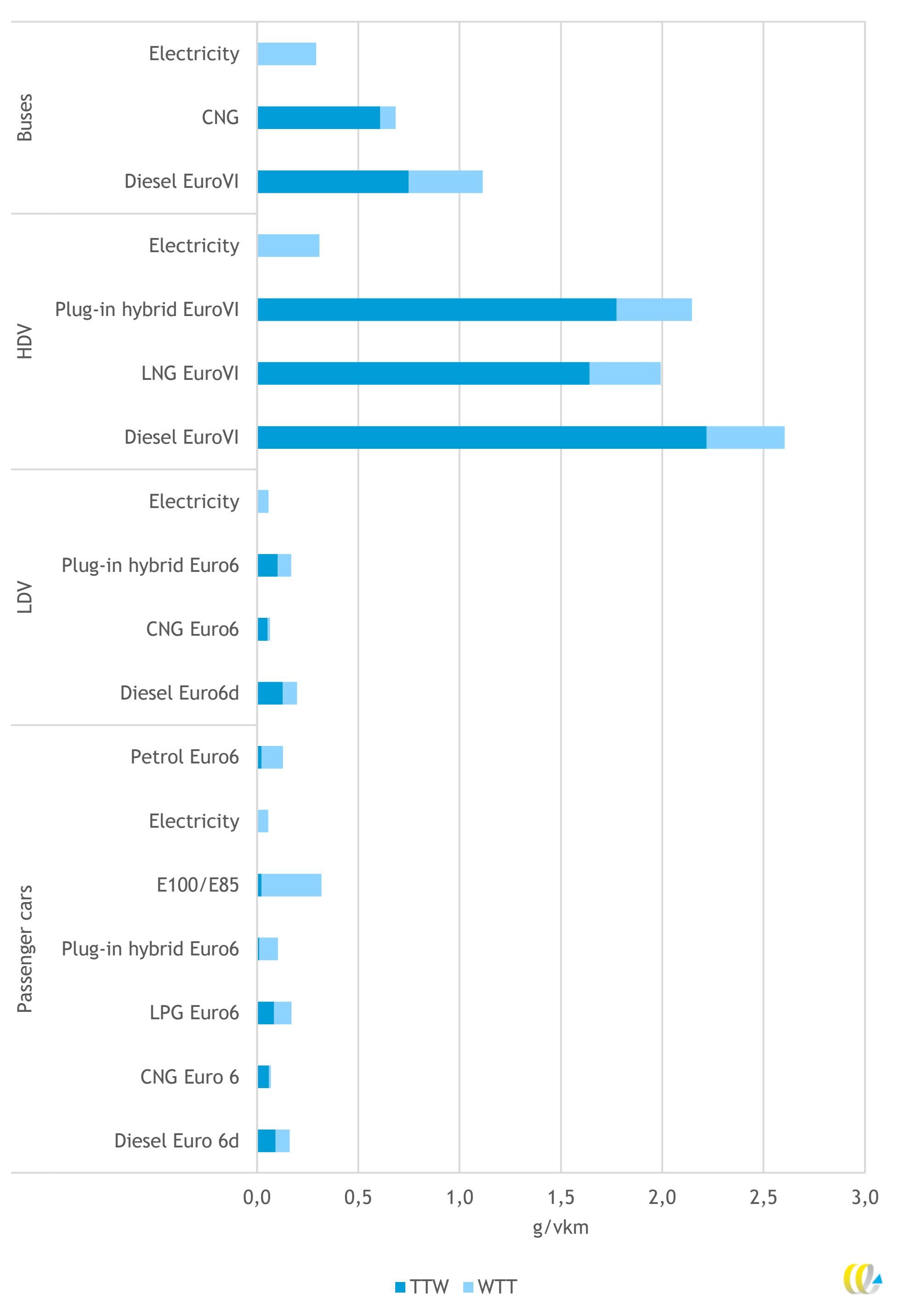
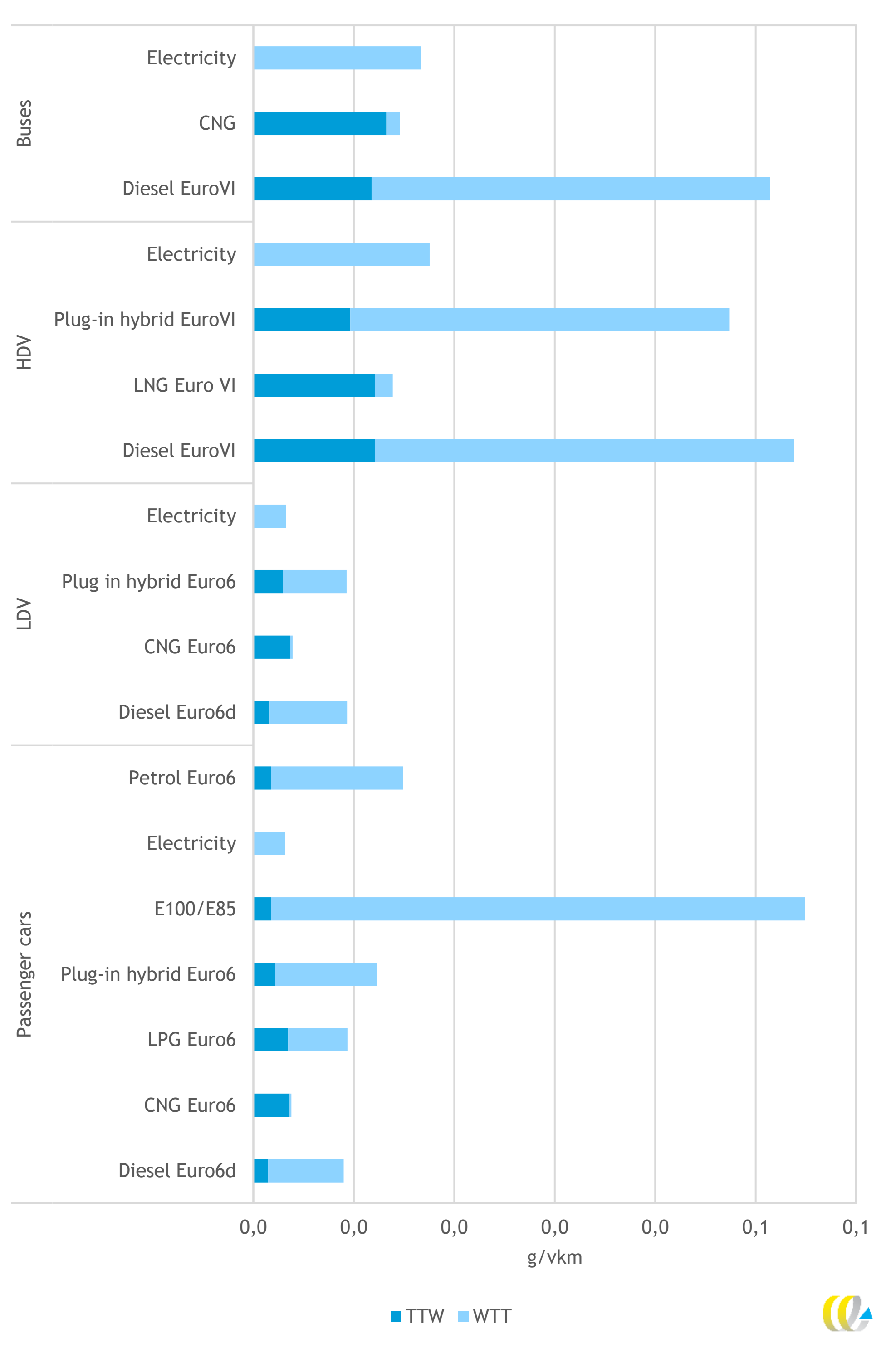


Figure 2 - Emission factors of PM_{10} (tank-to-wheel and well-to-tank) for different vehicle technologies



3.3 The scenarios

The main purpose of the scenarios is to show the ‘maximum potential’ of phasing out diesel and replacing it with different types of alternative fuels and/or drivetrains.
The term ‘maximum potential’ requires some further explanation. For each vehicle model considered in this study, we follow a two-step flow diagram that produces four different scenario variants (see Figure 3). Let us show how we arrive at each of the four scenario variants with the help of four examples:

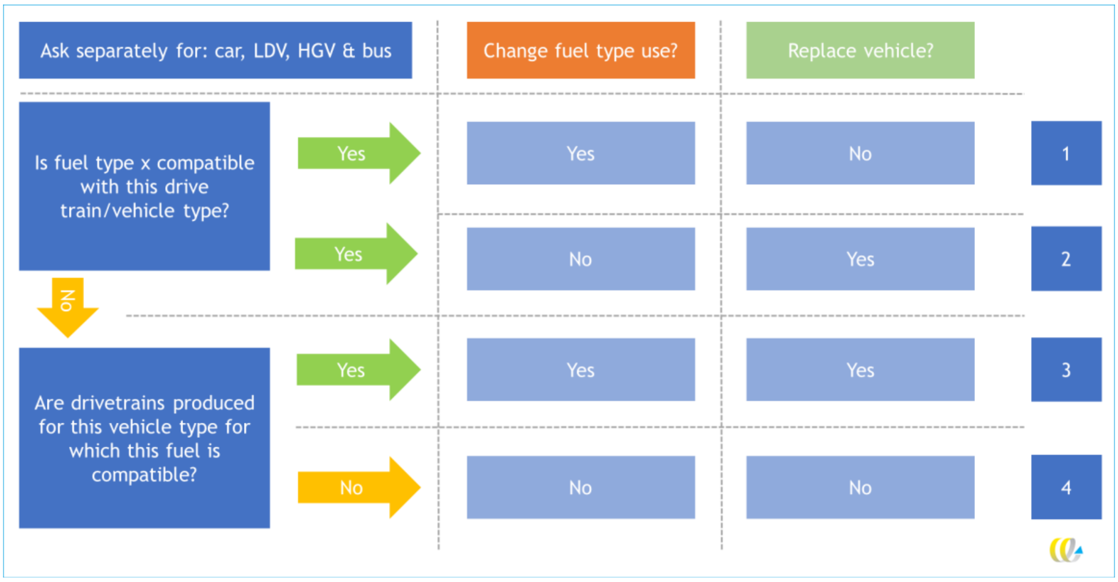
1. **Heavy goods vehicle on HVO:**
    - HVO is a diesel substitute that can be used in all current-generation diesel vehicles.
    - Therefore, the answer to the question ‘Is fuel type x compatible with this drivetrain/vehicle type?’ is “Yes”.
    - Since HVO is an alternative fuel but a ‘drop-in’ fuel at the same time, the vehicles need not be replaced.
    - We thus arrive at scenario ‘variant’ 1.

2. **Passenger car on conventional diesel:**
    - Regular fossil diesel can be used in all current passenger cars.
    - Therefore, the answer to the question ‘Is fuel type x compatible with this drivetrain/vehicle type?’ is “Yes”.
    - The fuel type however need not be changed since we are considering conventional diesel.
    - To let the scenario not having any effect on emissions, the vehicles will have to be replaced with the newest Euro 6 diesel cars

3. **Passenger car on LPG:**
    - Liquid petroleum gas (LPG) can only be applied in petrol (or Otto) engines.
    - Therefore, the answer to the question ‘Is fuel type x compatible with this drivetrain/vehicle type?’ is “No”.
    - The next question, ‘Are drivetrains produced for this vehicle type for which this fuel is compatible?’ should be answered with “Yes”, there are passenger cars produced that run on LPG.
    - We thus arrive at scenario ‘variant’ 3.

4. **Light commercial vehicle (LCV) on E85:**
    - Ethanol 85 is a petrol substitute and can only be applied in petrol (or Otto) engines.
    - Therefore, the answer to the question ‘Is fuel type x compatible with this drivetrain/vehicle type?’ is “No”.
    - The next question, ‘Are drivetrains produced for this vehicle type for which this fuel is compatible?’ should be answered with “No”, there are no LCV’s produced
    - We thus arrive at scenario ‘variant’ 4.

Figure 3 - Flow diagram to determine the change in fuel type and/or vehicle per scenario



Using Figure 3 we constructed the seven fuel type/drivetrain scenarios we distinguish in this study. They are shown in Table 10. Let us highlight some aspects of the table:

- Four vehicle types/modes are distinguished, passenger cars, light-duty vehicles or vans, heavy goods vehicles, and buses[11].
- The percentages indicate the share of diesel use that is replaced by the alternative fuel shown in the table. Thus, in Scenario 1, 100% of all diesel used by passenger cars in the baseline is replaced by CNG in 2030.
- In Scenario 1 we combine two natural gas types (CNG and LNG) since their environmental impact is very comparable. CNG is used mostly in light-duty vehicles and buses. CNG however is also a possible fuel for smaller HGV's which are used in short-distance urban (delivery) transport. For HGV's we, therefore, apply a combination of CNG and LNG, where the latter is applied to long-distance HGV's.
- All scenarios except Scenario 3 assume both a change in fuel type and in vehicle type. A change in vehicle type entails that all old/existing vehicles in the baseline year 2030 using diesel will be replaced by new vehicles. We thus do not assume any retrofitting of old vehicles. Since newer vehicles emit less NO_x and PM per kilometre due to European emission standards, the impact on emissions of these scenarios is a combination of alternative fuels and younger (cleaner) vehicles.
- All but one scenario (Scenario 6) assume a change of fuel type (a shift from diesel to a substitute). Scenario 6 is an outlier since it assumes fossil diesel will be equal to the use in the baseline, but the vehicles using them will be replaced by the newest versions with the stringent emission legislation (i.e. Euro 6 for passenger cars and LCV's and Euro VI for HGV's and buses).
- Scenarios 2 and 4 apply fuel alternatives (LPG and ethanol) which are applicable only in petrol (or otto) engines. Since modern LCV's, HGV's and buses with internal combustion engines do not use petrol, these scenarios only assume a fuel change in passenger cars.

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[11] Motorcycles are not shown in the table since there are no feasible substitutes for motorcycles that fits one of the fuel types we distinguish in this study, plus this mode uses no diesel in the baseline. Motorcycles are however included in all the emission and external cost calculations that follow to ensure a comparable scope to the 2018 study to which this study is an update (and extension).

Table 10 - Overview of the scenario characteristics per vehicle type (percentage of diesel use replaced in 2030)

	Scenario	Car	LCV	HGV	Bus	Fuel change?	Vehicle change?
1	CNG/LNG	100% diesel→ CNG Euro 6	100% diesel→ CNG Euro 6	50/50% diesel→ CNG/LNG Euro VI	100% diesel→ CNG EVI	Yes	Yes
2	LPG	100% diesel → LPG Euro 6	x	X	X	Yes	Yes
3	HVO (biodiesel)	100% diesel→ HVO	100% diesel→ HVO	100% diesel→ HVO	100% diesel→HVO	Yes	No
4	PHEV	100% diesel→ PHEV petrol Euro 6	100% diesel→ PHEV diesel Euro 6	100% diesel→ PHEV diesel Euro VI	X	Yes	Yes
5	E85 (bioethanol)	100% diesel→ E85 Euro 6	x	X	X	Yes	Yes
6	Eur o6/VI diesel	100% diesel→ diesel Euro 6	100% diesel→ diesel Euro 6	100% diesel→ diesel Euro VI	100% diesel→ diesel Euro VI	No	Yes
7	ZE vehicles	100% D→E	100% D→E	100% D→E	100% D→E	Yes	Yes

In Table 10 we can now clearly see that not all scenarios lead to changes in all vehicle types. In Scenarios 2 and 5 for example, only diesel passenger cars are replaced with an alternative fuel whereas LCV's, HGV's and buses remain unchanged. The same is true for Scenario 4 in which buses are left unchanged.

Although these differences still adhere to our principle of 'maximum potential reduction' some care is warranted in interpreting the impacts of the different scenarios in the next chapters. A relatively strong overall emission reduction in the road transport sector is more likely in scenarios in which more vehicles are impacted. Therefore, Scenarios 2 and 5 may lead to relatively smaller emission reduction impacts overall, their effectiveness in reducing emissions for a specific vehicle type may be much higher. Where relevant, we will get back to this in describing the outcomes in Chapters 4 and 5.

4 Emission impacts

In this chapter, we show what the impacts on NO_x and PM emissions are of replacing diesel use by each of the seven fuel type/drivetrain scenarios described in Chapter 3. The steps taken to arrive at these emission figures are described in Chapter 2.

4.1 Overall baseline emissions in EU27 and 9 Member States

In Figure 4 we see the levels of NO_x and $PM1_0$ emissions from road transport in the nine selected Member States in the years 2016 and 2030 (baseline). It is clear that due to policies already in place, emissions from both NO_x and PM_{10} will decrease substantially in this period. The differences in 'autonomous' emission reduction differ per Member State as can be seen in Table 11. For the EU27 the decrease in NO_x emissions is 60% between 2016 and 2030. For PM_{10} this is almost 70%. For the individual Member States the reduction range from
-30% to -73% for NO_x and -37% to -72% for PM_{10}. Autonomous emission reductions are lowest in Bulgaria (NO_x) and Estonia (PM_{10}) and highest in Germany (NO_x) and Spain (PM_{10}).

Figure 4 - NO_x and PM_{10} emission levels in 2016 compared to 2030 for EU27

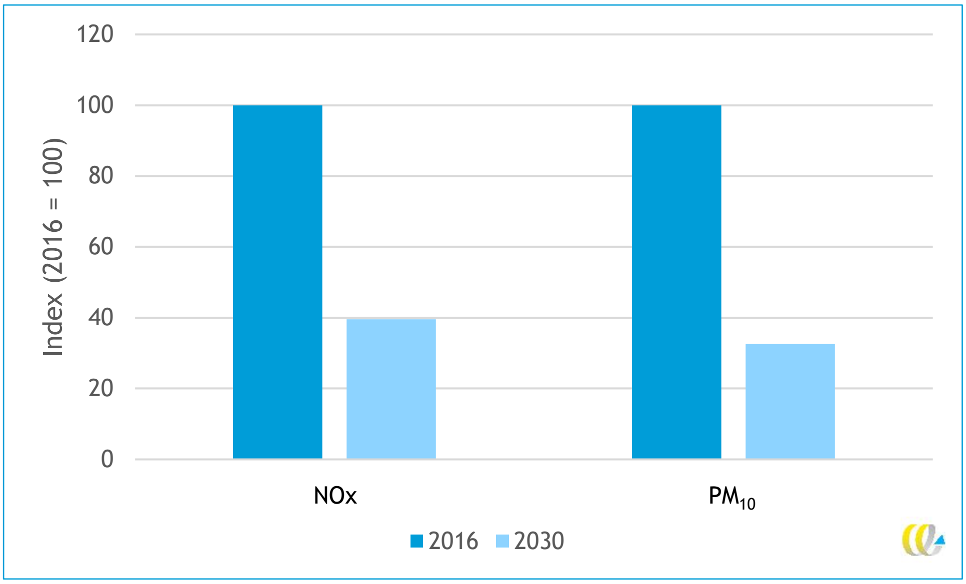


Table 11 – Baseline emissions of NO_x and PM_{10} in 2016 and 2030 and the percentage change over this period

	NO_x (mln kg)			PM_{10} (mln kg)		
	2016	*2030*	*Change*	*2016*	*2030*	*Change*
EU Aggregate	1.236	488	-60%	146	48	-67%
Bulgaria	33	23	-30%	2	1	-56%
Estonia	6	3	-50%	1	1	-37%
France	231	100	-57%	28	9	-68%
Germany	177	48	-73%	19	8	-58%
Hungary	17	8	-55%	2	1	-70%
Poland	93	58	-38%	14	4	-70%
Romania	37	15	-59%	3	1	-63%
Slovenia	10	5	-56%	1	0	-67%
Spain	148	55	-63%	15	4	-72%

Figure 5 and Figure 6 show the well-to-tank and tank-to-wheel emission levels of NO_x and PM_{10} separately in 2030 for the EU27 and the nine Member States. We see that TTW emissions are dominant and that WTT emissions account for roughly one-third of total NO_x emissions and roughly half of PM emissions. We can also clearly see that there are substantial differences between the Member States in terms of absolute emission levels. France, Germany, Poland, and Spain are by far the largest contributors to both NO_x and PM_{10} emissions of the selected Member States.

Figure 5 - NO_x emissions per country in 2030 in the baseline scenario

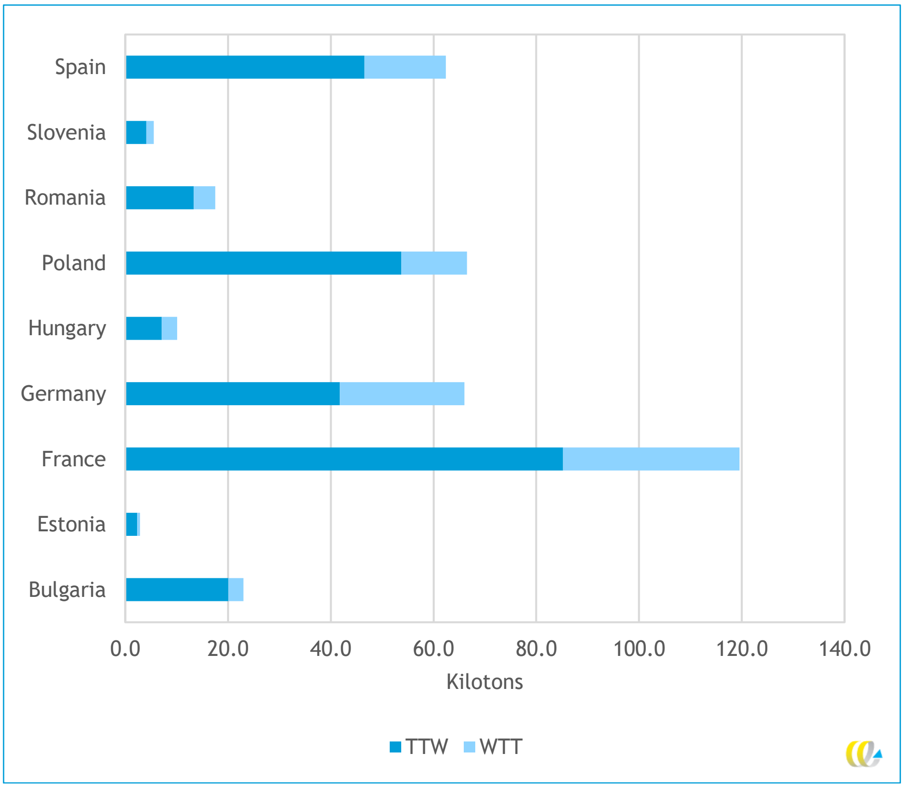
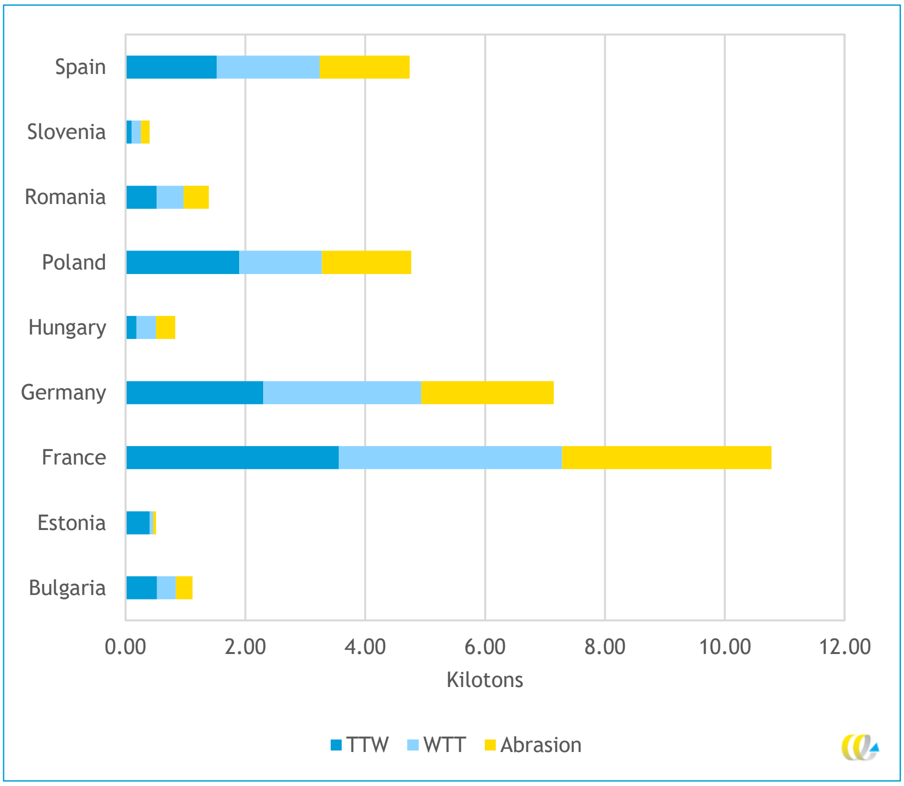


Figure 6 - PM_{10} emissions* (combustion, abrasion and well-to-tank) per country in 2030 in the baseline scenario



* $PM_{2.5}$ is part of PM_{10} and is shown in dark blue.

Finally, in this section, we show the difference in baseline emission factors for NO_x and PM in the different Member States and the EU27. Figure 7 and Figure 8 show the NO_x emission factor for cars and light-duty vehicles, heavy-duty vehicles and buses. It is clear that the differences between the selected Member States are quite substantial indicating some have an older vehicle fleet than others. Compared to the EU27 average Bulgaria, Estonia and Hungary show higher than average NO_x emission factors for light-duty vehicles (vans).
For passenger cars, only Bulgaria has a higher than EU27 average NO_x emission factor.
For heavy-duty vehicles, we see higher NO_x emission factors and thus older vehicle fleets in Bulgaria, Estonia, Poland and Romania.

Figure 7 - Average NO_x emission factor (gram/kilometre) for cars and light-duty vehicles

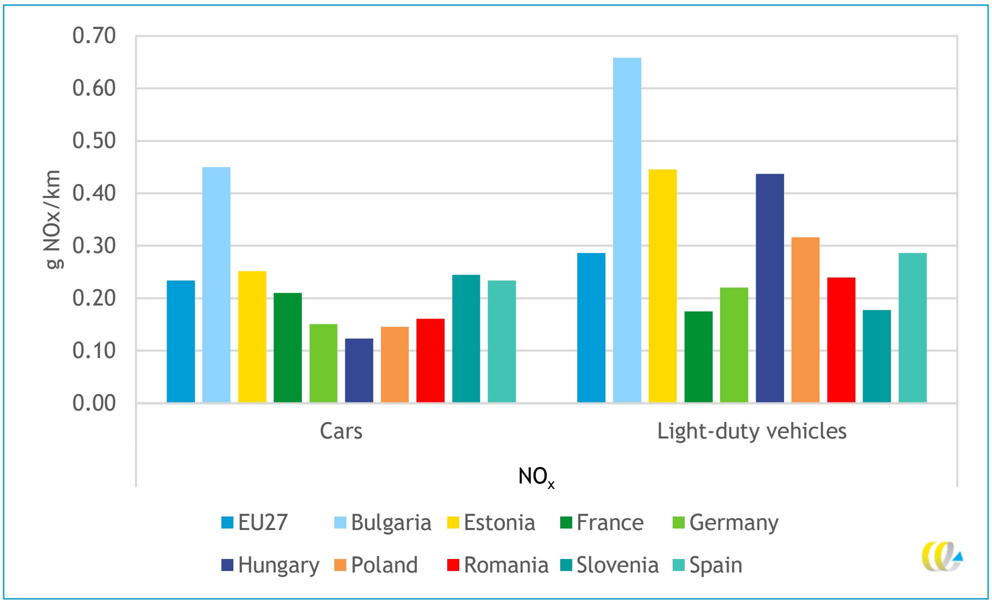
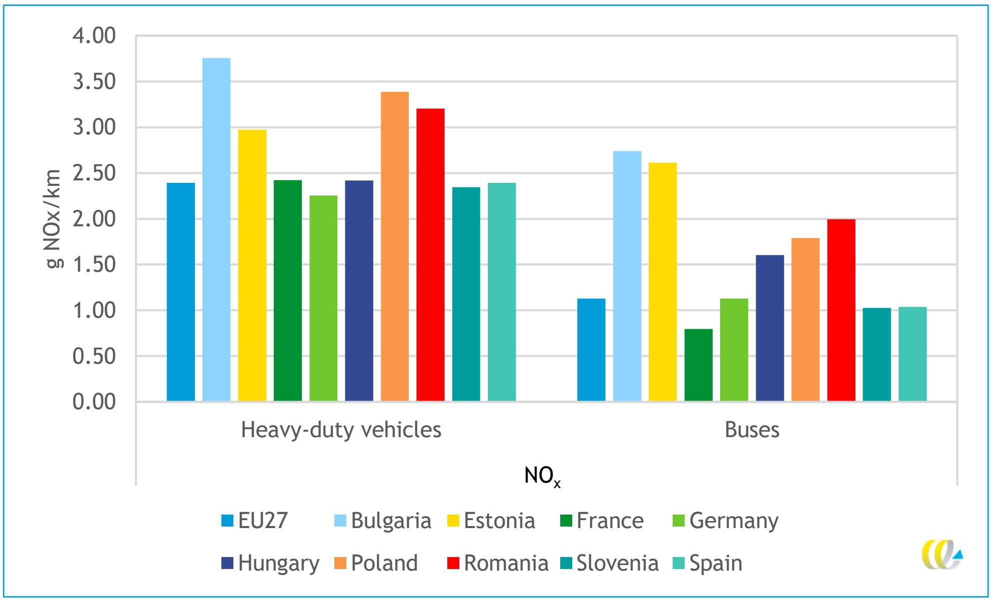


Figure 8 - Average NO_x emission factor (gram/kilometre) for heavy-duty vehicles



PM emission factors are shown in Figure 9 (cars and light commercial vehicles) and Figure 10 (heavy goods vehicles and buses). Again, we see high PM emission factors for cars in Bulgaria, and above EU27 average emission factors for light-duty vehicles in Bulgaria, Estonia and Hungary. For heavy-duty vehicles, we also roughly see the same pattern as for NO_x emission factors.

Figure 9 - Average PM emission factor (gram/kilometre) for cars and light-duty vehicles

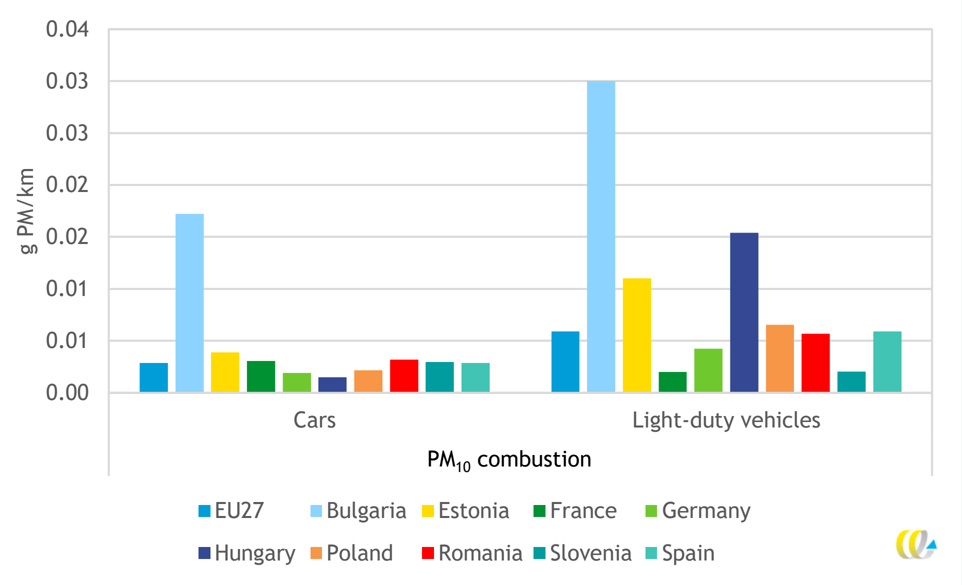
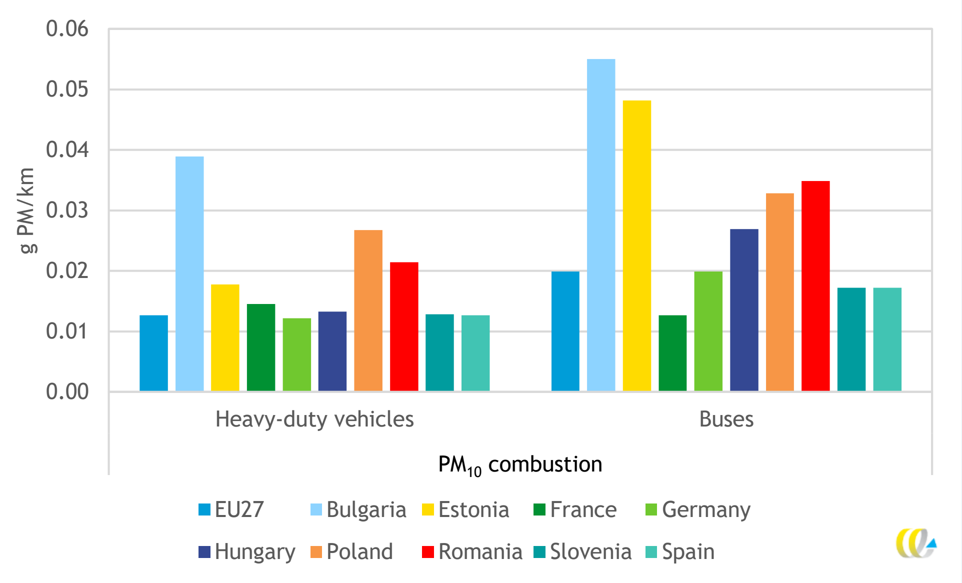


Figure 10 - Average PM emission factor (gram/kilometre) for heavy-duty vehicles



4.2 Scenario impact on tank-to-wheel emissions

In the two following sections, we explore the impacts of the seven technology scenarios on NO_x and PM_{10} tank-to-wheel (or exhaust) emissions. PM abrasion emissions are not discussed since they are constant over all scenarios. Impacts from abrasion are included in the external costs calculations that follow in Chapter 5.

We would like to note that since there are many differences between the Member States in terms of fleet size and composition, and also because the scenarios are not consistent in terms of targeting all vehicle types equally (see Section 3.1), the outcomes we present here may not always be intuitive. Where this is the case we provide additional information on the reasons why.

4.2.1 NO_x

We first look at the tank-to-wheel NO_x emissions from diesel combustion for all modes combined. Table 12 shows the relative change in these NO_x emissions in 2030 for the EU27 and nine Member States. The baseline is also included in the table and is set at 100%. Lower percentages than 100% indicate a decrease in emissions in 2030 as a result of the implementation of other fuels and/or vehicles to replace diesel. Large reductions are highlighted in dark green whereas small reductions are highlighted in dark orange.
A number of interesting findings can be derived from Table 12:

- All but one scenario (the HVO biodiesel scenario) show a decrease in NO_x tank-to-wheel emissions compared to the baseline. The reductions are highest in Scenarios 1, 4 and 7.
- The zero-emission vehicle scenario is the most effective in reducing NO_x emissions.
- Scenarios 2 and 5 are the least effective in reducing emissions. We should note, however, that this is in large part because only passenger cars are affected, and the emissions of other vehicle modes remain unchanged (see Chapter 3).
- Scenario 3, substituting all fossil diesel with HVO, does not result in tank-to-wheel NO_x reduction compared to the baseline. This is because the level of NO_x exhaust emissions is determined by the emission control technology in road vehicles, and not by the type of fuel used. Since in this scenario, the existing fleet remains in place, the impact on NO_x emissions is negligible.
- The Euro 6/VI diesel scenario (removing all existing diesel vehicles and replacing them with Euro 6 for light-duty and Euro VI for heavy-duty vehicles) is fairly effective in reducing NO_x emission. Roughly half of the NO_x emissions in 2030 can be reduced in this way.
- There are quite substantial differences between the nine Member States. Roughly we see higher effectiveness in countries with a relatively older vehicle fleet (Bulgaria, Estonia, and Slovenia) and lower reductions in countries with a newer fleet (Germany, France). It should be noted that countries with a newer vehicle fleet already have lower emission levels in the baseline, which explains the lower impact of these scenarios.
- The relative share of the vehicle categories in the transport performance also affects the outcomes. For example, it might seem counter-intuitive that Estonia (with a relatively old fleet) achieves less emission reduction than France (with a relatively new fleet) in Scenarios 2, 4 and 5. The reason for this is that Estonia has a relatively large share in HGV's and buses, whereas France has relatively more passenger cars and LCV's. Since the relative improvement is largest for passenger cars, France scores relatively well (even though Estonia relatively improves more for all individual vehicle categories).

Table 12 - Relative change in total NO_x emissions (tank-to-wheel) in 2030 for each scenario

	Baseline	1. CNG/LNG	2. LPG *	3. HVO (biodiesel)	4. Plug-in hybrid*	5. E85 (bioethanol)*	6. Euro 6/VI diesel	7. Electricity
EU27	100%	37%	74%	100%	37%	63%	57%	0%
Bulgaria	100%	23%	60%	100%	28%	53%	32%	0%
Estonia	100%	29%	77%	100%	44%	68%	43%	0%
France	100%	36%	65%	100%	30%	48%	59%	0%
Germany	100%	46%	79%	100%	40%	59%	70%	0%
Hungary	100%	39%	88%	100%	34%	69%	61%	0%
Poland	100%	42%	94%	100%	46%	88%	60%	0%
Romania	100%	41%	88%	100%	47%	78%	59%	0%
Slovenia	100%	40%	64%	100%	33%	49%	60%	0%
Spain	100%	35%	60%	100%	27%	43%	52%	0%

* Scenarios 2, 4 and 5 do not impact all vehicle types (see Section 3.1).

Let us zoom in a little on the differences in outcomes for different vehicle modes. Figure 11 and Figure 12 show the reduction per scenario for passenger cars and heavy goods vehicles separately. Some findings are:

- Figure 8 reveals that three scenarios for HGV's show no reduction in NO_x emissions. This is purely because Scenarios 2 and 4 assume no change in diesel use for LCV's and HGV's since they require petrol engines which are not feasible for these vehicle types. The other scenario without impact is Scenario 3 (HVO) but this is equivalent to passenger cars.
- We also see that the relative reduction of the other scenarios for HGV's is on average lower than for passenger cars. This is because the HGV vehicle fleet is relatively young (newer vehicles) compared to the passenger car fleet. As a result, adding newer vehicles will also have a larger impact on emissions for passenger cars as compared to HGV's.

Figure 11 - Residual NO_x emissions (TTW) per scenario compared to baseline of passenger cars in 2030

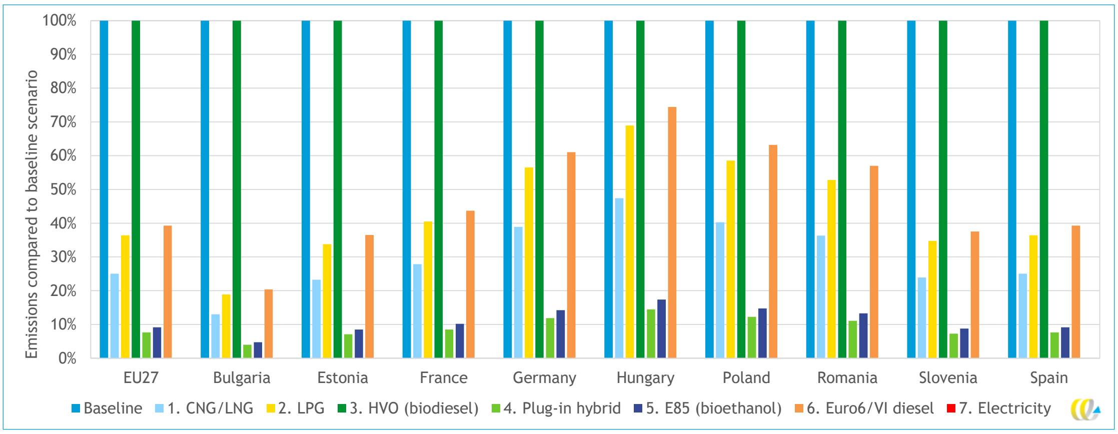
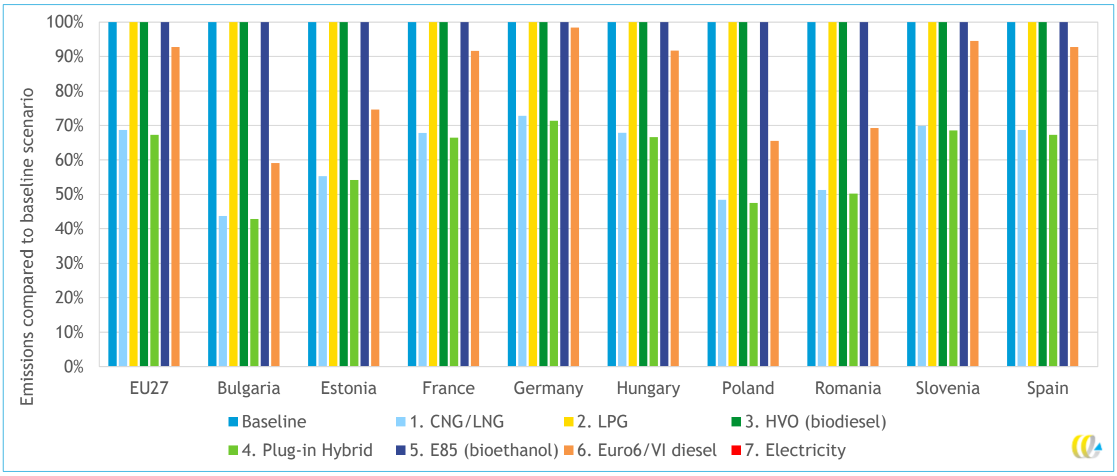


Figure 12 - Residual NO_x emission (TTW) per scenario compared to baseline of heavy goods vehicles in 2030



4.2.2 PM_{10}

Table 13 shows the relative change in PM_{10} combustion emission in 2030 for the EU27 and nine Member States for all modes combined. Some interesting findings are:

- In contrast to NO_x, we see several scenarios that result in an increase in PM_{10} emissions compared to the baseline. CNG/LNG and LPG are most prominent in this respect. These increases are to be expected if we consider the higher emission per kilometre for these fuel types (see Section 3.2). Scenario 5 also shows an increase for one Member State. This can be explained by the high share of Euro 6 passenger cars (with relatively low emissions) in this country in 2030[12].
- Scenario 6 (Euro 6/VI diesel) and 4 (plug-in hybrid) perform quite well in terms of reducing PM_{10} emissions from combustion.
- Similar to NO_x, Scenario 7 (zero-emission vehicles) outperforms every other scenario in terms of reducing emissions.

Table 13 - Relative change in total PM_{10} emissions (tank-to-wheel) in 2030 for each scenario

	Baseline	1. CNG/LNG	2. LPG *	3. HVO (biodiesel)	4. Plug-in hybrid*	5. E85 (bioethanol)*	6. Euro 6/VI diesel	7. Electricity
EU27	100%	97%	110%	100%	52%	82%	49%	0%
Bulgaria	100%	21%	57%	100%	20%	52%	13%	0%
Estonia	100%	75%	93%	100%	38%	65%	35%	0%
France	100%	131%	107%	100%	71%	75%	62%	0%
Germany	100%	167%	164%	100%	74%	94%	72%	0%
Hungary	100%	94%	139%	100%	48%	105%	44%	0%
Poland	100%	89%	121%	100%	49%	94%	48%	0%
Romania	100%	83%	104%	100%	46%	81%	42%	0%
Slovenia	100%	129%	110%	100%	70%	77%	65%	0%
Spain	100%	111%	115%	100%	51%	72%	49%	0%

* Scenarios 2, 4 and 5 do not impact all vehicle types (see Section 3.1).

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[12] Hungary shows an increase in PM_{10} emissions in Scenario 5. This is because the bioethanol scenario only applies to passenger cars. These interesting results can be explained by the relative high share of Euro 6 diesel passenger cars in Hungary in 2030 (see Table 27). Since the NO_x emissions of diesel Euro 6 passenger cars are slightly lower than the NO_x emissions of petrol Euro 6 passenger cars fuelled by E85, the result is an increase in emissions. Note that the shares of euroclasses per country are self-reported by the member states.

If we look at passenger cars and heavy goods vehicles separately (Figure 13 and Figure 14) we see that:

- The increases in PM_{10} emissions for Scenarios 1 and 2 do not occur for HGV's, only for passenger cars. In the case of LPG, the explanation is simple: for HGV's LPG is not a viable option and therefore a shift towards LPG for HGV's was not part of the scenario. For new CNG/LNG trucks, the PM_{10} emissions are lower compared to most diesel trucks. For passenger cars, this is not the case.
  Figure 14 reveals that three scenarios for HGV's show no reduction in PM_{10} emissions. For Scenarios 2 and 4 this is purely because they assume no change in diesel use for LCV's and HGV's since they require petrol engines which are not feasible for these vehicle types. The other scenario without impact is Scenario 3 (HVO), but this is equivalent to passenger cars.

Figure 13 - Relative reduction per scenario in PM_{10} emission (TTW) of passenger cars in 2030

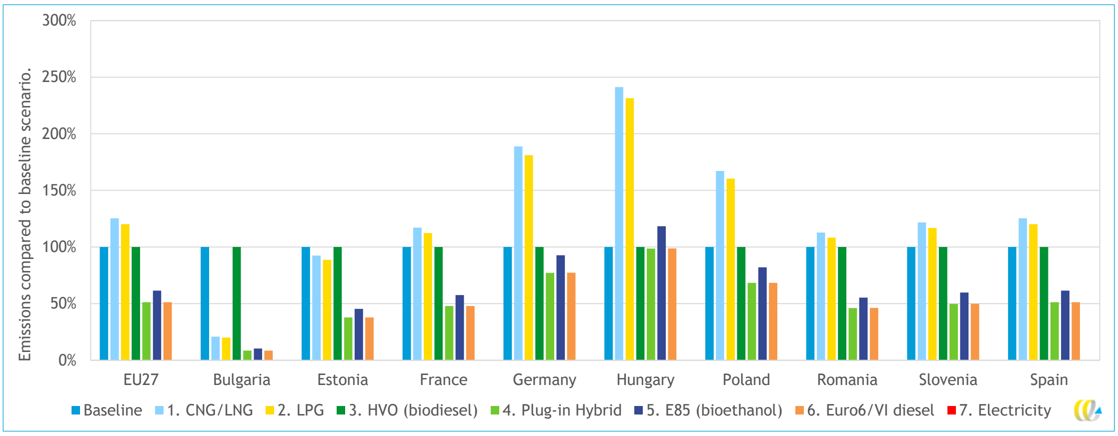
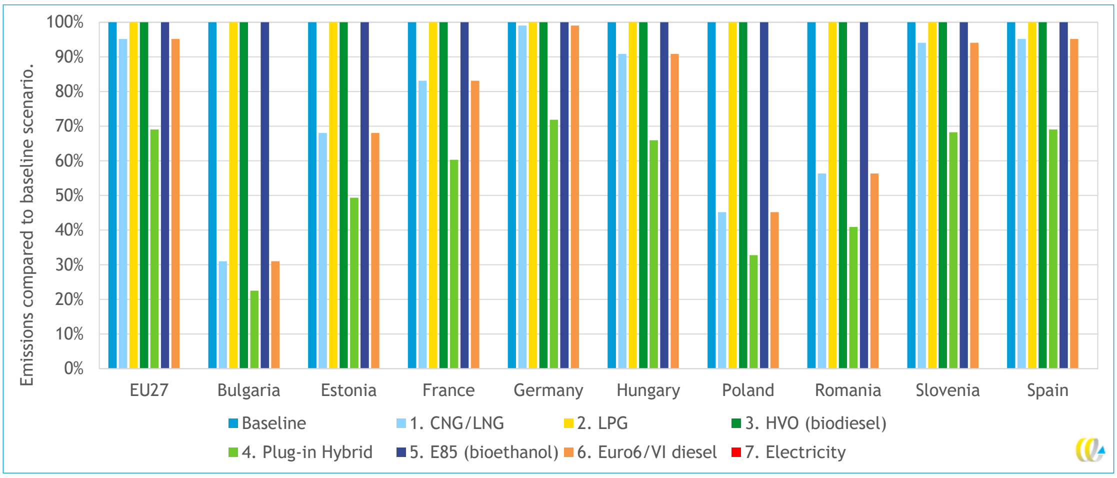


Figure 14 - Relative reduction per scenario in PM_{10} emission (TTW) of HGV's in 2030



4.3 Scenario impact on WTT emissions

As we saw in Chapter 3, the well-to-tank (WTT) emissions which are associated with the production of the fuels or energy carriers can contribute substantially to overall (well-to-tank) emissions, particularly for PM emissions. Since production techniques for the energy carriers considered in the various scenarios differ, they also result in different levels of WTT emissions. Below we describe these impacts separately for NO_x and PM.

4.3.1 NO_x

Table 14 shows the relative change in well-to-tank NO_x emission in 2030 for the EU27 and nine selected Member States. Some interesting findings are:

- All but one scenario show a status quo or increase of WTT NO_x emissions in 2030. This means that all alternative fuels, except CNG and LNG, perform equal or worse than diesel in terms of emissions produced during their production.
- For most scenarios, the differences between the Member States are fairly small. This is because the production process of these fuels was assumed equal in each country[13]. The differences in performance purely arise from the slight differences in efficiencies of the current fleet between the Member States.
- Bioethanol (E85) and to a lesser extent HVO result in the highest increase in NO_x emissions compared to diesel.
- Scenario 1 (CNG and LNG) is the only scenario considered that results in an additional decrease in NO_x emissions on top of the tank-to-wheel NO_x emission reduction (see Section 4.2.1). The relative reduction is roughly two-thirds in all scenarios. However, recall from Section 3.2 that the absolute WTT NO_x emission levels are small compared to the TTW NO_x emissions (see Figure 1).
- The zero-emission scenario gives a somewhat mixed image with reductions of up to 35% on the one hand and increases of up to about 25% on the other hand. These differences are the result of the differences in electricity production mixes in the various Member States - those with a higher share of renewables have lower well-to-tank emissions. An overview of the emission factors of energy production per country is included in Table 24, Table 25 and Table 26.

Table 14 - Relative change in total NO_x emissions (well-to-tank) in 2030 for each scenario

	Baseline	1. CNG/LNG	2. LPG *	3. HVO (biodiesel)	4. Plug-in hybrid*	5. E85 (bioethanol)*	6. Euro 6/VI diesel	7. Electricity
EU27	100%	27%	108%	152%	110%	241%	99%	80%
Bulgaria	100%	27%	106%	152%	114%	234%	97%	107%
Estonia	100%	27%	107%	152%	106%	229%	98%	66%
France	100%	25%	109%	152%	113%	259%	99%	85%
Germany	100%	27%	110%	152%	111%	261%	100%	70%
Hungary	100%	32%	105%	152%	114%	181%	99%	124%
Poland	100%	32%	107%	152%	115%	207%	100%	110%
Romania	100%	29%	107%	152%	107%	222%	99%	73%
Slovenia	100%	31%	107%	152%	109%	219%	99%	85%
Spain	100%	26%	109%	152%	109%	261%	98%	66%

* Scenarios 2, 4 and 5 do not impact all vehicle types (see Section 3.1).

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[13] Since fuels such as diesel, CNG and LPG can be produced anywhere and transported, it is not possible to distinguish between countries.

4.3.2 PM_{10}

Table 15 shows the relative change in well-to-tank PM_{10} emission in 2030 for the EU27 and nine selected Member States. Some interesting findings are:

- For WTT PM_{10} emissions Scenario 1 (CNG and LNG) performs by far the best.
- The zero-emission scenario leads to reductions of on average 50% in all scenarios although the range is quite large between the Member States as a result of the differences in the electricity mix.
- Of all other scenarios, only Scenario 2 (LPG) and Scenario 6 (Euro 6/VI diesel) show a minor decrease in WTT PM_{10} emissions.
- Similar to NO_x, Scenario 5 (E85) performs worst in terms of WTT PM_{10} emissions. The production of ethanol results in relatively high PM_{10} emissions.

Table 15 - Relative change in total PM_{10} emissions (well-to-tank) in 2030 for each scenario

	Baseline	1. CNG/LNG	2. LPG	3. HVO (biodiesel)	4. Plug-in hybrid*	5. E85 (bioethanol)*	6. Euro 6/VI diesel	7. Electricity
EU27	100%	2%	89%	224%	107%	362%	99%	42%
Bulgaria	100%	2%	87%	224%	109%	351%	97%	56%
Estonia	100%	2%	90%	224%	105%	340%	98%	35%
France	100%	2%	88%	224%	110%	395%	99%	45%
Germany	100%	2%	89%	224%	110%	397%	100%	37%
Hungary	100%	2%	95%	224%	105%	250%	99%	65%
Poland	100%	2%	93%	224%	108%	298%	100%	58%
Romania	100%	2%	91%	224%	105%	326%	99%	38%
Slovenia	100%	2%	91%	224%	105%	321%	99%	45%
Spain	100%	2%	88%	224%	109%	399%	98%	35%

* Scenarios 2, 4 and 5 do not impact all vehicle types (see Section 3.1).

4.4 Scenario impact on WTW emissions

Adding well-to-tank and tank-to-wheel emissions results in well-to-wheel (WTW) emissions. Below we describe the WTW impacts separately for NO_x and PM.

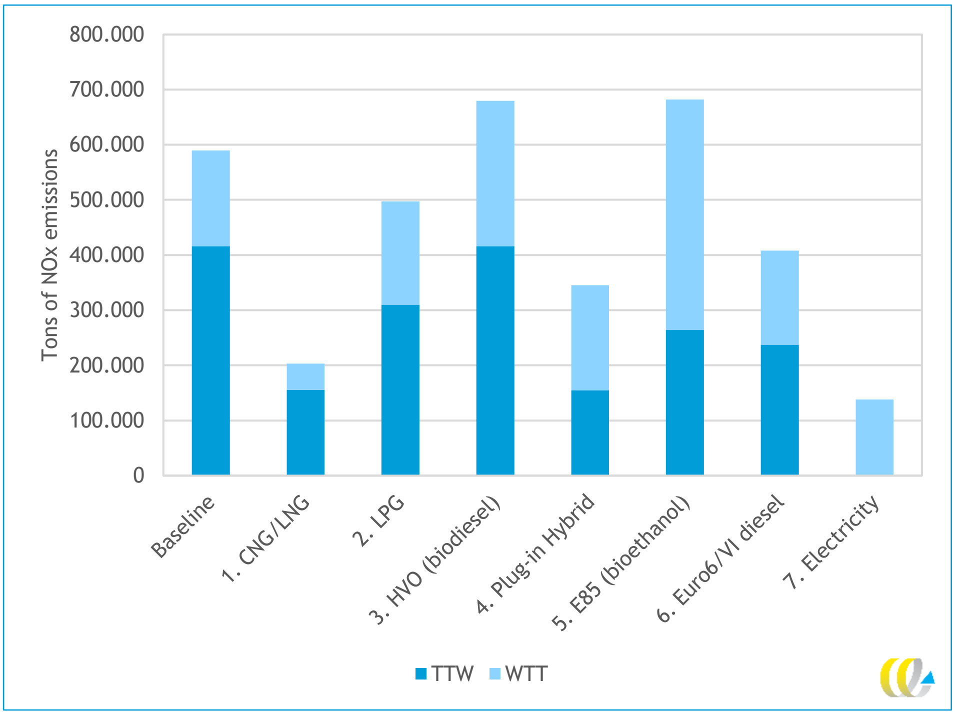
4.4.1 NO_x

Figure 15 shows the relative change in WTW NO_x emission in 2030 for the EU27 and each of the seven scenarios. A number of interesting findings can be derived from:

- Scenario 7 (zero-emission vehicles) remains the scenario with the largest reductions in NO_x emissions.
- Scenario 1 (CNG/LNG) scores only slightly less well than the scenario of the zero-emission vehicle. This is mainly because the tank-to-wheel NO_x emissions of CNG and LNG are relatively low compared to baseline (but still higher than the zero-emission in the zero-emission scenario), while for well-to-tank NO_x emissions CNG and LNG outperform Scenario 7 (zero-emission)). The plug-in hybrid scenario and Euro 6/VI diesel scenarios also lead to an improvement in NO_x emissions.
- Some scenarios (3 and 5) predominantly show increases in the WTW NO_x emissions. For Scenario 3, this is a result of the fact that there is little difference in the tank-to-wheel emissions of HVO and that the well-to-tank NO_x emissions are slightly higher. For E85 well-to-tank NO_x emissions are high (Section 4.2.1), but since in this scenario existing

vehicles are replaced with new vehicles, the relative increase in WTW NO_x emissions is compensated and on par with Scenario 3 (HVO).

Figure 15 – Well-to-wheel NO_x emissions in the different scenarios in the EU27

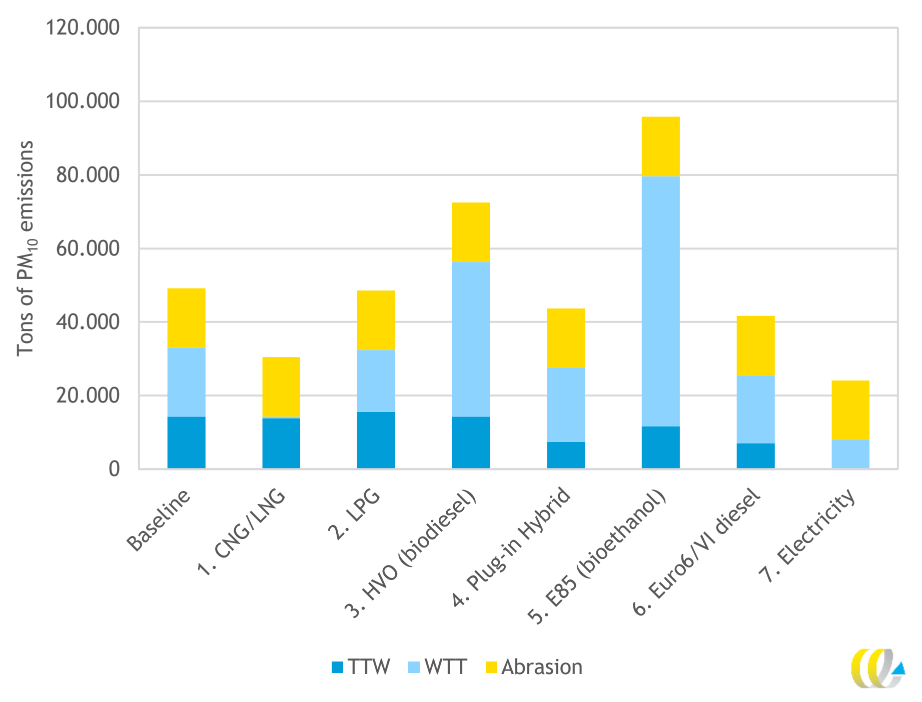


4.4.2 PM_{10}

Figure 16 shows the relative change in WTW PM emission in 2030 for the EU27 in each of the seven scenarios. The findings we described for NO_x in the previous section also apply to PM. In addition, we see that:

- the increases in emissions for Scenarios 3 and 5 are more substantial than for NO_x;
- when comparing this table with the earlier tables in this chapter, we see that for each scenario the WTT emissions for PM have a stronger negative impact on WTW emissions than for NO_x;
- the non-exhaust emissions (abrasion) remain constant in each scenario since these cannot be mitigated with different vehicle technology.

Figure 16 - Well-to-wheel PM_{10} emissions in the different scenarios in the EU27



5 Impact on external costs

In this chapter, we convert the emission levels to external costs expressed in euro.
We examine how high external costs from diesel emissions are in 2016 and 2030, both in the baseline and the seven technology scenarios.

Section 5.1 adopts the scope of external costs of the 2018 study. This means that only tank-to-wheel emissions of air pollutants are included. This allows us to make comparisons between the previous study and this update. Recall that Table 3 in Chapter 1 gives an overview of the main differences in scope between this study and the 2018 study.
Section 5.2 continues with an extension of the scope of the external costs, by quantifying (monetising) the impacts of CO_2 emissions, congestion, noise, traffic safety and well-to-tank emissions.

5.1 Costs of TTW air pollution emissions from road transport

Table 16 shows the costs of road traffic-related air pollution in 2030 for petrol and diesel vehicles for the baseline scenario. The table shows that the most important sources of air pollution costs are diesel vehicles, as these contribute about three-quarters of the costs from emissions. Diesel passenger cars, diesel LCV's and HGV's are the main contributors. Buses and coaches and motorcycles take up a smaller share of the total costs from air pollution.

Table 16 - Total costs of road traffic related air pollution* in 2030 (in million €, both health and non-health)

Cost in 2030 (mln euro)	Passenger car		Bus + coach	MC	LCV		HGV	Total			Reduction 2016-2030
	Petrol	Diesel	Diesel	Petrol	Petrol	Diesel	Diesel	Petrol	Diesel	Total	Total
EU27	2.264	4.354	842	1.245	21	2.801	2.465	3.530	10.462	13.992	78%
Bulgaria	47	126	29	1	0	29	69	48	253	301	56%
Estonia	7	18	4	0	0	6	6	7	34	42	59%
France	579	2.067	154	136	45	960	461	760	3.642	4.402	69%
Germany	812	1.434	177	181	3	410	531	996	2.551	3.548	73%
Hungary	39	82	20	11	0	80	47	50	230	280	72%
Poland	127	375	95	22	2	184	612	151	1.265	1.415	63%
Romania	47	134	45	14	0	65	158	62	402	464	68%
Slovenia	17	66	4	2	0	17	37	19	124	143	66%
Spain	137	628	37	142	0	147	130	280	943	1.223	70%

* Excluding zero-emission and alternative fuels.

The overall level of costs in the baseline due to air pollution amounts to nearly 14.0 billion euros in 2030 for the EU27. As we can see in Table 16 this is a substantial decrease from the cost level in 2016 which amounts to 63.8 billion euros (see Table 17).

The effect of the technological scenarios on air pollution costs is shown in Table 17.
We can see that health costs remain the by far dominant cost component of air pollutant costs in all scenarios. We can also see that external cost reductions are possible by replacing diesel with alternative fuels and drivetrains. Particularly techniques with zero-

tailpipe emissions have a large potential. For the zero-emission scenario, only emissions from wear and tear remain (plus the tailpipe emissions from petrol vehicles as these are assumed to remain in the fleet). Scenario 7 (ZE) would reduce costs from air pollution by 10.1 billion euros in 2030, which is a reduction of more than 70% compared to the baseline. Scenarios 1 (CNG and LNG), 4 (plug-in hybrid) and 6 (Euro 6/VI diesel) are also quite effective in reducing external costs from air pollution at 35, 43 and 32% respectively. Scenarios 3 (HVO) does not result in a decrease in external costs. Scenarios 2 (LPG) and 5 (E85) deliver the lowest decrease in external costs from air pollution.

Table 17 - Main results: costs for direct air pollution (TTW) from road transport in EU27 in 2016 and 2030 for various scenarios (costs in billion euros)

	Total costs	Cost savings compared to 2016	Health costs	Health costs (% of total)	Health costs borne by governments (73% of health costs)
2016					
	63.8		58.5	91.7%	42.7
2030					
Baseline	14.0	49.9	12.8	91.4%	9.3
1. CNG/LNG	9.1	54.8	8.5	93.5%	6.2
2. LPG	12.2	51.6	11.3	92.2%	8.2
3. HVO	14.0	49.9	12.8	91.4%	9.3
4. Plug-in hybrid	8.0	55.8	7.4	92.7%	5.4
5. E85 (bioethanol)	10.7	53.1	9.9	92.1%	7.2
6. Euro6/VI diesel	9.5	54.3	8.7	91.8%	6.4
7. Electricity	3.9	59.9	3.7	94.4%	2.7

Comparison with previous study

In the 2018 study, CE Delft concluded that the total costs of road traffic-related air pollution in the EU28 in 2016 were between 67 and 80 billion euros and that due to policies in place, external costs from air pollution would drop to 20 to 26 billion euro in 2030. The updated cost figures in this study are in the same order of magnitude, but somewhat lower.

There are a number of reasons for this:

- The current study looks at the EU27 whereas the 2018 study looked at EU28. Approximately 10% of emissions and external costs from air pollution are now excluded from the analysis.

- A new baseline scenario from GAINS was used to calculate the trend in emissions between 2016 and 2030. The NAPCP baseline assumes a stronger decrease in emissions as a result of more effective and ambitious (national) measures.

5.2 Costs of other external effects

Transport causes other externalities than air pollution alone. In this section, we extend the scope of external costs with the following additional impacts (for more details see Chapter 2):

- **well-to-tank emissions from air pollution,** the WTT emissions from NO_x and PM have been quantified in Chapter 4 as we have seen but were not yet part of the calculation of the external costs carried out in the previous section;
- **well-to-tank CO_2 emissions**, the costs of well-to-tank CO_2 emissions;
- **tank-to-wheel CO_2 emissions**, the costs of tank-to-wheel CO_2 emissions;
- **accidents**, direct, indirect and intangible costs of traffic incidents, both fatalities and injuries (hospitalisations);
- **noise**, engine and tyres on surfaces are the main sources of noise pollution which besides nuisance can result in health damage;
- **congestion**, and traffic delays resulting in a loss of time.

In Table 18, the external costs (analogous to Table 17) are shown with the added external cost elements. The year 2016 and 2030 baselines are given plus the seven fuel technology scenarios. Overall is it very noticeable that the total level of external costs increases from 64 billion to 721 billion euros when the additional external impacts are included. Accidents (261 billion euro) and congestion (241 billion euro) add the most to the overall external costs.

Between 2016 and 2030 we observe an autonomous drop in external costs from 721 billion to 605 billion euros. This drop is dominantly the result of the reduction of air pollutants and climate impacts, as vehicles become on average less polluting and more fuel-efficient (and partly due to the market penetration of zero-emission vehicles).

Consistent with the findings in the previous section we see that several fuel/drivetrain options result in external cost reductions compared to the baseline levels. More specifically we see that:

- Well-to-tank air pollution costs decrease in scenarios 1 (CNG/LNG) and 7 (EV) but remain more or less constant in Scenarios 2 (LPG), 4 (plug-in hybrid) and 6 (Euro 6/VI) and even increase in Scenarios 3 (HVO) and 5 (E85).

- External costs from tank-to-wheel CO_2 emissions show a substantial drop in Scenario 3 (HVO) and 7 (ZE) only. Scenarios 1, 2, 4, 5 and 6 lead to a much lower reduction of external costs from climate impacts. None of the scenarios results in an increase in external costs from CO_2 emissions, compared to the baseline.

- Full-electric vehicles (Scenario 4) make less noise at lower speeds as at these speeds combustion engines noise levels are dominant over tire noise. Therefore, this scenario has slightly lower noise costs[14].

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[14] Plug-in hybrids also have lower noise costs when driving using the electric motor. However, we were not able to quantify this due to insufficient information about real-life noise production levels of plug-in hybrid vehicles for all vehicle types.

- Consistent with the methodology outlined in Chapter 3, we see no differences per scenario for accidents and congestion (same level as in the baseline). We would recommend gathering data on the Member States or even city-specific congestion information to finetune these results.

- Including additional external impacts in the external cost calculations on top of external costs from air pollution, shows a larger potential to reduce these costs when replacing diesel with alternative fuels and drivetrains, especially with electric vehicles. For policymakers, this serves as an additional justification for policy measures to replace diesel use in road transport.

- External cost reductions range between 5 billion euros (Scenario 6) and 45 billion euros (Scenario 7). Looking only at external costs from air pollution reveals external cost reductions ranging from 0 to 10 billion euros. Expanding the scope of external costs can therefore provide an argument (and justification to the public) for policymakers to introduce additional measures to curb road transport emissions and allocate a greater budget for these measures.

- Although not part of this study, we can confidently state that non-technical measures leading to fewer motorised movements, like promoting active mobility (walking and cycling), can lead to even greater reductions in external costs from transport, as this leads to fewer traffic accidents, emissions, noise, and less congestion.

Table 18 - External costs of petrol and diesel transport in 2016 and 2030 for different scenarios (costs in billion euros)

	Tank-to-wheel air pollution	Well-to-tank air pollution	Well-to-tank CO_2	Tank-to-wheel CO_2	Accidents	Noise	Congestion 2016	Total external costs	Reduction compared to 2030
2016									
	64	6	22	72	261	56	241	721	
2030									
Baseline	14	4	17	54	236	54	221	600	
1. CNG/LNG	9	2	10	46		54		578	3.6%
2. LPG	12	4	13	51		54		592	1.3%
3. HVO	14	6	10	18		54		559	6.8%
4. Plug-in hybrid	8	4	19	45		54		588	2.0%
5. E85 (bioethanol)	11	8	18	41		54		589	1.8%
6. Euro 6/VI diesel	9	4	17	53		54		595	0.9%
7. ZE vehicles	4	3	27	17		46		555	7.4%

6 Conclusions

In this report, we have looked at the impacts of diesel road transport on external costs and the extent to which different fuel types and vehicle technologies can reduce these external impacts. In this final chapter, we summarise the conclusions that were drawn in the previous chapters.

Before we start summing up the conclusions, recall that there are many different fuel and drivetrain combinations which potentially could replace diesel vehicles. In examining the pros and cons of adopting these fuels, it is important not to overlook the consequences of their use on, among other things, air quality. The aim of the scenarios is therefore to look at the impacts on air pollution, external costs, and health impacts in particular when replacing diesel with alternative fossil or biobased fuels. In order to make a comprehensive comparison, we also include a 'zero-emission' scenario in which diesel vehicles are replaced by full-electric vehicles. Also, recall that the seven scenarios constructed in this study are hypothetical and aim to reveal the maximum potential of diesel substitution: they do not reflect likely realistic fleet developments. Also, be aware that numbers in the tables in this report may not add up due to rounding.

We now continue with the main conclusions.

Substituting diesel vehicles with zero-emission vehicles is a very effective way to reduce the impact of air pollution and associated external costs
When comparing the seven scenarios examined in this study, it is clear that substituting diesel vehicles with full-electric vehicles is the most effective option to reduce tank-to-wheel emissions and associated external costs. The zero-emission scenario is roughly twice as effective as the second-best scenario. This conclusion is still valid when we include well-to-tank emissions, i.e. the air pollution associated with the production of fuels/energy carriers.

Plug-in hybrid and natural gas can reduce NO_x emissions-related external costs from road transport, but to a lesser extent than full-electric vehicles
Of the non-zero-emission scenarios, diesel substitution with either plug-in hybrid vehicles or compressed natural gas (CNG) and liquid natural gas (LNG) deliver the relatively largest reduction of NO_x emissions and associated external costs[15]. However, due to the co-benefits with climate impact, a shift toward zero-emission vehicles remains preferable. Tank-to-wheel PM emissions on the other hand are reduced far less with CNG and LNG. Moreover, for natural gas, there are concerns about the level of ultrafine particles and associated health impacts which could not be explicitly modelled and quantified in this study. PM emissions would also be reduced by replacing older diesel vehicles with the newest Euro 6 and Euro VI standard vehicles or plug-in hybrid vehicles, although this is much less effective than replacing them with zero-emission vehicles.

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[15] This is without taking into account the possibly higher ultrafine particle emissions of CNG and LNG vehicles.

Renewable petrol and diesel substitutes deliver little in terms of reducing air pollution-related external costs from transport
Both hydrotreated vegetable oil (HVO) and ethanol (E85) have limited benefits in terms of replacing diesel use. For HVO, this is because this fuel type can be used in the current vehicle fleet and the exhaust emissions remain practically the same whether regular diesel or HVO is used. Provided HVO is produced from truly renewable sources, it has substantial benefits in terms of reducing well-to-wheel emissions. We should note that in the more distant future when electricity production is expected to shift to higher shares of renewable production, the relative advantage of HVO will decrease. For E85, a petrol substitute, the limited impact on air pollution-related costs, results from the fact that only passenger cars are eligible for this type of fuel. Light commercial vehicles and heavy-duty vehicles cannot benefit from this fuel type.

Countries with an on average older vehicle fleet benefit more from a shift toward alternative fuels and vehicle technologies
As could be expected, an older vehicle fleet, and particularly a low share of Euro 6 passenger cars and LCV's and Euro VI heavy-duty vehicles, leads to higher emissions in the baseline and consequently to a greater impact of alternative fuel and drivetrain scenarios.

Broadening the scope of external costs from road transport reveals a much larger potential for reduction and policy intervention
Including additional impacts in the external cost calculations on top of external costs from air pollution shows a larger potential to reduce these costs when replacing diesel with alternative fuel and drivetrains. Expanding the scope of external costs can therefore provide an argument (and justification to the public) for policymakers to introduce additional measures to curb road transport emissions and allocate a greater budget for these measures. External cost reductions range between 5 billion euros (Scenario 6) and 45 billion euros (Scenario 7). Looking only at external costs from air pollution reveals external cost reductions ranging from 0 to 10 billion euros.

Further reductions in external costs possible with non-technical policy interventions
As an aside, we can confidently state that non-technical measures, like promoting active mobility (walking and cycling), leading to fewer motorised movements are very likely to lead to even greater reductions in external costs from road transport if this leads to fewer traffic accidents and less congestion.

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A Emission factors

In the different technology scenarios, diesel-fuelled vehicles are exchanged for different technology. The main goal of this exercise is to compare the emissions of different pollutants and the external costs. In order to make this comparison, the relative performance of certain technologies concerning the emission of different pollutants needs to be estimated. The emission factors which were used for these calculations are presented in this annexe.

The tank-to-wheel emission factors for NO_x and PM_c (combustion) are presented in Table 19 to Table 22. The emissions are presented as a percentage relative to the emissions of diesel Euro 6. Since the diesel fleet in 2030 is different for each country (see Annex B for the fleet composition per country), the emission factors in the baseline scenario are unique for each country. For this reason, a baseline emission factor is included for each country. For HVO, the tank-to-wheel emissions were assumed to be equal to the emissions of diesel vehicles. Therefore, these emission factors are equivalent to the country-specific emission factors for diesel, which are included in the table. The content of these tables is for the most part based on *STREAM Freight Transport 2020* (CE Delft, 2021). Some emission factors for passenger transport are not included in this study. In these cases, the emission factors were constructed with the use of (Geilenkirchen et al., 2020). The absolute emission factors for diesel Euro 6 vehicles are also in line with this source.

The tank-to-wheel CO_2 emissions and all well-to-tank emissions were calculated from the energy use per fuel type. These emission factors are corrected for the current average use of biofuels in the fuel mix. Table 23 contains an overview of these emission factors.

The emissions related to electricity production depend on the electricity mix per country: if a country has a higher share of renewables in the electricity mix, the corresponding emission factors are lower[16]. Table 24 to Table 26 present the assumed emission factors of electricity production in 2030 per country.

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[16] For a precise calculation of thee mission factors, different types of electricity generation such as coal, natural gas, wind, biomass, etc. should be distinguished. However, because this data was not available for all countries, we have chosen to estimate the share of renewables per country based on (IRENA, 2015).

Table 19 - Tank-to-wheel emission factors of *passenger cars*

	Energy (MJ/km)	NO$_x$ (g/km)	PM$_c$ (g/km)
Diesel Euro 6d	2.11	0.09	0.00
Diesel EU27	103%	255%	195%
Diesel Bulgaria	108%	491%	1172%
Diesel Estonia	104%	274%	265%
Diesel France	103%	229%	209%
Diesel Germany	100%	164%	129%
Diesel Hungary	100%	134%	101%
Diesel Poland	101%	158%	146%
Diesel Romania	102%	175%	217%
Diesel Slovenia	102%	266%	201%
Diesel Spain	103%	255%	195%
CNG Euro 6	76%	64%	244%
LPG Euro 6	90%	93%	234%
Plug-in hybrid Euro 6	77%	13%	147%
E100/E85 flex Euro 6	104%	23%	120%
Electricity	47%	0%	0%
Petrol Euro 6	104%	23%	120%

Table 20 - Tank-to-wheel emission factors of *light commercial vehicles*

	Energy (MJ/km)	NO$_x$ (g/km)	PM$_c$ (g/km)
Diesel Euro 6d	2.16	0.13	0.002
Diesel EU27	101%	204%	295%
Diesel Bulgaria	101%	470%	1501%
Diesel Estonia	101%	318%	551%
Diesel France	100%	125%	100%
Diesel Germany	100%	157%	212%
Diesel Hungary	101%	312%	770%
Diesel Poland	101%	226%	327%
Diesel Romania	101%	171%	284%
Diesel Slovenia	100%	127%	101%
Diesel Spain	101%	204%	295%
CNG Euro 6	97%	41%	228%
Plug-in hybrid Euro 6	88%	80%	180%
Electricity	47%	0%	0%

Table 21 - Tank-to-wheel emission factors of *heavy-duty vehicles*

	Energy (MJ/km)	NO$_x$ (g/km)	PM$_c$ (g/km)
Diesel Euro VI	11.70	2.22	0.012
Diesel EU27	100%	135%	141%
Diesel Bulgaria	98%	212%	433%
Diesel Estonia	99%	168%	197%
Diesel France	100%	137%	161%
Diesel Germany	100%	127%	135%
Diesel Hungary	100%	137%	148%
Diesel Poland	98%	191%	297%
Diesel Romania	98%	181%	238%
Diesel Slovenia	100%	133%	143%

	Energy (MJ/km)	NO_x (g/km)	PM_c (g/km)
Diesel Spain	100%	135%	141%
LNG Euro 6	112%	74%	100%
Plug-in hybrid Euro 6	89%	80%	80%
Electricity	47%	0%	0%

Table 22 - Tank-to-wheel emission factors of *buses*

	Energy (MJ/km)	NO_x (g/km)	PM_c (g/km)
Diesel Euro VI	11.12	0.75	0.01
Diesel EU27	101%	151%	169%
Diesel Bulgaria	103%	366%	468%
Diesel Estonia	103%	349%	410%
Diesel France	100%	106%	108%
Diesel Germany	101%	151%	169%
Diesel Hungary	101%	214%	229%
Diesel Poland	102%	239%	279%
Diesel Romania	102%	267%	297%
Diesel Slovenia	101%	137%	146%
Diesel Spain	101%	139%	147%
CNG	112%	81%	112%
Electricity	47%	0%	0%

Table 23 - Emission factors based on fuel use

	Tank-to-wheel	Well-to-tank		
Fuel type	CO_{2e} (g/MJ)	CO_{2e} (g/MJ)	NO_x (g/MJ)	PM_{10} (g/MJ)
Diesel	68.9	22.1	0.033	0.0036
Petrol	70.4	20.7	0.049	0.0060
LPG	66.8	6.9	0.045	0.0031
HVO	1.1	9.4	0.050	0.0080
CNG	59.1	9.2	0.006	0.0001
LNG	59.1	14.4	0.027	0.0011
Ethanol	0.0	29.4	0.160	0.0295

Table 24 - NO_x emissions of electricity production

NO_x emissions (g/MJ)	2016	2020	2030
EU27	0.07	0.06	0.06
Bulgaria	0.08	0.08	0.08
Estonia	0.08	0.07	0.05
France	0.08	0.07	0.06
Germany	0.07	0.06	0.05
Hungary	0.09	0.09	0.09
Poland	0.08	0.08	0.08
Romania	0.06	0.05	0.05
Slovenia	0.07	0.06	0.06
Spain	0.06	0.06	0.05

Table 25 – PM_{10} emissions of electricity production

PM_{10} emissions (g/MJ)	2016	2020	2030
EU27	0.004	0.004	0.003
Bulgaria	0.004	0.004	0.004
Estonia	0.005	0.004	0.003
France	0.004	0.004	0.003
Germany	0.004	0.003	0.003
Hungary	0.005	0.005	0.005
Poland	0.005	0.005	0.004
Romania	0.003	0.003	0.003
Slovenia	0.004	0.004	0.003
Spain	0.003	0.003	0.003

Table 26 - CO_{2e} emissions of electricity production

CO_{2e} emissions (g/MJ)	2016	2020	2030
EU27	108	103	90
Bulgaria	125	124	121
Estonia	131	115	74
France	125	117	96
Germany	105	97	79
Hungary	143	142	139
Poland	134	131	124
Romania	89	87	82
Slovenia	105	102	96
Spain	98	91	74

B Euro classes per country in 2030

In the ‘NAPCP’ scenario of GAINS, which was used as a baseline in this study, for each country, a distinct distribution of Euro classes per vehicle type is assumed. Since the emissions per used fuel depend on the Euro class of the vehicle, the countries with an older fleet have relatively high emissions. A direct result of this is that, when replacing vehicles in countries with an old vehicle fleet, the potential emission reductions are relatively high. For this reason, we include an overview of the assumed fleet composition for diesel vehicles per country[17]. These are included in Table 27 to Table 30.

Table 27 - Fleet composition of diesel passenger cars in 2030

% of fleet - passenger car	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5	Euro 6	Euro 6d
EU27	0	0	2	6	17	8	67
Bulgaria	1	12	11	11	16	34	15
Estonia	0	0	4	11	14	10	61
France	0	0	3	6	11	8	72
Germany	0	0	1	2	3	11	83
Hungary	0	0	0	0	4	4	92
Poland	0	0	1	2	4	5	87
Romania	0	0	3	6	3	5	83
Slovenia	0	0	2	4	16	15	62
Spain	0	0	2	6	17	8	67

Table 28 - Fleet composition of diesel LCV’s in 2030

% of fleet - LCV’s	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5	Euro 6	Euro 6d
EU27	0	0	3	4	8	4	80
Bulgaria	1	12	11	11	16	34	15
Estonia	0	1	4	15	13	6	61
France	0	0	0	1	1	15	83
Germany	0	1	1	3	5	4	87
Hungary	0	2	9	14	9	3	63
Poland	0	1	3	5	11	0	80
Romania	0	0	3	6	4	0	88
Slovenia	0	0	0	1	3	8	88
Spain	0	0	3	4	8	4	80

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[17] For the EU27, no fleet composition could be downloaded from the GAINS database. Therefore, the composition was estimated based on the activity data and emissions which could be downloaded.

Table 29 - Fleet composition of diesel HDV's in 2030

% of fleet - passenger car	Euro I	Euro II	Euro III	Euro IV	Euro V	Euro VI
EU27	0	0	0	2	6	92
Bulgaria	3	2	9	10	17	59
Estonia	0	0	3	6	19	72
France	0	0	1	1	4	94
Germany	0	0	0	0	1	99
Hungary	0	0	0	2	6	92
Poland	1	2	6	10	14	67
Romania	0	0	6	12	11	72
Slovenia	0	0	0	1	4	95
Spain	0	0	0	2	6	92

Table 30 - Fleet composition of diesel buses in 2030

% of fleet - passenger car	Euro I	Euro II	Euro III	Euro IV	Euro V	Euro VI
EU27	0	1	2	2	3	92
Bulgaria	2	4	9	10	17	58
Estonia	0	4	7	12	19	58
France	0	0	0	0	2	98
Germany	0	1	2	2	3	92
Hungary	0	1	2	7	11	78
Poland	1	1	5	6	11	76
Romania	0	1	7	10	9	73
Slovenia	0	0	1	1	5	93
Spain	0	0	1	2	5	92