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JEC Tank-To-Wheels report v5: Passenger cars

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context

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Contents

Abstract

This Tank-to-Wheel (TTW) report describes the final use of the various fuels and corresponding powertrain options. The TTW study described in this report includes several different fuel–powertrain configurations for conventional 1 (i.e. "ICE-only") as well as electrified (i.e. "xEV") powertrain variants. These variants are considered for 2015 (including technologies in the market in the years 2013 up to 2017) to represent the current state-of-the-art in automotive industry and for 2025+ (to give an outlook on the future technical development of passenger cars) based upon the likely market-average technology development expected by EUCAR and AVL experts.

1 Introduction

The study of current and future automotive powertrains and associated fuels in the European market consists of two parts: First, the issues related to fuel production and provision are covered in the Well-to-Tank report (WTT) of the study, and second the Tank-to-Wheel (TTW) report describes the final use of the various fuels and corresponding powertrain options. The Well-to-Wheels (WTW) report finally provides the integrated view of the relative merits of the wide range of options studied.

The Tank-to-Wheel study described in this report includes several different fuel–powertrain configurations for conventional[1] (i.e. "ICE-only") as well as electrified (i.e. "xEV") powertrain variants. These variants are considered for 2015 (including technologies in the market in the years 2013 up to 2017) to represent the current state-of-the-art in automotive industry and for 2025+ (to give an outlook on the future technical development of passenger cars) based upon the likely market-average technology development expected by EUCAR and AVL experts.

All fuel–powertrain configurations are investigated for fuel consumption, electric energy consumption and Greenhouse Gas (GHG) emission based on the homologation test cycle. In case of 2015 variants, the New European Driving Cycle (NEDC) is evaluated, whereas in case of 2025+ variants the Worldwide harmonized Light duty Test Procedure (WLTP) is investigated. The study is founded on a generic C-segment vehicle as an average market reference. All conventional or xEV variants are derived from this reference based on protection of pre-defined vehicle performance criteria. The xEV variants include definitions of appropriate powertrain topologies and system architectures, educated estimations of Hybrid functionalities and operational strategies, and powertrain components including optimized layout and a proper mass balance. For detailed investigation, all variants are modelled in the system simulation tool AVL CRUISE. Data, models and strategies have been discussed and mutually agreed between the EUCAR Task Force and AVL to ensure a high quality of results.

It should be noted that all investigated powertrain variants only represent theoretical vehicle configurations and do not correlate to any existing vehicle or brand. However, the definitions made try to ensure, that the investigated powertrain variants provide a representative overview about todays and expected future automotive technologies and their impact on GHG emissions in European C-segment passenger cars.

1 Non-electrified vehicle variants driven by an ICE only are subsequently named as "conventional". This excludes Hybrid vehicles, which fall into the xEV category.

Acknowledgements

This JEC Consortium study was carried out jointly by experts from the JRC (EU Commission's Joint Research Centre), EUCAR (the European Council for Automotive R&D), and CONCAWE (the oil companies' European association for environment, health and safety in refining and distribution) assisted by experts from the Forschungsgesellschaft for Internal Combustions Engines and Thermodynamics (FVT) [2].

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2 The Forschungsgesellschaft for Internal Combustions Engines and Thermodynamics mbH (FVT) is a spin-off of the Institute for Internal Combustions Engines and Thermodynamics (IVT) at the Graz University of Technology (TU Graz). There is a close cooperation between the two institutions which is based on sharing the staff and infrastructure to a large extend.

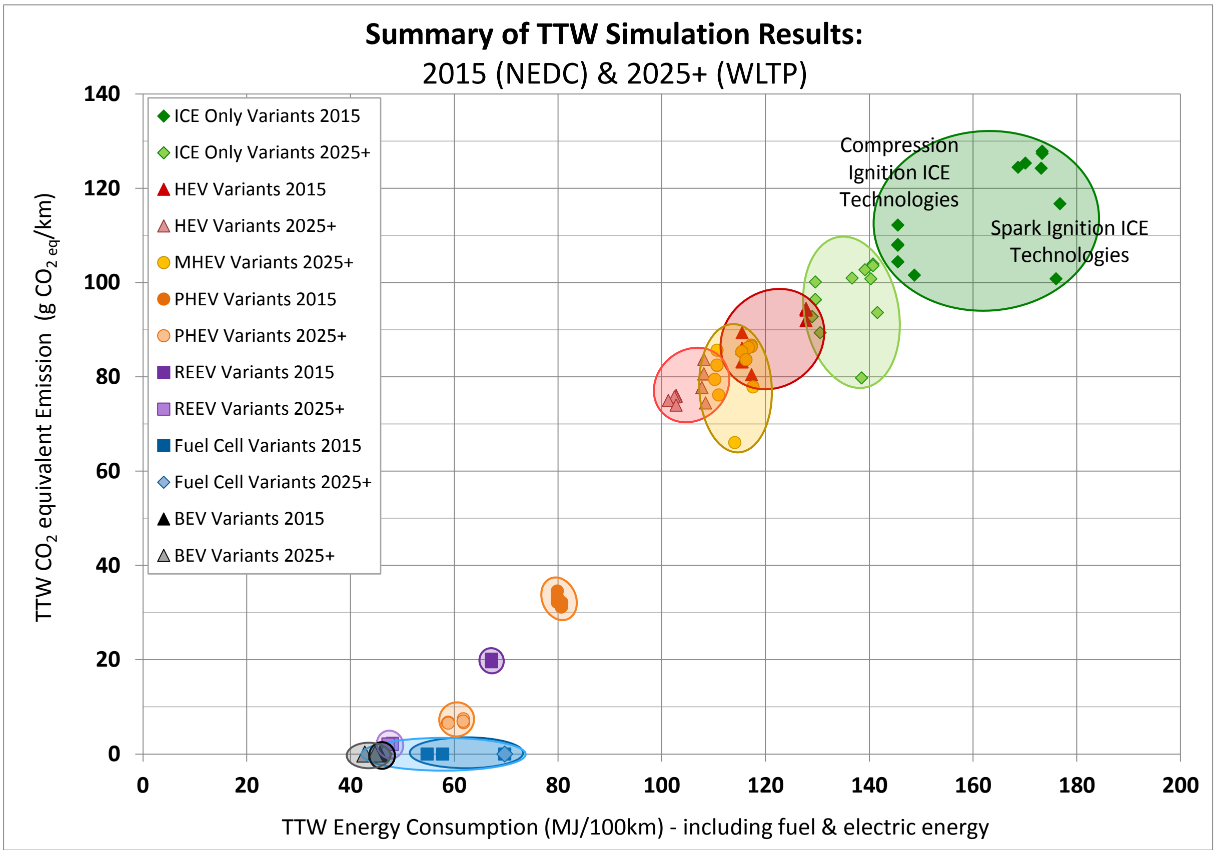
2 Executive summary

Chapter 3 introduces the fuels and powertrain configurations covered in this TTW study. Conventional powertrains include the ICE technologies of Direct Injection Spark Ignition, e.g. Otto engine (DISI) and Direct Injection Compression Ignition, e.g. Diesel engine (DICI). Electrification of conventional powertrains is covered in terms of a 48V Mild Hybrid Electric Vehicle (MHEV), a Hybrid Electric Vehicle (HEV), a Plug-In Hybrid Electric Vehicle (PHEV) and a Range Extender Electric Vehicle (REEV). The 48V MHEV, only considered for 2025+, in principle shows the same functionality as the HEV, but represents a simpler approach compared to the dedicated HEV development. Additionally, pure electric powertrains like Battery Electric Vehicle (BEV) and Fuel Cell driven Electric Vehicle (FCEV) are investigated.

A description of all analysed combinations of these powertrains with corresponding fuel variants for 2015 and 2025+ is given in chapter 3.4. The methodology used for the simulation study is described in chapter 4. The detailed description of investigated powertrain configurations and their component specifications for 2015 variants is given in chapter 5, and for 2025+ variants in chapter 6. Finally, detailed summary diagrams showing the results for TTW CO_2 equivalent emission and energy consumption including the evaluation of error bars are given in chapter 7.

In the following overview diagram, all results are summarized in terms of CO_2 equivalent emission and energy consumption for 2015 and 2025+ variants:

Figure 2-1: Summary of TTW Simulation Results for 2015 (NEDC) & 2025+ (WLTP) Variants; note that electric energy consumption includes charging losses



3 Fuels & Powertrain configurations

3.1 Fuel Properties

The properties of the fuels considered in this study are listed in Table 3-1. Fuel properties are defined based on current average technology and used for simulation of 2015 as well as 2025+ variants to enable comparability of results. For all properties specific bandwidths exist, which are described in the Well-to-Tank part of the report.

For the vehicle simulation, the fuel properties are taken into consideration in two different ways: For some main fuels like Gasoline E5, Gasoline High Octane, CNG, E100 and Diesel B7 stationary ICE fuel consumption maps are specifically designed for the various ICE technologies and implemented into the powertrain simulation models for detailed calculation. The impacts of the other fuels are derived from these calculations based on their properties as given in Table 3-1.

Table 3-1: Fuel properties for WTW study version 5

Fuel Type	Density	RON / CN	LHV	Elemental composition of Carbon
	*kg/m³ i.N.**	---	*MJ/kg*	*%m*
Gasoline E5	745,8	95	42,3	84,7
Gasoline E10	748,3	95	41,5	82,8
Gasoline High Octane spec. #1	761,0	100	42,4	84,8
Gasoline High Octane spec. #2	759,0	102	41,6	83,3
Diesel B0	832,0	51,0	43,1	86,1
Diesel B7 market blend	836,1	53,0	42,7	85,4
LPG	550,0	---	46,0	82,4
CNG	0,775	82**	48,0	73,5
E100	794,0	108,0	26,8	52,2
FAME	890,0	56,0	37,2	77,3
DME	670,0	55,0	28,4	52,2
FT-Diesel	780,0	70,0	44,0	85,0
HVO	780,0	70,0	44,0	85,0
Hydrogen	0,084	#	120,0	---
**) All values are related to standard conditions according to DIN 1343 & ISO 2533;*				
***) Methane number based on EN 16723*				

3.2 Reference C-segment vehicle

All simulations are based on a generic reference vehicle, representing a standard market-average European C-segment 5-seater sedan. This reference vehicle enables a comparison across various fuels and associated powertrain technology combinations covered in this report. The vehicle is virtual and does not represent a specific model nor is it claimed to be representative of the European passenger car fleet.

3.2.1 Main vehicle specification

The C-segment reference vehicle model, representative for NEDC in year 2015, is equipped with a 1.4L displacement IL4 TGDI (DISI) ICE, a 6 speed Manual Transmission (MT) and Front Wheel Drive (FWD). Table 3-2 shows the main reference vehicle characteristics used in vehicle simulation. Herein the curb weight is defined as the total weight of the vehicle with standard equipment, all necessary operating consumables (e.g. motor oil and coolant), and a 90% full tank of fuel, while not loaded with either driver, passengers or cargo.

The C-segment reference vehicle model, representative for WLTP in year 2025+, is equipped with a 1.5L IL4 TGDI (DISI) ICE, a 6 speed Manual Transmission (MT) and Front Wheel Drive (FWD). In comparison to 2015, the curb mass is reduced by 110kg, and the driving resistance is revised to cover the different homologation procedure of the WLTP: The air drag coefficient is reduced from 0.28 to 0.25, whereas the rolling resistance coefficient is kept the same (Table 3-2).

Table 3-2: Characteristics of the generic C-segment reference vehicle

Generic C-segment reference vehicle with 1.4L DISI ICE for NEDC (2015)			Reference Vehicle for WLTP 2025+
Curb Mass incl. Driver, 90% fuel	kg	1310,0	1200,0
Lenght	mm	4326,5	
Width (without exterior mirror)	mm	1789,4	
Height	mm	1484,8	
Cross-Sectional area	m²	2,2	
Air drag coefficient	-	0,28	0,25
Rolling resistance coefficient	-	0,007	0,007
Wheel base	mm	2638,9	
Height of gravity center	mm	600,0	
Distance of gravity center from front axle	mm	1200,0	
Dynamic rolling radius	mm	309,0	

3.2.2 Vehicle mass

For the 2015 conventional variants the vehicle masses (i.e. curb weight including driver) are specified as 1310kg for DISI and 1370kg for DICI. For the 2025+ conventional variants, the corresponding vehicle masses are reduced by 110kg. All other vehicle variant masses (Conventional & xEV) are determined based on a mass balance calculation for the main powertrain components ICE, Fuel Cell, E-machines, Battery, Transmission, xEV wiring harness, Tank systems & fuel content. Vehicle masses for driving performance simulations are defined as curb weight (excl. driver) plus 200kg.

For vehicle gradeability, the Gross Vehicle Mass (GVM) is used, which is defined as follows: 2015 vehicle variants all show the same GVM of 1820kg, whereas 2025+ vehicle variants all show the same payload of 510kg. The corresponding values for GVM and payload for all conventional vehicle variants are shown in Table 3-3.

Table 3-3: Vehicle GVM and payload definition for conventional variants

Vehicle Payload and Gross Vehicle Mass for Conventional ("ICE only") Variants		2015		2025+	
		DISI	DICI	DISI	DICI
Curb Mass incl. Driver, 90% fuel	kg	1310	1370	1200	1260
Payload	kg	510	450	510	
Gross Vehicle Weight	kg	1820		1710	1770

3.2.3 Vehicle minimum performance criteria

To guarantee a fair comparison between all investigated vehicle variants, minimum "customer performance" criteria are defined to ensure that each powertrain-fuel configuration meets the same customer expectations for driveability. Therefore all conventional or xEV variants are derived from the reference C-segment vehicle in a way, that specific measures in powertrain component layout (e.g. adaptation of ICE displacement or transmission ratios) are undertaken to fulfil the minimum performance criteria in all variants. These performance criteria are simulated in detail and reached by all variants[3]. The vehicle minimum performance criteria are summarized in Table 3-4.

Please note that the top-speed criterion for all BEV and REEV variants is reduced in general to reflect the market in the 2015 timeframe. The driving range criterion for BEV is clearly reduced compared to the other variants. For 2025+ there is a short range (200km) and a long range (400km) BEV variant defined; this reflects an assumed market trend of BEVs offering also a cost-effective solution. In both cases, the driving range is higher but still clearly below 500km (all other variants) due to restricted battery capacities. However, acceleration and gradeability criteria are identical.

3 There are 2 exceptions: 2015 conv. DME variant exceeds 0-100km/h criterion by 0,2s due to the additional tank system; 2015 FC REEV variant exceeds 0-100km/h criterion by 0,3s due to high total mass; given the usual commonality of components in powertrain variants, no special ICE / E-machine with slightly higher power is defined.

The vehicle minimum performance criteria are partially exceeded by far: For example the total driving range of 2015 conventional “ICE only” DISI variants is in the order of 1000km, which is well in line with benchmark vehicles representing 2015 market-average. Correspondingly, the system layout of xEV variants is in general done in a way to conserve this characteristic and ensure a total driving range of comparable magnitude.

Table 3-4: Vehicle minimum performance criteria (abbreviations see the appendix)

Vehicle Minimum Performance Criteria			2015					2025+				
			DISI DICI Hybrid DISI Hybrid DICI	PHEV SI PHEV CI PHEV FC	REEV SI REEV FC	BEV	FCEV	DISI DICI DISI MHEV DICI MHEV Hybrid DISI Hybrid DICI	PHEV SI PHEV CI PHEV FC	REEV SI REEV CI REEV FC	BEV	FCEV
Time lag for 0-100 km/h	(peak power)	s	11	11	11	11	11	11	11	11	11	11
Time lag for 80-120 km/h (for MT6 in 5th gear)	(peak power)	s	11	11	11	11	11	11	11	11	11	11
Gradeability at 1 km/h	(peak torque)	%	30%	30%	30%	30%	30%	30%	30%	30%	30%	30%
Gradeability at 10km/h or idle creep speed in 1st gear	(continuous power & torque)	%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%
Minimum Top speed	(continuous power)	km/h	180	180	140	140	180	180	180	150	150	180
	(pure electric, continuous power)	km/h	#	140	140	140	180	#	150	150	150	180
Total driving range		km	500	500	500	150	500	500	500	500	200 / 400*	500
Battery powered driving range		km	#	50	100	150	#	#	100	200	200 / 400*	#
Fuel consuming range		km	500	450	400	#	500	500	400	300	#	500

**) In 2025+ a short range (200km) as well as a long range (400km) BEV are considered.*

3.3 Powertrain configurations

3.3.1 Conventional (“ICE only”) variants

The conventional variants DISI (baseline fuel Gasoline E5) and DICI (baseline fuel Diesel B7) are equipped with a 6-speed MT for both 2015 and 2025+ variants. Transmission ratios are defined based on benchmark of comparable European C-segment gasoline and diesel vehicles in the market. All variants for both 2015 and 2025+ are equipped with Engine Start/Stop functionality. In case of 2025+ Engine Start/Stop is done via an E-machine, which is connected to the crankshaft either directly or via a single ratio gear set; this E-machine will have up to 4kW maximum power and cover the electric energy demand of the Auxiliaries in WLTP purely via recuperation.

In case of Gasoline High Octane, a dedicated engine with adapted compression ratio[4] is foreseen for both 2015 and 2025+. In case of E100, no dedicated engine is foreseen[5], as there is no usage of E100 expected in Europe until 2025+ timeframe. In case of CNG, a dedicated engine with adapted compression ratio is foreseen for both 2015 and 2025+. In 2015, the CNG engine is equipped with Multi Point Injection (MPI) and designed for a broad range of methane numbers (as available in EU market), including also gasoline operation. In 2025+, the CNG engine is equipped with DI and specifically designed for a defined (high) methane number[6], following EU Automotive CNG Standard EN16723-2 from July 2017; it is a real mono-valent configuration without the possibility to use gasoline fuel.

In case of LPG and DME, the respective ICEs are optimized for their specific fuel type in general. In 2015, they do also operate with respective standard gasoline or diesel (bi-valent configuration). In 2025+, they represent real mono-valent configurations without the possibility to use standard fuel. Note that today’s fuel injection systems for DME are based on existing Diesel common rail systems and will be optimized for 2025+ variants.

In case of Fischer-Tropsch Diesel (FT-Diesel) or Hydro-treated Vegetable Oil (HVO), 2015 results for all variants are based on a standard engine which is not especially adapted for the special fuel type, whereas 2025+ results are all based on a fuel-dedicated engine[7].

4 Performance targets only need to be fulfilled with the dedicated High Octane fuel; using lower Octane Gasoline like E5 would result in reduced engine performance, nevertheless the engine is assumed to be able to run on E0 or E5.

5 The engine is designed for Gasoline (E5) and will adapt its calibration to efficiently use E100.

6 Consequently, engine power is reduced in case of using lower methane content fuels.

7 This also includes all xEV variants such as MHEV, HEV, PHEV and REEV.

3.3.2 Fuel tank systems of Conventional ("ICE only") variants

All conventional variants DISI and DICI are equipped with a 55L standard size fuel tank for 2015. This is reduced to a 35L fuel tank for 2025+ to ensure a comparable driving range for the more efficient future powertrains. The CNG fuel tank system is defined as a 150kg 3-cylinder steel tank system for 2015 and an improved 50kg type 4 2-cylinder composite tank system for 2025+. The LPG & DME fuel tank system is defined to 80L tank size for 2015 and reduced to a 60L tank size for 2025+. CNG, LPG and DME vehicles for 2015 are equipped with an additional 14L gasoline or diesel tank, respectively; for 2025+, no additional gasoline or diesel fuel tank is used.

3.3.3 xEV variants

The following powertrain topologies are considered as representative for electrified vehicles:

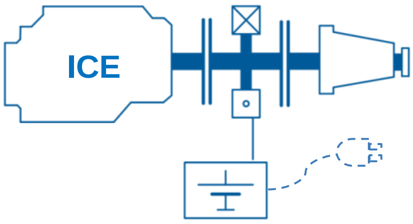
3.3.3.1 Mild Hybrid Electric Vehicle (MHEV), Hybrid Electric Vehicle (HEV) & Plug-In Hybrid Electric Vehicle (PHEV):

A P2 parallel Hybrid configuration is selected for MHEV, HEV and PHEV, as shown in Figure **3-1**. A six speed automatic transmission with a dry clutch as launch element is used for all variants in both 2015 and 2025+. The transmission ratios are adapted from conventional variants in a way to conserve the vehicle traction capability. The P2 configuration is selected to generally represent the full Hybrid CO_2 emission reduction potential, as it is today seen as the predominant topology in European Hybrid development. Although the 2015 HEVs on European market are mainly powersplit HEVs, their impact on vehicle energy consumption and GHG emission, which is relevant for this study, is considered largely equivalent to the respective impact of parallel HEVs.

The 48V MHEV, only applied in 2025+, in principle shows the same functionality as the HEV, but represents a simpler add-on approach compared to the dedicated HEV development. Although including full Hybridization from functionality perspective, this 48V variant is called "Mild" Hybrid, to be better distinguished from the standard "Full" Hybrid with dedicated engine and transmission development.

The minimum battery powered driving range requested for the PHEV is 50km in 2015 and 100km in 2025+, it is able to run the complete NEDC in 2015 as well as the complete WLTP in 2025+ purely electrically. The MHEV and HEV variants show a restricted battery powered driving range of less than 5 km.

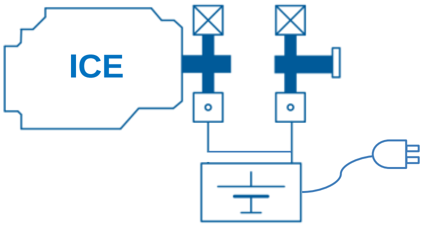
Figure 3-1: P2 parallel Hybrid topology



3.3.3.2 Range Extender Electric Vehicle (REEV)

A series Hybrid configuration is defined for the REEV with SI and CI ICEs, as shown in Figure 3-2. For 2015, a single gear transmission is used, whereas for 2025+ a dual gear transmission is implemented. The battery powered driving range for the REEV is 100km in 2015 and 200km in 2025+.

Figure 3-2: Series Hybrid topology

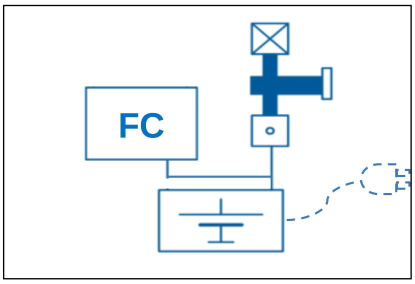


3.3.3.3 *Fuel Cell Electric Vehicle (FCEV), Fuel Cell driven Plug-In Electric Vehicle (PHEV FC) & Fuel Cell driven Range Extender Electric Vehicle (REEV FC)*

A Hybrid configuration is selected for all Fuel Cell (FC) driven variants, as shown in Figure 3-3. In all variants, the FC is coupled to the HV Bus via a DCDC converter. Similar to the REEV, for 2015 a single gear transmission is used, whereas for 2025+ a dual gear transmission is implemented. The FC system power level is defined based on the vehicle minimum performance criteria as shown in Table 3-4: In case of 2015, the FCEV and PHEV FC require a 65kW FC system power, whereas for 2025+ this power is reduced to 55kW for both variants mainly due to the improved vehicle driving resistance. The REEV FC requires a 35kW FC system power in both 2015 and 2025+.

The battery powered driving range for the PHEV FC and REEV FC is defined in the same way as for the ICE driven variants.

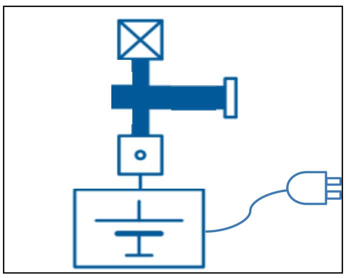
Figure 3-3: Series Hybrid topology for FC vehicles



3.3.3.4 *Battery Electric Vehicle (BEV)*

The drivetrain schematic for the BEV is shown in Figure 3-4. The battery powered driving range for the BEV is 150km for 2015. In case of 2025+, two different variants are defined: A short-range BEV with a driving range of 200km, and a long-range BEV with a driving range of 400km. Similar to the REEV, for 2015 a single gear transmission is used, whereas for 2025+ a dual gear transmission is implemented.

Figure 3-4: Drivetrain schematic for BEV



3.3.4 xEV technologies

All xEV E-machines are based on Brushless Permanent Magnet Synchronous Machine technology. E-machine power densities range from 1300W/kg for BEV to 800W/kg for HEV in 2015 and from 1500W/kg for BEV to 1000W/kg for HEV in 2025+. For the 2025+ 48V MHEV the E-machine power density is estimated to 950kW/kg. E-machine power and torque levels are determined based on the requirement of >90%

recuperation potential in WLTC and appropriate Electric Launch & Driving in WLTC wherever useful. E-machine continuous-to-peak power ratios are designed in the range between 0.5 and 0.7, which is common for automotive applications. Finally, Generator E-machines for the Series Hybrid configurations show a power density of 1300W/kg for 2015 and 1500W/kg for 2025+. In general, E-machine efficiency improvement potentials from 2015 to 2025+ are foreseen based on improvement in control efficiency, better hardware and more efficient packaging, less switching losses and lower thermal losses.

All xEV batteries are based on Li-Ion technology and designed for a voltage range between 300V and 400V. Battery system energy densities range from 120Wh/kg for BEV to 40Wh/kg for HEV in 2015 and from 160Wh/kg for BEV to 60Wh/kg for (M)HEV in 2025+. Battery system power densities range from 600W/kg for BEV to 1000W/kg for HEV in 2015 and from 600W/kg for BEV to 1300W/kg for (M)HEV in 2025+. Useable Charge of State range (also known as Depth of Discharge) is set between 80% for BEV and 30% for HEV in 2015 and between 90% for BEV and 40% for (M)HEV in 2025+. Battery power levels are defined according to E-machine power requirements including losses; battery capacities are defined according to energy throughput in WLTP operation for (M)HEV and due to the Electric Driving range as defined in Table 3-4 for all other variants.

All Fuel Cell Systems are based on Proton Exchange Membrane (PEM) technology, as it is common for automotive applications.

3.3.5 Fuel tank systems of xEV variants

In case of 2015, all HEV, PHEV and REEV (Gasoline only) variants are equipped with a 55L standard size fuel tank. In case of 2025+, to ensure a comparable driving range for the more efficient future powertrains, this is reduced to a 35L fuel tank for MHEV and HEV, and further reduced to a 28L fuel tank for PHEV and a 21L fuel tank for REEV 2025+.

The 2025+ CNG MHEV fuel tank system is defined as a 50kg type 4 2-cylinder composite tank system. The 2025+ LPG MHEV fuel tank system is defined to a 60L tank size. The 2025+ DME MHEV and HEV fuel tank system is defined to a 60L tank size, which is further reduced to 48L for DME PHEV and 36L for DME REEV. CNG, LPG and DME xEV variants for 2015 are equipped with an additional 14L gasoline or diesel tank, respectively; for 2025+, no additional gasoline or diesel fuel tank is used (truly monovalent configuration).

Hydrogen fuel tank systems represent Compressed Gaseous Hydrogen (CGH2) technology. In both 2015 and 2025+, the fuel tank capacity is assumed to 4kg, which gives a driving distance well above the 500km minimum criterion. All FC variants are simulated based on a generic tank system of 90kg.

3.3.6 Auxiliaries

The following auxiliary systems are considered in the vehicle simulation: Steering pump (all EPS), Vacuum pump for braking system, ICE water pump, ICE oil pump, transmission oil pump and cooling systems for xEV Batteries and E-machines. Additionally the vehicle electric base load is estimated to 200W (ICE active) and 150W (Electric Driving) average power. Corresponding fuel consumption impacts due to partial or full electrification of these auxiliaries are covered in the vehicle simulation for all variants. The Battery voltage level for vehicle electrics is assumed to 12 V for all variants 2015 & 2025+.

3.4 Analysed fuel & powertrain configurations

All fuel–powertrain configurations for conventional as well as electrified powertrain variants are shown in Table 3-5. These configurations are considered for both 2015 (including market-average technologies in a range from approximately 2013 up to 2017) to represent today's state of the art in automotive industry, and for 2025+ (to give an outlook on the expected future development of drivetrain technologies) based upon the likely market-average technology development foreseen by EUCAR and AVL experts.

Exceptions for consideration in 2015 and 2025+ are the MHEV and REEV CI configurations, which are considered in 2025+ only, and the BEV, where two different range variants are defined in 2025+. All fuel–powertrain configurations are investigated based on the homologation test cycle relevant at the point in time: the 2015 variants are evaluated with the NEDC, whereas in 2025+ variants are investigated with the WLTP.

All configurations are either calculated directly (marked in blue in Table 3-5) via enhanced system simulation based on AVL CRUISE simulation models (see also chapter 4.1), or derived from these simulated results based on their specific fuel properties (marked in grey in Table 3-5).

Table 3-5: Matrix of fuel-powertrain combinations investigated in the current TTW study; variants marked in blue are modelled in powertrain simulation in detail; variants marked in grey are derived from them based on their fuel properties. All variants are considered for 2015 and 2025+ except the following: MHEV and REEV CI are considered for 2025+ only, and BEV 2025+ is defined in two different range variants.

	DISI	DISI MHEV	DICI	DICI MHEV	Hybrid DISI	Hybrid DICI	PHEV SI	REEV SI	PHEV CI	REEV CI	BEV	FCEV	PHEV FC	REEV FC
Gasoline E5	blue	blue			blue		blue	blue						
Gasoline E10 market blend	grey	grey			grey		grey	grey						
Gasoline high Octane spec. #1	blue	blue			grey		grey	grey						
Gasoline high Octane spec. #2	blue	blue			grey		grey	grey						
Diesel B0			grey	grey		grey			grey	grey				
Diesel B7 market blend			blue	blue		blue			blue	blue				
LPG	grey	grey												
CNG	blue	blue												
E100	blue	blue			grey		grey	grey						
FAME			grey	grey		grey			grey	grey				
DME			grey	grey		grey			grey	grey				
FT-Diesel			blue	blue		grey			grey	grey				
HVO			grey	grey		grey			grey	grey				
Electricity							blue	blue	blue	blue	blue		blue	blue
Hydrogen												blue	blue	blue

3.5 xEV operation

All xEV vehicles include a control unit, which contains the Hybrid modes (also called functionalities or features) and steers the operational strategies for all actively controlled powertrain components such as ICE, E-machine and Fuel Cell. Such a control unit is implemented in the vehicle simulation accordingly. The basic architecture of this control unit for ICE driven variants including all the xEV operation modes is divided into three levels as shown in Table 3-6: In the first level, the decision is made, if the ICE is turned on or off; in the second level the ICE state is further divided into two sub-states, to differentiate if the vehicle is basically in traction or braking mode; finally, in the third level, in case the ICE is active and used for traction, there is an additional subdivision of states to differentiate for the combined use of the ICE and the E-machine: Either the E-machine is deactivated (state "ICE ON Traction"), or it is activated to support enhancement of the overall ICE efficiency via Load Point Moving (LPM, state "ICE ON Traction LPM") or to just provide additional torque beyond the maximum torque capacity of the ICE (Boost, "ICE ON Traction Boost"). These modes as well as the corresponding operation strategies are described in detail in the following sections. In case of ICE driven variants they are schematically shown in Figure 3-5 for Parallel Hybrid and in Figure 3-6 for Series Hybrid configurations. In the Series Hybrid the modes are basically the same as in the Parallel Hybrid. As the RE is decoupled from the drivetrain, the RE operation is optimized at each output power demand along its optimum RE operation line, which is also shown in Figure 3-6.

The decision on activating a specific xEV mode is always started on level 1, after which level 2 and finally level 3 (see detailed explanation in 3.5.1 to 3.5.4) is checked consecutively: First, the allocation is made, if the

ICE has to be ON or OFF; after this the next decision on level 2 is made, if the vehicle is in traction or braking (i.e. negative torque at wheel) mode; finally, the sub-modes of level 3 are identified.

Table 3-6: Basic architecture of the control unit including all xEV operation modes

xEV operation modes		
Level 1	*Level 2*	*Level 3*
ICE ON	ICE ON Traction	ICE ON Traction
		ICE ON Traction LPM
		ICE ON Traction Boost
	ICE ON Braking	ICE ON Braking
ICE OFF	ICE OFF Traction	ICE OFF Traction
	ICE OFF Braking	ICE OFF Braking

Figure 3-5: xEV operation modes for ICE driven Parallel Hybrid (MHEV, HEV, PHEV) variants; the schematic BSFC lines represent the ICE operation only

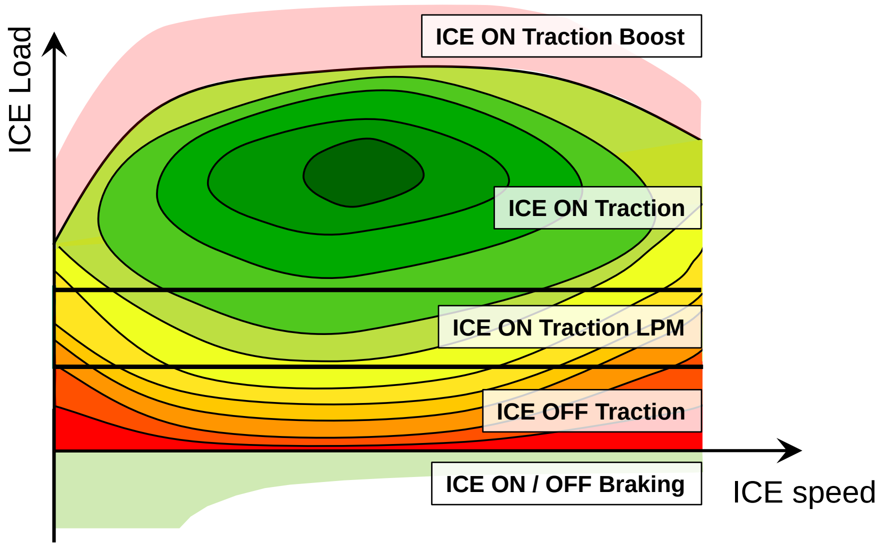
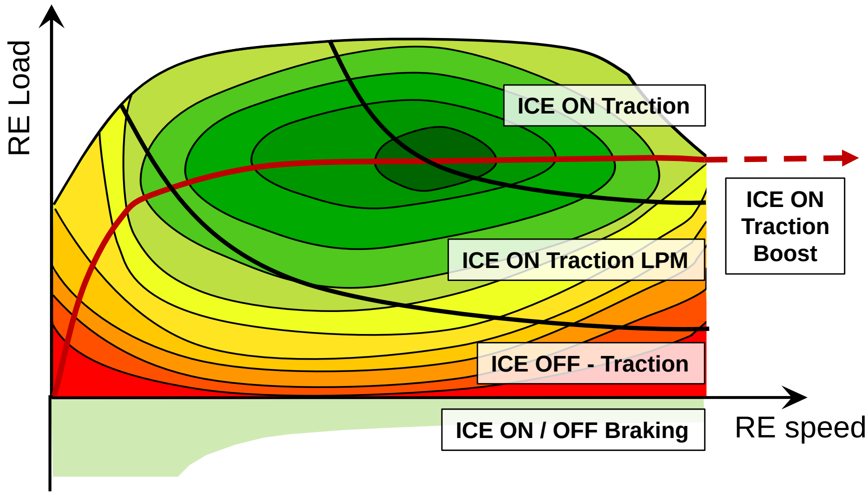


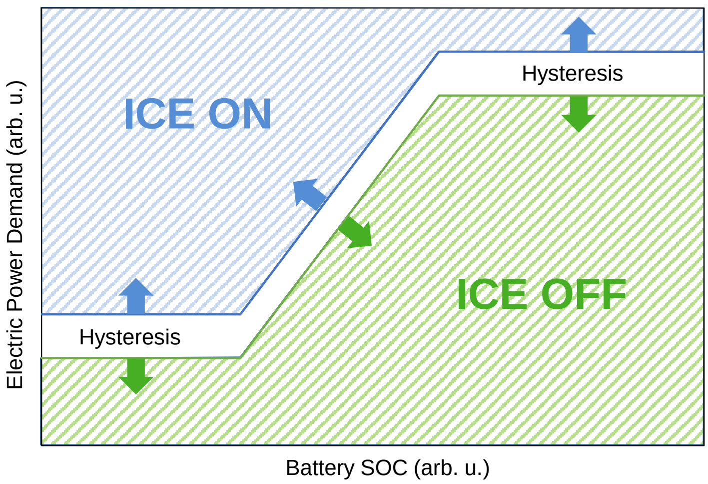
Figure 3-6: xEV operation modes for ICE driven Series Hybrid (REEV) variants; the schematic BSFC lines represent the complete Range Extender (RE) module (ICE & generator operation combined); the red line represents the optimum RE operation line along which the RE load is distributed exclusively



3.5.1 ICE ON / OFF

Activation and deactivation of the ICE is mainly controlled via the calculated electric power demand for the current driving situation. If this power demand exceeds a battery SOC dependent upper threshold, the combustion engine is turned on, and will only be turned off once the power demand falls below a lower threshold, following a typical hysteresis behaviour (see Figure 3-7). At low SOC, these thresholds are shifted down to a lower power demand level, which protects the battery from critical discharging. Consequently, at high SOC these thresholds are shifted up to a higher power demand level to enable extensive use of Electric Driving. In addition to the power demand, other criteria also influence the activation and deactivation of the combustion engine, such as a minimum engine running time, component limitations (e.g. maximum E-machine torque or battery output power) or the actual engine temperature.

Figure 3-7: Basic operation strategy for ICE activation / deactivation



3.5.2 ICE ON

3.5.2.1 ICE ON Traction

The xEV operation mode “ICE ON Traction” is further subdivided into three sub-modes, which describe the contribution of the E-machine to the operation of the ICE:

ICE ON Traction

The ICE is used exclusively, if it can work with reasonably high efficiency or low BSFC, respectively, and if the torque demand does not exceed the maximum ICE performance.

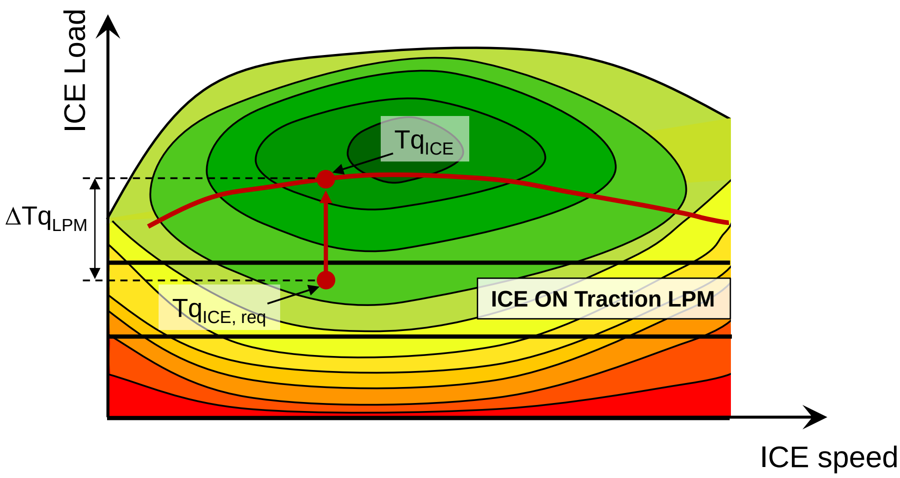
ICE ON Traction LPM

Load Point Moving (LPM) is activated if the torque demand at wheel is lower than a calibrated threshold, so that the ICE would have to work with insufficient efficiency or high BSFC, respectively. In such a case, LPM is used to move engine operation to higher load to increase efficiency:

$$Tq_{ICE} = Tq_{ICE,req} + \Delta Tq_{LPM}$$

Here TqICE is the actual ICE torque, TqICE, req is the traction torque required at the ICE crankshaft for driving, and ΔTq_{LPM} is the additional (calibrated) torque to increase the load of the ICE accordingly, see Figure 3-8. In LPM operation, TqICE is limited by the so-called “Maximum torque line”: ICE load points shifted to higher torque levels do not exceed this line to ensure overall powertrain efficiency optimization. This Maximum torque line, shown in red color in Figure 3-8, depends on velocity & engine speed due to NVH considerations.

Figure 3-8: ICE ON Traction LPM mode for Parallel Hybrid (MHEV, HEV, PHEV) variants; the red line represents the Maximum torque line for LPM operation



As shown in Figure 3-5 and Figure 3-6, the LPM functionality is in principle available for both Parallel (MHEV, HEV, PHEV) and Series Hybrid (REEV) configuration. However, in the Series Hybrid the speed and load of the ICE are independent from the driving conditions: The Range Extender module (combined system of ICE and generator) is optimized to work along its optimal operating line (i.e. the line that combines the lowest fuel consumption per generated electric power for all possible operation points). The Range Extender electric power PRE is defined by the following equation:

$$P_{RE} = P_{RE,req} + \Delta P_{LPM}$$

Here PRE, req is the electric power required by the traction E-machine for driving, and ΔP_{LPM} is the additional (calibrated) electric power to increase the load of the Range Extender accordingly.

ICE ON Traction Boost

The E-machine is used in addition to the maximum available ICE torque to improve full-load performance. This so-called “Boost” functionality requires sufficient battery SOC. In the homologation test cycles NEDC and WLTP there is always sufficient engine torque available to perform the cycle driving, and hence within this study, this mode is only activated in case of full load performance such as e.g. 0-100km/h acceleration.

3.5.2.2 ICE ON Braking

Regenerative Braking is applied in situations where the driver requires negative traction power. In case of the (M)HEV and PHEV variants, during such phases the ICE is disengaged by opening its separation clutch to allow a maximum of recuperated energy, provided by the E-machine. For safety and comfort reasons, conventional friction brakes are enabled and added during severe deceleration situations. However, due to limited deceleration in NEDC and WLTP operation, no such restriction in regenerative braking needs to be considered accordingly.

3.5.3 ICE OFF

3.5.3.1 ICE OFF Traction

The ICE OFF Traction mode is also well known as "Electric Driving". It is applied in case of sufficient available Battery energy as well as E-machine power, to avoid low efficiency operation of the ICE (see chapter 3.5.1).

3.5.3.2 ICE OFF Braking

This mode is similar to ICE ON Braking (chapter 3.5.2.2); however, the ICE is allowed to be turned OFF.

3.5.4 Fuel Cell operation

The operational strategy for all Fuel Cell driven variants (FCEV, PHEV FC, REEV FC) is optimized to operate the Fuel Cell at a maximum efficiency within a suitable range of the battery SOC. This control logic consists of four different operation modes, defined as a function of the battery SOC and the required electric power PREQ (derived from the traction torque requested by the driver) as shown in Table 3-7, with PFC as the electric power output of the FC system, and POPT and k as calibration parameters[8]. Herein PFC = POPT and PFC = k ∗ PREQ represent the "ICE ON Traction LPM" mode equivalent for FC driven variants, PFC = 0 represents the "ICE OFF Traction" mode equivalent for FC driven variants, and finally PFC = PREQ represents the "ICE ON Traction" mode equivalent for FC driven variants.

Table 3-7: xEV operational strategies in case of FC driven variants

Required Power / SOC	$< P_{OPT}$	$> P_{OPT}$
$< SOC_{MIN}$	$P_{FC} = P_{OPT}$	$P_{FC} = P_{REQ}$
$> SOC_{MIN}$	$P_{FC} = 0$	$P_{FC} = k * P_{REQ}$

8 The operating strategy implemented in all FC driven variants is based on the "Load Follower Energy Management Strategy" extracted by the paper "P. R. Akula, L. Jandhyala, F. Herb, A. Narayana, Development of Energy Management Strategies and Analysis with Standard Drive Cycles for Fuel Cell Electric Vehicles, SAE International, 2012"

4 Simulation Methodology

4.1 AVL CRUISE as Simulation Environment

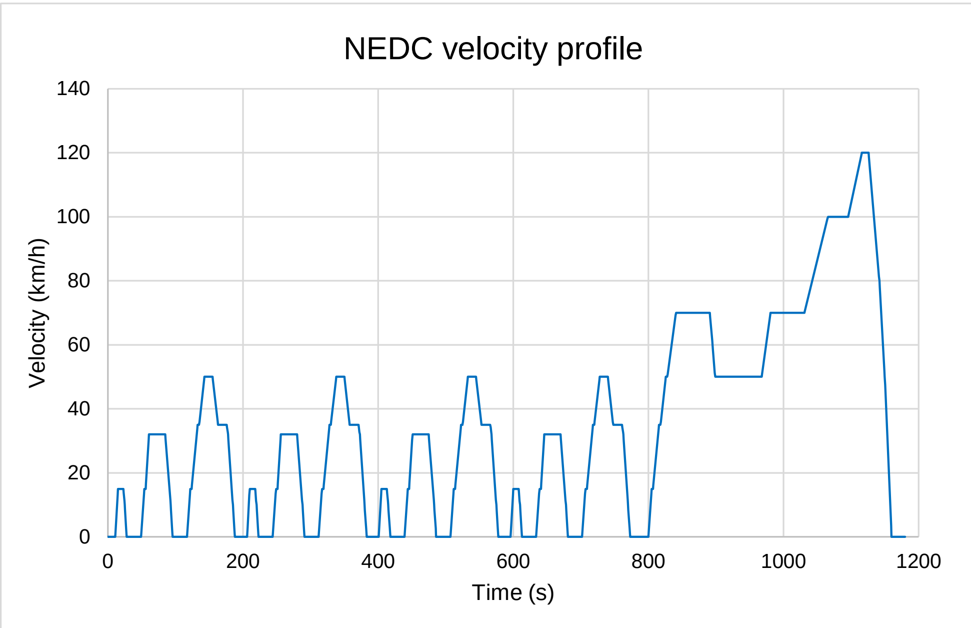
AVL CRUISE is an enhanced vehicle and powertrain system level simulation tool, which supports everyday tasks in vehicle system and driveline analysis in all vehicle and powertrain development phases, from concept planning through to start of production and beyond. Its application envelope covers the full range of conventional vehicle powertrains including highly advanced Hybrid systems and pure electric vehicles. The CRUISE modelling library includes mechanical powertrain components, Hybrid electric components like Battery and E-machine, Vehicle, driver, test track and freely definable simulation use cases like test cycles or performance tasks. Controller functions and operational strategies can easily be implemented using standard C-code or embedded MATLAB / Simulink models (integrated as compiled -.dll or FMU). As a widespread used simulation tool, AVL CRUISE is a well-proven environment for the detailed analysis of all investigated drivetrain configurations as given in the current study.

4.2 Test Cycles & Constraints

4.2.1 NEDC

The New European Driving cycle (NEDC) is defined in the European legislation (UN ECE R 83). It consists of the two phases, “Urban” (repeated four times and including an ICE cold start at the beginning) and “Extra Urban”. The overall velocity profile shown in Figure 4-1 allows deviations of up to ± 2km/h and ± 1s in test-driving. Gear changes for vehicle variants with manual transmission (all pure ICEs) are defined by legislation, whereas gear changes for vehicles with automatic transmission are chosen due to shifting strategies based on the specific xEV control. In the Homologation procedure, the Inertia Test Weight (ITW) classes are defined for dyno measurements. However, in the current TTW analysis the calculation of NEDC fuel consumption is done based on the actual vehicle weight in running order instead of using the ITW classes: This measure allows showing the fuel consumption impacts of different powertrain component masses in the various vehicle variants.

Figure 4-1: Velocity profile of the New European Driving cycle



4.2.1.1 Evaluation of PHEV & REEV

The European Legislation UN ECE R 101 (Rev 3) considers two separate rules for evaluation of the fuel consumption FC_{CERT} of an externally chargeable Hybrid electric vehicle (such as PHEV and REEV), which are both based on the weighting of Charge Depleting (CD) and Charge Sustaining (CS) operation modes partial results. The first rule, shown in the following equation and in Figure 4-2, is based on evaluation of only one single NEDC in CD operation:

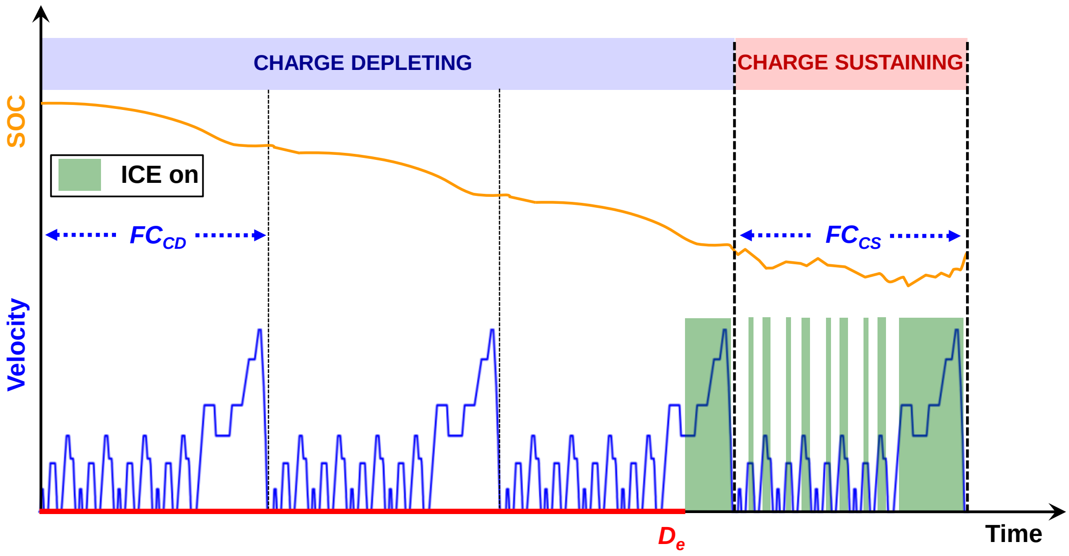
$$FC_{CERT} = \frac{D_e \cdot FC_{CD} + 25 \cdot FC_{CS}}{D_e + 25}$$

FC_{CD}: Fuel Consumption with fully charged battery (Charge Depleting) in l/100km

FC_{CS}: Fuel Consumption with battery in minimum SOC (Charge Sustaining) in l/100km

D_e: All Electric Range (AER) in km

Figure 4-2: Schematic evaluation of the fuel consumption of an externally chargeable Hybrid electric vehicle (such as PHEV and REEV), based on the UN ECE R 101 (Rev 3) §3.2.3.2.1



The second rule, shown in the following equation and in Figure 4-3, is based on evaluation of several consecutive NEDCs in CD operation until a break-off criterion (SOC in one complete NEDC less than 3%) is reached:

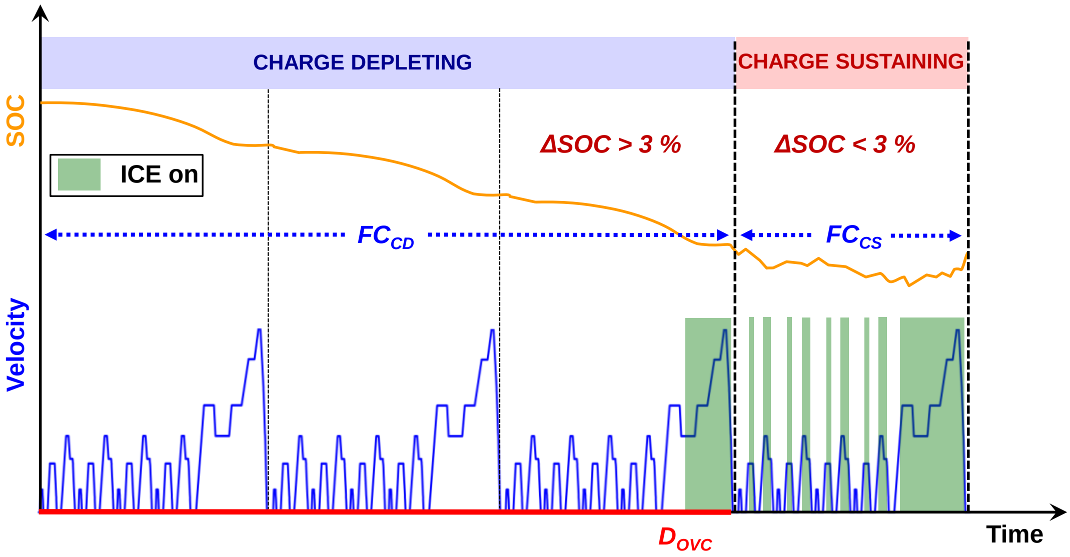
$$FC_{CERT} = \frac{D_{OVC} \cdot FC_{CD} + 25 \cdot FC_{CS}}{D_{OVC} + 25}$$

FC_{CD}: Fuel Consumption with fully charged battery (Charge Depleting) in l/100km

FC_{CS}: Fuel Consumption with battery in minimum SOC (Charge Sustaining) in l/100km

D_{OVC}: Complete (OVC) Range in CD operation in km

Figure 4-3: Schematic evaluation of the fuel consumption of an externally chargeable Hybrid electric vehicle (such as PHEV and REEV), based on the UN ECE R 101 (Rev 3) §3.2.3.2.2



In principle, any OEM is free to choose either the first or the second rule for evaluation. However, both rules lead to rather similar results, mainly influenced by minor differences in calibration of the main xEV modes. In the current study, the second rule (see Figure **4-3**) is chosen for evaluation, as it uses the complete CD operation for evaluation, similar to the rules in WLTP; this way, results are less influenced by calibration of the main xEV modes (e.g. in case of empty or full battery).

For both PHEV and REEV the corresponding result for electric energy consumption E_{CERT} based on the European Legislation UN ECE R 101 (Rev 3) is calculated via the same weighting equations as shown below, if the fuel consumption (CD, CS and overall) is simply replaced by the corresponding electric energy consumption values. It is shown below for the chosen second rule of evaluation:

$$E_{CERT} = \frac{D_{OVC} \cdot E_{CD} + 25 \cdot E_{CS}}{D_{OVC} + 25}$$

E_{CD}: Electric energy consumption with fully charged battery (Charge Depleting) in kWh/100km

E_{CS}: Electric energy consumption with battery in minimum SOC (Charge Sustaining) in kWh/100km

D_{OVC}: Complete (OVC) Range in CD operation in km

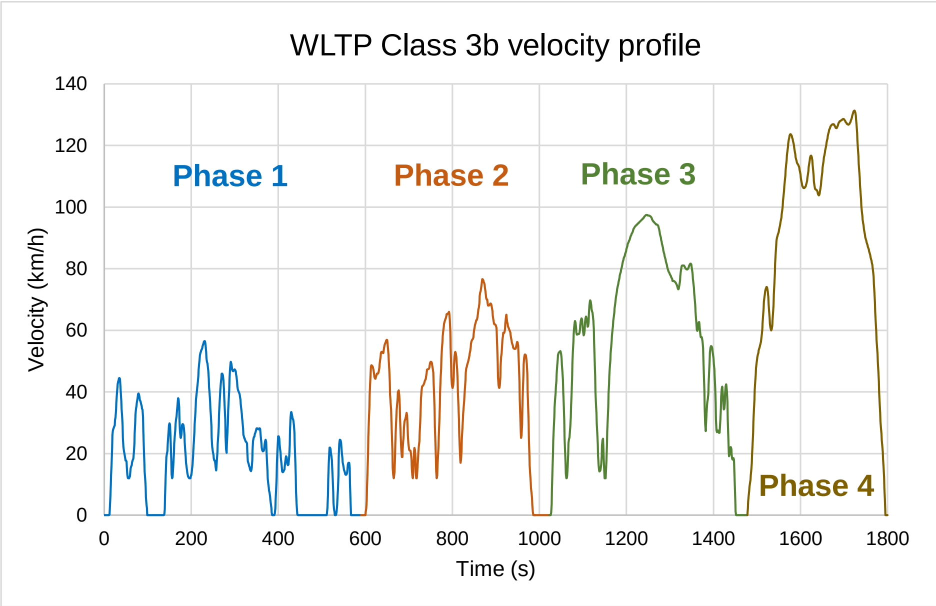
In a similar manner, this weighting equation is also used to calculate the H_2 consumption in case of FC driven PHEV and REEV variants.

4.2.2 WLTP

The Worldwide harmonized Light duty Test Procedure (WLTP) is defined in the European legislation in UN ECE GTR No. 15 in several classes. Class 3b considers vehicle applications with a rated ICE power to curb weight ratio of > 34 W/kg and a maximum vehicle speed of ≥ 120 km/h, which includes all market-average C-segment passenger car variants (conventional as well as xEV) considered in the study. The corresponding test cycle (WLTC) consists of 4 phases including an ICE cold-start at the beginning. The overall velocity profile shown in

Figure **4-4** allows deviations of up to ± 2km/h and ± 1s in test-driving, similar to the NEDC. Gear changes for vehicle variants with manual transmission are defined by legislation, whereas gear changes for vehicles with automatic transmission can be chosen due to shifting strategies based on the specific xEV control.

Figure 4-4: Velocity profile of the Class 3b Worldwide harmonized Light duty Test Cycle

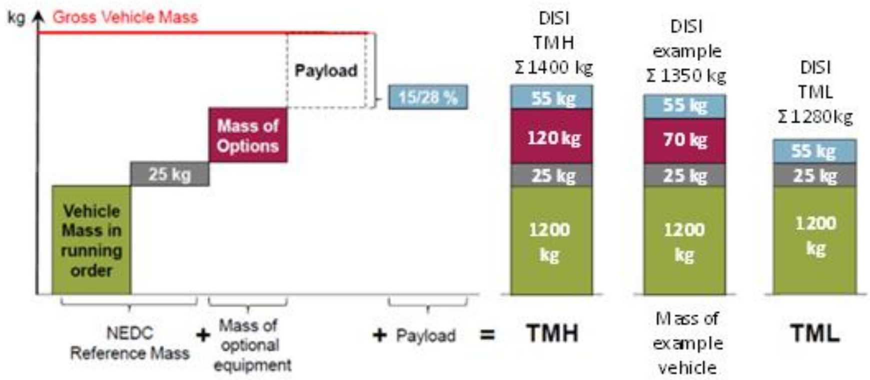


The Test Mass in WLTP is defined as described in Figure 4-5: It's the vehicle mass in running order (i.e. curb mass incl. driver) plus 25kg (the result of summation is equal to the NEDC reference mass) plus the mass of options (which refers to optional features that influence mass like AC, tow hitch,…) plus 15% of the residual payload (considered in case of a maximum mass of options). To avoid having to test every variant inside a vehicle family (specified in ECE/TRANS/WP.29/GRPE/2016/3, §5.6), there are definitions of Test Mass High (TMH, vehicle variant with max. mass of options) and Test Mass Low (TML, vehicle variant without any options), which can be used to calculate the fuel economy for other variants via interpolation. In case of a well-defined vehicle including a concrete Mass of Options, as given in the current study, the corresponding Test Mass is evaluated accordingly. Figure 4-5 shows an example for the DISI 2025+ Gasoline E5 variant as specified below:

- *Vehicle mass in running order:* 1200kg
- *Maximum mass of options:* 120kg
- *Mass of options of chosen C-segment vehicle:* 70kg
- *Gross Vehicle Mass (GVM)*: 1710kg

Based on these definitions, the residual payload is 365kg, of which 15% gives ~55kg. So finally, the Test Mass is 1350kg.

Figure 4-5: Test Mass definition in WLTP



4.2.2.1 *Evaluation of PHEV & REEV*

The European Legislation UN ECE GTR No. 15 considers the following rule for evaluation of the fuel consumption $FC_{weighted}$ of an externally chargeable Hybrid electric vehicle (such as PHEV and REEV) which is based on the weighting of CD and CS operation including so-called utility factors:

$$FC_{weighted} = \sum_{j=1}^{k} \left(UF_j \cdot FC_{CD,j}\right) + \left(1 - \sum_{j=1}^{k} UF_j\right) \cdot FC_{CS}$$

UF_j: Utility factor of WLTC phase j

$FC_{CD,j}$: Fuel Consumption of phase "j" during CD operation in l/100km

FC_{CS}: Fuel Consumption in WLTC CS operation in l/100km

j: Index of phase considered

k: Index of phase 4 of last WLTC in CD operation

Herein, the WLTC phases are simply counted consecutively by the index "j", e.g. j=5 represents phase 1 of the second WLTC in CD operation. A break-off criterion for the CD operation is defined, similar to NEDC, in a way that less than 4% of the energy required for driving the whole cycle should be supplied by the battery. The utility factors are especially defined for each single phase in case of consecutive WLTC operation. The corresponding numbers (rounded) are shown for the first 4 complete WLTC cycles in Figure **4-6**.

Figure 4-6: Definition of utility factors (UF) depending on the consecutive WLTC operation phase

Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
UF	0.096	0.128	0.155	0.134	0.041	0.055	0.067	0.059	0.018	0.025	0.031	0.029	0.009	0.013	0.016	0.016

In a similar manner as shown for the NEDC, the electric energy consumption $E_{weighted}$ is calculated using the same weighting equation as for fuel consumption, if the fuel consumption (CD and CS) in the equation above is simply replaced by the corresponding electric energy consumption values of the single phases.

In a similar manner, this weighting equation is also used to calculate the H_2 consumption in case of FC driven PHEV and REEV variants.

4.2.3 Performance tests

The investigation of the minimum performance criteria shown in Table 3-4 requires the simulation of corresponding vehicle performance driving tests. The following performance tests are considered:

- Full Load Acceleration from 0 to 100 km/h
- Elasticity from 80 to 120 km/h

- Vehicle Top Speed
- Gradeability @ 1 km/h
- Gradeability @ 10 km/h

4.3 Methodology

4.3.1 Modelling Methodology

All input data used in the vehicle simulation are defined in close cooperation by EUCAR and AVL experts. Data include efficiencies of the main powertrain components ICE, transmission, E-machine, battery, power electronics and fuel cell system in various different layouts. ICE maps are defined based on stationary fuel consumption maps for hot ICE condition. The NEDC and WLTP cold start fuel consumption is modelled based on the AVL CRUISE standard semi-empiric ICE temperature model, which includes impacts of ICE internal and external cooling circuits as well as ICE fuel consumption gain based on increased ICE FMEP at cold temperatures. Corresponding ICE thermal model calibration is done based on an AVL database, and the main effects of ICE electrification e.g. like Start-Stop or an improved ICE thermal management are taken into account.

For all simulation models (conventional and xEV) a draft layout of components including initial model setup and calibration is defined and followed by a model refinement in an iterative approach to fulfil the defined vehicle targets. Simulation results are checked for plausibility by frequent discussions and alignments between EUCAR and AVL, taking into account comparisons to various market-average benchmark vehicles available on today's automotive market.

4.3.2 xEV control logic

xEV variants in general include a control unit, which steers the xEV modes, calculates the torque split between ICE and E-machine(s) and masters the operational strategies of all actively controlled powertrain components (such as ICE, transmission, E-machine, clutches, brakes). Such a control unit is also covered in vehicle simulation. Calibration parameters are used to determine the specific xEV behaviour of each variant. Battery State-Of-Charge (SOC) is ensured to be balanced for all CS operation modes in HEV, PHEV and REEV. The control unit for all xEV variants is modelled in MATLAB / Simulink and is embedded in AVL CRUISE simulation models via a special AVL CRUISE – MATLAB interface. The xEV operational modes included for 2015 and 2025+ variants in this study are shown in Table 3-6 and described in detail in chapter 3.5.

4.3.3 Evaluation of GHG Emissions

The total Tank-to-Wheel GHG emissions are evaluated referring to CO_2 exhaust emissions on the one hand, and Methane (CH_4) and Nitrous Oxide (N_2O) exhaust emissions on the other hand. CO_2 emissions are calculated directly in AVL CRUISE simulation, whereas CH_4 and N_2O emissions are added to the simulation results. They are estimated based on the EURO 6 legislation limits for Total Hydro Carbon (THC) and NOx, respectively, as shown in Table 4-1:

The first column in Table 4-1 shows the EURO 6 emission limits for THC and NOx, which – at the time of writing this report - are valid for the whole period 2015 to 2025 and should therefore be representative for the evaluations in the study. To ensure every vehicle variant fulfilling these limits in real life operation, the typical engineering goal in ICE development is to design the engine (and emission aftertreatment system) in a way to keep emissions significantly below these limits. Hence, in case of Gasoline fuel, for instance, typically 70% of EURO 6 THC limits are really emitted as THC on an average NEDC or WLTP homologation test, and among these, appr. 7% consist of CH_4. Thus, finally, the tailpipe CH_4 GHG emission for a Gasoline fuel is estimated to be appr. 5% of the EURO 6 emission limit, which is given in the second column of Table 4-1. In the same way, all the percentage numbers in the second column are derived, defining the total GHG emission percentages of the CH_4 over the THC and the N_2O over the total NOx emission limit, respectively. In case of CNG fuel, these percentage numbers are also aligned with results in the EU-funded research project INGAS[9].

9 A. Gerini, M. Hoppe, "Integrated GAS powertrain – Low emissions, CO2 optimized and efficient CNG engines for passengers cars (PC) and light duty vehicles (LDV)", EU FP7-SST-2007-RTD-1, SP B0, April 2012

To obtain the resulting CO_2 equivalent emissions of CH_4 and N_2O, the Global Warming Potential (GWP) factors for CH_4 and N_2O are considered: These factors are aligned with the WTT Version 5 report and are defined[10] to be 25 g CO_2 equivalent / g CH_4 and 298 g CO_2 equivalent / g N_2O, expressing the GHG effect of the specific gas. Finally, the total CO_2 equivalent emissions $CO_{2,\,eq}$ are derived based on the following relations, and shown in the last column in Table 4-1:

$$CO_{2,eq}(CH_4)\left[\frac{g_{CO2,eq}}{km}\right] = THC/1000 \cdot \frac{CH_4}{THC} \cdot GWP(CH_4)$$

$$CO_{2,eq}(N_2O)\left[\frac{g_{CO2,eq}}{km}\right] = NO_x/1000 \cdot \frac{N_2O}{NO_x} \cdot GWP(N_2O)$$

THC, NO_x: legislation limits in mg/km in terms of THC or NO_x emissions

CH_4 / THC: percentages of the CH_4 over the total THC emission limit

N_2O / NO_x: percentages of the N_2O over the total NO_x emission limit

GWP: Global Warming Potential factor

In case of fully electrified vehicles (BEV, FCEV, PHEV FC and REEV FC), no CO_2, Methane or Nitrous Oxide is emitted. In case of xEV variants with a Plug-In feature (PHEV and REEV), the CH_4 and N_2O emissions have a reduced impact due to the battery powered driving. Based on the European legislation for Plug-In featured vehicle variants, as described for NEDC in chapter 4.2.1.1 and for WLTP in chapter 4.2.2.1, the appropriate weighting equation is therefore also considered to determine the CO_2 equivalent emissions $CO_{2,\,eq,\,weighted}$ based on the following relation:

$$CO_{2,eq,weighted}(CH_4, N_2O) = CO_{2,eq,CS}(CH_4, N_2O)\frac{CO_{2,weighted}}{CO_{2,CS}}$$

$CO_{2,\,eq,\,CS}$: CO_2 equivalent emissions of CH_4 or N_2O in Charge Sustaining

$CO_{2,\,weighted}$: Weighted CO_2 simulation result

$CO_{2,\,CS}$: CO_2 simulation result in Charge Sustaining

Table 4-1: Impact of CH_4 and N_2O emission for fuels combustion transformed to GHG (CO_2 equivalent) emissions

2015 & 2025+		EURO 6 THC or NO_x limits (mg/km)	Percentage (N_2O or CH_4) of limit	GWP factor (-)	GHG emissions (gCO_{2eq}/km)
CH_4	Gasoline	100	5%	25	**0,13**
	LPG	100	5%	25	**0,13**
	CNG	100	60%	25	**1,50**
	Diesel	90	10%	25	**0,23**
N_2O	Gasoline	60	3%	298	**0,54**
	LPG	60	3%	298	**0,54**
	CNG	60	3%	298	**0,54**
	Diesel	80	5%	298	**1,19**

A potential additional source of CO_2 emission might be given by the consumption of urea (e.g. AdBlue) in case of use of Selective Catalytic Reduction (SCR) for reduction of NOx emissions in Diesel Exhaust Aftertreatment Systems. This urea consumption would in principle contribute to overall CO_2 emissions in the order of a few tenth of g/km in NEDC or WLTP operation. However, a detailed definition and layout of Exhaust Aftertreatment systems is not done in this study, therefore this small effect is neglected in the simulations.

10 GWP factors are taken from IPCC AR4 Climate Change Synthesis Report, 2007

4.3.4 Error Assessment

The general approach for error assessment is based on the evaluation of impacts of main parameters and data (like ICE maps or powertrain component efficiencies) to the overall result based on experience. Fixed boundaries like vehicle mass, driving resistance or performance criteria are not considered to have any impact to the estimated errors. Due to the complexity of the analysed systems, the chosen approach of error assessment is to isolate the main subsystems responsible for the total Tank-to-Wheel CO_2 emissions, which in case of conventional vehicles lead to:

$$CO_2\left(\frac{g}{km}\right) = \frac{EF}{D} \cdot \int \frac{P_{veh} \cdot BSFC}{\varepsilon_{dr}} dt$$

CO_2: Tank-to-Wheel CO_2 emissions

EF: Specific CO_2 Emission Factor

D: Cycle distance

P_{veh}: Traction power required by the vehicle

BSFC: ICE Brake Specific Fuel Consumption

ε_{dr}: Total driveline efficiency

Within a simplified approach, the total error *$Err(CO_2)$* of the Tank-to-Wheel CO_2 emissions is defined by the following equation for conventional variants:

$$Err(CO_2) \approx Err(P_{veh}) + Err(\varepsilon_{dr}) + Err(BSFC)$$

$Err(P_{veh})$: Error in the estimation of the vehicle traction power

$Err(\varepsilon_{dr})$: Error in the estimation of the total driveline efficiency

Err(BSFC): Error in the estimation of the average ICE specific fuel consumption

Based on the same approach, the error for xEV variants derives to:

$$\begin{aligned} Err(CO_2) \approx\ & [Err(P_{veh}) + Err(\varepsilon_{dr}) + Err(BSFC)\ ] \cdot c_{ICE,alone} \\ & + [Err(P_{veh}) + Err(\varepsilon_{dr}) + Err(\varepsilon_{EM}) + Err(\varepsilon_{Batt})] \cdot c_{ICE,off} \\ & + \ [Err(P_{veh}) + Err(\varepsilon_{dr}) + Err(BSFC) + Err(\varepsilon_{EM}) + Err(\varepsilon_{Batt})] \\ & \cdot c_{ICE,LPM} \end{aligned}$$

$Err(\varepsilon_{EM})$: Error in the estimation of the E-machine efficiency

$Err(\varepsilon_{Batt})$: Error in the estimation of the battery efficiency

$c_{ICE,\ alone}$: Weighting factor for pure ICE operation

$c_{ICE,\ off}$: Weighting factor for pure Electric Driving operation

$c_{ICE,\ LPM}$: Weighting factor for combined operation of ICE and E-machine

In the detailed definition of the errors of each specific subsystem, the following considerations were assumed:

2025+ variants are in general characterized by an increased error of approx. 10% to 50% higher than 2015 variants, due to the uncertain forecast of the technological development. In conventional vehicles the main inaccuracy is due to the ICE simulation (challenging definition of a representative ICE for each technological solution, simulation approach chosen based on fuel consumption maps). The resulting overall error is in the range of 2.5% to 4.8% for 2015 variants, and 3.5% to 6.9% for 2025+ variants. Partially electrified vehicles are characterized, on average, by higher uncertainty due to their higher complexity. Those with a Plug-In characteristic (PHEV, REEV) on the other hand show also partially reduced errors due to the impact of the weighting of CD and CS phases. The resulting overall error is in the range of 4.0% to 5.8% for 2015 variants, and 4.4% to 6.9% for 2025+ variants. The considered Battery Electric Vehicles are lean systems (unique power source and simple transmission), however the high mass of the battery and the uncertainty in charging efficiency have their impact to error estimation. The resulting overall error is 3.7% for 2015 and 4.2% for 2025+. Finally, the FC driven variants show a lower technological maturity. The resulting errors are high in both 2015 (4.5% to 6.7%) and 2025+ variants (5.2% to 9.1%).

All the obtained errors are displayed together with the Tank-to-Wheel CO_2 equivalent emissions and energy consumption results, by means of dedicated error bars (Figure 7- 1 to Figure 7-9).

4.3.5 Charging Losses

Results for Electric energy consumption are derived for all variants with a Plug-In device. They are a direct outcome of vehicle simulation referring to energy consumed from the battery. To derive results under real TTW boundaries – system boundary is the Electric Vehicle Supply Equipment (EVSE) - all vehicle related energy losses during battery charging must be added to these simulated results. Such losses include losses from the charge cord, the on-board charger, the battery (due to charging currents) and finally the 12V losses from all the auxiliary electronics active during the charging process. The overall charging losses are determined from the difference between the charging energy taken from the plug/EVSE and the energy finally stored in the battery. Based on homologation procedures as defined in the European legislation (UN ECE R 101) for NEDC, and very similar (Commission Regulation 2017/1151) for WLTP, charging losses must be determined following a certain procedure: After preconditioning the vehicle, the battery is fully charged during the soak phase; afterwards the homologation test procedure for NEDC or WLTP, respectively, is executed for a complete CD test, after which the battery must be fully recharged again. Charging losses refer to this final recharging procedure.

The definition of charging losses for the current study is made based on European industry average values for 2015 available to AVL. In case of 2025+, the losses are assessed considering significant improvements in charging infrastructure and technology, due to the expected BEV market ramp-up. Therefore, charging losses are estimated as 20% for 2015 and improved to 15% for 2025+. These numbers represent a split of 90% of charging at home or at work with mainly a charging power of around 7kW (around 11kW respectively for 2025+), and residual 10% of charging in public area (such as e.g. shopping malls, parking garage or gas station on highway) with high charging power of 50kW or beyond.

5 2015 configurations & results

5.1 Vehicle configurations

In the following, the 2015 conventional as well as electrified vehicle variants are described in detail regarding their main component specifications. In terms of definition of the components technologies for 2015, a range from approximately 2013 up to 2017 is considered to represent today's market-average state of the art in automotive industry in a more general way. Specifications include the main ICE description, a definition of rated and peak power and torque of E-machines, peak power of Fuel Cell systems, and peak power and energy content of Batteries. A detailed mass balance for all subsystems is included. The general description of the vehicle parameters and powertrain topologies is given in chapter 3.

5.1.1 Mass balance & main data

Table 5-1: Mass balance for SI variants 2015

Mass balance SI Powertrain Variants 2015		**DISI**			**Hybrid DISI**	**PHEV50 SI**	**REEV100 SI**
		Gasoline[1]	LPG	CNG	Gasoline[1]	Gasoline[1]	Gasoline[1]
Powertrain							
ICE mass	kg	145	145	145	145	145	135
Gearbox mass	kg	50	50	50	80	80	10
Fuel cell module mass	kg	#	#	#	#	#	#
Electric Components							
eMachine mass[2]	kg	#	#	#	31	40	65
Generator (REEV) mass[2]	kg	#	#	#	#	#	39
Battery mass[2]	kg	#	#	#	39	105	142
xEV wiring harness mass	kg	#	#	#	11	15	20
Storage System							
Tank System Mass	kg	15	45	160	15	15	15
Fuel Tank Net Capacity	L (kg)	55	80	26kg	55	55	55
Additional Fuel Tank Net Capacity	L	#	14L Gasoline	14L Gasoline	#	#	#
Total Fuel Mass	kg	37	49	33	37	37	37
Vehicle							
Curb weight incl. Driver, 90% fuel	kg	1310	1352	1451	1421	1500	1526
Performance Mass	kg	1435	1477	1576	1546	1625	1651
Payload	kg	510	468	369	399	320	294
WLTP Test Mass	kg	#	#	#	#	#	#
Gross Vehicle Mass	kg	1820	1820	1820	1820	1820	1820

1) Same vehicle mass is assumed for gasoline fuel variants: Gasoline E5, Gasoline E10 market blend, Gasoline High Octane spec. #1 & 2 and E100
2) Masses include the whole system (e.g. E-machine power electronics, cooling system, etc.)

Table 5-2: Mass balance for CI variants 2015

Mass balance CI Powertrain Variants 2015		DICI		Hybrid DICI		PHEV50 CI	
		Diesel[1]	DME	Diesel[1]	DME	Diesel[1]	DME
Powertrain							
ICE mass	kg	165	165	165	165	165	165
Gearbox mass	kg	50	50	80	80	80	80
Fuel cell module mass	kg	#	#	#	#	#	#
Electric Components							
eMachine mass[2]	kg	#	#	31	31	40	40
Generator (REEV) mass[2]	kg	#	#	#	#	#	#
Battery mass[2]	kg	#	#	39	39	105	105
xEV wiring harness mass	kg	#	#	11	11	15	15
Storage System							
Tank System Mass	kg	15	45	15	45	15	45
Fuel Tank Net Capacity	L (kg)	55	80	55	80	55	80
Additional Fuel Tank Net Capacity	L	#	14L Diesel	#	14L Diesel	#	14L Diesel
Total Fuel Mass	kg	41	59	41	59	41	59
Vehicle							
Curb weight incl. Driver, 90% fuel	kg	1370	1418	1481	1529	1560	1608
Performance Mass	kg	1495	1543	1606	1654	1685	1733
Payload	kg	450	402	339	291	260	212
WLTP Test Mass	kg	#	#	#	#	#	#
Gross Vehicle Mass	kg	1820	1820	1820	1820	1820	1820

1) Same vehicle mass is assumed for diesel fuel variants: Diesel B0, Diesel B7, FAME, FT-Diesel and HVO
2) Masses include the whole system (e.g. E-machine power electronics, cooling system, etc.)

Table 5-3: Mass balance for pure electric variants 2015 in relation to the DISI "ICE only" variant

Mass balance BEV/FC Powertrain Variants 2015		DISI	BEV150	FCEV	PHEV50 FC	REEV100 FC
		Gasoline	Electricity	Hydrogen	Hydrogen	Hydrogen
Powertrain						
ICE mass	kg	145	0	0	0	0
Gearbox mass	kg	50	10	10	10	10
Fuel cell module mass	kg	#	#	150	150	120
Electric Components						
eMachine mass[1]	kg	#	65	65	65	65
Generator (REEV) mass[2]	kg	#	#	#	#	#
Battery mass[1]	kg	#	168	39	85	142
xEV wiring harness mass	kg	#	20	20	20	20
Storage System						
Tank System Mass	kg	15	0	90	90	90
Fuel Tank Net Capacity	L (kg)	55	#	4kg	4kg	4kg
Additional Fuel Tank Net Capacity	L	#	#	#	#	#
Total Fuel Mass	kg	37	0	4	4	4
Vehicle						
Curb weight incl. Driver, 90% fuel	kg	1310	1326	1441	1487	1514
Performance Mass	kg	1435	1451	1566	1612	1639
Payload	kg	510	494	379	333	306
WLTP Test Mass	kg	#		#	#	#
Gross Vehicle Mass	kg	1820	1820	1820	1820	1820
1) Masses include the whole system (e.g. E-machine power electronics, cooling system, etc.)						

A DCDC converter is included in all xEV components wherever appropriate. In case of the FC driven variants the FC system is always connected to the HV bus via a DCDC converter. The corresponding DCDC conversion losses are included in the simulation models (either implemented in the component losses or modelled, in particular, as e.g. in case of the FC driven variants). DCDC converter losses for LV power supply is neglected.

The auxiliaries in 2015 variants are partially electrified as follows: The Steering Pump is fully electrified (EPS) for Conventional ("ICE only") and xEV variants; the Brake Vacuum Pump is mechanical for Conventional ("ICE only") variants and electrified for xEV variants; the Water Pump is mechanical for Conventional ("ICE only") variants and electrified for xEV variants; the (ICE) Oil Pump is mechanical for all variants; finally the (transmission) Oil Pump, including an automated transmission, is mechanical for Conventional ("ICE only") variants and electrified for xEV variants.

5.1.2 ICE specifications

The RON for the Gasoline blends and CN for Diesel fuels are defined in the fuel properties Table 3-1. Slight RON / CN changes for fuels (e.g. Diesel B0: CN 51, Diesel B7: CN 53) do not require ICE map adaptions in this simulation work, as the estimations of ICE maps for specific fuels are based on a comparable level of accuracy, and slight RON / CN effects are considered not to be significant compared to the overall simulation accuracy.

Regulated Emissions (e.g. NOx, PM, …) are not simulated in the current TTW analysis. However, all ICE maps prepared for simulation of 2015 variants are assumed to comply with the legislative emissions standards for EURO 6. Electrification is considered as an Add-On technology for 2015 xEV variants in general, therefore no adaptations (e.g. ICE downsizing) are made for the 2015 xEV ICEs in relation to the conventional ICE definitions.

Table 5-4: ICE specifications for 2015 variants

2015 ICE Specifications		DISI, Hybrid DISI, PHEV50 SI					REEV100 SI	DICI, Hybrid DICI, PHEV50 CI
		Gasoline E5, Gasoline E10, LPG	Gasoline High Octane spec. #1	Gasoline High Octane spec. #2	CNG	E100	Gasoline E5, E10, Gasoline High Octane, E100	Diesel B0, Diesel B7, FAME, DME, FT-Diesel, HVO
ICE Type / Technology	---	- TGDI - DVVT - Compression Ratio 10.0					- NA - High-expansion Atkinson cycle - Cooled EGR	- Common Rail - Cooled HP-EGR - VGT Turbocharger - Close coupled LNT / cDPF
Measures for alternative fuel usage	---	#	- Increased Compression to 11.0 - Adapted Calibration	- Increased Compression to 11.5 - Adapted Calibration	- Increased Compression to 11.0 - Adapted Calibration - Change of Fuel Injection (PISI)	- Adapted Calibration	#	#
Displacement	L	1,4	1,4	1,4	1,4	1,4	1,2	1,6
No. of Cylinders	---	IL4	IL4	IL4	IL4	IL4	IL3	IL4
No. of Strokes	---	4	4	4	4	4	4	4
Specific Power	kW/L	~65	~65	~65	~65	~65	~39	~53
Maximum Power @ speed	kW (PS) / rpm	91 @ 4000	91 @ 4000	91 @ 4000	91 @ 4000	91 @ 4000	47 @ 5000	85 @ 4000
Maximum Torque @ speed	Nm / rpm	240 @ 1500-3500	240 @ 1500-3500	240 @ 1500-3500	240 @ 1500-3500	240 @ 1500-3500	95 @ 4000	300 @ 1500-2500
Maximum Speed	rpm	6000	6000	6000	6000	6000	6000	5000

5.1.3 xEV specifications

The xEV components specifications of the 2015 variants were designed and optimized in correlation to the given boundary conditions and vehicle minimum performance criteria of the current TTW study.

Table 5-5 gives an overview of the considered electrified components, the requirements to be achieved and the main specifications. The values reported in the table in case of the Electric Machine and the Generator show the peak and, in parenthesis, the continuous power and torque. Concerning the Li-Ion Battery Pack, the total as well as the useable energy (in parenthesis) is outlined.

Table 5-5: 2015 xEV component specifications

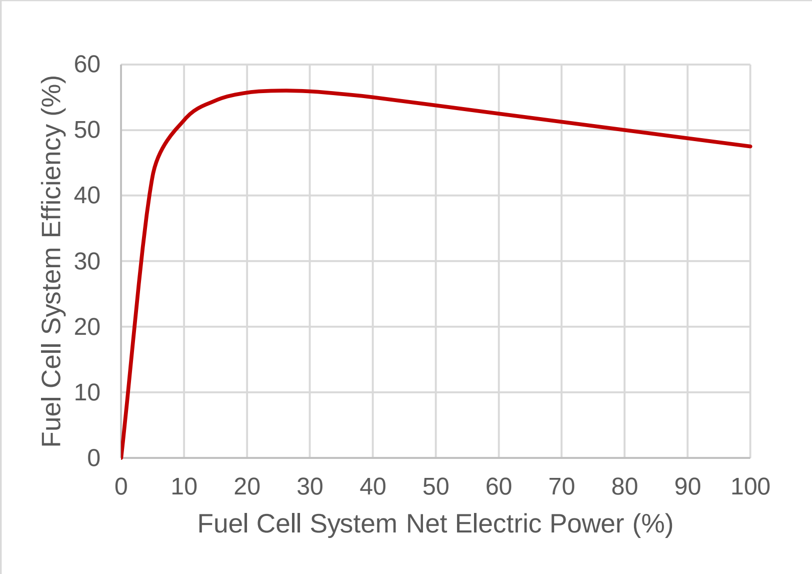
Variant	Component	Specific	Unit	Requirements to meet the performance criteria	Value*
HEV	E-machine	Power	kW	*Complete regenerative braking during the NEDC*	**25** (12.5)
		Torque	Nm	*Complete regenerative braking during the NEDC*	**150** (100)
	Battery Pack	Power	kW	*Required electric power from/to the E-machine*	**30**
		Energy	kWh	*Complete regenerative braking and 160.000km lifetime in NEDC*	**1.54** (0.45)
PHEV	E-machine	Power	kW	*Driving of the NEDC purely electrically => Peak Power*	**40** (22.5)
		Torque	Nm	*Electric Driving up to 140 km/h => Continuous Power*	**200** (120)
	Battery Pack	Power	kW	*Required electric power from/to the E-machine*	**50**
		Energy	kWh	*50 km AER and 160.000km lifetime in NEDC*	**10.5** (6.83)
REEV	E-machine	Power	kW	*Acceleration and Elasticity => Peak Power & Torque*	**85** (50)
		Torque	Nm	*Gradeability 20% => Continuous Torque*	**200** (120)
	Generator	Power	kW	*Fitting to the ICE*	**50** (50)
		Torque	Nm		**100** (100)
	Battery Pack	Power	kW	*Required electric power from/to the E-machine*	**90**
		Energy	kWh	*100 km AER and 160.000km lifetime in NEDC*	**15.1** (12.1)
BEV	E-machine	Power	kW	*Acceleration and Elasticity => Peak Power & Torque*	**85** (50)
		Torque	Nm	*Gradeability 20% => Continuous Torque*	**200** (120)
	Battery Pack	Power	kW	*Required electric power from/to the E-machine*	**90**
		Energy	kWh	*200 km AER and 160.000km lifetime in NEDC*	**20.8** (16.6)
FCEV	E-machine	Power	kW	*Acceleration and Elasticity => Peak Power & Torque*	**85** (50)
		Torque	Nm	*Gradeability 20% => Continuous Torque*	**200** (120)
	FC System	Power	kW	*Electric Driving up to 180 km/h*	**65**
	Battery Pack	Power	kW	*Required electric power from/to the E-machine*	**30**
		Energy	kWh	*Complete regenerative braking and 160.000km lifetime in NEDC*	**1.54** (0.45)
PHEV FC	E-machine	Power	kW	*Acceleration and Elasticity => Peak Power & Torque*	**85** (50)
		Torque	Nm	*Gradeability 20% => Continuous Torque*	**200** (120)
	FC System	Power	kW	*Electric Driving up to 180 km/h*	**65**
	Battery Pack	Power	kW	*Required electric power from/to the E-machine*	**90**
		Energy	kWh	*50 km AER and 160.000km lifetime in NEDC*	**8.5** (5.5)
REEV FC	E-machine	Power	kW	*Acceleration and Elasticity => Peak Power & Torque*	**85** (50)
		Torque	Nm	*Gradeability 20% => Continuous Torque*	**200** (120)
	FC System	Power	kW	*Electric Driving up to 140 km/h*	**35**
	Battery Pack	Power	kW	*Required electric power from/to the E-machine*	**90**
		Energy	kWh	*100 km AER and 160.000km lifetime in NEDC*	**15.1** (12.1)

**) E-machine, Generator: The values show the peak and (in parenthesis) the continuous power and torque;*
Li-Ion Battery Pack: The values show the total and (in parenthesis) the useable energy

Figure 5-1 shows the Fuel Cell System Efficiency characteristic used for all FC driven variants (FCEV, PHEV FC and REEV FC). This efficiency characteristic is based on averaging the data of over 50 FC driven Gen 1 and Gen 2 vehicles operating in the United States in the period 2003 to 2012, referring to the US National Renewable Energy Laboratory (NREL) Technical Report NREL/TP-5600-54860[11], published in 2012; it is assumed that this average FC System efficiency characteristic represents a good approximation of what could be expected as a representative market average for a 2015 series development FC System. Impacts of FC cooling pump losses and other FC related ancillaries are included in the FC system efficiencies. The FC module is assumed to operate in a way that the FC starting phase is only lasting a few seconds; hence, the starting phase of the FC is neglected in simulation.

11 K. Wipke, S. Sprik, J. Kurtz, T. Ramsden, C. Ainscough, and G. Saur, „National Fuel Cell Electric Vehicle Learning Demonstration", Final Report, Technical Report NREL/TP-5600-54860, July 2012

Figure 5-1: Fuel Cell System Efficiency



5.2 Simulation results

In the following result tables, the results for electric energy consumption in case of variants including a Plug-In feature are always given both with and without consideration of Battery charging losses. In general, according to the legislative regulations for NEDC and WLTP, respectively, charging losses are to be included in reference values of electric energy consumption for all Plug-In featured vehicle variants.

5.2.1 Results for Conventional ("ICE only") variants

Table 5-6: Simulation Results for "ICE only" variants 2015

Simulation Resuts: 2015 Conventional ("ICE only") Variants	Curb Mass	Fuel Tank Capacity	Fuel Consumption		Energy Consumption			GHG emissions			
					Fuel	Electric	Total	as CO_2	as CH_4	as N_2O	TOTAL
NEDC	kg	L (kg)	l/100km	kg/100km	MJ/100km	MJ/100km	MJ/100km	gCO_2/km	gCO_2eq/km	gCO_2eq/km	gCO_2eq/km
DISI ("ICE only") 2015											
Gasoline E5	1310	55	5,49	4,10	173,33	#	173,33	127,17	0,13	0,54	127,83
Gasoline E10 market blend	1310	55	5,58	4,18	173,33	#	173,33	126,71	0,13	0,54	127,37
Gasoline high Octane spec. #1	1310	55	5,28	4,01	170,08	#	170,08	124,64	0,13	0,54	125,30
Gasoline high Octane spec. #2	1310	55	5,34	4,05	168,68	#	168,68	123,76	0,13	0,54	124,42
LPG	1352	80	6,99	3,84	176,77	#	176,77	116,02	0,13	0,54	116,69
CNG	1451	26 kg	#	3,67	176,02	#	176,02	98,76	1,50	0,54	100,79
E100	1310	55	8,14	6,46	173,16	#	173,16	123,58	0,13	0,54	124,24
DICI ("ICE only") 2015											
Diesel B0	1370	55	4,06	3,38	145,49	#	145,49	106,50	0,23	1,19	107,91
Diesel B7 market blend	1370	55	4,08	3,41	145,49	#	145,49	106,62	0,23	1,19	108,04
FAME	1370	55	4,39	3,91	145,49	#	145,49	110,78	0,23	1,19	112,19
DME	1418	80	7,81	5,24	148,70	#	148,70	100,14	0,23	1,19	101,56
FT-Diesel	1370	55	4,24	3,31	145,49	#	145,49	102,98	0,23	1,19	104,40
HVO	1370	55	4,24	3,31	145,49	#	145,49	102,98	0,23	1,19	104,40

The results of 2015 DISI and DICI conventional variants in the current study are well in line with the results of correlating variants in the JEC WTW Version 4 report: Both DISI as well as DICI 2015 results clearly indicate an average of corresponding 2010 and 2020+ Version 4 study results.

5.2.2 Results for xEV variants

5.2.2.1 *HEV*

Table 5-7: Simulation Results for Hybrid variants 2015

Simulation Resuts: 2015 Hybrid Variants **NEDC**	Curb Mass	Fuel Tank Capacity	Fuel Consumption		Energy Consumption			GHG emissions			
					Fuel	Electric	Total	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L (kg)	l/100km	kg/100km	MJ/100km	MJ/100km	MJ/100km	gCO_2/km	gCO_2eq/km	gCO_2eq/km	gCO_2eq/km
Hybrid DISI 2015											
Gasoline E5	1421	55	4,05	3,02	127,83	#	127,83	93,79	0,13	0,54	94,45
Gasoline E10 market blend	1421	55	4,12	3,08	127,83	#	127,83	93,45	0,13	0,54	94,11
Gasoline high Octane spec. #1	1421	55	3,97	3,01	127,83	#	127,83	93,68	0,13	0,54	94,34
Gasoline high Octane spec. #2	1421	55	4,05	3,07	127,83	#	127,83	93,79	0,13	0,54	94,45
LPG	#	#	#	#	#	#	#	#	#	#	#
CNG	#	#	#	#	#	#	#	#	#	#	#
E100	1421	55	6,01	4,77	127,83	#	127,83	91,23	0,13	0,54	91,89
Hybrid DICI 2015											
Diesel B0	1481	55	3,22	2,68	115,47	#	115,47	84,52	0,23	1,19	85,94
Diesel B7 market blend	1481	55	3,23	2,70	115,47	#	115,47	84,62	0,23	1,19	86,03
FAME	1481	55	3,49	3,10	115,47	#	115,47	87,92	0,23	1,19	89,33
DME	1529	40	6,17	4,13	117,32	#	117,32	79,02	0,23	1,19	80,43
FT-Diesel	1481	55	3,36	2,62	115,47	#	115,47	81,73	0,23	1,19	83,15
HVO	1481	55	3,36	2,62	115,47	#	115,47	81,73	0,23	1,19	83,15

5.2.2.2 *PHEV*

Table 5-8: Simulation Results for PHEV variants 2015; note that Electric Energy Consumption includes charging losses

Simulation Resuts: 2015 PHEV Variants **NEDC**	Curb Mass	Fuel Tank Capacity	Fuel Consumption		Energy Consumption			GHG emissions			
					Fuel	Electric	Total	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L (kg)	l/100km	kg/100km	MJ/100km	MJ/100km	MJ/100km	gCO_2/km	gCO_2eq/km	gCO_2eq/km	gCO_2eq/km
PHEV50 SI 2015											
Gasoline E5	1500	55	1,38	1,03	43,52	37,21	80,73	31,93	0,04	0,18	32,15
Gasoline E10 market blend	1500	55	1,40	1,05	43,52	37,21	80,73	31,82	0,04	0,18	32,04
Gasoline high Octane spec. #1	1500	55	1,35	1,03	43,52	37,21	80,73	31,90	0,04	0,18	32,11
Gasoline high Octane spec. #2	1500	55	1,38	1,05	43,52	37,21	80,73	31,93	0,04	0,18	32,15
LPG	#	#	#	#	#	#	#	#	#	#	#
CNG	#	#	#	#	#	#	#	#	#	#	#
E100	1500	55	2,05	1,62	43,52	37,21	80,73	31,06	0,04	0,18	31,28
PHEV50 CI 2015											
Diesel B0	1560	55	1,25	1,04	44,69	35,16	79,85	32,71	0,09	0,45	33,25
Diesel B7 market blend	1560	55	1,25	1,05	44,69	35,16	79,85	32,75	0,09	0,45	33,29
FAME	1560	55	1,35	1,20	44,69	35,16	79,85	34,03	0,09	0,45	34,56
DME	1608	80	2,39	1,60	45,46	35,16	80,63	30,62	0,09	0,45	31,16
FT-Diesel	1560	55	1,30	1,02	44,69	35,16	79,85	31,63	0,09	0,45	32,17
HVO	1560	55	1,30	1,02	44,69	35,16	79,85	31,63	0,09	0,45	32,17

5.2.2.3 *REEV*

Table 5-9: Simulation Results for REEV variants 2015; note that Electric Energy Consumption includes charging losses

Simulation Resuts: 2015 REEV Variants **NEDC**	Curb Mass	Fuel Tank Capacity	Fuel Consumption		Energy Consumption			GHG emissions			
					Fuel	Electric	Total	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L (kg)	l/100km	kg/100km	MJ/100km	MJ/100km	MJ/100km	gCO_2/km	gCO_2eq/km	gCO_2eq/km	gCO_2eq/km
REEV100 SI 2015											
Gasoline E5	1526	55	0,86	0,64	27,18	40,02	67,20	19,94	0,03	0,12	20,09
Gasoline E10 market blend	1526	55	0,88	0,66	27,18	40,02	67,20	19,87	0,03	0,12	20,01
Gasoline high Octane spec. #1	1526	55	0,84	0,64	27,18	40,02	67,20	19,92	0,03	0,12	20,06
Gasoline high Octane spec. #2	1526	55	0,86	0,65	27,18	40,02	67,20	19,94	0,03	0,12	20,09
LPG	#	#	#	#	#	#	#	#	#	#	#
CNG	#	#	#	#	#	#	#	#	#	#	#
E100	1526	55	1,28	1,01	27,18	40,02	67,20	19,40	0,03	0,12	19,54

5.2.2.4 *BEV*

Table 5-10: Simulation Results for BEV 2015; note that Electric Energy Consumption includes charging losses

Simulation Resuts: 2015 BEV Variants **NEDC**	Curb Mass	Fuel Tank Capacity	Fuel Consumption		Energy Consumption			GHG emissions			
					Fuel	Electric	Total	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L (kg)	l/100km	kg/100km	MJ/100km	MJ/100km	MJ/100km	gCO_2/km	gCO_2eq/km	gCO_2eq/km	gCO_2eq/km
BEV150 2015											
Electricity	1326	#	#	#	#	45,66	45,66	0,00	0,00	0,00	0,00

5.2.2.5 FCEV, PHEV FC & REEV FC

Table 5-11: Simulation Results for FC driven variants 2015; note that Electric Energy Consumption includes charging losses

Simulation Resuts: 2015 FC Variants **NEDC**	Curb Mass	Fuel Tank Capacity	Fuel Consumption		Energy Consumption			GHG emissions			
					Fuel	Electric	Total	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L (kg)	l/100km	kg/100km	MJ/100km	MJ/100km	MJ/100km	gCO_2/km	gCO_2eq/km	gCO_2eq/km	gCO_2eq/km
FCEV 2015											
Hydrogen	1441	4	#	0,58	69,73	0,00	69,73	0,00	0,00	0,00	0,00
PHEV50 FC 2015											
Hydrogen	1487	4	#	0,23	28,13	29,62	57,75	0,00	0,00	0,00	0,00
REEV100 FC 2015											
Hydrogen	1514	4	#	0,12	14,61	40,17	54,78	0,00	0,00	0,00	0,00

FCEV simulation result for 2015 shows a distinctively lower Hydrogen fuel consumption than currently available Fuel Cell Electric Vehicles like e.g. the Toyota Mirai (0,76kg/100km H_2). However, the FCEVs which are available on the market belong to higher vehicle segments than the reference vehicle in this report. Thus, differences in fuel consumption can be explained by the lower vehicle driving resistance of the C-segment reference vehicle defined for this study including vehicle mass and hence rolling resistance on the one hand, and air drag coefficient on the other hand. In addition, the vehicle performance criteria of the currently available Fuel Cell Electric Vehicles are likely different to the ones defined in the current TTW study.

6 2025+ configurations & results

6.1 Vehicle configurations

In the following, the 2025+ conventional as well as electrified vehicle variants are described in detail regarding their main component specifications. The definitions of the component technologies for 2025+ is assessed based upon the likely market-average technology development estimated by EUCAR and AVL experts. The specifications include the main ICE description, a definition of rated and peak power and torque of E-machines, peak power of Fuel Cell systems, and peak power and energy content of Batteries. A detailed mass balance for all subsystems is included. The general description of the vehicle parameters and powertrain topologies is given in chapter 3.

6.1.1 Mass balance & main data

Table 6-1: Mass balance for SI variants 2025+

Mass balance SI Powertrain Variants 2025+		DISI			DISI MHEV			Hybrid DISI	PHEV100 SI	REEV200 SI
		Gasoline[1]	LPG	CNG	Gasoline[1]	LPG	CNG	Gasoline[1]	Gasoline[1]	Gasoline[1]
Powertrain										
ICE mass	kg	145	145	145	145	145	145	135	135	135
Gearbox mass	kg	50	50	50	80	80	80	80	80	10
Fuel cell module mass	kg	#	#	#	#	#	#	#	#	#
Electric Components										
eMachine mass[2]	kg	#	#	#	26	26	26	25	42	57
Generator (REEV) mass[2]	kg	#	#	#	#	#	#	#	#	33
Battery mass[2]	kg	#	#	#	20	20	20	19	146	178
xEV wiring harness mass	kg	#	#	#	11	11	11	11	15	20
Storage System										
Tank System Mass	kg	15	30	50	15	30	50	15	15	15
Fuel Tank Net Capacity	L (kg)	35	60	17kg	35	60	100	35	28	21
Additional Fuel Tank Net Capacity	L	#	#	#	#	#	#	#	#	#
Total Fuel Mass	kg	23	30	15	23	30	15	23	19	14
Vehicle										
Curb weight incl. Driver, 90% fuel	kg	1200	1222	1227	1287	1309	1314	1275	1419	1429
Performance Mass	kg	1325	1347	1352	1412	1434	1439	1400	1544	1554
Payload	kg	510	510	510	510	510	510	510	510	510
WLTP Test Mass	kg	1350	1372	1377	1437	1459	1464	1425	1569	1579
Gross Vehicle Mass	kg	1710	1732	1737	1797	1819	1824	1785	1929	1939

1) Same vehicle mass is assumed for gasoline fuel variants: Gasoline E5, Gasoline E10 market blend, Gasoline High Octane spec. #1/2, E100
2) Masses include the whole system (e.g. E-machine power electronics, cooling system, etc.)

Table 6-2: Mass balance for CI variants 2025+

Mass balance CI Powertrain Variants 2025+		**DICI**		**DICI MHEV**		**Hybrid DICI**		**PHEV100 CI**		**REEV200 CI**	
		Diesel[1]	DME	Diesel[1]	DME	Diesel[1]	DME	Diesel[1]	DME	Diesel[1]	DME
Powertrain											
ICE mass	kg	165	165	165	165	165	165	165	165	155	155
Gearbox mass	kg	50	50	80	80	80	80	80	80	10	10
Fuel cell module mass	kg	#	#	#	#	#	#	#	#	#	#
Electric Components											
eMachine mass[2]	kg	#	#	26	26	25	25	42	42	57	57
Generator (REEV) mass[2]	kg	#	#	#	#	#	#	#	#	33	33
Battery mass[2]	kg	#	#	20	20	19	19	146	146	178	178
xEV wiring harness mass	kg	#	#	11	11	11	11	15	15	20	20
Storage System											
Tank System Mass	kg	15	30	15	30	15	30	15	30	15	30
Fuel Tank Net Capacity	L (kg)	35	60	35	60	35	60	28	48	21	36
Additional Fuel Tank Net Capacity	L	#	#	#	#	#	#	#	#	#	#
Total Fuel Mass	kg	26	36	26	36	26	36	21	29	16	22
Vehicle											
Curb weight incl. Driver, 90% fuel	kg	1260	1285	1347	1372	1345	1370	1488	1511	1488	1509
Performance Mass	kg	1385	1410	1472	1497	1470	1495	1613	1636	1613	1634
Payload	kg	510	510	510	510	510	510	510	510	510	510
WLTP Test Mass	kg	1410	1435	1497	1522	1495	1520	1638	1661	1638	1659
Gross Vehicle Mass	kg	1770	1795	1857	1882	1855	1880	1998	2021	1998	2019

1) Same vehicle mass is assumed for diesel fuel variants: Diesel B0, Diesel B7, FAME, FT-Diesel and HVO
2) Masses include the whole system (e.g. E-machine power electronics, cooling system, etc.)

Table 6-3: Mass balance for pure electric variants 2025+ in relation to the DISI "ICE only" variant

Mass balance BEV/FC Powertrain Variants 2025+		DISI	BEV200	BEV400	FCEV	PHEV100 FC	REEV200 FC
		Gasoline	Electricity	Electricity	Hydrogen	Hydrogen	Hydrogen
Powertrain							
ICE mass	kg	145	0	0	0	0	0
Gearbox mass	kg	50	10	10	10	10	10
Fuel cell module mass	kg	#	#	#	130	130	110
Electric Components							
eMachine mass[1]	kg	#	57	57	57	57	57
Generator (REEV) mass[2]	kg	#	#	#	#	#	#
Battery mass[1]	kg	#	154	308	19	119	178
xEV wiring harness mass	kg	#	20	20	20	20	20
Storage System							
Tank System Mass	kg	15	0	0	90	90	90
Fuel Tank Net Capacity	L (kg)	35	#	#	4kg	4kg	4kg
Additional Fuel Tank Net Capacity	L	#	#	#	#	#	#
Total Fuel Mass	kg	23	0	0	4	4	4
Vehicle							
Curb weight incl. Driver, 90% fuel	kg	1200	1208	1362	1297	1397	1436
Performance Mass	kg	1325	1333	1487	1422	1522	1561
Payload	kg	510	510	510	510	510	510
WLTP Test Mass	kg	1350	1358	1512	1447	1547	1586
Gross Vehicle Mass	kg	1710	1718	1872	1807	1907	1946
1) Masses include the whole system (e.g. E-machine power electronics, cooling system, etc.)							

A DCDC converter is included in all xEV components wherever appropriate. In case of the FC driven variants the FC system is always connected to the HV bus via a DCDC converter. The corresponding DCDC conversion losses are included in the simulation models (either implemented in the component losses or modelled in particular, as e.g. in case of the FC driven variants). DCDC converter losses for LV power supply is neglected.

The auxiliaries in 2025+ variants (Steering Pump (EPS), Brake Vacuum Pump, Water Pump, (ICE) Oil Pump and (transmission) Oil Pump) are in general fully electrified.

6.1.2 ICE specifications

The RON for the Gasoline blends and CN for Diesel fuels are defined in the fuel properties Table 3-1. Slight RON / CN changes for fuels (e.g. Diesel B0: CN 51, Diesel B7: CN 53) do not require ICE map adaptions in this simulation work, as the estimations of ICE maps for specific fuels are based on a comparable level of accuracy, and slight RON / CN effects are considered not to be significant compared to the overall simulation accuracy.

Regulated Emissions (e.g. NOx, PM, ...) are not simulated in the current TTW analysis. However all ICE maps prepared for simulation of 2025+ variants are assumed to comply with the legislative emissions standards for EURO 6. In contrast to 2015, the definition of 2025+ ICE specifications is adapted to the degree of electrification of xEV variants: Electrification is not just seen as an Add-On technology like in 2015, but as an integrated system design approach, where the ICE is optimized together with the E-machines (used for propulsion) in terms of combined system performance. Accordingly, in case of the HEV and the PHEV, the Gasoline ICEs are downsized and downrated (reduced in their maximum power). Diesel ICEs are not downsized and only slightly downrated to prevent complex NOx after-treatment systems. Both Gasoline and Diesel ICEs are improved significantly in terms of technology for electrified variants.

Table 6-4: ICE Specifications for SI variants 2025+

2025+ SI ICE Specifications		DISI DISI MHEV					Hybrid DISI PHEV100 DISI	REEV200 SI
		Gasoline E5, Gasoline E10, LPG	Gasoline High Octane spec. #1	Gasoline High Octane spec. #2	CNG	E100	Gasoline E5, E10 Gasoline High Octane, E100	Gasoline E5, E10 Gasoline High Octane, E100
ICE Type / Technology	---	- TGDI - Miller with DVVT - Compression Ratio 12.0 - VTG - Integrated exhaust manifold (water cooled) - GPF - 3 Way Catalysator - Cooled EGR (LP or HP) - Water charge air cooler - Beltless					- TGDI - Miller DVVT - VTG - CR ~ 12.5 to 14.0 - Integrated exhaust manifold (water cooled) - GPF - 3 Way Cat. - Cooled EGR (LP) - Water charge air cooler - Beltless	- Atkinson - CR 14.0 to 16.0 - Cooled low temperature EGR - Isolated Intake - Extremely Low Friction
Measures for alternative fuel usage	---	#	- Increased CR of 13.0 - Adapted Calibration	- Increased CR of 13.5 - Adapted Calibration	- Increased CR of 14.0 - Adapted Calibration - Change to CNG Direct injection - GPF removed	- Adapted Calibration	In case of Gasoline High Octane: Increased CR and adapted Calibration	In case of Gasoline High Octane: Increased CR and adapted Calibration
Displacement	L	1,5	1,5	1,5	1,5	1,5	1,2	1,2
No. of Cylinders	---	IL4	IL4	IL4	IL4	IL4	IL3	IL3
No. of Strokes	---	4	4	4	4	4	4	4
Specific Power	kW/L	~65	~65	~65	~65	~65	65	40
Maximum Power @ speed	kW (PS) / rpm	98 @ 5500	98 @ 5500	98 @ 5500	98 @ 5500	98 @ 5500	78 @ 4000	49 @ 5000
Maximum Torque @ speed	Nm / rpm	240 @ 1500-3500	240 @ 1500-3500	240 @ 1500-3500	240 @ 1500-3500	240 @ 1500-3500	181 @ 2000-4000	95 @ 2000-5000
Maximum Speed	rpm	6000	6000	6000	6000	6000	6000	6000

Table 6-5: ICE Specifications for CI variants 2025+

2025+ CI ICE Specifications		DICI DICI MHEV		Hybrid DICI PHEV100 DICI	REEV200 CI
		Diesel B0, Diesel B7, FAME, DME	FT-Diesel, HVO	Diesel B0, Diesel B7, FAME, DME, FT-Diesel, HVO	Diesel B0, Diesel B7, FAME, DME, FT-Diesel, HVO
ICE Type / Technology	---	- Low friction engine - 2000 bar Common Rail - VGT Turbocharger - Cooled LP-EGR - Cooled HP-EGR, with cooler bypass - close coupled LNT / SDPF - e-Catalyst -Fast thermal engine warm-up measures - Beltless		- Low friction engine - 1800 bar Common Rail - WG Turbocharger - Cooled LP-EGR + Cooled HP-EGR, w. cooler bypass - DOC / SDPF (e-Catalyst) - no VVT -Fast thermal engine warm-up measures - Beltless	- Extremely Low Friction - Cost optimized Common Rail FIE ~1300bar- WG Turbocharger optimized to BSFC "sweet spot" - Simplified EGR system (High pressure- or Low pressure EGR) - DOC – SDPF, e-Cat
Measures for alternative fuel usage	---	#	- Adaptation of Combustion timing - Optimized Fuel Injection Strategy - Optimized EGR Strategy	In case of FT-Diesel & HVO: Adaptation of Combustion timing, Optimized Fuel Injection Strategy & Optimized EGR Strategy	In case of FT-Diesel & HVO: Adaptation of Combustion timing, Optimized Fuel Injection Strategy & Optimized EGR Strategy
Displacement	L	1,6	1,6	1,6	1,0
No. of Cylinders	---	IL4	IL4	IL4	IL3
No. of Strokes	---	4	4	4	4
Specific Power	kW/L	~56	~56	51	40
Maximum Power @ speed	kW (PS) / rpm	90 @ 4000	90 @ 4000	82 @ 3600	40 @3500
Maximum Torque @ speed	Nm / rpm	310 @ 1600-2500	310 @ 1600-2500	270 @ 2000-2500	119@2000-2500
Maximum Speed	rpm	5000	5000	5000	4200

6.1.3 xEV specifications

The xEV components specifications of the 2025+ variants were designed and optimized in correlation to the given boundary conditions and vehicle minimum performance criteria of the current TTW study. Table 6- gives an overview of the considered electrified components, the requirements to be achieved and the main specifications. The values reported in the table in case of the Electric Machine and the Generator show the peak and, in parenthesis, the continuous power and torque. Concerning the Li-Ion Battery Pack, the total as well as the useable energy (in parenthesis) is outlined.

Table 6-6: 2025+ xEV component specifications

Variant	Component	Specific	Unit	Requirements to meet the performance criteria	Value*
MHEV HEV	E-machine	Power	kW	*Complete regenerative braking during the WLTP*	**25** (12.5)
		Torque	Nm	*Complete regenerative braking during the WLTP*	**150** (100)
	Battery Pack	Power	kW	*Required electric power from/to the E-machine*	**30**
		Energy	kWh	*Complete regenerative braking and 160.000km lifetime in WLTP*	**1.16**(0.35)
PHEV	E-machine	Power	kW	*Driving of the WLTP purely electrically => Peak Power*	**50** (30)
		Torque	Nm	*Electric Driving up to 150 km/h => Continuous Power*	**260** (140)
	Battery Pack	Power	kW	*Required electric power from/to the E-machine*	**55**
		Energy	kWh	*100 km AER and 160.000km lifetime in WLTP*	**20.8** (15.6)
REEV	E-machine	Power	kW	*Acceleration and Elasticity => Peak Power & Torque*	**85** (50)
		Torque	Nm	*Gradeability 20% => Continuous Torque*	**200** (120)
	Generator	Power	kW	*Fitting to the ICE*	**50** (50)
		Torque	Nm		**120** (120)
	Battery Pack	Power	kW	*Required electric power from/to the E-machine*	**90**
		Energy	kWh	*200 km AER and 160.000km lifetime in WLTP*	**28.6** (25.7)
BEV	E-machine	Power	kW	*Acceleration and Elasticity => Peak Power & Torque*	**85** (50)
		Torque	Nm	*Gradeability 20% => Continuous Torque*	**200** (120)
	Battery Pack	Power	kW	*Required electric power from/to the E-machine*	**90**
		Energy short range	kWh	*200 km AER and 160.000km lifetime in WLTP*	**24.7** (22.2)
		Energy long range	kWh	*400 km AER and 160.000km lifetime in WLTP*	**49.4** (44.5)
FCEV	E-machine	Power	kW	*Acceleration and Elasticity => Peak Power & Torque*	**85** (50)
		Torque	Nm	*Gradeability 20% => Continuous Torque*	**200** (120)
	FC System	Power	kW	*Electric Driving up to 180 km/h*	**55**
	Battery Pack	Power	kW	*Required electric power from/to the E-machine*	**30**
		Energy	kWh	*Complete regenerative braking and 160.000km lifetime in WLTP*	**1.16**(0.35)
PHEV FC	E-machine	Power	kW	*Acceleration and Elasticity => Peak Power & Torque*	**85** (50)
		Torque	Nm	*Gradeability 20% => Continuous Torque*	**200** (120)
	FC System	Power	kW	*Electric Driving up to 180 km/h*	**55**
	Battery Pack	Power	kW	*Required electric power from/to the E-machine*	**90**
		Energy	kWh	*100 km AER and 160.000km lifetime in WLTP*	**16.9** (12.7)
REEV FC	E-machine	Power	kW	*Acceleration and Elasticity => Peak Power & Torque*	**85** (50)
		Torque	Nm	*Gradeability 20% => Continuous Torque*	**200** (120)
	FC System	Power	kW	*Electric Driving up to 150 km/h*	**35**
	Battery Pack	Power	kW	*Required electric power from/to the E-machine*	**90**
		Energy	kWh	*200 km AER and 160.000km lifetime in WLTP*	**28.6** (25.7)

**) E-machine, Generator: The values show the peak and (in parenthesis) the continuous power and torque;*
Li-Ion Battery Pack: The values show the total and (in parenthesis) the useable energy

The Fuel Cell System Efficiency characteristic for all 2025+ variants is the same as defined in 2015 (see Figure 5-1). It is assumed that in the upcoming years the development of FC Systems will mainly focus on cost reductions for series application, and not on a further improvement of the system efficiency that outperforms existing (larger and higher performing) FCEVs as described in chapter 5.2.2.5.

6.2 Simulation results

In the following tables, the results for electric energy consumption in case of variants including a Plug-In feature are always given both with and without consideration of Battery charging losses. In general, according to the legislative regulations for NEDC and WLTP, respectively, charging losses are to be included in reference values of electric energy consumption for all Plug-In featured vehicle variants. 2025+ simulation results partially include in addition a so-called “Technology Walk”, which shows in detail the foreseen improvements in technology development in comparison to the 2015 variants, as they were assessed by EUCAR and AVL experts to their best available knowledge. In case of Plug-In featured variants (PHEV & REEV) there is no “Technology Walk” evaluated, as the legislative rules for calculating weighted results out of CD and CS operation are completely different in NEDC and WLTP, and therefore not comparable.

6.2.1 Results for Conventional ("ICE only") variants

Table 6-7: Simulation Results for "ICE only" variants 2025+

Simulation Resuts: 2025+ Conventional ("ICE only") Variants **WLTP**	Curb Mass	Fuel Tank Capacity	Fuel Consumption		Energy Consumption			GHG emissions			
					Fuel	Electric	Total	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L (kg)	l/100km	kg/100km	MJ/100km	MJ/100km	MJ/100km	gCO_2/km	gCO_2eq/km	gCO_2eq/km	gCO_2eq/km
DISI ("ICE only") 2025+											
Gasoline E5	1200	35	4,46	3,33	140,74	#	140,74	103,26	0,13	0,54	103,92
Gasoline E10 market blend	1200	35	4,53	3,39	140,74	#	140,74	102,89	0,13	0,54	103,55
Gasoline high Octane spec. #1	1200	35	4,32	3,28	139,19	#	139,19	102,00	0,13	0,54	102,67
Gasoline high Octane spec. #2	1200	35	4,33	3,29	136,69	#	136,69	100,29	0,13	0,54	100,95
LPG	1222	60	5,60	3,08	141,59	#	141,59	92,93	0,13	0,54	93,59
CNG	1227	17kg	#	2,89	138,51	#	138,51	77,71	1,50	0,54	79,75
E100	1200	35	6,59	5,24	140,31	#	140,31	100,13	0,13	0,54	100,80
DICI ("ICE only") 2025+											
Diesel B0	1260	35	3,61	3,01	129,63	#	129,63	94,88	0,23	1,19	96,30
Diesel B7 market blend	1260	35	3,63	3,04	129,63	#	129,63	94,99	0,23	1,19	96,41
FAME	1260	35	3,92	3,48	129,63	#	129,63	98,70	0,23	1,19	100,11
DME	1285	40	6,86	4,60	130,55	#	130,55	87,92	0,23	1,19	89,34
FT-Diesel	1260	35	3,76	2,93	129,00	#	129,00	91,31	0,23	1,19	92,73
HVO	1260	35	3,76	2,93	129,00	#	129,00	91,31	0,23	1,19	92,73

In comparison to the 2015 results evaluated for NEDC, the 2025+ results show that the difference in fuel consumption between SI and CI variants is significantly reduced. In 2015 in NEDC, the MT gearshift pattern is the same for both fuels. In combination with typically shorter gear ratios for SI vehicle transmissions compared to CI vehicle transmissions, this leads to reduced ICE speeds and higher loads (and hence better ICE and transmission efficiency) for the CI variants. In 2025+ in WLTP, the MT gearshift pattern depends on ICE and vehicle specifications. This leads to higher gears, thus significant engine downspeeding, and higher loads for the SI variants. Consequently, the SI variants are able to catch up in terms of efficiency compared to the CI variants.

Table 6-8: Technology Walk 2015 → 2025+ for DISI "ICE only" variants

Technology Walk for DISI Baseline Powertrain Variant DISI BASE 2015 (NEDC) → DISI BASE 2025+ (WLTP)		**NEDC 2015**	**WLTP 2025+**	**Potential**
		Specific component Cycle Energy Losses		**Relative weighted Improvement**
		kJ/km	**kJ/km**	**%**
Engine	**New ICE 2025+**	**1339,1**	**979,3**	**20,8%**
Transmission	**Higher specific energy throughput in WLTP overcompensates improved gearbox** Improved gear lubrication for reduction of churning losses The increased energy throughput in WLTP still rises the specific energy demand	**49,8**	**54,2**	**-0,3%**
Auxilliaries	**Auxilliaries supplied by recuperation via ~4kW Starter Generator** A 12V starter generator of ~4kW max. power allows generation of electric energy from recuperation to fully supply the electrified auxilliaries in 2025+.	**35,8**	**0**	**2,1%**
Rolling Resistance	**Higher test mass in WLTP overcompensates weight reduction** The curb weight of the vehicle has been reduced by 110kg for 2025+ However the test weight definitions in WLTP still lead to a higher test weight in 2025+.	**89,9**	**92,7**	**-0,2%**
Air Resistance	**Higher average velocity in WLTC overcompensates improved aerodynamics** Reduction of Air drag coefficient from 0.28 to 0.25 Increased average speed overcompensates improvements in aerodynamics	**129,4**	**168,6**	**-2,3%**
Braking Energy	**Higher braking demand in WLTP** Due to the change to the more dynamic WLTC more energy is lost inside the brakes	**83,5**	**108,5**	**-1,4%**
Sum		**1727,5**	**1403,3**	**18,8%**

Table 6-9: Technology Walk 2015 → 2025+ for DICI "ICE only" variants

Technology Walk for DICI Baseline Powertrain Variant DICI BASE 2015 (NEDC) → DICI BASE 2025+ (WLTP)		**NEDC 2015**	**WLTP 2025+**	**Potential**
		Specific component Cycle Energy Losses		**Relative weighted Improvement**
		kJ/km	**kJ/km**	**%**
Engine	**New ICE 2025+**	**1055,8**	**869,3**	**12,9%**
Transmission	**Higher specific energy throughput in WLTP overcompensates improved gearbox** Improved gear lubrication for reduction of churning losses The increased energy throughput in WLTP still rises the specific energy demand	**42,1**	**47,3**	**-0,4%**
Auxilliaries	**Auxilliaries supplied by recuperation via ~4kW Starter Generator** A 12V starter generator of ~4kW max. power allows generation of electric energy from recuperation to fully supply the electrified auxilliaries in 2025+.	**35,9**	**0**	**2,5%**
Rolling Resistance	**Higher test mass in WLTP overcompensates weight reduction** The curb weight of the vehicle has been reduced by 110kg for 2025+ However the test weight definitions in WLTP still lead to a higher test weight in 2025+.	**94,1**	**96,8**	**-0,2%**
Air Resistance	**Higher average velocity in WLTC overcompensates improved aerodynamics** Reduction of Air drag coefficient from 0.28 to 0.25 Increased average speed overcompensates improvements in aerodynamics	**129,4**	**168,6**	**-2,7%**
Braking Energy	**Higher braking demand in WLTP** Due to the change to the more dynamic WLTC more energy is lost inside the brakes	**89,9**	**110,2**	**-1,4%**
Sum		**1447,1**	**1292,3**	**10,7%**

6.2.2 Results for xEV variants

6.2.2.1 MHEV

Table 6-10: Simulation Results for MHEV variants 2025+

Simulation Resuts: 2025+ MHEV Variants **WLTP**	Curb Mass	Fuel Tank Capacity	Fuel Consumption		Energy Consumption			GHG emissions			
					Fuel	Electric	Total	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L (kg)	l/100km	kg/100km	MJ/100km	MJ/100km	MJ/100km	gCO_2/km	gCO_2eq/km	gCO_2eq/km	gCO_2eq/km
MHEV DISI 2025+											
Gasoline E5	1287	35	3,72	2,77	117,29	#	117,29	86,05	0,13	0,54	86,71
Gasoline E10 market blend	1287	35	3,78	2,83	117,29	#	117,29	85,74	0,13	0,54	86,41
Gasoline high Octane spec. #1	1287	35	3,62	2,75	116,70	#	116,70	85,52	0,13	0,54	86,18
Gasoline high Octane spec. #2	1287	35	3,66	2,77	115,41	#	115,41	84,68	0,13	0,54	85,34
LPG	1309	60	4,65	2,56	117,59	#	117,59	77,18	0,13	0,54	77,84
CNG	1314	17kg	3,07	2,38	114,05	#	114,05	63,99	1,50	0,54	66,03
E100	1287	35	5,46	4,34	116,23	#	116,23	82,95	0,13	0,54	83,61
MHEV DICI 2025+											
Diesel B0	1347	35	3,09	2,57	110,63	#	110,63	80,98	0,23	1,19	82,39
Diesel B7 market blend	1347	35	3,10	2,59	110,63	#	110,63	81,07	0,23	1,19	82,49
FAME	1347	35	3,34	2,97	110,63	#	110,63	84,23	0,23	1,19	85,65
DME	1372	40	5,83	3,91	110,96	#	110,96	74,73	0,23	1,19	76,15
FT-Diesel	1347	35	3,21	2,51	110,25	#	110,25	78,04	0,23	1,19	79,46
HVO	1347	35	3,21	2,51	110,25	#	110,25	78,04	0,23	1,19	79,46

The 48V MHEV in principle shows the same functionality as the HEV, but represents a simpler add-on approach compared to the dedicated HEV development (high voltage electrification, especially designed ICE). The limited power of up to 25kW is already sufficient to ensure efficient Hybrid operation for both recuperation as well as electric driving.

6.2.2.2 HEV

Table 6-11: Simulation Results for HEV variants 2025+

Simulation Resuts: 2025+ Hybrid Variants **WLTP**	Curb Mass	Fuel Tank Capacity	Fuel Consumption		Energy Consumption			GHG emissions			
					Fuel	Electric	Total	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L (kg)	l/100km	kg/100km	MJ/100km	MJ/100km	MJ/100km	gCO_2/km	gCO_2eq/km	gCO_2eq/km	gCO_2eq/km
Hybrid DISI 2025+											
Gasoline E5	1275	35	3,26	2,43	102,75	#	102,75	75,39	0,13	0,54	76,05
Gasoline E10 market blend	1275	35	3,31	2,48	102,75	#	102,75	75,12	0,13	0,54	75,78
Gasoline high Octane spec. #1	1275	35	3,18	2,42	102,42	#	102,42	75,05	0,13	0,54	75,71
Gasoline high Octane spec. #2	1275	35	3,21	2,43	101,28	#	101,28	74,31	0,13	0,54	74,97
LPG	#	#	#	#	#	#	#	#	#	#	#
CNG	#	#	#	#	#	#	#	#	#	#	#
E100	1275	35	4,83	3,83	102,75	#	102,75	73,33	0,13	0,54	73,99
Hybrid DICI 2025+											
Diesel B0	1345	35	3,02	2,51	108,12	#	108,12	79,14	0,23	1,19	80,55
Diesel B7 market blend	1345	35	3,03	2,53	108,12	#	108,12	79,23	0,23	1,19	80,65
FAME	1345	35	3,27	2,91	108,12	#	108,12	82,32	0,23	1,19	83,73
DME	1370	40	5,70	3,82	108,44	#	108,44	73,03	0,23	1,19	74,45
FT-Diesel	1345	35	3,14	2,45	107,75	#	107,75	76,27	0,23	1,19	77,68
HVO	1345	35	3,14	2,45	107,75	#	107,75	76,27	0,23	1,19	77,68

Table 6-12: Technology Walk 2015 → 2025+ for DISI Hybrid variants

Technology Walk for DISI HEV Powertrain Variant DISI HEV 2015 (NEDC) → DISI HEV 2025+ (WLTP)		NEDC 2015	WLTP 2025+	Potential
		Specific component Cycle Energy Losses		Relative weighted Improvement
		kJ/km	kJ/km	%
Engine	**New ICE 2025+**	850,4	640,7	16,7%
Transmission	**Improved gearbox, partially compensated by higher specific energy throughput in WLTP** Improved gearing, more efficient oil pump, reduction of drag losses, improved shifting efficiency The increased energy throughput in WLTP still rises the specific energy demand	77,5	48,2	2,3%
Auxilliaries	**Reduced specific energy consumption due to higher average velocity in WLTP** While the efficiency of the auxilliaries will slightly improve, the addition of more electric components is expected to compensate this effect. Due to the higher average velocity the energy consumption/km reduces in WLTC.	28,4	21,3	0,6%
Electric Machine	**Improved Electric Machine and Inverter** Improvement in control efficiency Better Hardware and more efficient packaging Less switching losses & Lower thermal losses	63,1	39,3	1,9%
Battery	**Improved Energy and Power Densities** Higher Power density of 1.3kW/kg vs. 1.0kW/kg Higher Energy Density of 60Wh/kg vs. 40Wh/kg	3,4	3,0	0,0%
Rolling Resistance	**Higher test mass in WLTP overcompensates weight reduction** The curb weight of the vehicle has been reduced by 136kg for 2025+ However the test weight definitions in WLTP still lead to a higher test weight in 2025+.	96,5	98,7	-0,2%
Air Resistance	**Higher average velocity in WLTC overcompensates improved aerodynamics** Reduction of Air drag coefficient from 0.28 to 0.25 Increased average speed overcompensates improvements in aerodynamics	132,2	168,9	-2,9%
Sum		1257,2	1026,1	18,4%

Table 6-13: Technology Walk 2015 → 2025+ for DICI Hybrid variants

Technology Walk for DICI HEV Powertrain Variant DICI HEV 2015 (NEDC) → DICI HEV 2025+ (WLTP)		NEDC 2015	WLTP 2025+	Potential
		Specific component Cycle Energy Losses		Relative weighted Improvement
		kJ/km	kJ/km	%
Engine	**New ICE 2025+**	723,6	681,6	3,7%
Transmission	**Improved gearbox, partially compensated by higher specific energy throughput in WLTP** Improved gearing, more efficient oil pump, reduction of drag losses, improved shifting efficiency The increased energy throughput in WLTP still rises the specific energy demand	71,2	45,2	2,3%
Auxilliaries	**Reduced specific energy consumption due to higher average velocity in WLTP** While the efficiency of the auxilliaries will slightly improve, the addition of more electric components is expected to compensate this effect. Due to the higher average velocity the energy consumption/km reduces in WLTC.	28,2	30,4	-0,2%
Electric Machine	**Improved Electric Machine and Inverter** Improvement in control efficiency Better Hardware and more efficient packaging Less switching losses & Lower thermal losses	67,2	37,6	2,6%
Battery	**Improved Energy and Power Densities** Higher Power density of 1.3kW/kg vs. 1.0kW/kg Higher Energy Density of 60Wh/kg vs. 40Wh/kg	3,0	3,5	0,0%
Rolling Resistance	**Higher test mass in WLTP overcompensates weight reduction** The curb weight of the vehicle has been reduced by 136kg for 2025+ However the test weight definitions in WLTP still lead to a higher test weight in 2025+.	100,6	102,8	-0,2%
Air Resistance	**Higher average velocity in WLTC overcompensates improved aerodynamics** Reduction of Air drag coefficient from 0.28 to 0.25 Increased average speed overcompensates improvements in aerodynamics	132,2	168,9	-3,2%
Sum		1132,8	1078,0	4,8%

6.2.2.3 PHEV

Table 6-14: Simulation Results for PHEV variants 2025+; note that Electric Energy Consumption includes charging losses

Simulation Resuts: 2025+ PHEV Variants **WLTP**	Curb Mass	Fuel Tank Capacity	Fuel Consumption		Energy Consumption			GHG emissions			
					Fuel	Electric	Total	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L (kg)	l/100km	kg/100km	MJ/100km	MJ/100km	MJ/100km	gCO_2/km	gCO_2eq/km	gCO_2eq/km	gCO_2eq/km
PHEV100 SI 2025+											
Gasoline E5	1419	28	0,29	0,21	9,07	49,78	58,85	6,66	0,01	0,04	6,71
Gasoline E10 market blend	1419	28	0,29	0,22	9,07	49,78	58,85	6,63	0,01	0,04	6,68
Gasoline high Octane spec. #1	1419	28	0,28	0,21	9,04	49,78	58,83	6,63	0,01	0,04	6,68
Gasoline high Octane spec. #2	1419	28	0,28	0,21	8,94	49,78	58,73	6,56	0,01	0,04	6,61
LPG	#	#	#	#	#	#	#	#	#	#	#
CNG	#	#	#	#	#	#	#	#	#	#	#
E100	1419	28	0,43	0,34	9,07	49,78	58,85	6,47	0,01	0,04	6,53
PHEV100 CI 2025+											
Diesel B0	1488	28	0,27	0,22	9,64	52,12	61,76	7,06	0,02	0,10	7,18
Diesel B7 market blend	1488	28	0,27	0,23	9,64	52,12	61,76	7,07	0,02	0,10	7,18
FAME	1488	28	0,29	0,26	9,64	52,12	61,76	7,34	0,02	0,10	7,46
DME	1511	48	0,51	0,34	9,67	52,12	61,79	6,51	0,02	0,10	6,63
FT-Diesel	1488	28	0,28	0,22	9,61	52,12	61,73	6,80	0,02	0,10	6,92
HVO	1488	28	0,28	0,22	9,61	52,12	61,73	6,80	0,02	0,10	6,92

6.2.2.4 REEV

Table 6-15: Simulation Results for REEV variants 2025+; note that Electric Energy Consumption includes charging losses

Simulation Resuts: 2025+ REEV Variants **WLTP**	Curb Mass	Fuel Tank Capacity	Fuel Consumption		Energy Consumption			GHG emissions			
					Fuel	Electric	Total	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L (kg)	l/100km	kg/100km	MJ/100km	MJ/100km	MJ/100km	gCO_2/km	gCO_2eq/km	gCO_2eq/km	gCO_2eq/km
REEV200 SI 2025+											
Gasoline E5	1429	21	0,09	0,07	2,84	44,43	47,27	2,08	0,00	0,01	2,10
Gasoline E10 market blend	1429	21	0,09	0,07	2,84	44,43	47,27	2,08	0,00	0,01	2,09
Gasoline high Octane spec. #1	1429	21	0,09	0,07	2,84	44,43	47,27	2,08	0,00	0,01	2,10
Gasoline high Octane spec. #2	1429	21	0,09	0,07	2,84	44,43	47,27	2,08	0,00	0,01	2,10
LPG	#	#	#	#	#	#	#	#	#	#	#
CNG	#	#	#	#	#	#	#	#	#	#	#
E100	1429	21	0,13	0,11	2,84	44,43	47,27	2,03	0,00	0,01	2,04
REEV200 CI 2025+											
Diesel B0	1488	21	0,08	0,07	2,92	45,13	48,05	2,14	0,01	0,03	2,17
Diesel B7 market blend	1488	21	0,08	0,07	2,92	45,13	48,05	2,14	0,01	0,03	2,18
FAME	1488	21	0,09	0,08	2,92	45,13	48,05	2,22	0,01	0,03	2,26
DME	1509	36	0,15	0,10	2,93	45,13	48,05	1,97	0,01	0,03	2,01
FT-Diesel	1488	21	0,09	0,07	2,92	45,13	48,05	2,07	0,01	0,03	2,10
HVO	1488	21	0,09	0,07	2,92	45,13	48,05	2,07	0,01	0,03	2,10

6.2.2.5 BEV

Table 6-16: Simulation Results for BEV variants 2025+; note that Electric Energy Consumption includes charging losses

Simulation Resuts: 2025+ BEV Variants **WLTP**	Curb Mass	Fuel Tank Capacity	Fuel Consumption		Energy Consumption			GHG emissions			
					Fuel	Electric	Total	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L (kg)	l/100km	kg/100km	MJ/100km	MJ/100km	MJ/100km	gCO_2/km	gCO_2eq/km	gCO_2eq/km	gCO_2eq/km
BEV200 2025+											
Electricity	1208	#	#	#	#	42,77	42,77	0,00	0,00	0,00	0,00
BEV400 2025+											
Electricity	1362	#	#	#	#	44,71	44,71	0,00	0,00	0,00	0,00

Table 6-17: Technology Walk 2015 → 2025+ for (short-range) BEV variant

Technology Walk for BEV Powertrain Variant BEV150 2015 (NEDC) → BEV200 2025+ (WLTP)		NEDC 2015	WLTP 2025+	Potential
		Specific component Cycle Energy Losses		Relative weighted Improvement
		kJ/km	kJ/km	%
Transmission	**Change from single speed to dual speed gearbox** Introduction of a 2-speed transmission	22,7	17,0	1,6%
Auxilliaries	**Reduced specific energy consumption due to higher average velocity in WLTP** While the efficiency of the auxilliaries will slightly improve, the addition of more electric components is expected to compensate this effect. Due to the higher average velocity the energy consumption/km reduces in WLTC.	27,1	19,6	2,0%
Electric Machine	**Improved Electric Machine and Inverter** Improvement in control efficiency Better Hardware and more efficient packaging Less switching losses & Lower thermal losses	78,4	63,8	4,0%
Battery	**Improved Energy and Power Densities** Higher Energy Density of 160Wh/kg vs. 120Wh/kg	8,5	6,1	0,6%
Rolling Resistance	**Higher test mass in WLTP overcompensates weight reduction** The curb weight of the vehicle has been reduced by 107kg for 2025+ However the test weight definitions in WLTP still lead to a higher test weight in 2025+.	90,0	95,6	-1,5%
Air Resistance	**Higher average velocity in WLTC overcompensates improved aerodynamics** Reduction of Air drag coefficient from 0.28 to 0.25 Increased average speed overcompensates improvements in aerodynamics	132,3	168,8	-9,9%
Sum		370,0	372,1	-0,6%

6.2.2.6 FCEV, PHEV FC & REEV FC

Table 6-18: Simulation Results for FC driven variants 2025+; note that Electric Energy Consumption includes charging losses

Simulation Resuts: 2025+ FC Variants WLTP	Curb Mass	Fuel Tank Capacity	Fuel Consumption		Energy Consumption			GHG emissions			
					Fuel	Electric	Total	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L (kg)	l/100km	kg/100km	MJ/100km	MJ/100km	MJ/100km	gCO_2/km	gCO_2eq/km	gCO_2eq/km	gCO_2eq/km
FCEV 2025+											
Hydrogen	1297	4	#	0,58	69,74	0,00	69,74	0,00	0,00	0,00	0,00
PHEV100 FC 2025+											
Hydrogen	1397	4	#	0,05	6,00	39,96	45,97	0,00	0,00	0,00	0,00
REEV200 FC 2025+											
Hydrogen	1436	4	#	0,02	1,91	44,61	46,52	0,00	0,00	0,00	0,00

Table 6-19: Technology Walk 2015 → 2025+ for FCEV variant

Technology Walk for FCEV Powertrain Variant FCEV 2015 (NEDC) → FCEV 2025+ (WLTP)		NEDC 2015	WLTP 2025+	Potential
		Specific component Cycle Energy Losses		Relative weighted Improvement
		kJ/km	kJ/km	%
Fuel Cell	**Improvements focused op production process and cost reduction** Main focus of fuel cell development is expected to be towards production processes, reliability and reduction of system costs and less towards effeciency improvement. Due to the higher average load in WLTP the fuel cell has to be used more often above its optimum power which leads to higher specific energy losses in 2025+.	314,4	320,4	-0,9%
Transmission	**Change from single speed to dual speed gearbox** Introduction of a 2-speed transmission	23,2	17,4	0,8%
Auxilliaries	**Reduced specific energy consumption due to higher average velocity in WLTP** While the efficiency of the auxilliaries will slightly improve, the addition of more electric components is expected to compensate this effect. Due to the higher average velocity the energy consumption/km reduces in WLTC.	27,1	19,6	1,1%
Electric Machine	**Improved Electric Machine and Inverter** Improvement in control efficiency Better Hardware and more efficient packaging Less switching losses & Lower thermal losses	81,3	65,9	2,2%
Battery	**Improved Energy and Power Densities** Higher Power density of 1.3kW/kg vs. 1.0kW/kg Higher Energy Density of 60Wh/kg vs. 40Wh/kg	2,0	3,0	-0,1%
Rolling Resistance	**Higher test mass in WLTP overcompensates weight reduction** The curb weight of the vehicle has been reduced by 113kg for 2025+ However the test weight definitions in WLTP still lead to a higher test weight in 2025+.	97,9	101,4	-0,5%
Air Resistance	**Higher average velocity in WLTC overcompensates improved aerodynamics** Reduction of Air drag coefficient from 0.28 to 0.25 Increased average speed overcompensates improvements in aerodynamics	132,3	168,8	-5,3%
Sum		692,3	698,6	-0,9%

7 Summary

This summary provides an overview of all results for the considered fuel-powertrain combinations including error estimations. The figures below (Figure 7-1 to Figure 7-4) show CO_2 equivalent emission as well as energy consumption (Figure 7-5 to Figure 7-8) for both conventional and electrified variants. Energy consumption includes energy content of fuels (calculated from fuel consumption via LHV) and electric energy from battery charging (including charging losses, see chapter 4.3.5). Results for externally chargeable variants (such as PHEV and REEV) are weighted due to the homologation regulations valid at the respective time, as described in chapter 4.2.1.1 for NEDC and in chapter 4.2.2.1 for WLTP.

Diagrams are split for SI and CI ICEs and for 2015 and 2025+ variants. In case of Plug-In electrified variants, the electric energy consumption is additionally included. Finally, the pure electric variants are summed up in an additional figure (Figure 7-9). For better readability of the report, the considered fuel-powertrain combinations are always shown in specific color-codes throughout all diagrams and result tables. Detailed explanations of the results are given in chapter 5 for the 2015 and in chapter 6 for the 2025+ variants. In the 2015 SI results the CNG variant represents an exception, as the CNG fuel is port injected, but the gasoline fuel is directly injected.

Figure 7-1: Summary of CO_2 equivalent emission results for SI ICE Variants 2015

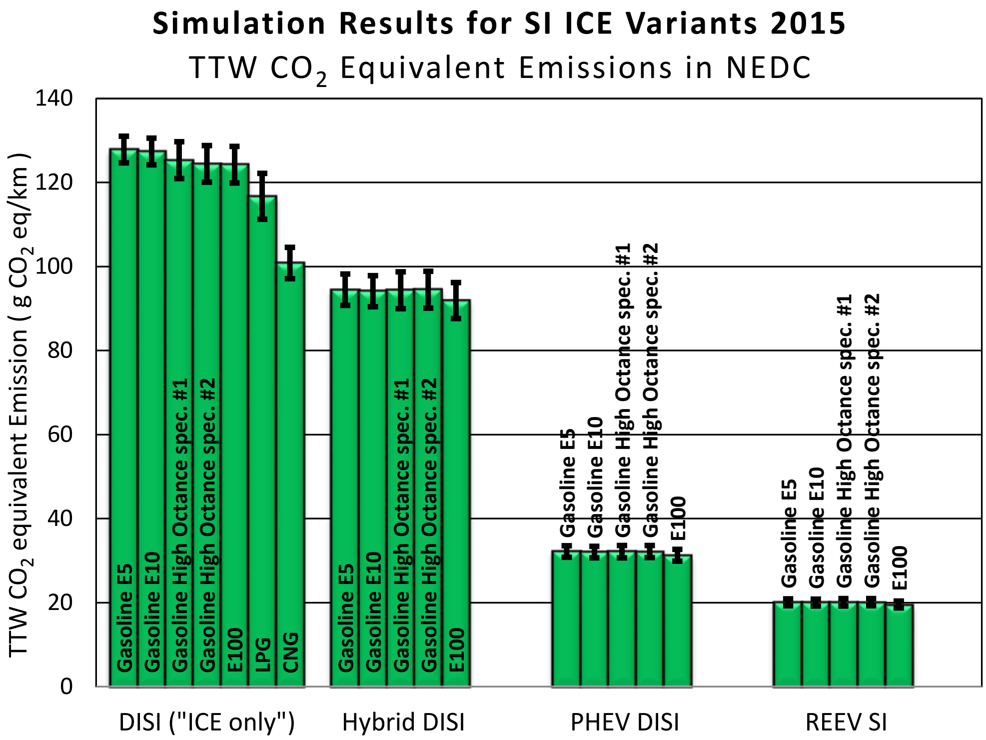


Figure 7-2: Summary of CO_2 equivalent emission results for CI ICE Variants 2015

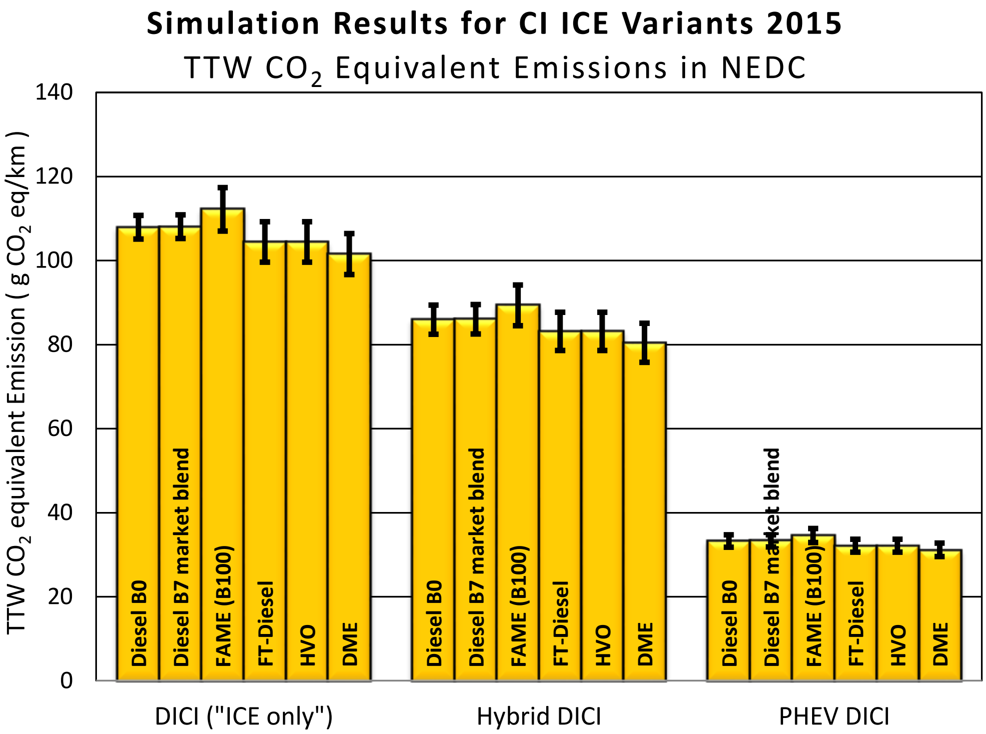


Figure 7-3: Summary of CO_2 equivalent emission results for SI ICE Variants 2025+

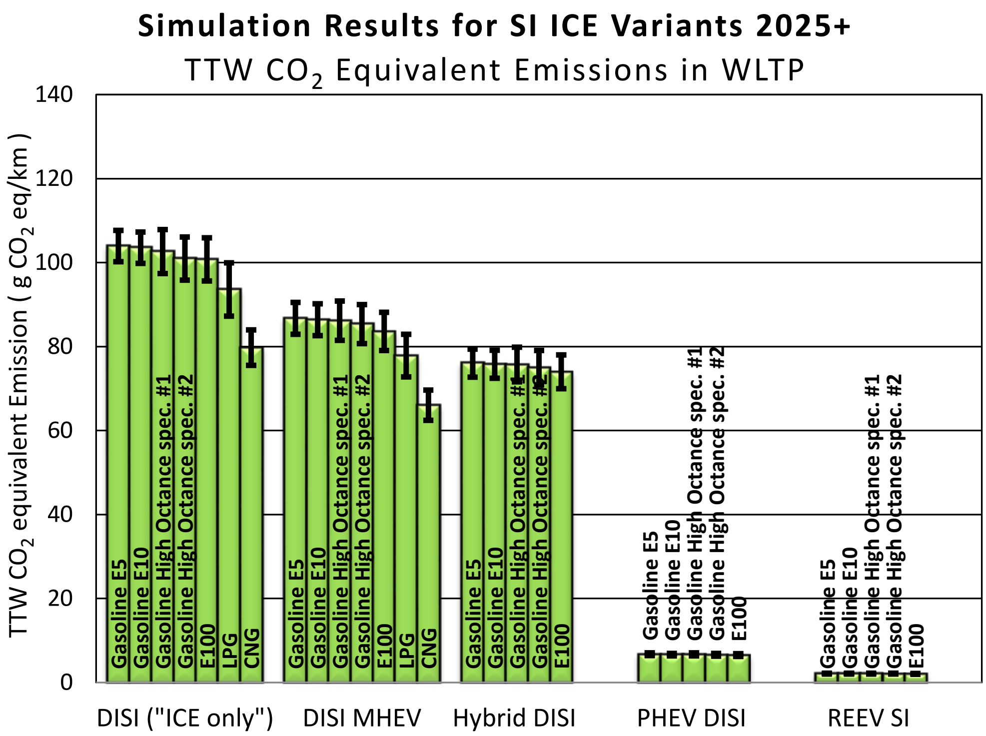


Figure 7-4: Summary of CO_2 equivalent emission results for CI ICE Variants 2025+

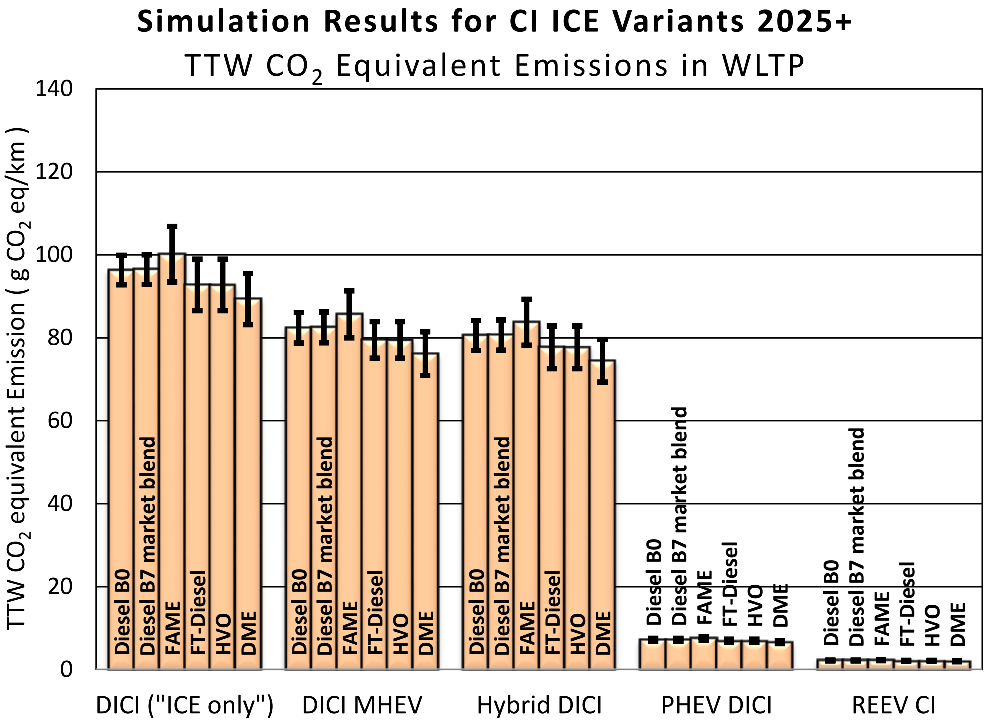


Figure 7-5: Summary of energy consumption results for SI ICE Variants 2015

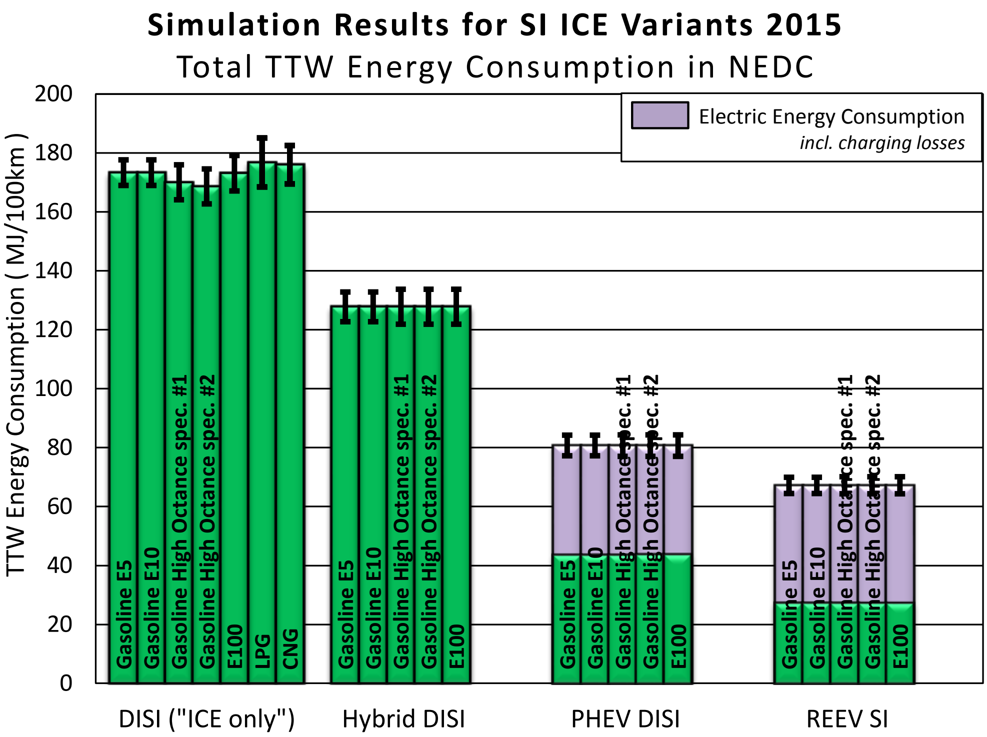


Figure 7-6: Summary of energy consumption results for CI ICE Variants 2015

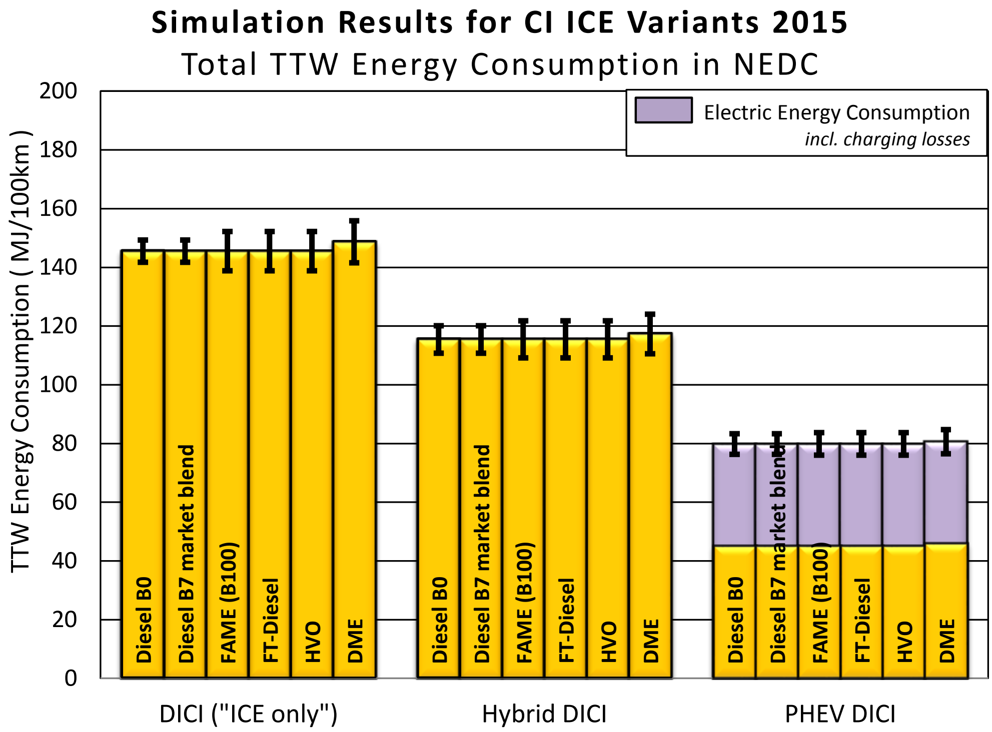


Figure 7-7: Summary of energy consumption results for SI ICE Variants 2025+

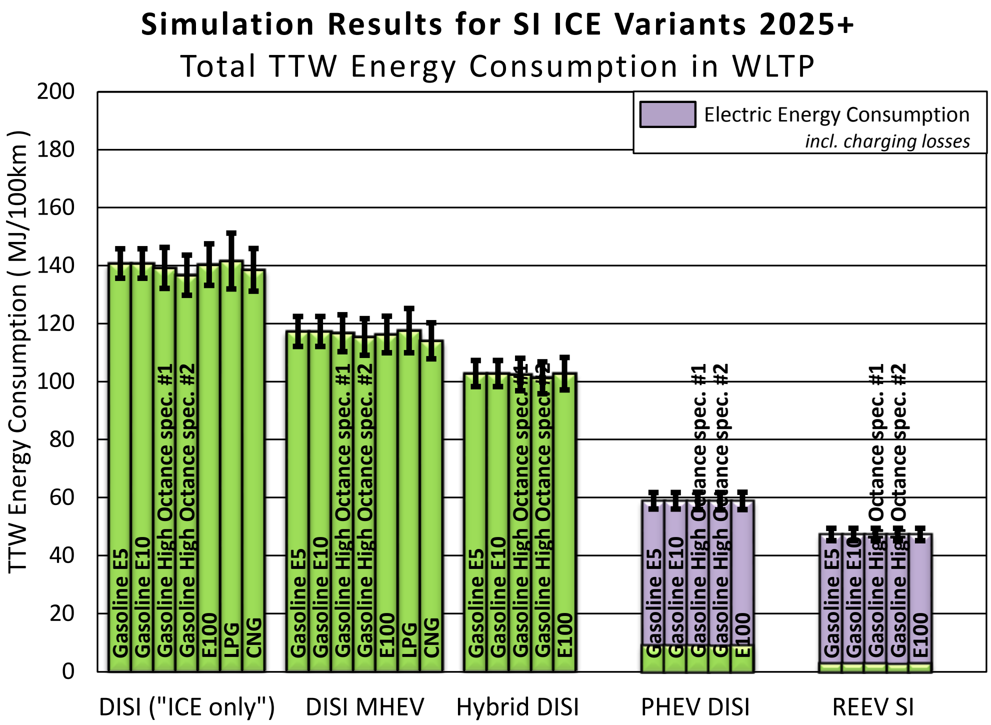


Figure 7-8: Summary of energy consumption results for CI ICE Variants 2025+

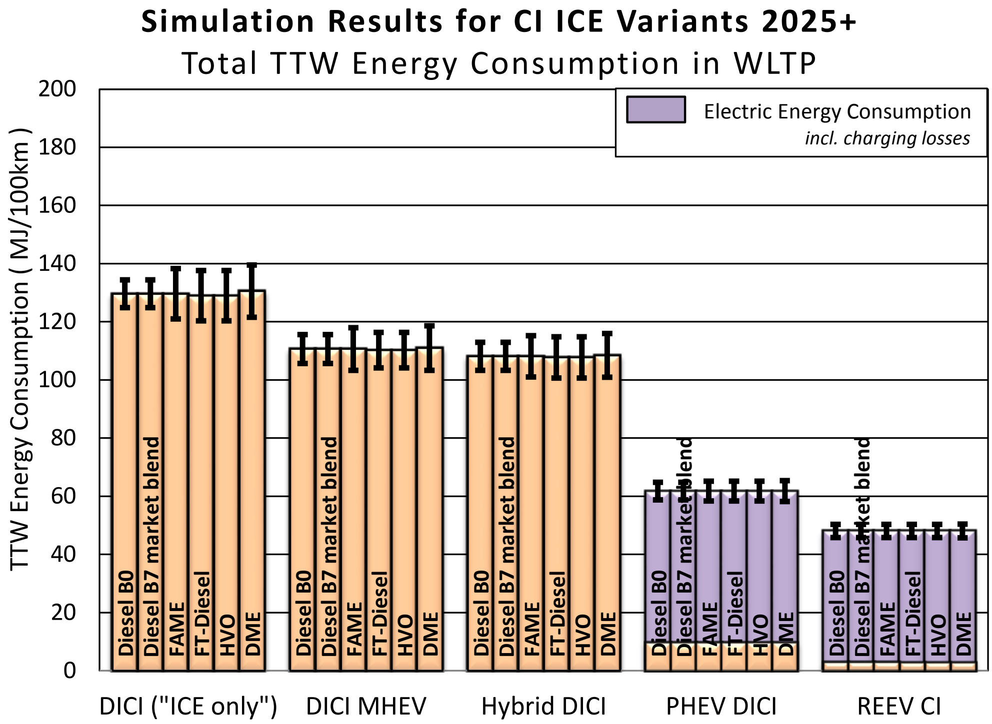
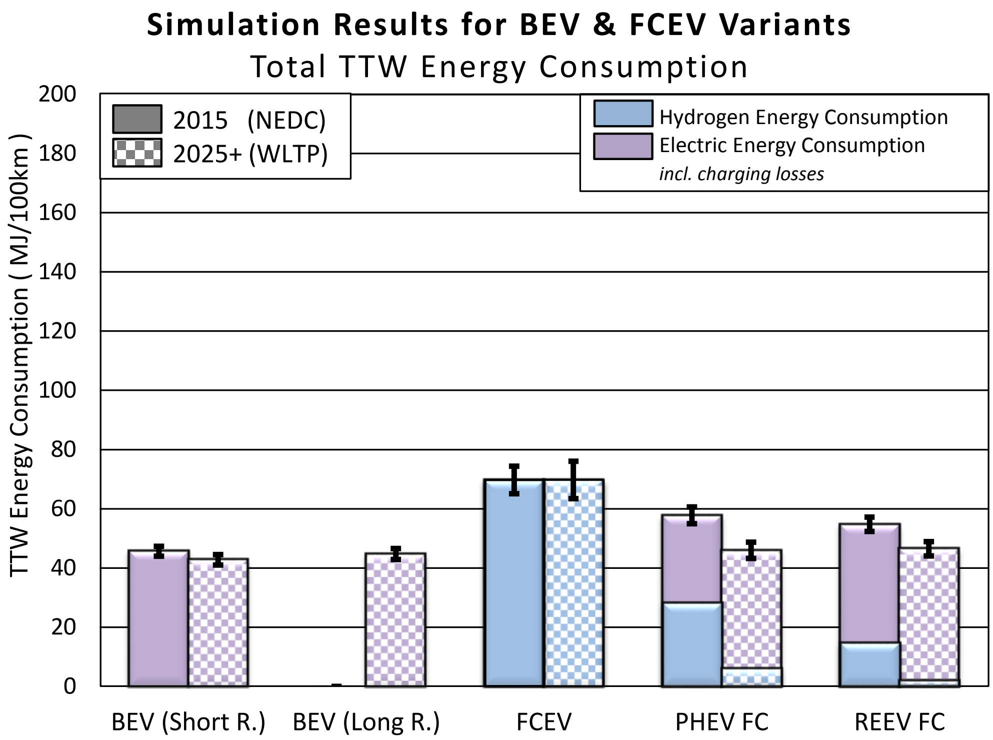


Figure 7-9: Summary of energy consumption results for BEV & FCEV Variants 2015 & 2025+



Annex 1. NEDC 2025+ (made available to EUCAR only)

Annex table 1: NEDC Simulation Results for “ICE only” variants 2025+

Simulation Resuts: 2025+ Conventional ("ICE only") Variants **NEDC**	Curb Mass	Fuel Tank Capacity	Fuel Consumption		Energy Consumption			GHG emissions			
					Fuel	Electric	Total	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L (kg)	l/100km	kg/100km	MJ/100km	MJ/100km	MJ/100km	gCO_2/km	gCO_2eq/km	gCO_2eq/km	gCO_2eq/km
DISI ("ICE only") 2025+											
Gasoline E5	1200	35	4,18	3,12	131,86	#	131,86	96,74	0,13	0,54	97,40
Gasoline E10 market blend	1200	35	4,25	3,18	131,86	#	131,86	96,39	0,13	0,54	97,06
Gasoline high Octane spec. #1	1200	35	4,05	3,08	130,43	#	130,43	95,59	0,13	0,54	96,25
Gasoline high Octane spec. #2	1200	35	4,01	3,05	126,73	#	126,73	92,98	0,13	0,54	93,64
LPG	1222	60	5,27	2,90	133,27	#	133,27	87,47	0,13	0,54	88,13
CNG	1227	17kg	#	2,72	130,40	#	130,40	73,16	1,50	0,54	75,20
E100	1200	35	6,20	4,92	131,83	#	131,83	94,09	0,13	0,54	94,75
DICI ("ICE only") 2025+											
Diesel B0	1260	35	3,18	2,65	114,18	#	114,18	83,58	0,23	1,19	84,99
Diesel B7 market blend	1260	35	3,20	2,67	114,18	#	114,18	83,67	0,23	1,19	85,09
FAME	1260	35	3,45	3,07	114,18	#	114,18	86,93	0,23	1,19	88,35
DME	1285	40	6,07	4,07	115,58	#	115,58	77,84	0,23	1,19	79,26
FT-Diesel	1260	35	3,32	2,59	113,93	#	113,93	80,64	0,23	1,19	82,06
HVO	1260	35	3,32	2,59	113,93	#	113,93	80,64	0,23	1,19	82,06

Annex table 2: NEDC Simulation Results for MHEV variants 2025+

Simulation Resuts: 2025+ MHEV Variants **NEDC**	Curb Mass	Fuel Tank Capacity	Fuel Consumption		Energy Consumption			GHG emissions			
					Fuel	Electric	Total	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L (kg)	l/100km	kg/100km	MJ/100km	MJ/100km	MJ/100km	gCO_2/km	gCO_2eq/km	gCO_2eq/km	gCO_2eq/km
MHEV DISI 2025+											
Gasoline E5	1287	35	2,93	2,19	92,47	#	92,47	67,84	0,13	0,54	68,50
Gasoline E10 market blend	1287	35	2,98	2,23	92,47	#	92,47	67,60	0,13	0,54	68,26
Gasoline high Octane spec. #1	1287	35	2,83	2,15	91,35	#	91,35	66,94	0,13	0,54	67,60
Gasoline high Octane spec. #2	1287	35	2,88	2,19	91,04	#	91,04	66,79	0,13	0,54	67,45
LPG	1309	60	3,68	2,03	93,18	#	93,18	61,16	0,13	0,54	61,82
CNG	1314	17kg	#	1,91	91,82	#	91,82	51,52	1,50	0,54	53,56
E100	1287	35	4,34	3,44	92,25	#	92,25	65,84	0,13	0,54	66,50
MHEV DICI 2025+											
Diesel B0	1347	35	2,54	2,11	91,01	#	91,01	66,62	0,23	1,19	68,03
Diesel B7 market blend	1347	35	2,55	2,13	91,01	#	91,01	66,69	0,23	1,19	68,11
FAME	1347	35	2,75	2,45	91,01	#	91,01	69,29	0,23	1,19	70,71
DME	1372	40	4,83	3,23	91,82	#	91,82	61,84	0,23	1,19	63,26
FT-Diesel	1347	35	2,60	2,03	89,24	#	89,24	63,17	0,23	1,19	64,58
HVO	1347	35	2,60	2,03	89,24	#	89,24	63,17	0,23	1,19	64,58

Annex table 3: NEDC Simulation Results for HEV variants 2025+

Simulation Resuts: 2025+ Hybrid Variants **NEDC**	Curb Mass	Fuel Tank Capacity	Fuel Consumption		Energy Consumption			GHG emissions			
					Fuel	Electric	Total	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L (kg)	l/100km	kg/100km	MJ/100km	MJ/100km	MJ/100km	gCO_2/km	gCO_2eq/km	gCO_2eq/km	gCO_2eq/km
Hybrid DISI 2025+											
Gasoline E5	1275	35	2,67	1,99	84,17	#	84,17	61,75	0,13	0,54	62,41
Gasoline E10 market blend	1275	35	2,71	2,03	84,17	#	84,17	61,53	0,13	0,54	62,19
Gasoline high Octane spec. #1	1275	35	2,55	1,94	82,27	#	82,27	60,29	0,13	0,54	60,95
Gasoline high Octane spec. #2	1275	35	2,60	1,97	81,99	#	81,99	60,16	0,13	0,54	60,82
LPG	#	#	#	#	#	#	#	#	#	#	#
CNG	#	#	#	#	#	#	#	#	#	#	#
E100	1275	35	3,96	3,14	84,17	#	84,17	60,07	0,13	0,54	60,73
Hybrid DICI 2025+											
Diesel B0	1345	35	2,49	2,07	89,22	#	89,22	65,31	0,23	1,19	66,72
Diesel B7 market blend	1345	35	2,50	2,09	89,22	#	89,22	65,38	0,23	1,19	66,80
FAME	1345	35	2,69	2,40	89,22	#	89,22	67,93	0,23	1,19	69,35
DME	1370	40	4,73	3,17	90,02	#	90,02	60,62	0,23	1,19	62,04
FT-Diesel	1345	35	2,55	1,99	87,48	#	87,48	61,92	0,23	1,19	63,34
HVO	1345	35	2,55	1,99	87,48	#	87,48	61,92	0,23	1,19	63,34

Annex table 4: NEDC Simulation Results for PHEV variants 2025+; note that Electric Energy Consumption includes charging losses

Simulation Resuts: 2025+ PHEV Variants **NEDC**	Curb Mass	Fuel Tank Capacity	Fuel Consumption		Energy Consumption			GHG emissions			
					Fuel	Electric	Total	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L (kg)	l/100km	kg/100km	MJ/100km	MJ/100km	MJ/100km	gCO_2/km	gCO_2eq/km	gCO_2eq/km	gCO_2eq/km
PHEV100 SI 2025+											
Gasoline E5	1419	28	0,45	0,33	14,08	35,06	49,14	10,33	0,02	0,08	10,43
Gasoline E10 market blend	1419	28	0,45	0,34	14,08	35,06	49,14	10,29	0,02	0,08	10,39
Gasoline high Octane spec. #1	1419	28	0,43	0,32	13,76	35,06	48,82	10,08	0,02	0,08	10,18
Gasoline high Octane spec. #2	1419	28	0,43	0,33	13,71	35,06	48,78	10,06	0,02	0,08	10,16
LPG	#	#	#	#	#	#	#	#	#	#	#
CNG	#	#	#	#	#	#	#	#	#	#	#
E100	1419	28	0,66	0,53	14,08	35,06	49,14	10,05	0,02	0,08	10,15
PHEV100 CI 2025+											
Diesel B0	1488	28	0,49	0,41	17,51	35,81	53,33	12,82	0,04	0,21	13,07
Diesel B7 market blend	1488	28	0,49	0,41	17,51	35,81	53,33	12,83	0,04	0,21	13,09
FAME	1488	28	0,53	0,47	17,51	35,81	53,33	13,34	0,04	0,21	13,59
DME	1511	48	0,93	0,62	17,63	35,81	53,44	11,87	0,04	0,21	12,12
FT-Diesel	1488	28	0,50	0,39	17,17	35,81	52,99	12,16	0,04	0,21	12,41
HVO	1488	28	0,50	0,39	17,17	35,81	52,99	12,16	0,04	0,21	12,41

Annex table 5: NEDC Simulation Results for REEV variants 2025+; note that Electric Energy Consumption includes charging losses

Simulation Resuts: 2025+ REEV Variants **NEDC**	Curb Mass	Fuel Tank Capacity	Fuel Consumption		Energy Consumption			GHG emissions			
					Fuel	Electric	Total	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L (kg)	l/100km	kg/100km	MJ/100km	MJ/100km	MJ/100km	gCO_2/km	gCO_2eq/km	gCO_2eq/km	gCO_2eq/km
REEV200 SI 2025+											
Gasoline E5	1429	21	0,24	0,18	7,62	33,03	40,65	5,59	0,01	0,05	5,64
Gasoline E10 market blend	1429	21	0,25	0,18	7,62	33,03	40,65	5,57	0,01	0,05	5,62
Gasoline high Octane spec. #1	1429	21	0,24	0,18	7,62	33,03	40,65	5,58	0,01	0,05	5,64
Gasoline high Octane spec. #2	1429	21	0,24	0,18	7,62	33,03	40,65	5,59	0,01	0,05	5,64
LPG	#	#	#	#	#	#	#	#	#	#	#
CNG	#	#	#	#	#	#	#	#	#	#	#
E100	1429	21	0,36	0,28	7,62	33,03	40,65	5,44	0,01	0,05	5,49
REEV200 CI 2025+											
Diesel B0	1488	21	0,23	0,19	8,11	33,42	41,53	5,93	0,02	0,11	6,06
Diesel B7 market blend	1488	21	0,23	0,19	8,11	33,42	41,53	5,94	0,02	0,11	6,07
FAME	1488	21	0,24	0,22	8,11	33,42	41,53	6,17	0,02	0,11	6,30
DME	1509	36	0,43	0,29	8,17	33,42	41,59	5,50	0,02	0,11	5,62
FT-Diesel	1488	21	0,24	0,18	8,11	33,42	41,53	5,74	0,02	0,11	5,86
HVO	1488	21	0,24	0,18	8,11	33,42	41,53	5,74	0,02	0,11	5,86

Annex table 6: NEDC Simulation Results for BEV variants 2025+; note that Electric Energy Consumption includes charging losses

Simulation Resuts: 2025+ BEV Variants **NEDC**	Curb Mass	Fuel Tank Capacity	Fuel Consumption		Energy Consumption			GHG emissions			
					Fuel	Electric	Total	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L (kg)	l/100km	kg/100km	MJ/100km	MJ/100km	MJ/100km	gCO_2/km	gCO_2eq/km	gCO_2eq/km	gCO_2eq/km
BEV200 2025+											
Electricity	1208	#	#	#	#	33,02	33,02	0,00	0,00	0,00	0,00
BEV400 2025+											
Electricity	1362	#	#	#	#	34,37	34,37	0,00	0,00	0,00	0,00

Annex table 7: NEDC Simulation Results for FC variants 2025+; note that Electric Energy Consumption includes charging losses

Simulation Resuts: 2025+ FC Variants **NEDC**	Curb Mass	Fuel Tank Capacity	Fuel Consumption		Energy Consumption			GHG emissions			
					Fuel	Electric	Total	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L (kg)	l/100km	kg/100km	MJ/100km	MJ/100km	MJ/100km	gCO_2/km	gCO_2eq/km	gCO_2eq/km	gCO_2eq/km
FCEV 2025+											
Hydrogen	1297	4	#	0,44	52,98	0,00	52,98	0,00	0,00	0,00	0,00
PHEV100 FC 2025+											
Hydrogen	1397	4	#	0,07	8,65	29,69	38,34	0,00	0,00	0,00	0,00
REEV200 FC 2025+											
Hydrogen	1436	4	#	0,04	4,74	33,56	38,30	0,00	0,00	0,00	0,00

List of abbreviations and definitions

AER	All Electric Range
B7	Diesel fuel with 7% Biodiesel
BEV	Battery Electric Vehicle
BSFC	Brake Specific Fuel Consumption
CD	Charge Depleting operation
CGH_2	Compressed Gaseous Hydrogen
CH_4	Methane, a greenhouse gas
CI	Compression Ignition
CN	Cetane Number
CNG	Compressed Natural Gas
CO_2	Carbon dioxide, the principal greenhouse gas
CONCAWE	The oil companies' European association for environment, health and safety in refining and distribution
CS	Charge Sustaining operation
DI	Direct injection
DICI	Direct Injection Compression Ignition
DISI	Direct Injection Spark Ignition
DLL	Dynamic Link Library
DME	Di-Methyl-Ether
E5	Gasoline fuel with 5% Ethanol
E10	Gasoline fuel with 10% Ethanol
E100	Pure Ethanol
ECE	Economic Commission for Europe
EPS	Electric Power Steering
EN	European Standard defined by the European Committee for Standardization
EUCAR	European Council for Automotive Research and Development
EVSE	Electric Vehicle Supply Equipment
FAME	Fatty Acid Methyl Ester, scientific name for bio-diesel made from vegetable oil and methanol

FC	Fuel Cell
FCEV	Fuel Cell driven Electric Vehicle
FMEP	Friction Mean Effective Pressure
FMU	Functional Mock-up Unit
FT	Fischer-Tropsch, the process named after its original inventors that converts syngas to hydrocarbon chains
FWD	Front Wheel Drive
GHG	GreenHouse Gas
GVM	Gross Vehicle Mass
HEV	Hybrid Electric Vehicle
HP	High Pressure
HV	High Voltage
HVO	Hydro-treated Vegetable Oil
IL	In-Line Engine Configuration
ICE	Internal Combustion ICE
ITW	Inertia Test Weight
JRC	Joint Research Centre (of the EU Commission)
LHV	Lower Heating Value ('Lower" indicates the heat of water condensation is not included)
LP	Low Pressure
LPG	Liquefied Petroleum Gas
LPM	Load Point Moving (in ICE operation)
MPI	Multi Point Injection
MT	Manual Transmission
N_2O	Nitrous oxide, a very potent greenhouse gas
NEDC	New European Drive Cycle
NOx	A mixture of various nitrogen oxides as emitted by combustion sources
OVC	Off Vehicle Charging
P2	Parallel Hybrid configuration with 2 clutches
PEM	Proton Exchange Membrane, a Fuel Cell technology

PHEV	Plug-In Hybrid Electric Vehicle
PHEV FC	Fuel Cell driven Plug-In Hybrid Electric Vehicle
PISI	Port Injection Spark Ignition
RE	Range Extender (Module)
REEV	Range Extender Electric Vehicle
REEV FC	Fuel Cell driven Range Extender Electric Vehicle
RON	Research Octane Number
SI	Spark Ignition
SCR	Selective Catalytic Reduction
SOC	State Of Charge (of a Battery)
TGDi	Turbo (Charged) Gasoline Direct Injection
THC	Total Hydro Carbon
TMH	Test Mass High (regarding WLTP)
TML	Test Mass Low (regarding WLTP)
TTW	Tank-To-Wheels, description of the burning of a fuel in a vehicle
WLTC	Worldwide harmonized Light duty Test Cycle
WLTP	Worldwide harmonized Light duty Test Procedure
WTT	Well-To-Tank: the cascade of steps required to produce and distribute a fuel (starting from the primary energy resource), including vehicle refuelling
WTW	Well-To-Wheels: the integration of all steps required to produce and distribute a fuel (starting from the primary energy resource) and use it in a vehicle
xEV	x-Electrified Vehicle, collective name for all electrified variants

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Annexe(s)

Annex 1: NEDC 2025+ (made available to EUCAR only)

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