

# **EU ROAD VEHICLE ENERGY CONSUMPTION AND CO2 EMISSIONS BY 2050**

**EXPERT-BASED SCENARIOS**

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## **Abstract**

To inform long-term policies on transport decarbonisation, the present paper analyses vehicle technology and operation options for European road transport CO<sub>2</sub> emission reduction by 2050. The investigation focusses on measures improving tank to wheel vehicle efficiency, but takes into account upstream emissions of electric vehicles. Measures for vehicle efficiency improvement, transport smoothing, and transport reduction, as well as possible 2050 road vehicle fleet compositions have been quantified through group discussion in the European Road Transport Advisory Council, composed of automotive industry, research and public authorities' representatives. Expert knowledge is combined with fleet impact modelling to calculate scenario results.

Outcomes show that tank to wheel road transport CO<sub>2</sub> emission reductions of up to 90% versus 1990 could be reached by 2050 through strong fleet electrification and if all measures achieve their best potential. Under ambitious fleet electrification scenarios, a CO<sub>2</sub> reduction of more than 60% is reached without measures, but causes substantial additional demand for low-carbon electricity. The study provides an outlook on the amounts of electricity and chemical fuels needed, but does not address the question of if and how the energy carriers can be produced on a low-carbon basis.

## **Highlights**

Ambitious EU road transport CO<sub>2</sub> reductions are technically feasible by 2050.

This requires a combined approach of fleet electrification and measures.

Electrification reduces CO<sub>2</sub>, vehicle and transport measures limit energy demand.

High demand of low-carbon electricity poses a substantial energy sector challenge.

A combined expert elicitation and modelling approach has been employed.

## Keywords

Road transport, CO<sub>2</sub> emissions, electrification, decarbonisation, modelling, expert discussion

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The scientific output expressed does not imply a policy position of the European Commission, nor a position of any of the institutions where authors are affiliated.

## Declaration of interest

Declarations of interest: none

## Abbreviations

CI	<i>Compression Ignition</i>
CV	<i>Commercial Vehicle</i>
DI	<i>Direct Injection</i>
DSL	<i>Diesel</i>
EP	<i>European Parliament</i>
ERTRAC	<i>European Road Transport Advisory Councils (ERTRAC)</i>
GHG	<i>Greenhouse Gas</i>
GSL	<i>Gasoline</i>
HCV	<i>High Capacity Vehicle</i>
HDV	<i>Heavy Duty Vehicle</i>
ICE	<i>Internal Combustion Engine</i>
LCV	<i>Light Commercial Vehicle</i>
LDV	<i>Light Duty Vehicle</i>
LEV	<i>Low Emission Vehicle</i>
MDT	<i>Medium Duty Truck</i>
PtX	<i>Fuels derived via Power to Liquid or Gas</i>
Rpm	<i>Revolutions per minute</i>
SI	<i>Spark Ignition</i>
TC	<i>Turbocharged</i>
TtW	<i>Tank to Wheel</i>
WHR	<i>Waste Heat Reduction</i>
WLTP	<i>Worldwide Harmonised Light Vehicle Test Procedure</i>
WtW	<i>Well-to-Wheel</i>
xEV	<i>Advanced Electrified Vehicles, comprising:</i>
BEV	<i>Battery Electric Vehicles</i>
FCEV	<i>Fuel Cell Electric Vehicles</i>
PHEV	<i>Plug-In Hybrid Electric Vehicles</i>

## Scenarios

HE	<i>High Electrification</i>
HEH	<i>High Electrification plus Hydrogen</i>
Mix	<i>Mixed scenario</i>

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## 1 - Introduction

The transport sector is confronted with the challenge of reducing emissions while transport demand grows at the same time. Road transport is currently the second largest source of CO<sub>2</sub> emissions in the European Union (EU), accounting for around a quarter of total emissions (EEA, 2018). About 94% of EU transport energy needs are covered by oil as of today (EC, 2016a). In the absence of ambitious steps towards decarbonisation, the 2016 EU Reference Scenario highlights that by 2050 road transport could account for the largest share of CO<sub>2</sub> emissions (EC, 2016c). This is partly due to a projected growth in transport demand of 40% for passenger transport and nearly 60% for freight transport between 2010 and 2050, according to the EU Reference Scenario.

Such trends contrast with the long-term goal to limit global warming to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C, as embraced by the EU with the ratification of the Paris agreement in 2016 (EC, 2016b). Recently, the European Commission has reinforced the commitment to transport decarbonisation with its Communication on a low-emission mobility strategy (EC, 2016a), which emphasizes the need to increase the efficiency of the transport system, deploy low-emission alternative energy for transport, and move towards low- and zero-emission vehicles. The EU has recently decided on post-2020 CO<sub>2</sub> standards for passenger cars and vans and the first European CO<sub>2</sub> standards for new trucks. Despite the clear need and political intention to move towards a low-carbon transport sector, efforts are hampered by uncertainty on key aspects such as necessary enabling conditions and technology options available. One key uncertainty for transport electrification is battery development and related prices. Recent findings have shown that battery costs may be declining more strongly than previously anticipated (Nykqvist & Nilsson, 2015; Bloomberg, 2017). Edelenbosch et al. (2018) find that electric vehicle market penetration strongly depends on battery costs, with uptake scenarios ranging from insignificant towards near-full 2050 electric vehicle market penetration in the absence of climate policy, depending on the battery cost trajectory.

Such uncertainties are reflected in the wide range of future market uptake scenarios of electrified powertrains found in literature. The European Climate Foundation (2016) showed a range of scenario assumptions on 2030 advanced electric vehicle sales shares from 15% to 85%. Recent EU policy has narrowed down the 2030 range at the lower end, setting benchmarks of 35% of zero- and low-emission vehicles for cars and 30% for vans in the 2030 new vehicle fleet (EU 2019), whereas in 2016, battery electric vehicles and plug-in hybrids represented only 1.1% of the new EU car fleet (EC 2017). There is still a lot of uncertainty with regard to the further development throughout 2050. Siskos et al. (2018) present energy system model scenarios for reaching a 60% transport greenhouse gas reduction in the EU by 2050. They show that 2050 electric car shares (battery electric, plug-in hybrid and fuel cell electric vehicles combined) would be 70% of car stock in an optimal trajectory, but would have to be higher than 90% if sluggish uptake occurs in the decade to come. Similarly, the EU28 decarbonization scenario presented by Karkatsoulis et al. (2017) shows a 70% stock share of battery and plug-in electric cars by 2050. While strong electrification is an option considered for light duty vehicles, studies find that ambitious truck decarbonisation remains challenging throughout 2050 (Dray et al. 2012, Siskos et al. 2018, Karkatsoulis et al. 2017).

The objective of the present paper is to provide an assessment for the CO<sub>2</sub>-reduction potential of vehicle technology and operation measures as contribution to a 2050 low-emission road transport system, aiming to contribute to the understanding of technically feasible solutions and of the relative effects of different measures. Intentionally, these investigations focus on vehicle technology and operational aspects primarily influencing the tank to wheel part of energy consumption and related CO<sub>2</sub> emissions. Upstream emissions of electricity production for electric vehicles are also calculated, using conventional knowledge. For the different scenarios and technologies considered, the study provides an overview on the amounts of electricity and

chemical energy carriers needed to operate a 2050 low-emission road transport vehicle fleet. The question if, how, and to what extent electricity and chemical energy carriers can be provided on a low carbon or even zero carbon basis is beyond the scope of the present investigation.

The approach is based on vehicle technology modelling techniques complemented by and interlinked with experts' knowledge of technologies and trends in vehicle technology and transport today. Baseline fleet specifications are taken from a fleet impact model, and expert group assessment is used to specify different feasible 2050 scenarios with regard to vehicle efficiency, transport demand and flow, as well as fleet composition. Fleet impact modelling is employed to assess scenario impacts on energy consumption, CO<sub>2</sub> emissions, and the degree to which policy targets can be fulfilled. This approach allows identifying main drivers of transport decarbonisation, to quantify and compare their impacts, separately as well as combined, and to point out major sources of uncertainty as well as research and development needs at an early stage. Results can inform policy with regard to feasible long-term targets, strategies to achieve them, and existing knowledge gaps.

The present study employs an approach that is not commonly used for investigating vehicle fleet scenarios and their energy consumption and emission impacts. In literature, fleet scenarios are typically model outputs, driven for example by past trends (e.g. Zachariadis *et al.*, 1995), assumed policies, price development or infrastructure availability. They can result from energy system models (e.g., *EU reference scenario 2016* (EC, 2016c), *EUCO27 and EUCO30 Scenarios* (E3MLab & IIASA, 2016), systems dynamics models (e.g., Harrison *et al.*, 2016a; Harrison *et al.*, 2017; Pasaoglu *et al.*, 2016; Shafiei *et al.*, 2012), simulation models (Kloess and Mueller, 2011), or user choice models (Kihm and Trommer, 2014). In other cases, assumptions are made based on a what-if approach (Thiel *et al.*, 2014; Pasaoglu *et al.*, 2012) or derived via extrapolation techniques (Sorrentino *et al.*, 2014). The present analysis, which is strongly based on the assessment of available options and their technical and market potentials and combines them with engine and vehicle modelling, complements previous analyses by investigating technical feasibility and boundaries. The main focus of the paper is therefore on technical measures and their tank to wheel impacts on energy consumption and emissions.

#### The paper is structured as follows:

- Section 2 explains the methods and data employed and the modelling approach, covering baseline settings, scenario development, and energy consumption and CO<sub>2</sub> emission calculation methodology.
- Section 3 presents the results regarding 2050 fleet activities, energy consumption and mix, and CO<sub>2</sub> emissions in different scenarios.
- The paper then concludes, outlines the study's scope and policy implications as well as need for further research in Section 4.

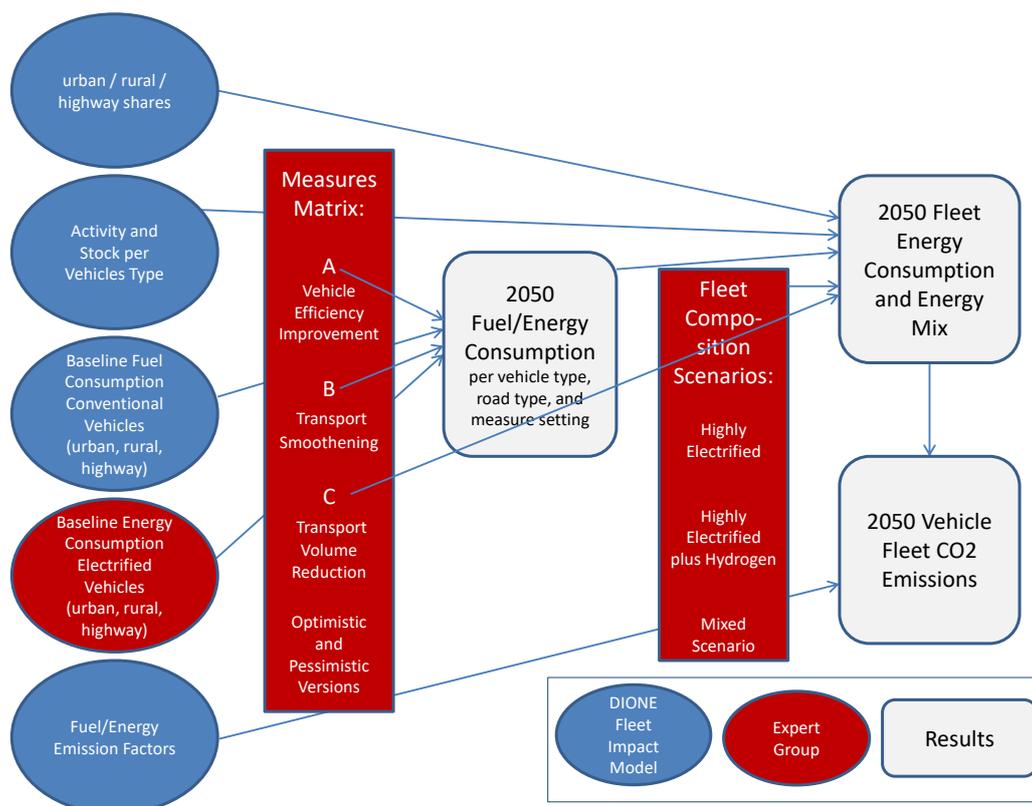
## 2 - Methodology and Data

In this section, the research methodology and the inputs used are described. First, an overview of the building blocks of the analysis and their interaction is given, followed by two sub-sections describing the methods and data employed to define the baseline and develop the scenarios, respectively. Two further sub-sections explain the fleet energy consumption and emission calculation from a tank to wheel perspective and the approach for estimating well to tank emissions of electrified vehicles.

### 2.1 Overview of the Approach

The study addresses road transport in 2050 with regard to vehicle fleet composition options, the efficiency of different vehicle technologies, and vehicle activities. This is done by defining a baseline scenario for 2050, then making scenario assumptions on measures that could be employed and their impacts as well as fleet penetration potential, and finally calculating 2050 road transport energy consumption and emissions under the different scenario settings.

**Figure 1** depicts the building blocks of the analysis. The bubbles on the left hand side show input parameters used to specify baseline conditions. Scenarios are derived from assumptions on measures to increase vehicle efficiency, transport efficiency, and activity represented in the first red box, and 2050 road vehicle fleet composition, as depicted in the second red box. Fleet impact modelling is employed to combine these inputs and calculate single vehicle as well as fleet energy consumption and CO<sub>2</sub> emissions in 2050. These elements are described in detail in the following sections.



**Figure 1: Flowchart of the study approach**

This study is based on two main sources for data, assumptions and calculation methodology, namely the **DIONE** fleet impact model, indicated by the blue shading of most bubbles in **Figure 1**,

and expert assessment complemented by vehicle modelling used in particular for defining scenarios, as indicated by red shading.

The **DIONE** fleet impact model (see Thiel et al., 2016; Harrison et al, 2016b) is developed and run at the European Commission's Joint Research Centre (JRC). It is based on the software Sibyl (Katsis et al., 2012), which has been developed from an earlier model version ("ForeMove", see Zachariadis and Samaras, 1999; Samaras et al., 1999). It is a road transport fleet projection tool that allows analysing scenarios of road vehicle stock, activity, energy consumption and CO<sub>2</sub> as well as air pollutant emissions up to 2050.

Expert group discussion was employed to derive consensus stakeholder assessment for key input parameters, and was held within the European Road Transport Advisory Council's (ERTRAC<sup>1</sup>) CO<sub>2</sub> working group, which offered a unique opportunity to establish a long-term, thorough group discussion process involving experts from industry, research and public authorities as well as different disciplinary backgrounds. The list of group members and their affiliations, as well as details on the group discussion process, are available in Annex 1.

## 2.2 Baseline definition

The elements of the baseline, i.e., fleet composition and activities, fuel and energy consumption are described in the following sections.

### 2.2.1 Vehicle types, stock and activity

In the present study, four vehicle categories are differentiated with regard to energy consumption, i.e.

- 2-wheelers; Small /medium size cars
- Large cars and SUVs, LCVs, Delivery vans < 7,5t
- City buses, MDT <12t
- Trucks > 7,5 t; Long distance buses

Each vehicle type can be either a conventional vehicle (CV, with spark ignition or compression ignition powertrain), or an advanced electrified vehicle (xEV), which comprises plug-in electric vehicles (PHEV), battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV). For each vehicle category and powertrain, fuel or energy consumption is specified for three driving profiles, i.e., urban, rural and highway operation conditions.

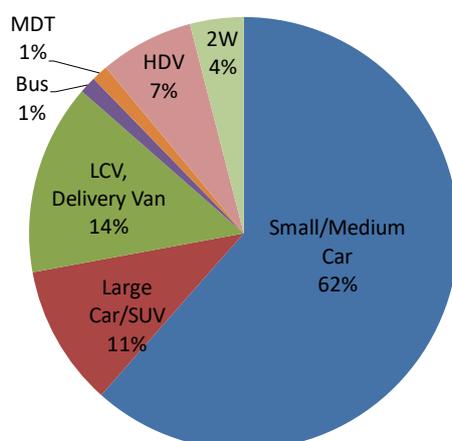
For the present study, 2050 total road vehicle fleet activity and stock was calibrated with the EU Reference Scenario 2016 (EC, 2016c), which is based on the assumption that the EU greenhouse gas and renewable energy targets for 2020 will be met and takes into account all policies agreed until 2014. The resulting 2050 baseline road transport activity amounts to a total of 5.1 trillion vehicle kilometres, which implies an increase by around 15% compared to today's road vehicle activity. Activity increases much more strongly in freight transport than in passenger transport (see **Table 1**).

**Table 1: 2050 Baseline Vehicle Activities, absolute values (trillion vkm) and changes compared to 2016 (% of 2016)**

	Baseline	
	trillion vehicle kilometers	versus 2016
Cars, LCVs & 2wheelers	4549	112%
Trucks, Vans, Busses	582	147%
<b>Total Road</b>	<b>5131</b>	<b>115%</b>

<sup>1</sup> ERTRAC is the European Technology Platform for road transport, which was set up to develop a common vision for road transport research in Europe, see <https://www.ertrac.org/>

Total activity is distributed to the vehicle categories based on the 2050 DIONE baseline activity distribution, shown in **Figure 2**. Nearly three quarters of total vehicle kilometres driven in 2050 are covered by passenger cars. A similar approach was followed for vehicle stock.



**Figure 2: Baseline 2050 road transport activity shares (% of vehicle-kilometres) by vehicle segment**

### **2.2.2 Baseline fuel consumption of conventional vehicles**

For conventional vehicles, it was assumed that 2050 baseline average fuel consumption of each vehicle type would be the same as the consumption of a 2015 new vehicle of the same type. This represents a diffusion of today's state of the art technology over the complete fleet by 2050, but no further efficiency improvement<sup>2</sup>.

Present new conventional vehicle fuel consumption by driving profile (urban, rural and highway) was taken from DIONE and is based on the COPERT<sup>3</sup> road transport emission inventory software. Using driving profile shares available from DIONE, weighted averages of fuel consumption for each vehicle type can be calculated. CO<sub>2</sub> emissions are derived using present fuel emission factors. The resulting baseline 2050 specific real-world fuel consumption and CO<sub>2</sub> emissions are shown in **Table 2**.

**Table 2: Baseline 2050 conventional vehicle fuel consumption, per vehicle segment and driving profile, and real world CO<sub>2</sub> emissions at present fuel greenhouse gas intensities, tank to wheel**

	Fuel	Urban Fuel Consumption (l/km)	Rural Fuel Consumption (l/km)	Highway Fuel Consumption (l/km)	Combined CO <sub>2</sub> Emissions, TtW (gCO <sub>2</sub> /km)
2-Wheeler / Small Car / Medium Car	GSL	0.07	0.05	0.06	135
Large Car / SUV	GSL	0.12	0.08	0.08	213
LCV / Delivery Van	DSL	0.10	0.07	0.12	252
Medium Duty Truck	DSL	0.21	0.15	0.16	450
Long Distance Bus	DSL	0.43	0.25	0.22	688
Heavy Duty Vehicle	DSL	0.38	0.25	0.24	678

<sup>2</sup> This assumption can be seen as a 'worst case' estimate. While it could be argued that some improvement over 2015 should occur due to 2021 and 2025/2030 new vehicle CO<sub>2</sub> standards already agreed in the EU, it is relatively difficult to predict what effect these targets, defined on the drive cycle, will have on vehicle real world energy consumption throughout 2050.

<sup>3</sup> For more information see: <http://emisiam.com/products/copert>

### **2.2.3 Baseline energy consumption of advanced electrified vehicles**

Similar to the approach followed for CV, energy consumption of present new xEV was used as a baseline for 2050 xEV fleet energy consumption, representing no further improvement. Their present energy consumption was calculated using a computational model available at BMW, and then confirmed in the expert group. The key vehicle specifications for BEV and FCEV and the resulting energy consumption are shown in **Table 3**.

**Table 3: Baseline 2050 Vehicle Specifications used for BEV and FCEV and resulting energy consumption**

	Cd*A [m2]	Mass [kg]	Powertrain efficiency [%]	Urban Energy Consumption [Wh/km]	Rural Energy Consumption [Wh/km]	Highway Energy Consumption [Wh/km]
Small car 2015 (Baseline)	0.32 x 2.5	1650	85	135	142	204
Large Car 2015 (Baseline)	0.3 x 2.8	2400	84	175	173	236

For Plug-in Hybrid Electric Vehicles (PHEV), fuel and energy consumption of the respective CV and BEV of the same segment were used for conventional mode and electric mode operation, respectively. The share of electric system operation per driving mode (urban, rural, highway) was estimated based on the assumptions that each trip will start in electrical mode and that urban trips are 100% electric. The remaining operation was assigned to combustion engine mode.

## **2.3 Scenario development**

Departing from the baseline, different scenarios are defined to explore the impact of measures on vehicle efficiency, transport efficiency, and activity, and of road vehicle fleet electrification by 2050, as specified in the following.

### **2.3.1 Vehicle and Transport Measures**

Different options exist to improve the efficiency of vehicles or of the transport system throughout 2050. In the present study, different measures were identified by the expert group, and their potential impacts by 2050 were quantified, based on quantitative modelling and expert knowledge. To capture uncertainty, for each measure, vehicle type, and drive profile, optimistic as well as pessimistic 2050 scenarios were developed. Optimistic represents the upper limit of the effect a measure could have according to the experts, and pessimistic gives the measures' minimum potentials. Note that the optimistic to pessimistic range for measures is used to cover uncertainty with regard to their potential by 2050 as prevails according to the experts. The potentials are technical properties of the measures and are independent of the degree of exploitation of the technologies.

The measures for reducing road transport carbon intensity can be bundled in three general categories:

## A - Vehicle efficiency improvement

Type “A” measures cover technical improvements that can be employed to increase the efficiency of engines or vehicle systems. For conventional vehicles, the effects of “A” type measures are specified in terms of percent savings in fuel consumption compared to 2015 baseline vehicles, which translates directly into percent CO<sub>2</sub> emissions. Measures considered include internal combustion engine efficiency improvement, efficiency improvement for xEV, waste heat recovery, energy management, hybridization, aerodynamics, weight and rolling resistance reductions. In most of these cases it was attempted to base the quantitative assessment of measures on engine and vehicle model calculations. For example, the assessment of combustion engine improvement for passenger cars involved the design of baseline and scenario engine maps and vehicle simulation in the **AVL CRUISE**<sup>4</sup> environment (see Annex A.2a for a detailed description).

The A measures applied on conventional engine operation and to vehicles considered in this study are listed in **Table 4**, which specifies their energy reduction potentials derived for each vehicle type and drive profile.

**Table 4: Energy consumption reduction potentials of measures of type A (vehicle improvement) and B (improvements of flow).**

The table specifies the share of energy consumption reduction of 2050 stock relative to 2015 reference vehicles when applying each measure separately.

Type	Measure	2-W; S/M Cars						L Cars, SUVs, LCVs, Vans < 7.5t						City Buses, Trucks <12t						Trucks > 7,5 t; Long Dist. Buses					
		Pessimistic			Optimistic			Pessimistic			Optimistic			Pessimistic			Optimistic			Pessimistic			Optimistic		
		U	R	H	U	R	H	U	R	H	U	R	H	U	R	H	U	R	H	U	R	H	U	R	H
A	Improvements gasoline engines	0.15	0.20	0.22	0.24	0.26	0.28	0.09	0.10	0.11	0.11	0.14	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A	Improvements diesel engines	0.10	0.15	0.20	0.15	0.18	0.23	0.08	0.09	0.10	0.10	0.12	0.14	0.03	0.04	0.04	0.05	0.07	0.09	0.03	0.04	0.04	0.05	0.07	0.09
A	Waste Heat Recovery	0.00	0.00	0.01	0.01	0.02	0.04	0.00	0.00	0.01	0.01	0.02	0.05	0.00	0.00	0.01	0.01	0.02	0.03	0.00	0.00	0.04	0.01	0.03	0.04
A	Total Vehicle Energy Management	0.01	0.01	0.00	0.04	0.02	0.02	0.01	0.01	0.00	0.04	0.02	0.02	0.01	0.01	0.00	0.04	0.02	0.02	0.01	0.01	0.00	0.06	0.03	0.03
A	Mild Electrification 48 Volt	0.04	0.02	0.00	0.08	0.04	0.02	0.06	0.03	0.00	0.10	0.06	0.02	0.03	0.02	0.00	0.05	0.03	0.01	0.02	0.01	0.00	0.03	0.02	0.01
A	Plug in Hybrid impr. in ICE mode	1.00	0.10	0.05	1.00	0.15	0.10	1.00	0.10	0.05	1.00	0.15	0.10	1.00	0.10	0.05	1.00	0.15	0.10	1.00	0.08	0.04	1.00	0.12	0.07
A	Improved Aerodynamics	0.00	0.02	0.04	0.01	0.03	0.07	0.00	0.02	0.04	0.01	0.03	0.07	0.01	0.01	0.02	0.01	0.02	0.05	0.02	0.03	0.05	0.04	0.07	0.10
A	Weight Reduction	0.05	0.03	0.02	0.10	0.07	0.05	0.07	0.05	0.04	0.15	0.11	0.08	0.05	0.03	0.03	0.10	0.06	0.06	0.03	0.02	0.02	0.06	0.03	0.03
A	Rolling Resistance	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.06	0.06	0.06
(A)	Rolling Resistance Pavement	0.00	0.00	0.00	0.02	0.02	0.02	0.00	0.00	0.00	0.02	0.02	0.02	0.00	0.00	0.00	0.02	0.02	0.02	0.00	0.00	0.00	0.02	0.02	0.02
B	Smoothering speed/Avoiding stops	0.05	0.05	0.05	0.15	0.15	0.15	0.05	0.05	0.05	0.15	0.15	0.15	0.05	0.05	0.05	0.15	0.15	0.15	0.05	0.05	0.05	0.15	0.15	0.15
B	Platooning	0.00	0.00	0.06	0.00	0.00	0.15	0.00	0.00	0.06	0.00	0.00	0.15	0.00	0.00	0.06	0.00	0.00	0.15	0.00	0.00	0.05	0.00	0.00	0.12

For BEV and FCEV, rather than applying improvement factors, 2050 energy consumption was calculated using the same vehicle modelling approach as for their baseline energy consumption, but improving their weight, aerodynamics and efficiency as specified in **Table 5**.

**Table 5: Vehicle Specifications used for Optimistic and Pessimistic 2050 Scenario BEV and FCEV and resulting energy consumption**

	Cd x A [m <sup>2</sup> ]	Mass [kg]	Power-train efficiency [%]	Urban Energy Consumption [Wh/km]	Rural Energy Consumption [Wh/km]	Highway Energy Consumption [Wh/km]
Small Car 2050, Pessimistic	0.25 x 2,5	1250	90%	94	99	145
Small Car 2050, Optimistic	0.19 x 2,3	1000	93	64	67	98
Large Car 2050, Pessimistic	0.26 x 2,75	2000	91	120	123	175
Large Car 2050, Optimistic	0.2 x 2,7	1700	94	86	87	125

<sup>4</sup> <https://www.avl.com/cruise>

## B - Improvements in traffic flow

Type “B” measures cover energy consumption or CO<sub>2</sub> reduction, again defined versus a 2015 baseline, due to improvements in driving conditions. The measures analysed were the overall potential for smoothing speed and avoiding stops in real traffic, e.g. through improving green light operation (see Annex A.2b for a detailed description of the modelling employed), and platooning. B measure impacts considered in this study are included in **Table 4**.

## C - Road transport reduction

Reductions in the kilometres driven, or in the numbers of vehicles on the road versus a 2015 baseline, are covered by type “C” measures. Measures considered in this study address reduced parking search traffic, intermodality of freight, coordination systems for freight, and increased truck capacity. The assumptions made for this study are quantified in **Table 6**. For a discussion of the estimates in the light of literature, see Annex A.2c.

**Table 6: Transport reduction potentials by 2050, versus 2015. Measures C(1) address reductions in activity per vehicle, measures C(2) reductions in the number of vehicles.**

*The table gives 2050 shares of reduction of the activity/number of vehicles over 2015 for each measure separately.*

Type	Measure	2-W; S/M Cars		L Cars, SUVs, LCVs, Vans < 7.5t		City Buses, Trucks <12t		Trucks > 7,5 t; Long Dist. Buses	
		Pessimistic	Optimistic	Pessimistic	Optimistic	Pessimistic	Optimistic	Pessimistic	Optimistic
C (1)	Reduced urban parking search traffic	0.04	0.1	0.02	0.06	0	0.02	0	0
C (2)	Intermodality of freight							0.02	0.05
C (1)	Coordination systems for freight (logistics)					0.05	0.1	0.05	0.1
C (2)	Increased truck capacity							0.05	0.1

The degree of implementation and the estimates of C measures’ impacts is much less elaborated compared to the efficiency measures. This was primarily due to the fact that projections of changes in the transport system as a whole were beyond the scope of the present exercise. Nevertheless, it is of importance to stress that there is a lack of fact-based research results regarding transport reduction and its consequent effects on CO<sub>2</sub> emissions from the introduction of measures such as ride-sharing, mobility as a service, autonomous vehicles and modal shifts. Therefore, these measures were not included in the study due to their inherent complexities and the corresponding high degree of uncertainty. Given the uncertainty in this area, transport reduction potentials were limited to low levels and will be further investigated in a follow-up step of the study.

### 2.3.2 Fleet compositions scenarios

Three 2050 road vehicle fleet composition scenarios by powertrain were established, varying in their degrees of fleet electrification. They can be described as follows:

- The **High Electrification (HE) scenario** describes a situation with maximum market uptake of plug-in hybrid electric vehicles (PHEV) and battery electric vehicles (BEV) all experts could agree on.
- The **High Electrification plus Hydrogen (HEH) scenario** also includes fuel cell electric vehicles (FCEV) running on hydrogen on top of the options in the HE scenario.
- The **Mixed (Mix) scenario** assumes substantially lower fleet electrification, where combustion-based propulsion dominates in most vehicle segments. No FCEV are considered. Shares of BEV are relatively modest; shares of PHEV and conventional vehicles are relatively high compared to the first two scenarios.

The HE and HEH scenarios, also named collectively “electrification scenarios” in the following, incorporate the fact that the EC transport white paper (EU, 2011) target of zero-emission urban transport by 2050 is reached. This fosters a combined 100% coverage of BEV, FCEV and PHEV powertrains in the car segments as well as for urban buses, light commercial vehicles, and medium duty trucks. For heavy duty vehicles and long-distance coaches, apart from PHEV and FCEV powertrains, hybridized advanced internal combustion engines remain an option throughout 2050. This study considers conventional fuel and liquid natural gas (LNG) versions. Gasoline was assumed to be the conventional fuel utilised for light duty vehicles and diesel for heavy duty.

These assumptions were made purely for simplicity and do not imply that these will be the fuels of choice in the future nor that ICEs are assumed to use only conventional fuels in 2050. In fact, fossil fuels are expected to be replaced by other types of chemical energy carriers such as renewable fuels, power-to-liquid etc. Finally, it was assumed that in 2050, combustion engines will have zero air pollutant emissions in real world driving. 2050 fleet composition for all scenarios is shown in **Table 7**.

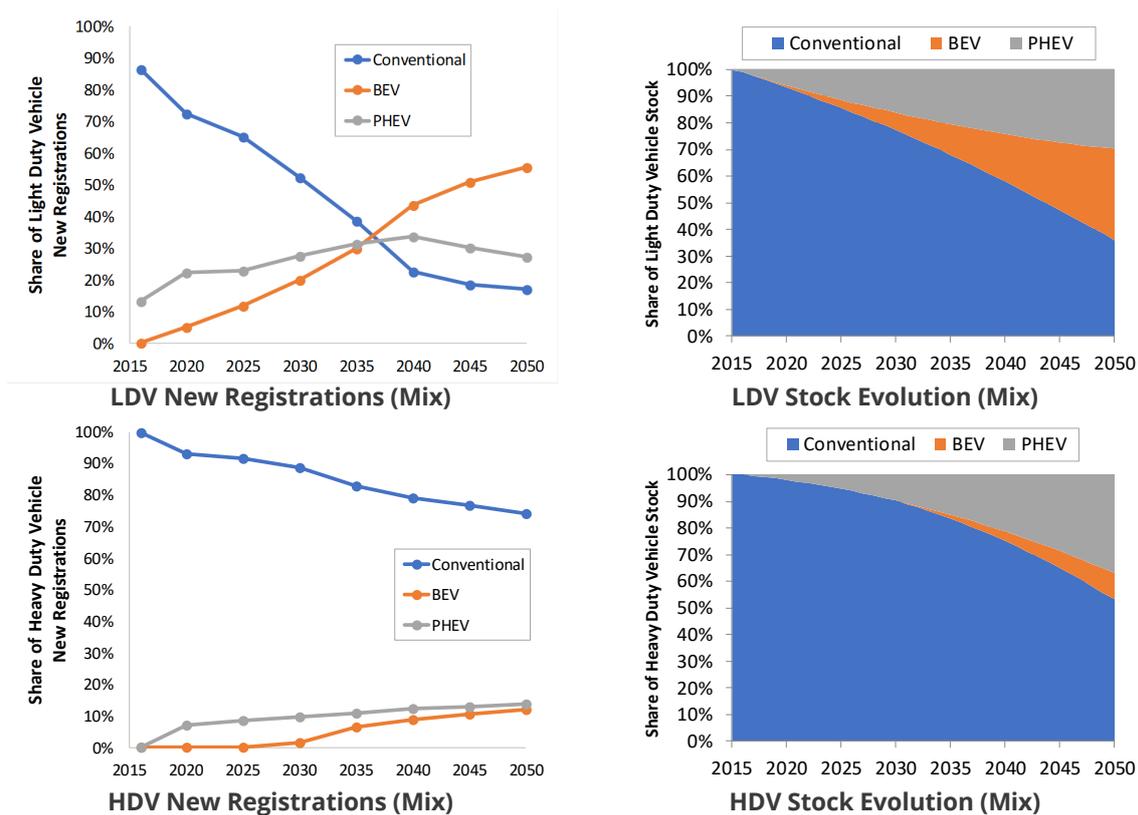
Advanced electrified car shares under the Mix scenario correspond roughly with what has previously been found necessary to reach a 60% decarbonisation of road transport in the EU by 2050 under optimal trajectories (Siskos et al. (2018), Karkatsoulis et al. (2017)), whereas the electrification scenarios HE and HEH show substantially stronger fleet electrification, which could result from a strong decline in battery costs, or else would need to be driven by stringent regulation (Edelenbosch et al. (2018)).

**Table 7: 2050 Fleet Composition for the scenarios HE/HEH/Mix (%); Powertrains and fuels: Adv. ICE – Advanced Internal Combustion Engine, PHEV – Plug-in Hybrid Electric Vehicle, BEV – Battery Electric Vehicle, FCEV – Fuel Cell Electric Vehicle, GSL – Gasoline, DSL – Diesel, LNG – Liquid Natural Gas. Light commercial vehicles and delivery vans (up to 7.5t) use the same measure efficiencies as the large car category but have a different fleet composition; Medium duty trucks (MDT, 7.5 to 12t) use the same measure efficiencies as city buses.**

	Small and Medium Car, 2W	Large Car, SUV	LCV, Delivery Van	City Bus	Medium Duty Truck	HDV, Coach
GSL adv. ICE	0/0/37.5	0/0/20	0/0/20			
DSL adv. ICE				0/0/0/50	0/0/15	40/40/60
GSL PHEV	0/0/25	50/25/60				
DSL PHEV			40/20/60		60/30/70	40/20/20
BEV	100/100/37.5	50/50/20	60/40/20	100/50/50	40/40/15	
FCEV		0/25/0	0/40/0	0/50/0	0/30/0	0/30/0
LNG						20/10/20

While the 2050 fleet composition scenarios were determined through expert group discussion, **Figure 3** illustrates trajectories of market uptake and stock composition for light duty (a, b) and heavy duty vehicles (c, d) compatible with 2050 fleet composition in the Mix scenario, assuming a roughly linearly increasing trend in BEV market shares and linearly decreasing trend in conventional vehicle shares.

As **Figure 3** (a) shows, the resulting shares of electrified vehicles in 2030 light duty vehicle (LDV) new registrations are 20% BEV and 28% PHEV, thus nearly half of all new 2030 LDV are advanced electrified vehicles (xEV) in the Mix scenario. To reach a 2050 stock composition as in the two electrification scenarios, xEV shares need to be substantially higher, which demonstrates the degree of ambition of the scenarios presented in this study.



**Figure 3: Exemplary market uptake and fleet composition trajectory for the Mix Scenario; for light duty vehicles (LDV - a,b) and heavy duty vehicles (HDV - c,d). Light duty vehicles comprise small cars, large cars, and vans, whereas heavy duty vehicles include busses, coaches, medium and heavy duty trucks.**

## 2.4 Tank to wheel fleet impact calculations

Calculations of 2050 road vehicle fleet tank to wheel energy consumption, energy mix and CO<sub>2</sub> emissions are based on the DIONE fleet impact model. To this aim, baseline fuel and energy consumption, vehicle activities and stock are transformed according to the scenario settings. The scenario-specific energy consumption per vehicle and driving profile is weighted by driving shares and combined with the fleet composition scenarios. The results are the real world energy consumption and mix, as well as tank to wheel real-world CO<sub>2</sub> emissions of the 2050 road vehicle fleet, calculated via the application of fuel and energy emission factors. The mathematical documentation of the fleet impact calculations is provided in Annex A.3. A graphical overview of the model inputs, interactions and outputs was shown in **Figure 1**.

The approach allows for applying single measures and for combining packages, in their optimistic and pessimistic variants respectively, resulting in a high number of possible scenarios. We limit the subsequent presentation of results to options where, for all three fleet composition scenarios,

- only one measure type (A, B or C) is applied, all optimistic or all pessimistic -> 3 measure types x 2 variants x 3 fleet compositions = 18 settings, or
- all measure types are applied, either all of them optimistic or pessimistic -> 2 variants x 3 fleet compositions= 6 settings.

## 2.5 Well to Wheel calculations for BEV and PHEV energy and CO<sub>2</sub>

While a full analysis of well to wheel (WtW) energy consumption and emissions for all powertrains is beyond the scope of this paper, a sensitivity calculation is carried out to highlight the order of magnitude of such impacts for BEV and PHEV. On top of battery to wheel electricity consumption addressed in the energy consumption calculation for xEV described in the previous section, electric vehicles require a higher total electricity production due to a series of losses, quantified in **Table 8**.

While power electronics and motor to wheel efficiency are included in the battery-to wheel calculations, grid to battery losses need to be factored in to calculate grid to wheel efficiencies. They can be derived as the product of grid, inverter and battery charging efficiencies from **Table 8**. A grid to battery efficiency of 86% is estimated for 2050, which means that total energy required is  $1/0.86 = 1.17$  times the amount of battery to wheel energy. Similar efficiencies are assumed for BEV and PHEV, and similar 2050 inverter and charging efficiencies for all vehicle segments. With the addition of vehicle to grid or grid-level energy storage, the efficiency could be significantly lower, however these are not accounted for in the present analysis.

**Table 8: Efficiency assumptions for electric vehicles throughout 2050, from grid to wheel. Source: ERTRAC (2017)**

	Grid Efficiency	Inverter AC/DC Efficiency	Battery Efficiency (Fast Charge)	Power Electronics Efficiency (DC/DC DC-AC)	Motor to wheel efficiency (WLTP)	Grid to wheel efficiency
BEV 2015 Range 250km	0.95	0.95	0.92	0.91	Min 0.86, Max 0.91	Min 0.65, Max 0.69
BEV 2050+ Range 600	0.96	0.96	0.93	0.92	Min 0.87, Max 0.92	Min 0.69, Max 0.73

To estimate the upstream CO<sub>2</sub> emissions of BEV and PHEV in 2050, the total energy consumption (charging plus losses) is multiplied by projected 2050 electricity carbon intensity. A factor of 0.082 tCO<sub>2</sub>/MWh is applied, taken from the EU Reference Scenario 2016 (*EU 2050 electricity and steam production emission intensity according to EC, 2016c*).

### 3 - Results and Discussion

In this section, the activity of the 2050 road vehicle fleet and its distribution over different powertrains is outlined, followed by a presentation of fleet energy consumption and CO<sub>2</sub> emissions under the different scenarios. Energy and CO<sub>2</sub> results are compared both with present data, as well as to scenario projections under the 2016 EU reference scenario (*EU, 2016c*) and the EUCO30 scenario (*E3MLab & IASA, 2016*), which is the more ambitious one of two scenarios designed to achieve the EU's 2030 climate and energy targets.

The present approach addresses technical emission reduction potential, with a strong focus on electrification and vehicle efficiency. The investigation of social innovations such as mobility as a service, sharing, or new mobility patterns are beyond the scope of the present paper. Well to wheel impacts or lifecycle implications, which play an important role in particular with view to the strong electrification assumed, cannot be fully covered here and merit further investigation.

#### 3.1. 2050 Road Transport Activity

In the scenarios, baseline 2050 activities as shown in **Table 1** apply for the HE, HEH and Mix scenarios. They are lowered if C type measures are taken, which result in a total 2050 fleet activity reduction by 1.8% in the pessimistic to 4.2% in the optimistic C measures case compared to baseline 2050 activity. The impact of C measures on total activity, as well as on light versus heavy duty vehicles separately, is shown in **Table 9**.

**Table 9: 2050 Vehicle Activities, with C measures, absolute values (trillion vkm) and changes compared to 2016 (% of 2016)**

	C measures, Pessimistic		C measures, Optimistic	
	trill. vkm	versus 2016	trill. vkm	versus 2016
Cars, LCVs & 2wheelers	4500	111%	4422	109%
Trucks, Vans, Busses	541	137%	496	125%
<b>Total Road</b>	<b>5040</b>	<b>113%</b>	<b>4918</b>	<b>111%</b>

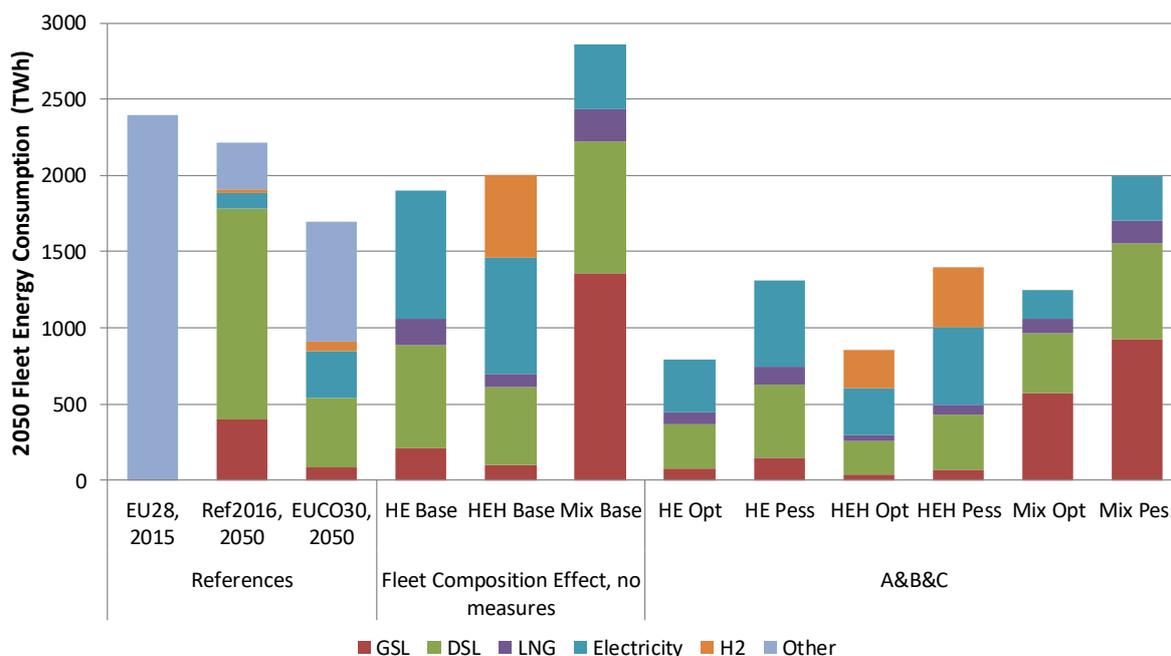
All scenarios constitute a shift towards electrified propulsion, to different extents (see **Table 10**). The share of total activity covered by xEV, i.e., the sum of PHEV, BEV and FCEV in 2050 ranges from more than 60% in the Mix scenario to around 95% in the HE and HEH scenarios. BEV alone make up for an activity share of 30 to 80%.

**Table 10: 2050 Fleet Activity distribution by powertrain in the three scenarios**

	HE	HEH	Mix
Advanced ICE	4.7%	4.0%	36.3%
PHEV	16.2%	8.1%	33.8%
BEV	79.1%	78.5%	30.0%
FCEV	0.0%	9.4%	0.0%

#### 3.2 - Energy Consumption and Energy mix

**Figure 4** gives an overview of 2050 road transport energy consumption and energy mix under different scenarios. The first three bars present references for comparison, the second three bars (labelled "Fleet Composition Effect, no measures") show 2050 road transport energy consumption derived by implementing the fleet composition scenarios only. The final six bars ("A&B&C") show energy consumption when all measures for efficiency improvement (A type), transport smoothing (B) and transport reduction (C) are implemented, in their optimistic and pessimistic version respectively. Thus, the figure exhibits the bandwidth of development options throughout 2050 covered by this study.



**Figure 4: 2050 road transport energy consumption for references and all scenarios, without measures applied and with all A, B and C measures applied. Scenarios: High Electrification (HE), High Electrification plus Hydrogen (HEH), and Mixed scenario (Mix), with Optimistic (Opt) and Pessimistic (Pess) measure versions.**

With the assumed fleet composition only and the projected activities, 2050 total road transport energy consumption (tank to wheels) is 1900 and 2000 TWh for the two electrification scenarios HE and HEH. This is in-between what is expected according to the EU reference scenario 2016 and the more ambitious EUCO30 scenario, as well as visibly below 2015 road transport energy consumption. However, the Mix scenario without measures shows a 2050 energy consumption of around 2800 TWh and thus a 20% increase compared to today. Note that energy consumption increase is driven by the assumed increase in transport activity throughout 2050. As activity is projected to increase over-proportionally in freight transport (see **Table 9**), notably in trucks, the Mix base scenario exhibits an energy consumption increase which is higher than average total road transport activity increase.

When all measures are implemented, in the two electrification scenarios, 2050 transport energy consumption tank to wheels can be reduced to 1300 and 1400 TWh in the pessimistic case, and to around 800 TWh if the optimistic version holds, achieving in the best case a reduction of two 65% versus present road transport energy consumption. Again, the Mix scenario remains at substantially higher levels of 2000 (pessimistic) and 1250 TWh (optimistic).

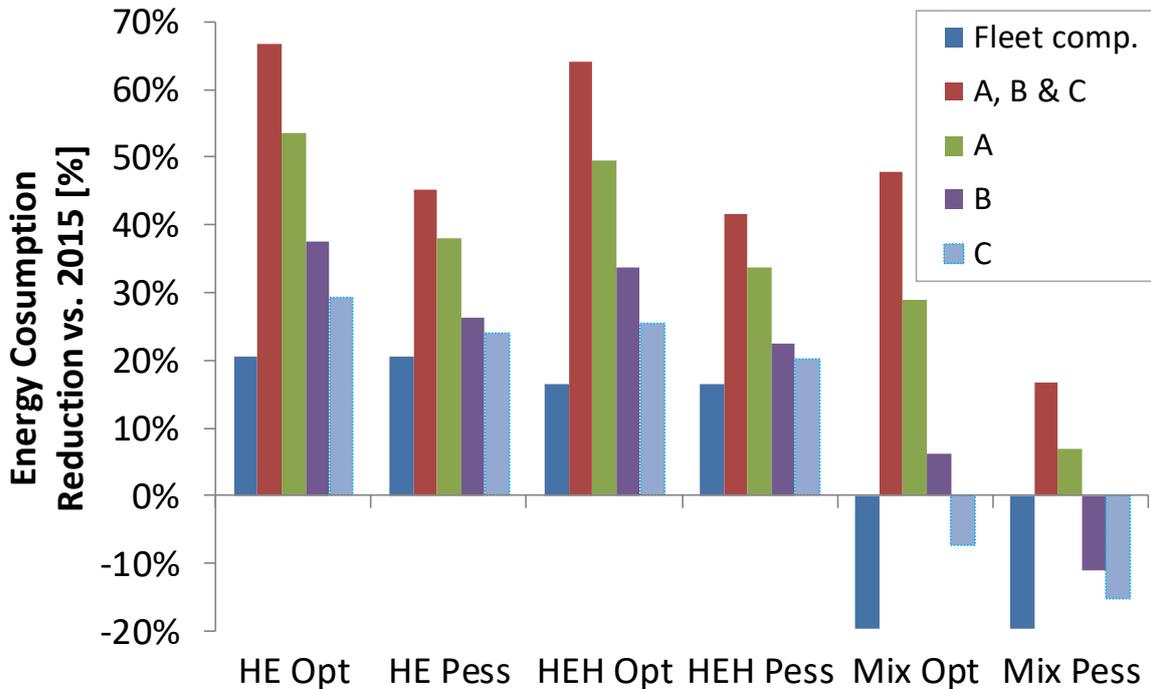
Regarding the energy mix, driven by the fleet powertrain composition, substantially different mixes of chemical fuels, electricity and hydrogen arise. Chemical fuels comprise gasoline (GSL), diesel (DSL), and liquid natural gas (LNG), which can be replaced by alternative fuels of either biofuel or transformed fossil fuel type. Their combined share remains at 85% in the Mix scenario but decreases to around 55% in the HE scenario and to 35% in the HEH scenario.

In the two electrification scenarios, the consumption of non-chemical fuels increases strongly:

- In the HE Base (without measures) scenario, 2050 road transport electricity consumption from battery to wheels is 840 TWh. Although this figure does not include losses from vehicle charging efficiency or energy grid losses, it can be seen that this is significant being equivalent to 30% of EU28 final energy consumption of electricity in 2015 (Eurostat, 2018).
- In the HEH Base (without measures) scenario, the sum of electricity and hydrogen consumption is even higher, at 1300 TWh. Thus in the absence of further measures to reduce transport energy consumption but with strong fleet electrification, the

consumption of electricity and hydrogen by transport can pose a substantial challenge to the energy sector.

**Figure 5** separates the energy consumption impacts of single measure types and of fleet electrification. In the two electrification scenarios, fleet electrification alone leads to an energy consumption reduction of 15 to 20% compared to 2015 (“Fleet composition” effect, blue bars), at the projected 2050 fleet activity, showing that electrification overcompensates the activity increase. This is not the case for the Mix scenario, where 2050 energy consumption is 20% higher than in 2015 if no measures are implemented.



**Figure 5: Energy Consumption reduction versus 2015, by scenario and measure type. Scenarios: High Electrification (HE), High Electrification plus Hydrogen (HEH), and Mixed scenario (Mix), with Optimistic (Opt) and Pessimistic (Pess) measure versions.**

For all three scenarios, the total energy reduction achieved by adding all measures (A, B & C, red bars in the figure) yields roughly an extra 50%pts of energy reduction over the fleet composition effect in the optimistic version, or 25%pts in the pessimistic variant. Of the measure types, A measures have the largest impact (roughly 30%pts optimistic / 20%pts pessimistic), followed by B (ca. 20%pts / 10%pts) and C (10%pts / 5%pts) for the two electrification scenarios. In the Mix scenario, the merit order of measures is maintained. Measures, in particular A and B measures, reduce energy consumption more significantly than in the electrification scenarios. Note that the combined potential of A, B and C measures is less than the sum of their separate potentials, due to overlap in the savings addressed.

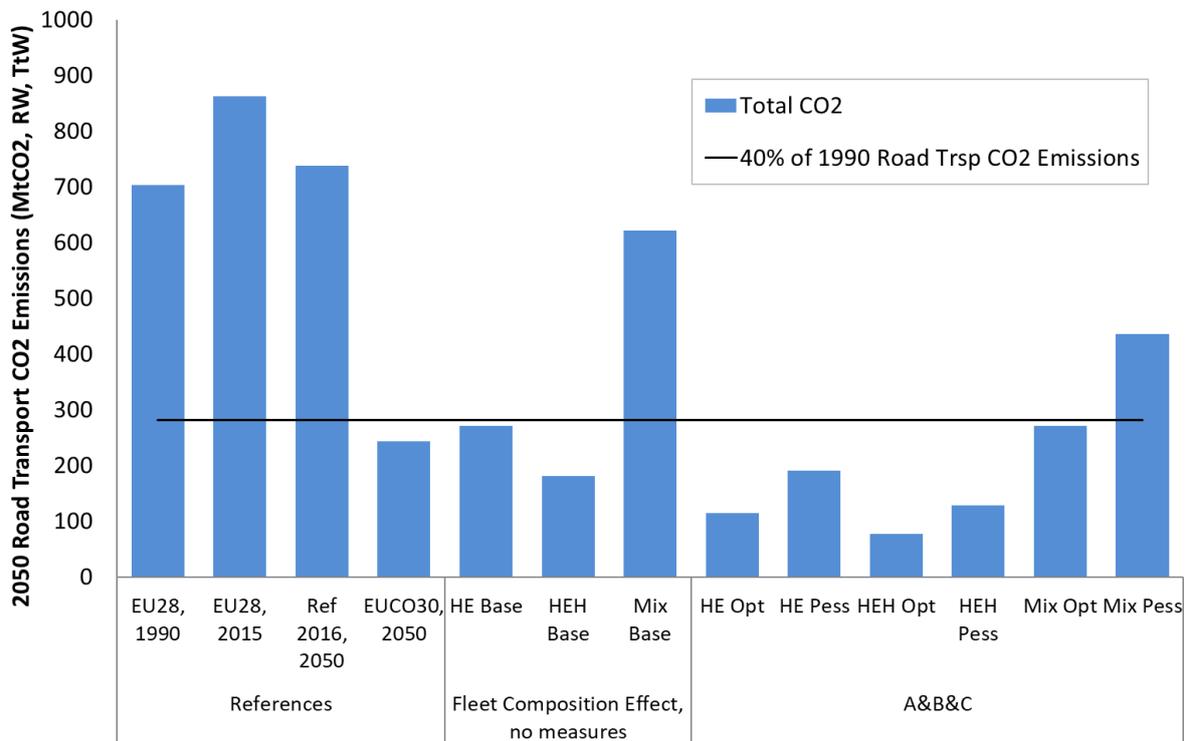
Upstream electricity losses are addressed **Table 11**. Grid to battery losses of electric energy for BEV and PHEV are shown in the second column, and grid to wheel electricity consumption is given in column three. By assumption, this is an extra 17% of electricity on top of battery to wheel electricity consumption, which amounts to 30 to 140 TWh under the different scenarios. Compared to total road transport tank to wheel energy consumption, it makes up for an additional 2 to 7% under the different scenarios.

**Table 11: 2050 BEV and PHEV upstream energy consumption (TWh)**

	Battery to wheel Electricity Consumption (TWh)	Grid-to-battery Electricity Losses (TWh)	Grid to wheel Electricity Consumption (TWh)
HE Base	842	140	982
HEH Base	763	127	890
Mix Base	430	72	501
HE Opt	346	58	404
HE Pess	565	94	659
HEH Opt	304	51	355
HEH Pess	507	85	592
Mix Opt	185	31	216
Mix Pess	287	48	335

### 3.3 - 2050 Transport CO2 Emissions

With view to the target of mitigating climate change, it is crucial to what extent the CO<sub>2</sub> emissions of transport can be reduced. Note that conventional fuels (GSL, DSL) are treated as 2015 standard fuel mixes and are accounted for with the present conventional fuel emission factors. Resulting emissions from chemical fuel combustion can be considered as an upper limit, as by 2050, these fuels could be substituted by alternative, lower-emission fuels to some extent, such that ICE TtW emissions could be substantially lower.



**Figure 6: 2050 road transport real-world tank to wheel CO<sub>2</sub> emissions (MtCO<sub>2</sub>), for references and all scenarios, without measures and with all A, B and C measures applied. Scenarios: High Electrification (HE), High Electrification plus Hydrogen (HEH), and Mixed scenario (Mix), with Optimistic (Opt) and Pessimistic (Pess) measure versions. Black line: 60% reduction versus 1990**

**Figure 6** shows the bandwidth of road vehicle CO<sub>2</sub> emissions in 2050 resulting from the different scenarios, in terms of tank to wheel (TtW) real-world CO<sub>2</sub> emissions. Emissions caused during extraction, transport or transformation of fuels are not considered.

The first four bars ("References") present benchmarks for comparison.

The second three bars ("*Fleet composition effects, no measures*") show 2050 road transport CO<sub>2</sub> emissions resulting from the respective fleet composition scenarios.

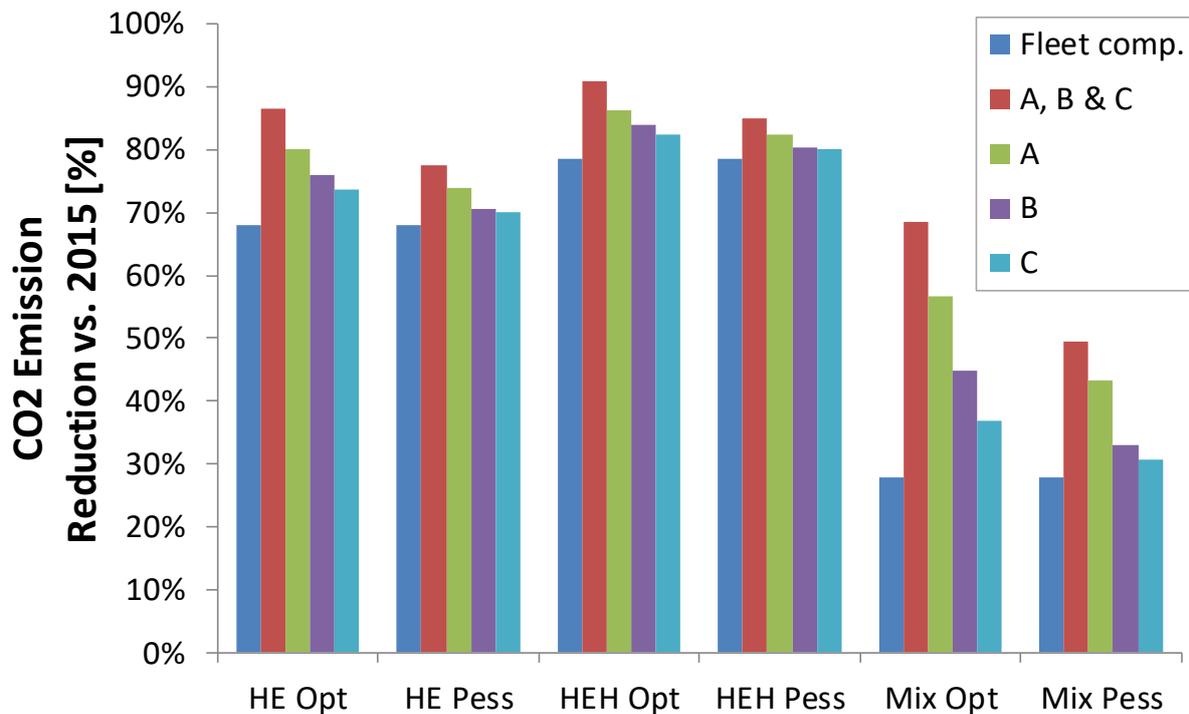
The final six bars ("*A&B&C*") present CO<sub>2</sub> emissions when all measures are implemented, in their optimistic and pessimistic versions, respectively.

At first glance, all scenarios reduce road transport CO<sub>2</sub> emissions compared to their 2015 level of 860 MtCO<sub>2</sub>, and also compared to the projection within the EU reference scenario 2016 of 740 MtCO<sub>2</sub> in 2050.

However, more ambitious reductions are needed to achieve the EU's policy targets. The European Commission's white paper on transport (*EU, 2011*) has set a 2050 target of reducing transport GHG emissions by 60% compared to 1990, represented by the black horizontal line in **Figure 6**. Targets set at the same time for aviation (40% sustainable low carbon fuels by 2050) and shipping (50% emission cut) as well as strong CO<sub>2</sub> emission reduction pledges made under the Paris Agreement suggest that road transport will have to reduce its emissions by more than 60%. Thus the White Paper target is not to be understood as the final benchmark for 2050 EU road transport emission reduction, and 2050 road transport emissions will need to stay well below the 280 MtCO<sub>2</sub> indicated.

The HEH scenario is the only one reducing CO<sub>2</sub> emissions to below 200 Mt by 2050 without further measures and reaching a 75% reduction versus 1990. When implementing all A, B and C measures, the two electrification scenarios with optimistic measures show emissions of 80 (HEH Opt) and 115 MtCO<sub>2</sub> (HE Opt), the former of which is a nearly 90% reduction versus 1990. In the pessimistic variant, 2050 emissions are 130 (HEH Pess) and 190 MtCO<sub>2</sub> (HE Pess). The Mix scenario achieves a roughly 60% reduction at 270 MtCO<sub>2</sub> in the optimistic, all measures case, but remains at 440 MtCO<sub>2</sub> (less than 40% reduction) in the pessimistic variant. Thus, even if all measures are employed and can achieve their optimistic potential, moderate fleet electrification as depicted in the Mix scenario is unlikely to be sufficient and would require decarbonisation of the chemical energy sources via introduction of sustainable fuels, e.g. advanced biofuels or fuels derived from renewable electric energy (PtX).

**Figure 7** shows the CO<sub>2</sub> reduction by 2050, compared to 2015, of fleet composition and the individual measure types separately. Differently from the order of magnitude of effects seen with regard to energy consumption in **Figure 5**, fleet electrification alone makes a large contribution to CO<sub>2</sub> reduction of 70 to 80% versus 2015 (which corresponds to 60 to 75% compared to 1990) in the electrification scenarios, but less than 30% in the Mix scenario. This is due to the large amount of zero-TtW emission fuels consumed in the electrification scenarios. In contrast, in the two electrification scenarios, single measure types make relatively small contributions of 2 to 8%pts in most cases. Measure types retain the same merit order as seen with regard to energy consumption reduction, with A measures being more effective than B and B more so than C, but with little margin. The impact of all measures combined varies with the degree of fleet electrification, i.e. they have the highest impact in the Mix scenario (a maximum contribution of about 40%pts in Mix Opt), followed by HE Opt (20%) and HEH Opt (10%pts). In the pessimistic variant, their effect is roughly half of the optimistic version impact.



**Figure 7: CO2 emission reduction versus 2015, by scenario and measure type. Scenarios: High Electrification (HE), High Electrification plus Hydrogen (HEH), and Mixed scenario (Mix), with Optimistic (Opt) and Pessimistic (Pess) measure versions.**

The fleet calculations also allow analysing CO<sub>2</sub> emissions by vehicle type, providing evidence that HDV will be the main emitters of CO<sub>2</sub> with a contribution between 50 and 80% of emissions by 2050 in the scenarios. More details on vehicle type emissions and the role of engine measures for emission reduction is provided in Annex A.4 to this paper.

While the dominant part of conventional vehicle emissions results from burning fuels during use, in the tank-to-wheel perspective xEV are treated as zero-emission. However, important quantities of emissions can be caused by the production of the electricity they use.

**Table 12** presents upstream emissions from BEV and PHEV, in absolute terms (MtCO<sub>2</sub>) as well as relative to the total TtW CO<sub>2</sub> emissions calculated for the respective scenarios. They range from 41 to 80 MtCO<sub>2</sub> for the base scenario versions with no measures applied, and from 18 to 54 MtCO<sub>2</sub> when all measures are applied. As can be seen, upstream emissions from electricity play a significant role in particular in the strong electrification scenarios, and merit further investigation.

**Table 12: 2050 BEV and PHEV upstream CO2 emissions**

	BEV/PHEV grid to wheel electricity CO <sub>2</sub> emissions (MtCO <sub>2</sub> )	Share of total scenario tank to wheel CO <sub>2</sub> emissions (%)
HE Base	80	30%
HEH Base	73	40%
Mix Base	41	7%
HE Opt	33	29%
HE Pess	54	28%
HEH Opt	29	37%
HEH Pess	48	38%
Mix Opt	18	7%
Mix Pess	27	6%

## 4 - Conclusions and Policy Implications

The present study casts light on the technical feasibility of energy consumption and CO<sub>2</sub> emission reductions from EU road transport by 2050 from a tank to wheels perspective. To this aim, a group of experts from automotive industry, research and public authorities has provided a thorough consensus assessment of the potentials of a wide range of vehicle measures, including options to increase vehicle efficiency, smoothen transport, and reduce vehicle activity throughout 2050.

They have also established three scenarios of road vehicle powertrain composition by 2050. An exemplary analysis of a market uptake trajectory to reach 2050 electrified vehicle stock shares of the least electrified scenario has shown that even this scenario requires nearly 50% of electrified cars and vans in the 2030 new fleet, which demonstrates the degree of ambition underlying the present scenarios. Using these inputs for fleet impact calculations based on the DIONE model, a number of conclusions can be drawn.

Scenario outcomes demonstrate that substantial tank to wheel reductions of CO<sub>2</sub> emissions from road transport are feasible by combining fleet electrification and the three types of measures. In the two more ambitious fleet composition scenarios, summarized as “electrification scenarios”, 2050 emission reductions of more than 70% versus 1990 can be achieved even if all measures perform only at the lower boundary of experts’ expectations (‘pessimistic’ version). With optimistic measure potential and electrification, CO<sub>2</sub> emissions from road transport could be reduced by 85 to 90% versus 1990.

In the Mix scenario, which represents a less rapid uptake of electrified vehicles, a 60% CO<sub>2</sub> reduction versus 1990 can still be reached with optimistic measure potential, but only 40% can be achieved in case the pessimistic assessment holds and there is no decarbonisation of chemical fuel sources such as the introduction of sustainable fuels or PtX. In case of strong electrification, the market uptake of electrified powertrains is the primary driver of CO<sub>2</sub> reduction, and less than 20 percentage points of CO<sub>2</sub> reduction are attributed to the measures.

While CO<sub>2</sub> emissions decrease substantially in all fleet composition scenarios considered even without any measures, energy consumption depends strongly on the successful application of measures. High energy consumption reductions of around 65% versus 2015 in the optimistic or 40+% in the pessimistic case can be achieved by combining both ambitious fleet electrification (as in the electrification scenarios) and all measures available. If fleet electrification remains at the more modest level of the Mix scenario, base energy consumption increases by 20% over its present level, but a maximum overall reduction of slightly below 50% (optimistic) or 20% (pessimistic) can still be achieved if all measures are applied.

Both with regard to CO<sub>2</sub> emission and energy consumption reduction, measure types exhibit a clear ranking. Highest benefits are expected from vehicle efficiency improvements, followed by transport smoothing, and finally activity reduction measures. The measure type ranking cannot be considered as fully consolidated. It turned out during expert group discussion that available evidence on the feasibility and impact of transport smoothing and activity reduction measures is limited, thus there were few measures the impact of which could be quantified reliably. Furthermore, the Delphi approach employed in the study entailed a bias towards technical measures and their emission potentials, where experts involved had very strong expertise. The knowledge base for assessing transport smoothening, in particular transport reduction measures, was comparatively less pronounced. Moreover, the expert group did not address social innovations, behavioural aspects, or potential radical transport system changes which could not be captured by the present approach. More research with regard to these measure types is warranted to complement the present approach, which has been successful in addressing feasibility and boundaries of technical measures for transport energy consumption and CO<sub>2</sub> emissions from a tank/battery to wheel perspective.

This papers’ primary focus is the technical feasibility of strong vehicle emission reduction, without explicitly investigating the conditions for such a transition. It is likely that policies will be a prerequisite for fleet electrification and efficiency increases of the order of magnitude demonstrated.

Moreover, the present study focused on vehicle technology and operations effects in the transport sector. It is obvious however that any of the scenarios would have major impacts on transport energy consumption. For example, the strongly electrified scenario without measures would cause an electricity consumption from transport (battery to wheels) of the order of magnitude of nearly one third of the present EU28 final electricity consumption. While in the transport sector, electric energy is counted as zero-emission from a tank to wheel perspective, the energy sector will face a challenge to provide high quantities of low-carbon electricity for transport. Complementary policies would be needed to ensure that transport emissions are not shifted to other sectors. Moreover, a life cycle perspective on vehicle emissions should be added for a full picture of the impacts of road transport electrification.

Another boundary of the present analysis consists of the properties of chemical fuels. It has been assumed that combustion engines consume conventional fuels with today's properties and emission factors. The present results can thus be seen as an upper boundary of the CO<sub>2</sub> the specified fleets could emit. No attempt was made to investigate the availability of alternative, low-carbon synthetic fuels by 2050, which might play an important role for transport decarbonisation in particular within more moderate electrification scenarios. Moreover, this analysis deals with CO<sub>2</sub> emissions, but does not consider air pollutant emissions from transport. While in the expert group, there was broad agreement that by 2050, any persisting combustion engines would be near zero-emission with regard to air pollutants, this assumption and its technical implementation merits further investigation.

It can be concluded that ambitious CO<sub>2</sub> emission reduction targets are technically feasible by 2050. Fleet electrification has been demonstrated to achieve high tank to wheel emission reductions even in the absence of other measures, but with the consequence of inducing high transport energy consumption. A combined approach fostering both electrification and measures for vehicle efficiency improvement, transport smoothing and transport reduction can limit transport energy consumption and the resulting challenge for the energy sector.

## References

- Bloomberg (2017), Bloomberg New Energy Finance Summit, Presentation by Michael Liebreich, 25 April 2017, <https://data.bloomberglp.com/bnef/sites/14/2017/04/2017-04-25-Michael-Liebreich-BNEFSummit-Keynote.pdf>
- Dalkey, N. (1969), An experimental study of group opinion: The Delphi method, In Futures, Volume 1, Issue 5, Pages 408-426, ISSN 0016-3287, [https://doi.org/10.1016/S0016-3287\(69\)80025-X](https://doi.org/10.1016/S0016-3287(69)80025-X)
- Dray, L. M., Schäfer, A. and M. E. Ben-Akiva (2012), Technology Limits for Reducing EU Transport Sector CO2 Emissions, Environmental Science & Technology 46 (9), pp. 4734-4741, 10.1021/es204301z
- European Climate Foundation (2016), Sultan modelling to explore the wider potential impacts of transport GHG reduction policies in 2030, <http://europeanclimate.org/>
- EC (2017), Commission staff working document. Impact assessment accompanying the document "Proposal for a Regulation of the European Parliament and of the Council setting emission performance standards for new passenger cars and for new light commercial vehicles as part of the Union's integrated approach to reduce CO2 emissions from light-duty vehicles and amending Regulation (EC) No 715/2007 (recast)", COM(2017) 676 final - SWD(2017) 651 final
- EC (2016a), A European Strategy for Low-Emission Mobility. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, COM(2016) 501 final
- EC (2016b), Communication from the Commission to the European Parliament and the Council. The Road from Paris: Assessing the implications of the Paris Agreement and accompanying the proposal for a Council decision on the signing, on behalf of the European Union, of the Paris agreement adopted under the United Nations Framework Convention on Climate Change, COM(2016) 110 final
- EC (2016c), EU Reference Scenario 2016: Energy, transport and GHG emissions. Trends to 2050. European Commission, [https://ec.europa.eu/energy/sites/ener/files/documents/ref2016\\_report\\_final-web.pdf](https://ec.europa.eu/energy/sites/ener/files/documents/ref2016_report_final-web.pdf)
- EC (2014), Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on the Deployment of Alternative Fuels Infrastructure
- Edelenbosch, O.Y., Hof, A.F., Nykvist, B., Girod, B., and D. P. van Vuuren (2018), Transport electrification: the effect of recent battery cost reduction on future emission scenarios, Climatic Change 151, pp. 95–108, <https://doi.org/10.1007/s10584-018-2250-y>
- EEA (2018), Annual European Union greenhouse gas inventory 1990-2016 and inventory report 2018. Submission to the UNFCCC Secretariat. European Environment Agency, [https://www.eea.europa.eu/publications/european-union-greenhouse-gas-inventory-2018/at\\_download/file](https://www.eea.europa.eu/publications/european-union-greenhouse-gas-inventory-2018/at_download/file), last access 17/12/2018
- EC (2017), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Europe on the Move. An agenda for a socially fair transition towards clean, competitive and connected mobility for all, COM/2017/0283 final
- E3MLab & IIASA (2016), Technical report on Member State results of the EU CO2 policy scenarios, [https://ec.europa.eu/energy/sites/ener/files/documents/20170125\\_-\\_technical\\_report\\_on\\_euco\\_scenarios\\_primes\\_corrected.pdf](https://ec.europa.eu/energy/sites/ener/files/documents/20170125_-_technical_report_on_euco_scenarios_primes_corrected.pdf)
- ERTRAC (2016), Future Light and Heavy Duty ICE Powertrain Technologies, [https://www.ertrac.org/uploads/documentsearch/id42/2016-06-09\\_Future%20ICE\\_Powertrain\\_Technologies\\_final.pdf](https://www.ertrac.org/uploads/documentsearch/id42/2016-06-09_Future%20ICE_Powertrain_Technologies_final.pdf)
- ERTRAC (2017), European Roadmap Electrification of Road Transport, 3<sup>rd</sup> Edition, June 2017, [https://www.ertrac.org/uploads/documentsearch/id50/ERTRAC\\_ElectrificationRoadmap2017.pdf](https://www.ertrac.org/uploads/documentsearch/id50/ERTRAC_ElectrificationRoadmap2017.pdf)

- EU (2011), White Paper 2011: Roadmap to a Single European Transport Area - Towards a competitive and resource efficient transport system. European Commission.
- EU (2019), Regulation (EU) 2019/631 of the European Parliament and of the Council of 17 April 2019 setting CO2 emission performance standards for new passenger cars and for new light commercial vehicles, and repealing Regulations (EC) No 443/2009 and (EU) No 510/2011), <https://eur-lex.europa.eu/eli/reg/2019/631/oj>
- Eurostat (2018), Supply, transformation and consumption of electricity - annual data [table nrg\_105a], downloaded on 02 August 2018.
- Harrison, G. and C. Thiel (2017), Policy insights and modelling challenges: The case of passenger car powertrain technology transition in the European Union. *European Transport Research Review* 9(3).
- Harrison, G., Thiel, C. and Jones L. (2016a), Powertrain Technology Transition Market Agent Model (PTTMAM): An Introduction. EUR 27740. Luxembourg (Luxembourg): Publications Office of the European Union; JRC100418.
- Harrison, G., Krause, J. and C. Thiel (2016b), Transitions and impacts of passenger car powertrain technologies in European member states. *Transport Research Procedia*, DOI: <http://10.1016/j.trpro.2016.05.418>
- IEA (2017), The future of trucks: Implications for energy and the environment, <https://www.iea.org/publications/freepublications/publication/TheFutureofTrucksImplicationforEnergyandtheEnvironment.pdf>
- Karkatsoulis, P., Siskos, P., Paroussos, L. and P. Capros (2017), Simulating deep CO2 emission reduction in transport in a general equilibrium framework: The GEM-E3T model, *Transportation Research Part D* 55, pp. 343–358
- Katsis, P., Papageorgiou, T., Ntziachristos, L., Kouridis, C. and G. Mellios (2012), Road transport CO2 emissions mitigation evaluation by means of a new software tool. *Transport and Air Pollution Conference*, Thessaloniki, November 26-27, 2012.
- Kihm, A. and S. Trommer (2014), The new car market for electric vehicles and the potential for fuel substitution. *Energy Policy* 73. 147-157.
- Kloess, M. and A. Müller (2011), Simulating the impact of policy, energy prices and technological progress on the passenger car fleet in Austria-A model based analysis 2010-2050. *Energy Policy* 39, 5045-5062.
- Pasaoglu, G., Harrison, G., Jones, L., Hill, A., Beaudet, A. and C. Thiel (2016), A system dynamics based market agent model simulating future powertrain technology transition: Scenarios in the EU light duty vehicle road transport sector. *Technological Forecasting and Social Change* 104, p. 133–146.
- Pasaoglu, G., Honselaar, M. and C. Thiel (2012), Potential vehicle fleet CO2 reductions and cost implications for various vehicle technology deployment scenarios in Europe, *Energy Policy*, 40 (2012), pp. 404-421, 10.1016/j.enpol.2011.10.025
- Samaras, Z., Ntziachristos, L., Toffolo, S., Magra, G., Garcia-Castro, A., Valdes, C., Vock, C. and W. Maier (2016), Quantification of the effect of ITS on CO2 emissions from road transportation, *Proceedings of Transport Research Arena*, April 2016, Warsaw, Poland.
- Samaras Z., Zachariadis, T., Holtmann, T., Rentz, O. and K.-H. Zierock (1999), A Methodology and a Database for Forecasting Anthropogenic Atmospheric Emissions in Europe, *Atmospheric Environment* 33, pp. 3389-3404.
- Shafiei, E., Thorkelsson, H., Ásgeirsson, E.I., Davidsdottir, B., Raberto M., and H. Stefansson (2012), An agent-based modeling approach to predict the evolution of market share of electric vehicles: A case study from Iceland. *Technological Forecasting and Social Change* 79. 1638-1653.
- Siskos, P., Zazias, G., Petropoulos, A., Evangelopoulou, A. and P. Capros (2018), Implications of delaying transport decarbonisation in the EU: A systems analysis using the PRIMES model, *Energy Policy* 121, pp. 48-60.

- Sorrentino, M., Rizzo, G., and L. Sorrentino (2014), A study aimed at assessing the potential of vehicle electrification on grid infrastructure and road-traffic green-house emissions. Appl. Energy 120, 31–40.
- Streetline (2016), <https://rctom.hbs.org/submission/streetline-leading-the-way-for-smart-parking/>
- Thiel, C., Drossinos, Y., Krause, J., Harrison, G., Gkatzoflias, D. and A.V. Donati (2016), Modelling electro-mobility: an integrated modelling platform for assessing European policies. Transport Research Procedia, DOI: <http://10.1016/j.trpro.2016.05.341>
- Thiel, C., Schmidt, J., Van Zyl, A. and E. Schmid (2014), Cost and well-to-wheel implications of the vehicle fleet CO2 emission regulation in the European Union. Transportation Research Part A – Policy and Practice 63; 25-42
- T&M and IRU (2017), Commercial Vehicle of the Future. A roadmap towards fully sustainable truck operations', <https://www.iru.org/sites/default/files/2017-07/iru-report-commercial-vehicle-of-the-future-en%20V2.pdf>
- Tsokolis, D., Tsiakmakis, S., Dimaratos, A., Fontaras, G., Pistikopoulos, P., Ciuffo, B., and Z. Samaras, Fuel consumption and CO2 emissions of passenger cars over the New Worldwide Harmonized Test Protocol, Applied Energy, Volume 179, 2016, Pages 1152-1165, ISSN 0306-2619, <https://doi.org/10.1016/j.apenergy.2016.07.091>.
- Zachariadis, T., Z. Samaras and K.-H. Zierock, "Dynamic Modeling of Vehicle Populations: An Engineering Approach for Emissions Calculations", Technological Forecasting and Social Change, 50, pp.135-149, 1995
- Zachariadis, T and Z. Samaras (1999), An Integrated Modeling System for the Estimation of Motor Vehicle Emissions, Journal of Air & Waste Management Association, 49:1010-1026.

## Annexes

### A.1 Expert Group Discussion

#### *A.1a) List of experts involved in the development of scenario inputs*

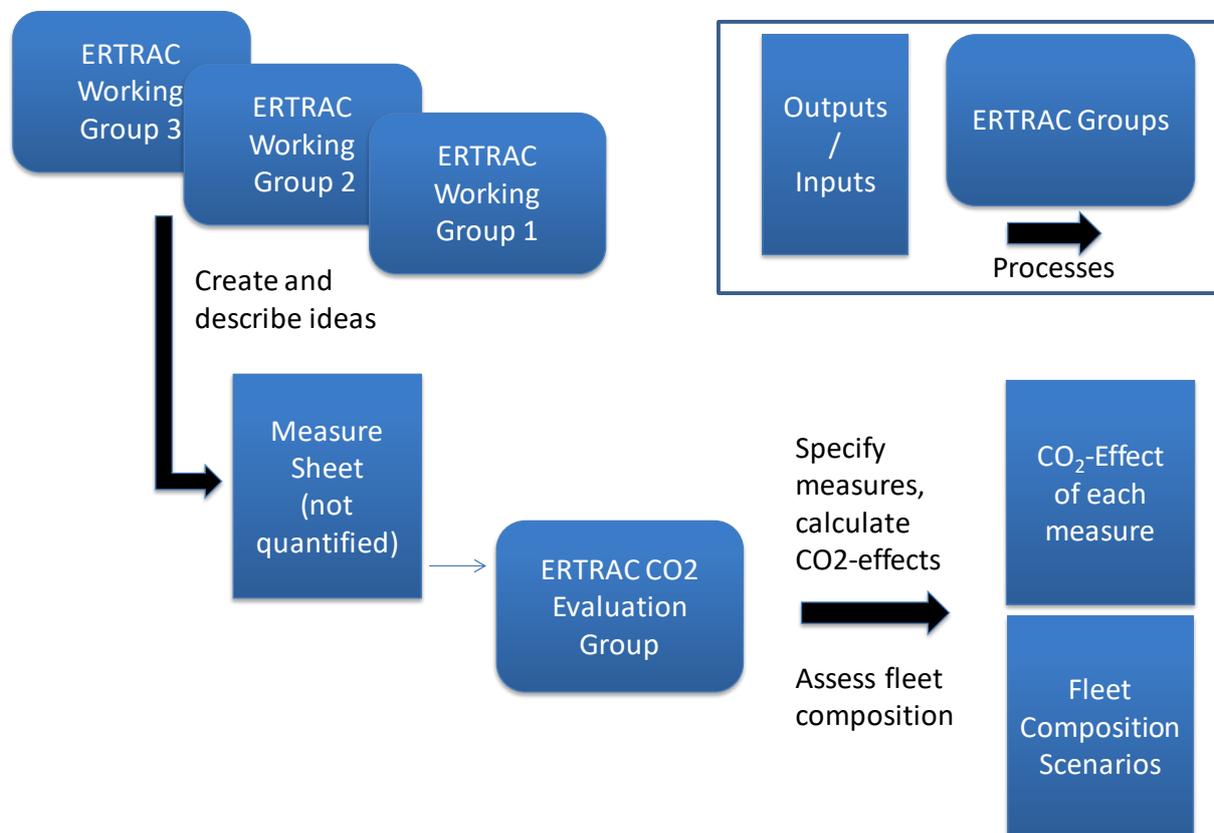
Josef Affenzeller (AVL)  
Thierry Coosemans (VUB)  
Georgios Fontaras (EC JRC)  
Rob Hofman, (RWS Netherlands)  
Jette Krause (EC JRC)  
Peter Kropf (BMW)  
Guenther Lichtblau (UBA AT)  
Staffan Lundgren, (VOLVO)  
Stephan Neugebauer,(ERTRAC/BMW)  
Christophe Petitjean (Valeo)  
Peter Prenninger (AVL)  
Zisis Samaras (Aristotle University of Thessaloniki)  
Stefan Schmerbeck, (Volkswagen)  
Christian Thiel (EC JRC)  
Andy Ward (Ricardo)

### A.1b) Description of the expert group discussion process

A total of eight half- to full-day group meetings took place between April 2016 and June 2017. Intermediate feedback from a larger set of stakeholders was sought in early 2017 at the ERTRAC annual conference, and a one-day workshop was held in autumn 2017, where the study methodology and preliminary outcomes were presented and discussed with ERTRAC members. Methodologically, the discussion process in the CO<sub>2</sub> working group was similar to the face-to-face version of the Delphi method (also called mini-Delphi), which is a questionnaire-based multi-round feedback process used to aggregate opinions from a diverse set of experts. The Delphi method was developed by Olaf Helmer, Norman Dalkey, and Nicholas Rescher at the US RAND project starting from the 1950s (Dalkey, 1969).

The group discussion process is shown in **Figure 8**. Information about possible measures was first collected from different ERTRAC working groups and assembled in a measure sheet. Then the ERTRAC CO<sub>2</sub> working group was tasked to evaluate each measure proposed and to quantify its CO<sub>2</sub> reduction effect.

Instead of a formalized questionnaire, the group received a measure sheet to populate with quantitative assessments of measures for road transport CO<sub>2</sub> emission reduction.



**Figure 8: Scheme of expert group discussion**

To benefit from the in-depth knowledge of different experts in specific areas, as well as from modelling tools available to them, in some cases individual experts provided detailed calculations or presentations with regard to specific measures. On the basis of such inputs, group discussions were held until consensus was reached. This procedure was applied for the assessment of combustion engine improvements (with expert inputs from Aristotle University of Thessaloniki, Ricardo, and AVL), calculations of future battery electric vehicle energy consumption (based on a calculation tool run at BMW), and changes in mobility patterns (using input from Vrije Universiteit Brussel).

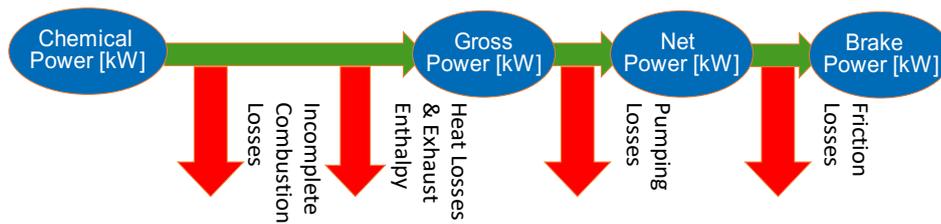
## A.2 Quantification of Measure Potentials

### *A.2a) A Measures: Assessment of combustion engine improvement*

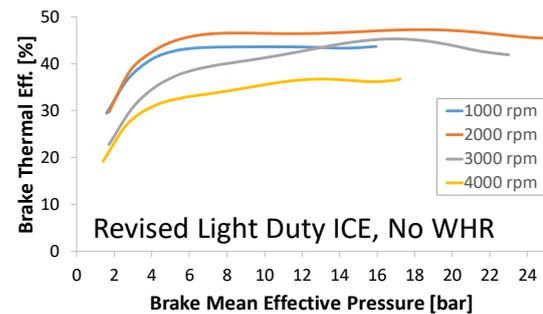
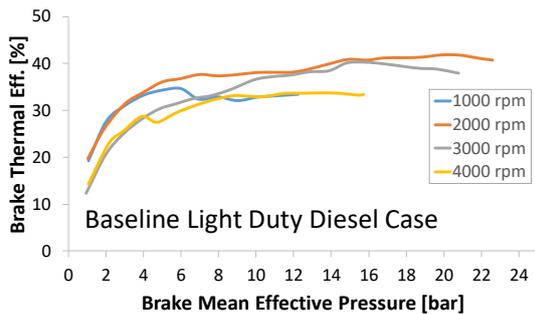
As an example, the assessment of combustion engine improvement for passenger cars involved the following steps, graphically presented in **Figure 9**. The first step consisted of the creation of a plausible internal combustion engine (ICE) efficiency and fuel consumption map equivalent to achieving 50% peak brake thermal efficiency, as targeted in the ERTRAC ICE roadmap (ERTRAC, 2016). In a second step, the possible CO<sub>2</sub> emission reduction expected for vehicles of several sizes was assessed. As shown in **Figure 9** (a) brake power was calculated using a subtraction of energies. In step (b) a class-leading engine of 1.5-1.6 l from the range of current production diesel was selected as baseline using measured benchmarking data at a resolution of 500 revolutions/min speed increments and 1 bar brake mean effective pressure load increments (a total in excess of 250 operating points). A new map was produced (c) by applying the same % change in the energy loss, across all operating points, to the losses that existed in the baseline map. The changes were a 10% reduction in pumping work, 10% reduction in friction and 30% reduction in in-cylinder heat transfer. Note that waste heat recovery was implemented as a separate measure in the measure sheet, so no allowance for this technology was applied in the map used for this calculation. This resulted in a peak efficiency value consistent with the ERTRAC ICE roadmap but lower than 50%, which would be achieved in combination with waste heat recovery. The new map was normalized over brake mean effective pressure in step (d) and then was applied to three different vehicles representative of the current fleet. In the final step (e), the CO<sub>2</sub> effect over the Worldwide Harmonised Light Vehicle Test Procedure (WLTP) cycle and its phases was simulated in the AVL CRUISE<sup>5</sup> environment for three vehicle types using models that were developed, validated and presented in detail by Tsokolis et al. (2016). The vehicle simulator consists of the main powertrain components (mechanical and electrical) along with their corresponding connections, functions and controllers that are necessary to approximate the vehicle operation. All input data for the simulation models (mass, driving resistance coefficients, engine map, gear ratios, transmission losses etc.) were provided either by industrial sources under non-disclosure agreements or public databases. Similar approaches were used for the evaluation of CO<sub>2</sub> effects for heavy duty vehicles. Also vehicle modelling was deployed for the informed assessment of plausible effects of improvements of aerodynamics, rolling resistance, electrical consumption etc. Analytic work was carried out by expert group members, and the results were discussed, refined and agreed by the whole group in subsequent expert group meetings.

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<sup>5</sup> <https://www.avl.com/cruise>



(a)

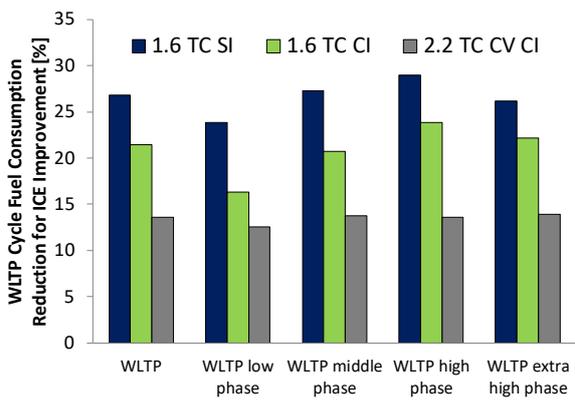


(b)

Vehicle description for ICE efficiency and green measures	Fuel	Injection	Aspiration	Start-Stop	Max Power	Empty Mass	Friction Coefficient	Drag Coefficient	Frontal Area
	[ - ]	[ - ]	[ - ]	[ - ]	[ kW ]	[ kg ]	[ - ]	[ - ]	[ m <sup>2</sup> ]
1.6 TC SI	Gasoline	DI	Turbo	YES	100	1300	0.010	0.31	2.14
1.6 TC CI	Diesel	DI	Turbo	YES	82	1293	0.008	0.29	2.31
2.2 TC CV CI	Diesel	DI	Turbo	YES	125	1970	0.011	0.34	3.9

(c)

(d)



Abbreviations used in (b) to (e)	
CI	Compression Ignition
CV	Commercial Vehicle
DI	Direct Injection
ICE	Internal Combustion Engine
rpm	Revolutions per minute
SI	Spark Ignition
TC	Turbocharged
WHR	Waste Heat Reduction
WLTP	Worldwide Harmonised Light Vehicle Test Procedure
1.6, 2.2	Cylinder volumes (l)

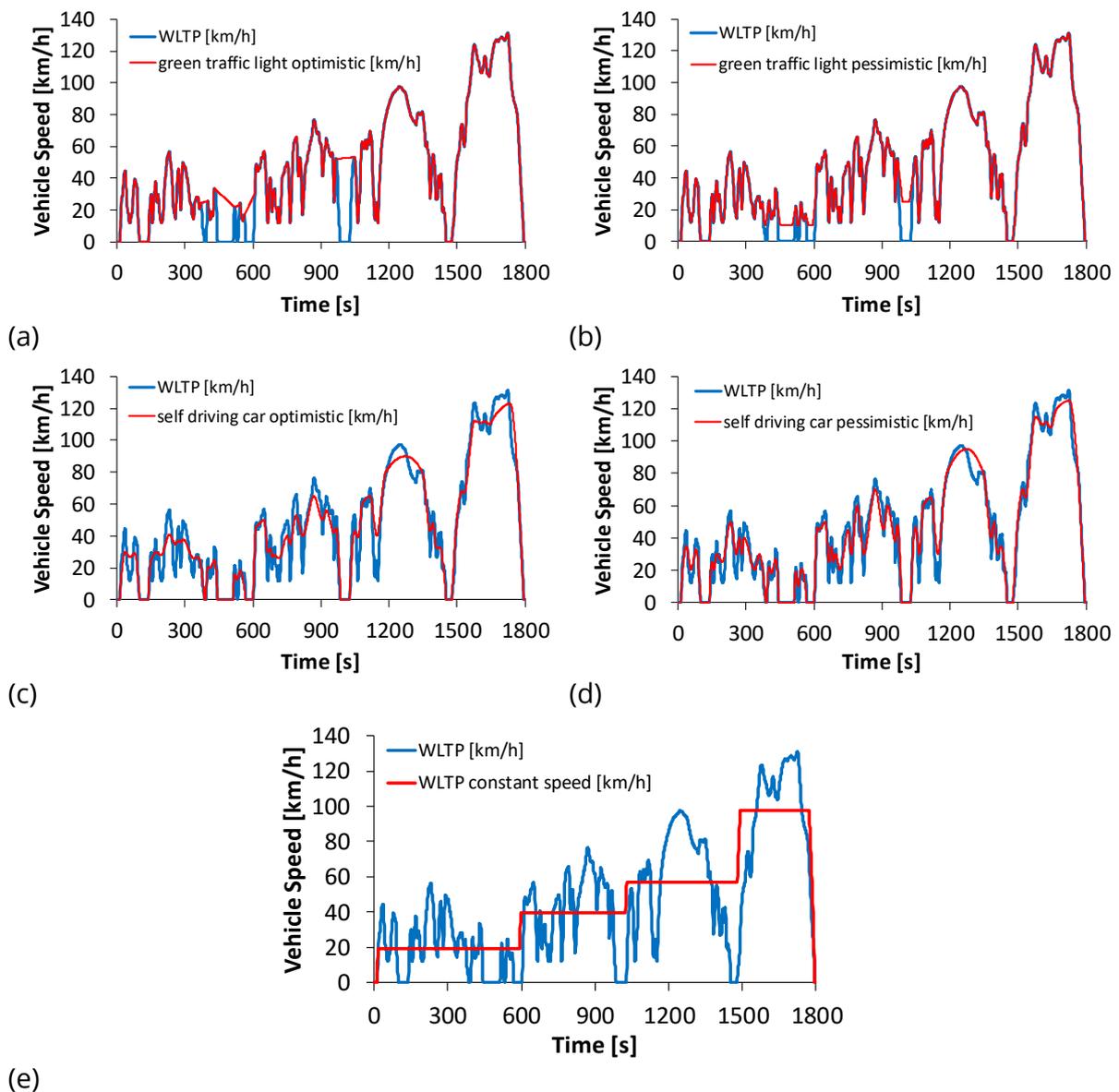
(e)

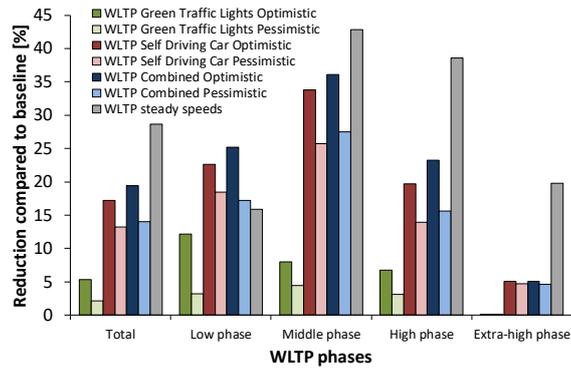
**Figure 9: Illustration of the steps followed for the assessment of combustion engine improvement for passenger cars**

A.2b) B Measures: Assessment of improvements in traffic flow

**Figure 10** illustrates the approach followed to assess the possible ranges of CO<sub>2</sub> impacts of different type B measures for passenger cars. **Figure 10** (a) and (b) show a simplified approach employed to assess the effect of traffic light management allowing a smoother flow (“green traffic

lights”). It is expected that the larger part of present traffic light stops at lower speeds can be avoided with this measure. To represent this, the WLTP drive cycle was modified as to lower the overall idle time (in both an optimistic and pessimistic case). **Figure 10** (c) and (d) show the effect that autonomous driving may have on smoothing accelerations, reducing the kinetic energy requirements during WLTP driving. **Figure 10** (e) shows an attempt to reach the theoretical maximum energy reduction when WLTP is replaced by steady state speeds, while keeping the same average speed and total distance of WLTP. Finally, **Figure 10** (f) presents the results on CO<sub>2</sub> emissions calculated for a mid-sized diesel passenger car with the same vehicle modelling tool deployed for Type A measures.





(f)

**Figure 10: Illustration of the steps followed for the assessment of type B measures for passenger cars**

### A.2c) C Measures: Assessment of measures transport reduction measures

In contrast to the assessment of A and B type measures, no formal modelling approach was used by the expert group for assessing the potentials of C measures. An explanation of how the values were derived and how they relate to findings from literature is given below.

#### Reduced parking search traffic

In the future, guided parking systems providing information on available parking slots in a timely manner could reduce the traffic induced by present searching. This measure applies to urban driving only. As an upper limit, 100 % of guided parking by 2050 was assumed. Roughly one third of passenger car city driving was estimated to be caused by parking search. With a third of car driving occurring within city centers, a two to ten percent range of passenger car activity reduction resulted (see **Table 6** in the main paper). This is roughly in line with the finding of a 10% reduction potential of urban CO<sub>2</sub> emissions due to smart parking found in Streetline (2016).

#### Intermodality of freight

Intermodality of freight could provide emission reduction potentials which are presently hard to assess. As stated by IEA (2017), there is also a risk that high-capacity vehicles (HCV) could potentially lead to a 'reverse' mode shift from rail to road freight as a result of improved efficiencies and cheaper goods transport by HCVs. The lack of reliable data limits the accuracy of efforts to assess this effect. The assessment of intermodality impacts is limited to a cautious two to five percent reduction of truck mileage for all road types, based on an expert assumption provided by Volvo.

#### Coordination systems for freight

Better coordination of freight, reducing empty or partly-charged truck running, offers further improvement potential. T&M and IRU (2017) show that measures for logistical efficiency improvements may lead to a reduction of 10% CO<sub>2</sub> emissions for long haul transport and 12% for regional deliveries by 2050. Based on the assumption that presently 30% of truck space is unused, experts agreed to assume a range of 5% (pessimistic) to 10% (optimistic) activity reduction through better coordination in logistics in this study.

#### Increased truck capacity

Increased capacity of large trucks, so-called high capacity vehicles (HCV) could reduce the number of truck kilometres on core road segments. Based on the assumption that 50% of the largest category of trucks could be replaced by HCV, and reduce the activity by 15 to 20% where applied, an activity reduction of 5 to 10% within that truck category is considered in this study.

### A.3 Mathematical Documentation of Fleet Impact Calculations

Formally, results are calculated as follows:

For a given set of powertrains  $P_i$ ,  $i=1,\dots,I$  and vehicle segments  $S_j$ ,  $j=1,\dots,J$  a set of road types  $RT_r$ ,  $r=1,\dots,R$  and a set of fuel types  $FT_f$ ,  $f=1,\dots,F$  baseline 2015 fuel consumption  $FC_{base_{i,j,r,f}}$  and electric energy consumption  $EC_{base_{i,j,r}}$  is determined from the input data, see **Table 2** and **Table 5** in the main paper.

**Table 13: List of variables used for fleet impact calculations**

Variable	Abbreviation	States	Index
Powertrain	$P_i$	GSL ICE, DSL ICE, GSL PHEV, DSL PHEV, BEV, FCEV, LNG	$i=1,\dots,7$
Segment	$S_j$	S /M car, L car, City Bus/MDT, Truck/Coach	$j=1,\dots,4$
Road Type	$RT_r$	Urban, rural, highway	$r=1,\dots,3$
Road Type Share	$RS_{j,r}$	$0 \leq RS_{j,r} \leq 1$ , $\sum_r RS_{j,r} = 1$	
Fuel Type	$FT_f$	GSL, DSL, LNG, H2	$f=1,\dots,4$
Activity	$A_j$		
Vehicle Type Share*	$VS_{i,j}$	$0 \leq VS_{i,j} \leq 1$ , $\sum_i VS_{i,j} = 1$	
A&B Measures	$M_{AB_m}$	Improvements gasoline engines, Improvements diesel engines, Waste Heat Recovery,....	$m=1,\dots,12$
CO <sub>2</sub> Reduction*	$CO_2red_{m,i,j}$	$0 \leq CO_2red_{m,i,j} \leq 1$	
Energy Consumption Reduction*	$Enred_{m,i,j}$	$0 \leq Enred_{m,i,j} \leq 1$	
C measures	$M_{C_n}$	Reduced parking search traffic, Ride Sharing, Intermodality of freight,...	$n=1,\dots,4$
Activity Reduction	$Actred_{m,j}$	$0 \leq Actred_{m,j} \leq 1$	
Electric Drive Share	$ES_{i,j}$	$0 \leq ES_{i,j} \leq 1$	

\* Different Scenarios are specified for these Variables

For each fleet composition scenario (HE, HEH, Mix) and measure scenario (optimistic or pessimistic), the following calculations are carried out.

#### Specific Fuel and Energy Consumption 2050

A set of A and B type measures  $M_{AB_m}$ ,  $m=1,\dots,M$  is available for reducing fuel or energy consumption of the respective vehicle type by a measure-scenario specific share  $CO_2red_{m,i,j}$  or  $Enred_{m,i,j}$ .

Fuel and energy consumption in 2050 for each vehicle type and road type is calculated as

$$FC_{2050_{i,j,r,f}} = FC_{base_{i,j,r,f}} * \prod_{CO_2red_{m,i,j} \in CO_2red_{M,i,j}} (1 - CO_2red_{m,i,j}) \quad (1)$$

and

$$EC_{2050_{i,j,r}} = EC_{base_{i,j,r}} * \prod_{Enred_{m,i,j} \in Enred_{M,i,j}} (1 - Enred_{m,i,j}) \quad (2)$$

which yields the specific fuel or energy consumption (litre fuel per 100km or kwh per km) for the different vehicle types in 2050. Total consumption of the different fuels results by multiplying (1) and (2) by activities, which are derived in equations (3) to (6).

### 2050 Vehicle Type Activities

Given total 2050 activity per segment  $A_j$  is split by given road type shares per segment  $RS_{j,r}$  and is attributed to the vehicle types (i.e., segments and powertrains) based on their respective shares  $VS_{i,j}$  for the respective fleet composition scenario (see **Table 7**):

$$A_{i,j,r} = A_j * RS_{j,r} * VS_{i,j} \quad (3)$$

A set of C type measures  $M_{C_n}$ ,  $n=1, \dots, N$  is available for reducing the activity of given vehicle segments on specific road types by a measure scenario specific share  $Actred_{m,j}$ . Scenario activities are derived as

$$A'_{i,j,r} = A_{i,j,r} * \prod_{Actred_{m,j} \in Actred_{M,j}} (1 - Actred_{m,j}) \quad (4)$$

Finally, activity needs to be split into distance driven by conventional engine and in electric mode, making use of the electric drive shares  $EVshare_{i,j}$  specified by the experts which is zero for purely conventional vehicles such as advanced ICE, one for BEV and FCEV, and  $0 < ES_{i,j} < 1$  for PHEV. Conventional drive shares result as  $CS_{i,j} = 1 - ES_{i,j}$ , and respective activities are:

$$A'_{conv_{i,j,r}} = A'_{i,j,r} * CS_{i,j} \quad (5)$$

$$A'_{el_{i,j,r}} = A'_{i,j,r} * ES_{i,j} \quad (6)$$

### Total Fuel and Energy Consumption

Total consumption of the different fuels per vehicle type and road type results as:

$$TFC_{2050_{i,j,r,f}} = FC_{2050_{i,j,r,f}} * A'_{conv_{i,j,r}} \quad (7)$$

and

$$TEC_{2050_{i,j,r}} = TEC_{2050_{i,j,r}} * A'_{el_{i,j,r}} \quad (8)$$

These results can be aggregated by vehicle powertrain or segment, road or fuel type for the purposes of analysis.

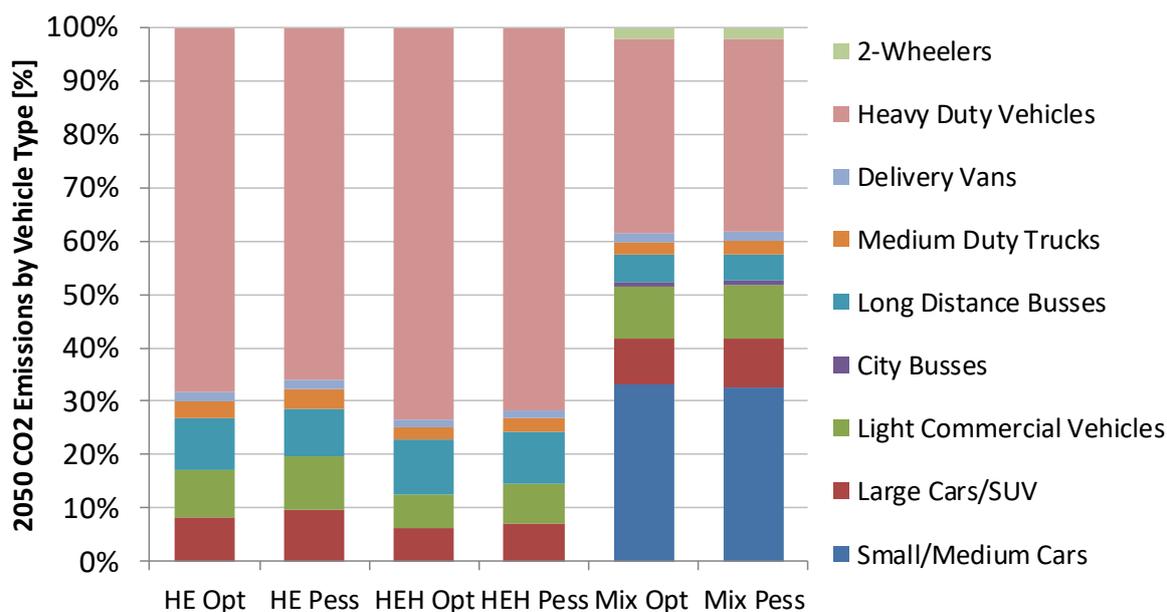
2050 CO<sub>2</sub> Emissions

CO<sub>2</sub> emissions for the respective scenario are derived from the fuel consumption by using emission factors  $Ef_f$  (gCO<sub>2</sub>/l fuel or gCO<sub>2</sub>/kWh energy) for the respective fuels:

$$CO2_{2050_{i,j,r,f}} = TFC_{2050_{i,j,r,f}} * EF_f \quad (10)$$

#### A.4 CO2 emissions by vehicle type and engine measure effect

The fleet calculations allow analysing CO<sub>2</sub> emissions by vehicle type, as shown in **Figure 11**. In line with the assumptions made, CO<sub>2</sub> emissions occur only for vehicle types where combustion engines are employed, i.e., advanced ICE and PHEV. Thus, e.g., there are no CO<sub>2</sub> emissions from small and medium cars in the HE and HEH scenarios, as these are 100% BEV. As obvious from the figure, heavy duty vehicles in the wider sense (including buses, medium duty trucks and delivery vans) contribute more than 80% of 2050 road transport CO<sub>2</sub> emissions in the two electrification scenarios, and nearly half of the emissions in the Mix scenario. Thus, by 2050, HDV are likely to become the main emitters in road transport, which shows that emission reduction in this segment is particularly crucial.



**Figure 11: 2050 road vehicle fleet CO<sub>2</sub> emission distribution by vehicle segments. Scenarios: High Electrification (HE), High Electrification plus Hydrogen (HEH), and Mixed scenario (Mix), with Optimistic (Opt) and Pessimistic (Pess) measure versions.**

In all scenarios, experts assumed HDV to have a high share of combustion engine propulsion (advanced ICE and PHEV) throughout 2050. It is therefore warranted to look into the technical potential for combustion engine improvement available until 2050. To this aim, the set of A measures was sub-split into engine improvement and other measures. CO<sub>2</sub> emission improvement through engine measures, as a %pt reduction versus 2015 emissions, is shown in **Table 14**. Numbers given here have to be seen in the context over overall A measure CO<sub>2</sub> reductions, as were shown in **Figure 7** in the main paper. For example, the total contribution of A measures to 2050 CO<sub>2</sub> emission reduction in the HE Opt scenario is around 10%pts, nearly 3%pts of which is due to engine measures. As the table shows, the less electrified the 2050 fleet, the higher the impact of engine measures. The highest relative contribution from engine measures of 10%pts is reached in the Mix scenario with optimistic measures, which has a total potential of 30%pts CO<sub>2</sub> reduction through A measures. The share of engine measures in total A measure CO<sub>2</sub> reduction ranges from 25 to 50%, and is higher for the pessimistic measure variants than for optimistic.

**Table 14: Contribution of engine measure to 2050 CO<sub>2</sub> emission reductions versus 2015 (%pts)**

	Opt	Pess
HE	2.8%	2.0%
HEH	1.9%	1.3%
Mix	10%	8%