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TANK-TO-WHEELS Report - Version 4.a

WELL-TO-WHEELS ANALYSIS OF FUTURE AUTOMOTIVE FUELS AND POWERTRAINS IN THE EUROPEAN CONTEXT

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Abstract

The JEC research partners [Joint Research Centre of the European Commission, EUCAR and CONCAWE] have updated their joint evaluation of the tank-to-wheels (TTW) energy use and greenhouse gas emissions for a wide range of potential future fuel and powertrain options.
This document is a revision of the fourth release of this study released in July 2013.
The original version was published in December 2003.

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TANK-TO-WHEELS (TTW) REPORT

VERSION 4a, April 2014

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Notes on version number:

This is version 4a of this report revising version 4 published in July 2013. The main changes and additions to the previous version are:

- Base year for Tank-to-Wheels evaluation moved from 2002 to 2010;
- Re-evaluation of 2010 conventional and Hybrid vehicle configurations;
- Introduction of additional fuels;
- Introduction of additional electrified vehicle configurations such as Plug-In Hybrid Electric Vehicles (PHEV), Range Extended Electric Vehicles (REEV) and Battery Electric Vehicles (BEV);
- Consideration of conventional and electrified vehicle configurations for 2020+;
- In contrast to the recent versions of the TTW report, no cost assessments have been made.

Acknowledgments

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 Ludwig-Bölkow-Systemtechnik GmbH (LBST) and AVL List GmbH (AVL).

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1 Introduction

The study of current and future automotive fuels and powertrains 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") vehicles. These configurations are considered for 2010 (representing vehicles on the market in the years 2008 to 2012) to characterize the current state-of-the-art in automotive industry. Version 3 of the TTW study used 2002 as base year. To give an outlook on the future technical development of passenger cars, configurations for 2020+ are presented. They are based on the technology development expected by EUCAR and AVL experts.

All fuel–powertrain configurations are investigated for fuel consumption, Greenhouse Gas (GHG) emission and electric energy consumption based on the New European Driving Cycle (NEDC). Real world driving may show different results due to a range of impacting parameters and customer choices like different driving habits, road conditions and cabin comfort needs. Other vehicle in-use issues impacting fuel consumption, e.g. component degradation, are also not taken into account.

The study is founded on a generic C-segment vehicle as a reference. All conventional or xEV configurations are derived from this reference and retain pre-defined vehicle performance criteria. The xEV configurations include definitions of powertrain topologies and system architectures, best engineering estimations of Hybrid functionalities and operational strategies, and powertrain components including optimized layout and a detailed mass balance. For detailed investigation all configurations are modeled in the system simulation tool AVL CRUISE based on data and control calibration delivered by EUCAR or estimated by AVL based on its internal database and experience. Data, models and strategies are widely discussed and mutually agreed between EUCAR and AVL to ensure a high quality of results.

It should be noted that all investigated powertrain configurations are theoretical vehicle configurations and do not represent any existing vehicle or brand. However the definitions made do ensure that the investigated powertrain configurations - conventional as well as their xEV derivatives - strive to provide a representative overview about todays and expected future automotive technologies and their GHG emissions in European C-segment passenger cars.

[1] Non-electrified vehicle configurations driven by an ICE only will subsequently be named as "conventional". This also excludes Hybrid vehicles, which fall into the xEV category.

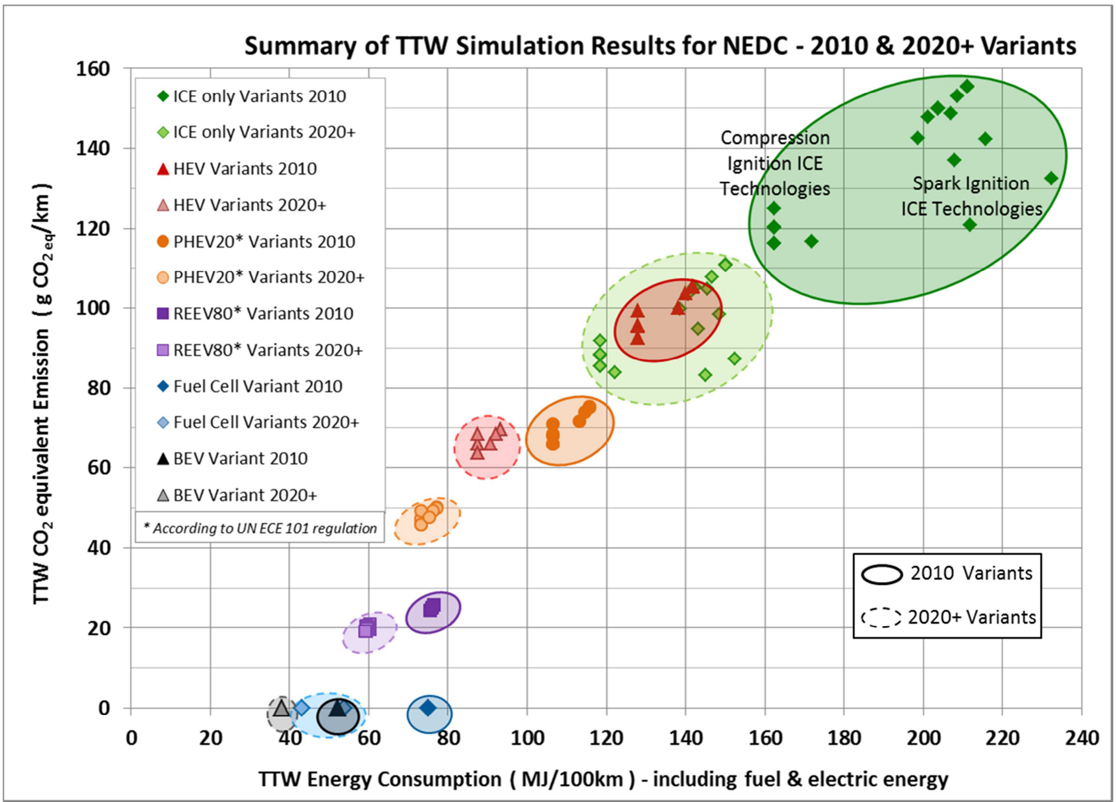
2 Executive Summary

The TTW simulation results are summarized in ***Figure 2-1*** showing the CO_2 equivalent emission and the energy consumption for 2010 and 2020+ configurations. All simulation runs were based on the New European Driving Cycle (NEDC).

A basic introduction of the fuels and powertrain configurations covered in the TTW study is given in chapter 3. Conventional powertrains include the ICE technologies of Port Injection Spark Ignition (PISI), Direct Injection Spark Ignition (DISI) and Direct Injection Compression Ignition (DICI). Electrification of conventional powertrains is done in terms of a Hybrid Electric Vehicle (HEV), a Plug-In Hybrid Electric Vehicle (PHEV) and a Range Extender Electric Vehicle (REEV). Additionally pure electric powertrains like the Battery Electric Vehicle (BEV) and the Fuel Cell driven Electric Vehicle (FCEV) are investigated. A description of all analyzed combinations of these powertrains with corresponding fuel configurations for 2010 and 2020+ is given in chapter 3.3.2. The methodology used for the simulation study is shown in chapter 4. Finally the detailed description of investigated powertrain configurations and their component specifications for 2010 configurations is given in chapter 5, and for 2020+ configurations in chapter 6.

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.

Figure 2-1: Summary of TTW simulation results for NEDC - 2010 & 2020+ configurations



3 Fuels & Powertrain Configurations

3.1 Fuel properties

The main properties of the fuels considered in the current study are listed in ***Table 3-1***. For each fuel type the density, the Research Octane Number (RON) or Cetane Number (CN), the Lower Heating Value (LHV), the mass portion of Carbon and the CO_2 emission factors are given. Fuel properties are defined based on 2010 specifications and are used for simulation of 2010 as well as 2020+ configurations to enable comparability of results. For some fuel properties the specifications give certain bandwidths and market fuels show variations within these ranges.

Table 3-1: Fuel properties for WTW study version 4

Fuel Type	Density	RON / CN	LHV	Elemental composition of Carbon	CO2 emission factor	
	kg/m^3 i.N.*	---	MJ/kg	%m	g/MJ	kg/kg
Gasoline	745	95	43.2	86.4	73.4	3.17
Gasoline E10	750	97	41.5	82.8	73.3	3.04
Gasoline E20 high RON	755	102	39.7	79.2	73.1	2.91
E85	786	106	29.2	56.9	71.6	2.09
LPG	550	**	46.0	82.4	65.7	3.02
CNG	0.790	**	45.1	69.2	56.2	2.54
Diesel	832	51	43.1	86.1	73.2	3.16
Diesel B7 market blend	836	51	42.7	85.4	73.4	3.13
FAME	890	56	37.2	77.3	76.2	2.83
FT Diesel	780	70	44.0	85.0	70.8	3.12
HVO	780	70 - 75	44.0	85.0	70.8	3.12
DME	670	55	28.4	52.2	67.3	1.91
Hydrogen (CGH2 & cCGH2)	0.084	#	120.1	0	0	0

*) All values are related to standard conditions according to DIN 1343 & ISO 2533; **) can vary significantly

For the vehicle simulation the fuel properties are taken into consideration in two different ways: For some main fuels like Gasoline, Gasoline E20 high RON, E85, Diesel, LPG and CNG ICE fuel consumption maps are specifically designed for the various ICE technologies and implemented into the powertrain simulated models for detailed calculation. The impacts of the other fuels are derived from these calculations based on their properties as given above.

3.2 Reference C-segment vehicle

All simulations are based on a generic or “virtual” reference vehicle, representing a common European C-segment 5-seater sedan for the time 2010 and 2020+. This reference vehicle is used as a tool for comparing the various fuels and associated technologies covered in this report; it is not claimed to be representative of the European fleet.

3.2.1 Main vehicle specification

The C-segment reference vehicle model year 2010 is equipped with a 1.4L DISI ICE, a 6 speed Manual Transmission (MT) and Front Wheel Drive (FWD). The main reference vehicle characteristics covered in vehicle simulation are given in ***Table 3-2***.

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

Generic C-segment reference vehicle with 1.4L DISI ICE (2010)			Improved Reference Vehicle for 2020+
Curb weight (incl. driver and 90% fuel)	kg	1310	1200 (*)
ITW class	kg	1360	1250
Length	mm	4326.5	
Width (without exterior mirror)	mm	1789.4	
Height	mm	1484.8	
Cross-sectional area	m^2	2.2	
Air drag coefficient	---	0.30	0.24
Rolling resistance coefficient	---	0.007	0.005
Wheel base	mm	2638.9	
Height of gravity center	mm	600	
Distance of gravity center from front axle	mm	1200	
Dynamic Rolling Radius	mm	309	
(*) Vehicle mass is reduced by 110 kg; Additional Information is shown in section "3.3.1.1 Vehicle mass"			

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 100% filled), fuel tank filled to 90% and a driver with 75kg (see EC Directive 95/48/EC).

3.2.2 Vehicle minimum performance requirements

To guarantee a fair comparison between all investigated vehicle configurations, minimum "customer performance" criteria are defined to ensure that each powertrain-fuel configuration meets the same customer expectations in terms of vehicle driveability. Therefore all conventional or xEV configurations are derived from the reference C-segment vehicle in a way, that specific measures in powertrain component layout (e.g. adaptation of ICE displacement) are undertaken to fulfill the minimum performance criteria in all configurations. These performance criteria are simulated in detail and guaranteed everywhere, but for sake of simplicity they are not shown in detail in the report. The vehicle minimum performance criteria are summarized in ***Table 3-3***.

Please note that the top-speed criterion for BEV and REEV is reduced in general to reflect the market in the 2010 timeframe. The driving range criterion for BEV is clearly reduced for 2010 compared to the other configurations, and higher but still clearly below 500km (all other configurations) for 2020+ due to restricted battery capacities. However, acceleration and gradeability criteria are identical.

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

		2010					2020+				
		PISI DISI DICI Hybrid SI Hybrid CI	PHEV SI PHEV CI	REEV SI	BEV	FCEV	PISI DISI DICI Hybrid SI Hybrid CI	PHEV SI PHEV CI	REEV SI REEV CI REEV FC	BEV	FCEV
Time to accelerate from 0-100 km/h	[s]	11	11	11	11	11	11	11	11	11	11
Elasticity for 80-120 km/h (1)	[s]	11	11	11	11	11	11	11	11	11	11
Gradeability at 1 km/h (2)	[%]	30	30	30	30	30	30	30	30	30	30
Gradeability at 10km/h	[%]	20	20	20	20	20	20	20	20	20	20
Minimum Top speed	[km/h]	180	180	130	130	180	180	180	130	130	180
Minimum Top speed pure electric	[km/h]	#	100	130	130	180	#	100	130	130	180
Total minimum driving range	[km]	500	500	500	120	500	500	500	500	200	500
Battery powered minimum driving range	[km]	#	20	80	120	#	#	20	80	200	#
Fuel consuming minimum driving range	[km]	500	480	420	#	500	500	480	420	#	500
(1): Elasticity, i.e. the time needed to accelerate from 80 to 120 km/h. The vehicle is driven in the second highest gear in case of Manual Transmissions, and according to the corresponding shifting strategies in case of Automatic Transmissions											
(2): Gradeability, i.e. the steepness of grade that a vehicle is capable of climbing at a defined speed											

3.3 Powertrain configurations

3.3.1 Basic description of powertrain configurations

3.3.1.1 Vehicle mass

For the 2010 conventional configurations the starting weight is the curb weight. This results in 1300kg for PISI, 1310kg for DISI and 1370kg for DICI. For the 2020+ configurations the corresponding vehicle masses are reduced by 110kg. All other configuration masses (Conventional & xEV) are determined based on a mass balance calculation of the propulsion system components of ICE, Fuel Cell, Transmission, E-machines, Battery, xEV wiring harness, Tank systems & fuel content that characterize the corresponding vehicle. For further details and an example see ***Table 5-1***. The driving performance simulations except for gradeability[2] are using the performance mass defined as curb weight with additional payload of 125kg.

For vehicle gradeability the Gross Vehicle Weight (GVW) is used, which is defined as follows: 2010 vehicle configurations all show the same GVW of 1900kg and the payload varies for the different configurations. This reflects that most alternative vehicles are assumed to be based on conventional vehicles and use the same glider, suspension, etc. For the 2020+ vehicle configurations it has been assumed that all vehicles are assumed to be constructed leading to the same payload performance, i.e. all show the same payload of 550kg but leading to different GVW. The corresponding values for GVW and payload for all conventional vehicle configurations are shown in ***Table 3-4*** and ***Table 3-5***.

Table 3-4: Vehicle GVW and payload definition for 2010 configurations

Vehicle mass for selected conventional vehicles and xEV variants in 2010		PISI	DISI	DICI	PHEV20 DISI	REEV80 DISI	BEV	FCEV
Curb weight (incl. Driver and 90% fuel)	kg	1300	1310	1370	1479	1548	1365	1458
Performance mass	kg	1425	1435	1495	1604	1673	1490	1583
Payload	kg	600	590	530	421	352	535	442
Gross vehicle weight	kg	1900	1900	1900	1900	1900	1900	1900

Table 3-5: Vehicle GVW and payload definition for 2020+ configurations

Vehicle mass for selected conventional vehicles and xEV variants in 2020+		PISI	DISI	DICI	PHEV20 DISI	REEV80 DISI	BEV	FCEV
Curb weight (incl. Driver and 90% fuel)	kg	1190	1200	1260	1333	1356	1230	1278
Performance mass	kg	1315	1325	1385	1458	1481	1355	1403
Payload	kg	550	550	550	550	550	550	550
Gross vehicle weight	kg	1740	1750	1810	1883	1906	1780	1828

3.3.1.2 Powertrain technologies & topologies

a) Conventional ("ICE only") configurations

Conventional configurations PISI, DISI and DICI are equipped with a 6-speed MT for both 2010 and 2020+ configurations (except PISI 2010 which has a 5 speed MT). Start-Stop functionality is only included for 2020+ configurations.

[2] Gradeability, i.e. the steepness of grade that a vehicle is capable of climbing at a defined speed

For the alternative fuels LPG, CNG and E85 the respective ICEs are optimized for their specific fuel type in general, but do also operate with gasoline in either mono-fuel[3] or bi-fuel[4] configuration.

In 2010 CNG fuel is assumed to use port fuel injection only, as direct CNG injection is expected to be established on the market by 2020+ or later. Hence in the current study all CNG ICEs are defined based upon port fuel injection for CNG fuel. However the gasoline fuel for the DISI CNG configurations is of course directly injected. The CNG ICE displacement is increased in relation to the gasoline reference ICE in order to compensate the additional vehicle mass (due to the tank system) and the reduced ICE volumetric efficiency (due to displacement of air by CNG in the intake manifold) to deliver the vehicle minimum performance targets. As an alternative measure also a direct injection technology for CNG could be used, but this technology is currently still in development and thus not covered in this report.

In 2010 fuel injection systems for DME are quite common for Heavy Duty applications but do not exist for passenger car applications. Therefore in the current study DME is considered only as theoretical fuel configuration for 2010 and even for 2020+, as any DME use in passenger cars is currently at research stage.

b) Fuel tank systems of conventional (“ICE-only”) configurations

All conventional configurations PISI, DISI and DICI are equipped with a 55L standard size fuel tank for 2010. This is reduced to a 35L fuel tank for 2020+ to ensure a comparable driving range for the more efficient future powertrains.

The conventional (gasoline, diesel) fuel tank system in LPG & DME vehicles is a standard 55L tank for 2010 (bi-fuel). The conventional (gasoline, diesel) fuel tank is reduced to a 14L tank (with 10kg tank system mass) for 2020+, which enables the LPG & DME vehicles to be classified as mono-fuel vehicles. The LPG & DME fuel tank system in LPG & DME vehicle configurations is reduced from an 80L tank size for 2010 to a 60L tank size in 2020+.

CNG configurations for both 2010 and 2020+ are defined as mono-fuel vehicles including a 14L gasoline fuel tank. CNG fuel tank system is defined as a 150kg 3-cylinder steel tank system for 2010, and an improved 50kg 2-cylinder composite tank system for 2020+.

c) xEV configurations

Within the actual TTW study the following powertrain topologies are considered as representative for electrified vehicles:

Hybrid Electric Vehicle (HEV) & Plug-In Hybrid Electric Vehicle (PHEV):

A parallel configuration including full Hybridization (i.e. battery powered driving is included) is selected for HEV and PHEV, combining an ICE with an E-Machine and a HV Battery. For 2010 the parallel configuration includes a 6 speed automatic transmission with a torque converter as launch element (P2 AT, ***Figure 3-1***), whereas for 2020+ the transmission is changed to a 8 speed automatic transmission and the torque converter is replaced by a dry clutch (P2, ***Figure 3-2***). The battery powered driving range for the PHEV is 20km, whereas for the HEV it is restricted to a few km, basically allowing launching the vehicle in electric driving mode. See ***Figure 8-1*** for details on the symbols used in the figures below.

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[3] Mono-fuel: any vehicle engineered and designed to be operated using a single fuel, but with a gasoline system for emergency purposes or starting only, with petrol tank capacity of no more than 15 liters
[4] Bi-fuel: any vehicle engineered and designed to be operated on two different fuels using two independent fuel systems, but not on a mixture of the fuels

Figure 3-1: P2 AT parallel Hybrid topology

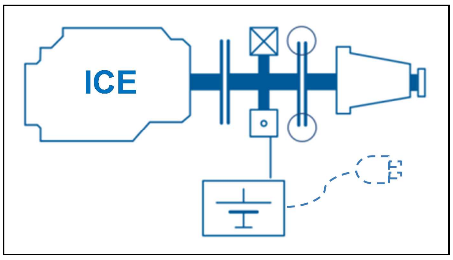
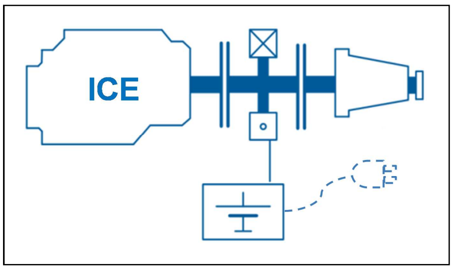


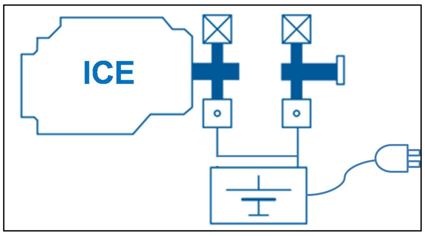
Figure 3-2: P2 parallel Hybrid topology



Range Extender Electric Vehicle (REEV):

A series configuration is selected for the REEV with SI and CI ICEs, as shown in ***Figure 3-3***. The battery powered driving range for the REEVs is 80km.

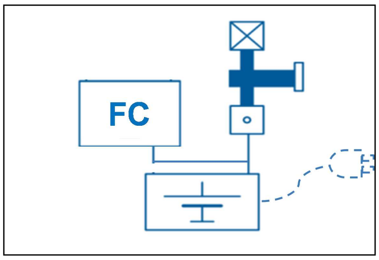
Figure 3-3: Series Hybrid topology



Fuel Cell Electric Vehicle (FCEV) & Fuel Cell Range Extender Electric Vehicle (REEV FC):

A series configuration is selected for both the FCEV and REEV FC, as shown in ***Figure 3-4***. The electric driving range for the FCEV is given as 500km for both 2010 and 2020+, for the REEV FC the battery-powered electric driving range is 80km similar to the other REEVs using an ICE as range extender. In general, no shifting transmission is used.

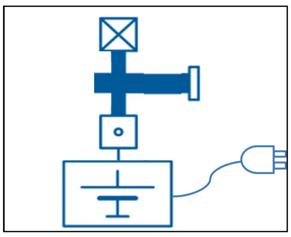
Figure 3-4: Series Hybrid topology for FC vehicles



Battery Electric Vehicle (BEV):

The drivetrain schematic for the BEV is shown in ***Figure 3-5***. The battery powered driving range for the BEV is given as 120km for 2010 and 200km for 2020+. No shifting transmission is used.

Figure 3-5: Drivetrain schematic for BEV



d) xEV technologies

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 90Wh/kg for BEV to 40Wh/kg for HEV in 2010 and from 120Wh/kg for BEV to 40Wh/kg for HEV in 2020+ configurations. Battery system power densities range from <600W/kg for BEV to 900W/kg for HEV in 2010, and from <600W/kg for BEV to 1150W/kg for HEV in 2020+ configurations. Charging losses within the vehicle, i.e. battery and power electronics, for externally chargeable configurations PHEV, REEV, REEV FC and BEV are considered for 3.x kW standard charging mode, which includes 20% charging losses for 2010 and a reduced 15% charging loss for 2020+ for all configurations[5].

All xEV electric traction motors are based on Brushless Permanent Magnet Synchronous Machine technology. E-Machine power densities range from 1200W/kg for BEV to 750W/kg for HEV in 2010 and from 1350W/kg for BEV to 850W/kg for HEV in 2020+ configurations. E-Machine continuous-to-peak power ratios are designed in the range between 0.5 and 0.7 which is common for automotive applications. Generator E-Machines for the Series Hybrid configurations are based on surface-mounted Brushless Permanent Magnet Synchronous Machine technology. Their power density is defined to 1300W/kg for 2010 and 1400W/kg for 2020+.

Fuel Cells are based on Proton Exchange Membrane (PEM) technology because it is commonly used for automotive applications.

e) Fuel tank systems of xEV configurations

xEV configurations HEV and PHEV are equipped with a 55L standard size fuel tank for 2010 similar to the conventional configurations (as 2010 the electrification is seen as an add-on technology), and a reduced 25L fuel tank for 2020+ to ensure a comparable driving range.

The SI and CI REEV are equipped with a 35L standard size fuel tank for 2010, and a reduced 25L fuel tank for 2020+.

Hydrogen fuel tank systems include both Compressed Gaseous Hydrogen (CGH2) and cryo Compressed Gaseous Hydrogen (cCGH2) technology. The specific weight of both CGH2 and cCGH2 tank systems are estimated to be 23kg/kgH2 for 2010 and 20kg/kgH2 for 2020+. In both 2010 and 2020+ the fuel tank capacity is assumed to be 4kg which gives a driving distance well above the 500km minimum criteria. Due to a negligible mass difference between CGH2 and cCGH2 technology for the targeted tank capacity of 4kg H2 only one simulation run for each FCEV 2010 and FCEV 2020+ configurations is done based on a generic tank system.

3.3.1.3 Auxiliaries

The following ICE-related auxiliary systems are considered in the vehicle simulation: Steering pump (HPS, EHPS or EPS), Vacuum pump for braking system, ICE water pump, ICE oil pump, transmission oil pump and cooling systems for xEV Batteries and E-Machines. Corresponding fuel consumption impacts due to partial or full electrification of these auxiliaries are covered in the vehicle simulation for all configurations. The Battery voltage level for vehicle electrics is assumed to be 12 V for all configurations 2010 & 2020+.

[5] The 3.x kW standard charging mode has been chosen as it should represent home and work place charging. Charging losses are based on:
http://www.green-cars-initiative.eu/public/documents/Electrification_Roadmap_Web.pdf/view

3.3.2 Analyzed fuel & powertrain configurations

All fuel–powertrain configurations for conventional as well as electrified vehicle configurations are shown in **Error! Reference source not found.**. These configurations are considered for 2010 (including technologies in a range from approximately 2008 up to 2012) to represent today's state of the art in automotive industry, and for 2020+ (to give an outlook on the expected future development of drivetrain technologies) based upon the likely technology development foreseen by EUCAR and AVL experts. To complete the REEV line-up, two additional configurations are given for 2020+: the REEV80 CI is considered in two different layouts, and the REEV80 FC.

Table 3-6: Matrix of fuel / powertrain combinations investigated in the current TTW study; configurations identified by blue colour are modelled in detail with a vehicle simulation; configurations identified by gray colour are derived from these simulations using the relevant fuel properties; all configurations are considered for 2010 and 2020+. Exceptions are marked in red: REEV80 FC** and REEV80 CI* are only considered for 2020+; REEV80 CI* in two different layouts.

Powertrain / Fuel	PISI	DISI	DICI	Hybird DISI	Hybrid DICI	PHEV20 DISI	REEV80 SI	PHEV20 DICI	REEV80 CI*	BEV	FCEV	REEV80 FC**
Gasoline	blue	blue		blue		blue	blue					
Gasoline E20 market blend	gray	gray		gray		gray	gray					
Gasoline E20 high RON	blue	blue		blue		blue	blue					
Diesel			blue		blue			blue	red			
Diesel B7 market blend			gray		gray			gray	gray			
LPG	blue	blue										
CNG	blue	blue										
E85	blue	blue		blue		blue	blue					
FAME			gray		gray			gray	gray			
DME			gray									
FT-Diesel			gray		gray			gray	gray			
HVO			gray		gray			gray	gray			
Electricity						blue	blue	blue	red	blue		red
Hydrogen (CGH2)											blue	red
Hydrogen (cCGH2)											blue	red

3.4 xEV operation

3.4.1 xEV functionalities

xEV configurations include a control unit which drives the operational strategy for all actively controlled powertrain components such as ICE, E-Machines and Fuel Cell. Such a control unit is covered in the vehicle simulation and includes charge depleting and charge sustaining phases separately. All xEV functionalities, that are included in the current TTW study, are described in the following sections.

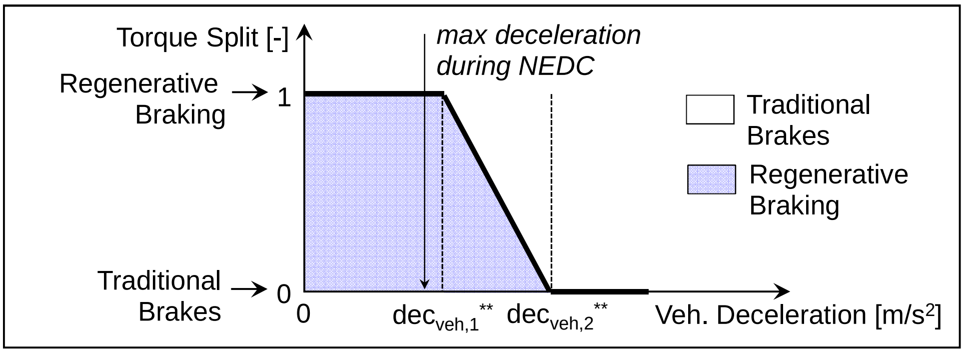
3.4.1.1 Start & Stop

In order to avoid the operation at ICE idle, the ICE is switched-off in case of vehicle standstill. The Start & Stop feature is active, if the ICE temperature is above a certain limit, and if no Battery charging demand is given due to low battery SOC.

3.4.1.2 Regenerative braking

Regenerative Braking is applied in situations where the driver requires negative traction power. In case of the HEV and PHEV configurations, during these phases the ICE is disengaged by opening its separation clutch and, in case of warm condition, it is switched-off.

Figure 3-6: xEV functionalities: regenerative braking



For safety and comfort reasons, traditional brakes are enabled during severe decelerations. Two parameters “decVeh,1” and “decVeh,2” define the linear transition between only regenerative braking (i.e. torque split equal to 1) and only traditional brakes (refer to ***Figure 3-6***). Due to limited deceleration in NEDC no restriction in regenerative braking is observed in general.

3.4.1.3 ICE / fuel cell off mode

ICE / Fuel Cell Off Mode (in public also known as “electric driving”) is applied to avoid low-efficiency operating points of the ICE (in HEV, PHEV and REEV configurations) or the Fuel Cell (in FCEV and REEV FC configurations), if enough Battery energy is available to drive the vehicle. This mode is typically selected in case of low driving power request.

3.4.1.4 ICE / fuel cell load point moving

ICE / Fuel Cell Load Point Moving (LPM) is applied to shift the operation of the ICE / Fuel Cell towards better efficiency conditions, and to increase the reserve of available energy in the Battery to be exploited e.g. during ICE / Fuel Cell Off Mode. The ICE / Fuel Cell LPM is typically activated at intermediate driving power request, if the ICE / Fuel Cell Off Mode is disabled.

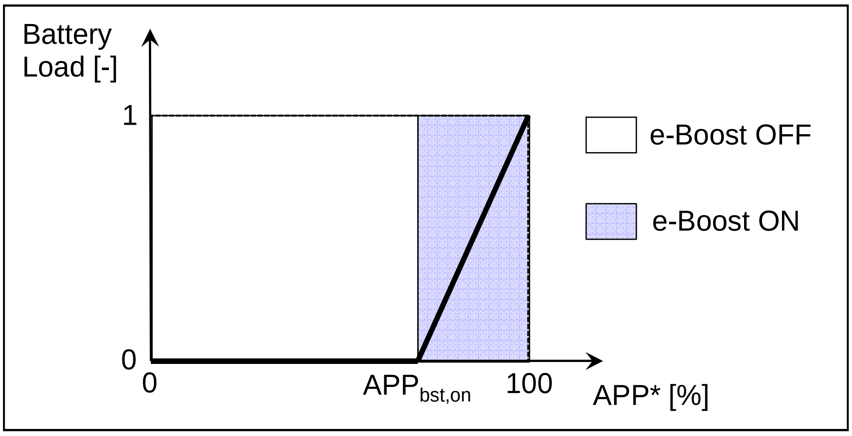
3.4.1.5 ICE / fuel cell alone mode

ICE / Fuel Cell Alone Mode is mainly applied in case the ICE / Fuel Cell works at high efficiency. This strategy implies no usage of the energy reserve of the battery.

3.4.1.6 Battery assistance

Battery Assistance (also called e-Boost) is applied to support the full load driving performance of the vehicle, if enough Battery energy is available.

Figure 3-7: xEV functionalities: battery assistance



This mode is linearly enabled, starting from a calibration limit in the Acceleration Pedal Position (APP) close to 100% (APPbst,on in ***Figure 3-7***). This function is not active during the NEDC. However, it is necessary to properly assess the full load driving performance of the vehicle, e.g. to meet the performance criteria.

3.4.2 xEV operational strategies

The xEV configurations considered in this study feature the operational strategies defined in ***Table 3-7***. Regarding the BEV, the ICE / Fuel Cell Off Mode indicates the operation, in which the vehicle produces positive traction power supported by the battery as the only available power source.

Table 3-7: Overview of the xEV operational strategies implemented

xEV operational strategies	HEV	PHEV	REEV	BEV	REEV FC	FCEV
Start & Stop	✓	✓				
Regenerative Braking	✓	✓	✓	✓	✓	✓
ICE / Fuel Cell Off Mode	✓	✓	✓		✓	✓
ICE / Fuel Cell Load Point Moving	✓	✓	✓		✓	✓
ICE / Fuel Cell Alone Mode	✓	✓	✓		✓	✓
Battery Assistance	✓	✓	✓		✓	✓

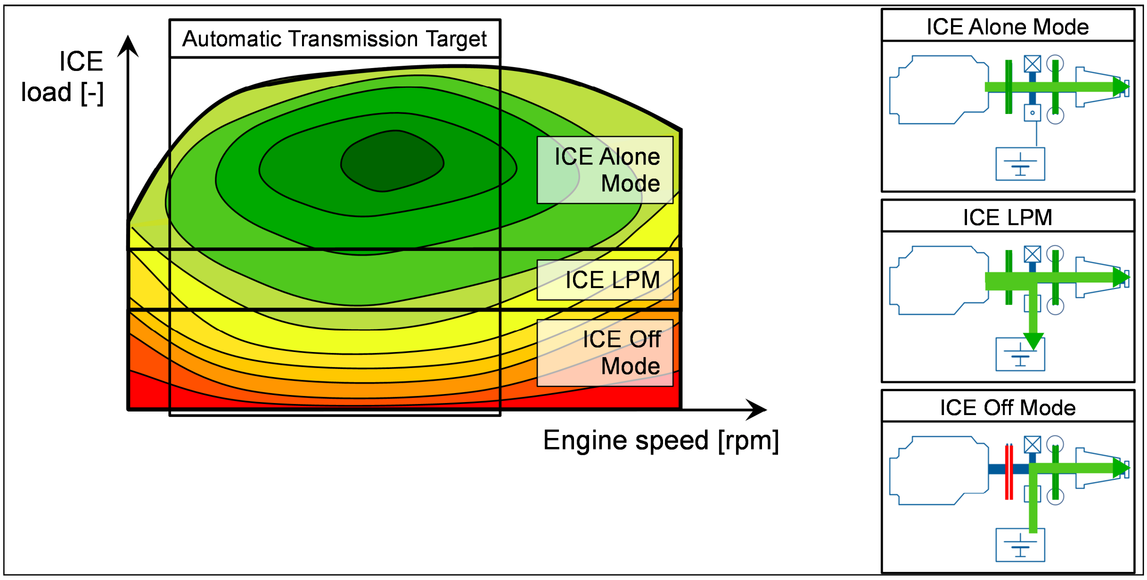
Concerning Start-Stop, Regenerative Braking and Battery Assistance, their activation is a straightforward consequence of the driver behaviour and the actual vehicle status: Stop-Start is activated, if the vehicle is at standstill and the ICE temperature is above a certain limit. Regenerative braking is activated in case of a negative torque request by the driver. Battery Assistance is activated in case of a full load request of the driver.

In case of the other operational strategies a detailed study was carried on, based on AVL experience, in order to optimize the energy management of the xEV powertrains. The following sections give a general overview of the methodologies adopted.

3.4.2.1 HEV and PHEV

ICE Off Mode is applied in case of available battery energy, to avoid low efficiency operation of the ICE. In particular it is applied in case of low vehicle velocity if the required traction torque is lower than a calibrated threshold (***Figure 3-8***).

Figure 3-8: xEV operational strategies: HEV and PHEV



ICE Load Point Moving is activated in case the ICE Off Mode is disabled and the required traction torque is lower than a calibrated threshold. The ICE torque is defined by the following equation:

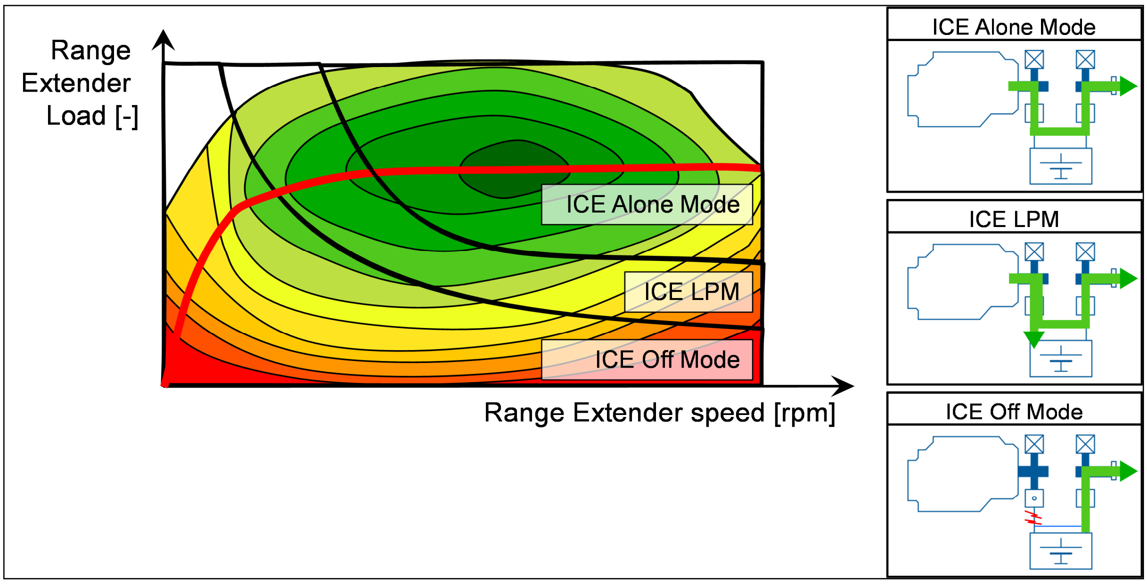
$$Tq_{ICE} = Tq_{req} + \Delta T_{LPM}$$

where Tq_{req} is the traction torque required at the ICE crankshaft for driving, and ΔT_{LPM} is the additional (calibrated) torque to increase the load of the ICE accordingly (***Figure 3-8***). The ICE Alone Mode is applied otherwise, in case of low specific fuel consumption operation of the ICE. In case of the PHEV, due to the Plug-In feature, two different calibrations of the operational strategy are required to simulate both the charge depleting and the charge sustaining phase.

3.4.2.2 REEV

The Range Extender Electric Vehicle features a Series Hybrid powertrain layout, where the speed and load of the ICE are independent from the driving conditions. Therefore the Range Extender module (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 ICE Off Mode is applied, in case of available Battery energy, to avoid low efficiency operation of the ICE. In particular it is applied in case of low vehicle velocity if the required electric power is lower than a calibrated threshold (***Figure 3-9***).

Figure 3-9: xEV operational Strategies: REEV



The ICE Load Point Moving is activated in case the ICE Off Mode is disabled and the required electric power is lower than a calibrated threshold. The Range Extender electric power is defined by the following equation:

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

Where $P_{req,el}$ 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 (***Figure 3-9***). The ICE Alone Mode is applied otherwise, in case of low specific fuel consumption operation of the range extender. Due to the Plug-In feature of the REEV, two different calibrations of the operational strategy are required to simulate both the charge depleting and the charge sustaining phase.

3.4.2.3 FCEV and REEV FC

The operational strategy for Fuel Cell driven configurations 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 (***Table 3-8***), with Popt and k as calibration parameters[6].

Table 3-8: xEV operational strategies: FCEV and REEV FC

Demanded Power / SOC	**< P_{opt}**	**> P_{opt}**
< SOC_{min}	$P_{fc} = P_{opt}$	$P_{fc} = P_{req}$
> SOC_{min}	$P_{fc} = 0$	$P_{fc} = k \cdot P_{req}$

[6] The operating strategy implemented in the FCEV and REEV FC is based on the “Load Follower Energy Management Strategy” extracted by the paper “Prasada Rao Akula, Lakshmi Jandhyala, Frieder Herb, Akash Narayana, Development of Energy Management Strategies and Analysis with Standard Drive Cycles for Fuel Cell Electric Vehicles, SAE International, 2012”

Herein $P_{fc}=P_{opt}$ and $P_{fc}=kP_{req}$ represent the "Fuel Cell Load Point Moving" functionality, $P_{fc}=0$ represents the "Fuel Cell Off" mode, and $P_{fc}=P_{req}$ represents the "Fuel Cell Alone" mode. In the case of the REEV FC, due to its Plug-In feature, two different calibrations of the operational strategy are required to simulate both the charge depleting and the charge sustaining phase.

4 Simulation Methodology

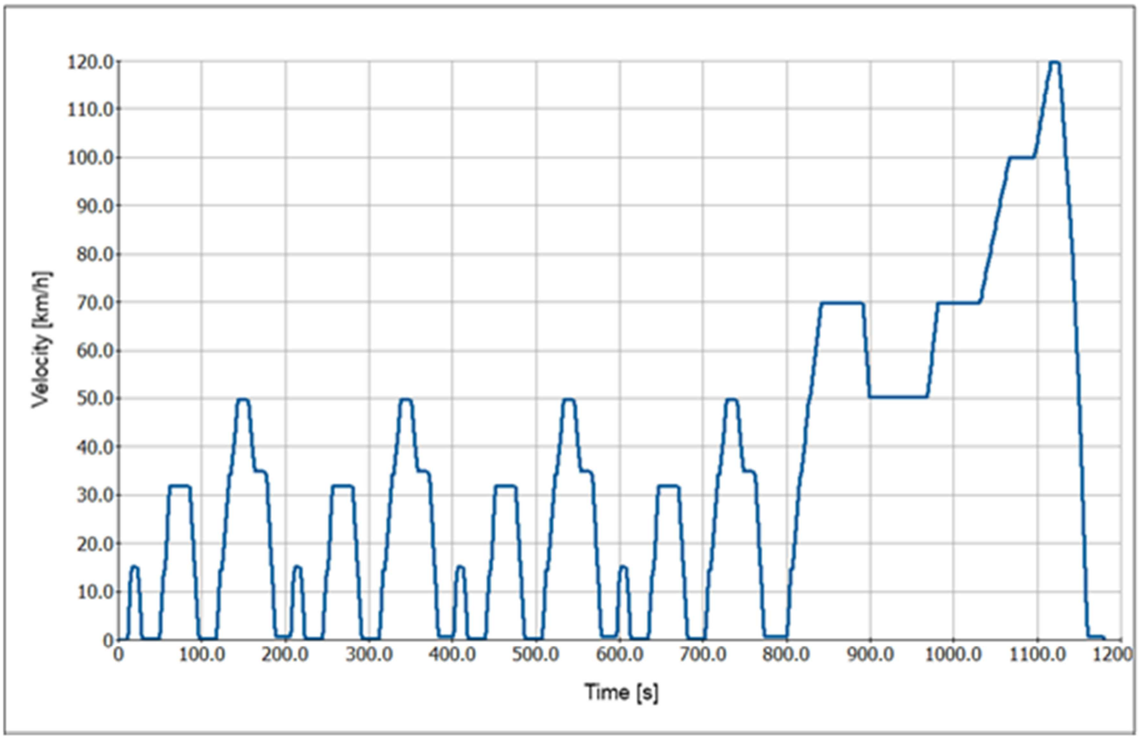
4.1 AVL CRUISE as simulation environment

AVL CRUISE is a 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. As a frequently used vehicle and powertrain 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 cycle & constraints

4.2.1 NEDC

Figure 4-1: Velocity profile of the New European Driving Cycle (NEDC)



The New European Driving cycle (NEDC) is defined in the European legislation (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 in test driving. Gear changes for conventional vehicle configurations with manual transmission (MT5 or MT6) are defined by legislation, whereas gear changes for xEV vehicles with automatic transmission are chosen due to shifting strategies based on the specific xEV control.

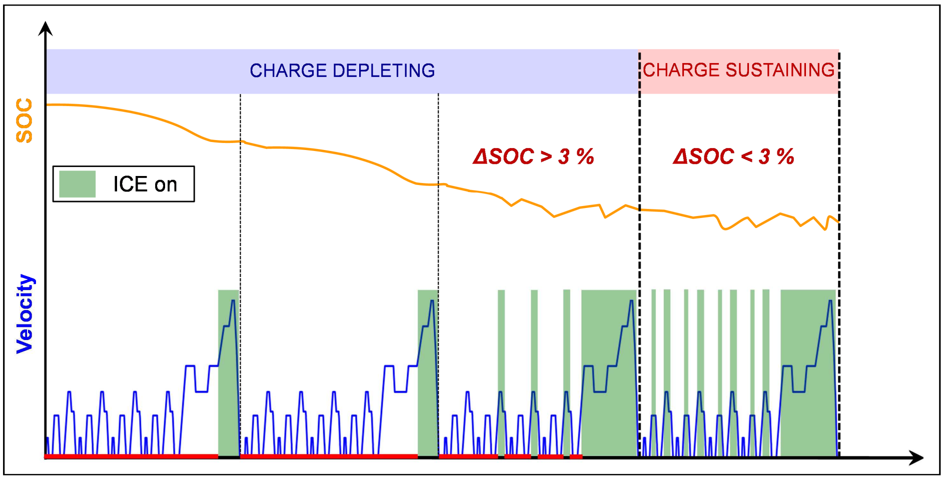
Shift indication, although showing relatively high fuel reduction potentials in conventional MT powertrains, is not considered in the current study in correlation to the actually existing NEDC related Homologation procedures. In this Homologation procedure the Inertia Test Weight (ITW) classes are defined for dynamometer measurements. However in the current TTW analysis the calculation of NEDC fuel consumption is done based on the actual vehicle weight instead of using the ITW classes: This measure allows showing the fuel consumption impacts of variable powertrain component masses in the different vehicle configurations in a more particular resolution.

To ensure comparability of results for 2010 and 2020+ configurations the NEDC is used as the reference driving cycle in general. It is expected, that by 2020+ the Worldwide harmonized Light vehicles Test Procedure (WLTP) will be an obligation in terms of vehicle fuel consumption and emission testing, whether in parallel to or instead of the NEDC. However at the time of elaboration of this study the WLTP is still not clearly defined in all its details. Therefore, it could not be used for the investigation in the current version of the TTW study.

Evaluation of PHEV & REEV

The European Legislation UN ECE R 101 (Rev 2) considers the following rule for evaluation of the fuel consumption ($FC_{Cert.}$) of a PHEV with intermittent ICE operation, which is based on the weighting of Charge Depleting (CD) and Charge Sustaining (CS) operation modes partial results:

Figure 4-2: Evaluation of a PHEV fuel consumption based on the UN ECE R 101 (Rev 2)



$$FC_{Cert.} = \frac{D_{ovc} \cdot FC_{ovc} + 25 \cdot FC_{CS}}{D_{ovc} \cdot + 25}$$

where:

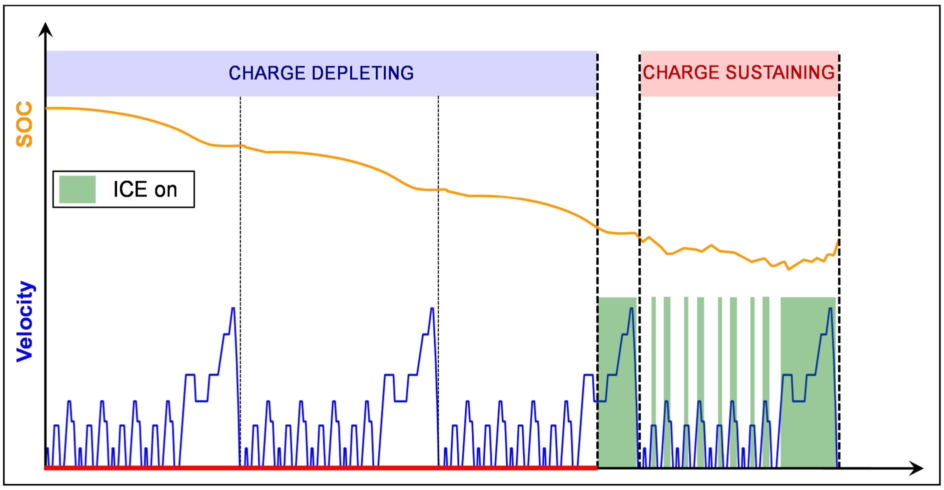
FC_{OVC}: Fuel Consumption during Charge Depleting

FC_{CS}: Fuel Consumption during Charge Sustaining

D_{OVC}: Total electric Range during Charge Depleting (marked in red)

The European Legislation UN ECE R 101 (Rev 2) considers the following rule for evaluation of the fuel consumption ($FC_{Cert.}$) of a REEV without intermittent ICE operation, which is based on the weighting of Charge Depleting (CD) and Charge Sustaining (CS) operation modes partial results:

Figure 4-3: Evaluation of a REEV fuel consumption based on the UN ECE R 101 (Rev 2)



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

where:

FC_{CD}: Fuel Consumption during Charge Depleting

FC_{CS}: Fuel Consumption during Charge Sustaining

D_e: All Electric Range (marked in red)

For both PHEV and REEV the corresponding result for electric energy consumption based on the European Legislation UN ECE R 101 (Rev 2) is calculated via the same weighting equation, if the fuel consumption (CD, CS and overall) in each equation is simply replaced by the corresponding electric energy consumption values.

4.2.2 Performance tests

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

- Full Load Acceleration from 0 to 100 km/h
- Elasticity[7] from 80 to 120 km/h
- Vehicle Top Speed
- Gradeability @ 1 km/h
- Gradeability @ 10 km/h

[7] Elasticity, i.e. the time needed to accelerate from 80 to 120 km/h. The vehicle is driven in the second highest gear in case of Manual Transmissions, and according to the corresponding shifting strategies in case of Automatic Transmissions.

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. Data include efficiencies of the main powertrain components ICE, transmission, E-Machine and Battery in various different layouts. ICE maps are defined based on stationary fuel consumption maps for hot ICE condition. The NEDC cold start fuel consumption is modelled based on the AVL CRUISE standard semi-empirical 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 (Friction Mean Effective Pressure) at cold temperature. Corresponding ICE thermal model calibration is done based on AVL database, and the main effects of ICE electrification e.g. like Start-Stop or an improved ICE thermal management are taken into account. The NEDC hot start fuel consumption results (not considered in detail in this study) are 8.0 to 11.9% lower than the corresponding cold start fuel consumption results.

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

4.3.2 xEV control logic

xEV configurations in general include a control unit which steers the torque split and operational strategies of all actively controlled powertrain components. Such a control unit is also covered in vehicle simulation including CD and CS phases separately. Battery State-Of-Charge (SOC) is ensured to be balanced for all CS operation modes in HEV, PHEV and REEV. The control unit is modelled for all xEV configurations in AVL CRUISE based on C-code programming and a basic control function calibration. The following xEV functionalities are included for 2010 and 2020+ vehicles in the current TTW study:

- Start & Stop
- Regenerative Braking
- Battery powered driving
- Load Point Moving
- Boost

These functionalities are explained and defined for the specific xEV configurations in detail in chapters 5 and 6.

4.3.3 Evaluation of GHG emission

The total Tank-to-Wheel GHG emissions are evaluated referring to CO_2 exhaust emissions on the one hand and CH_4 and N_2O exhaust emissions on the other hand[8]. CO_2 emissions are calculated directly in AVL CRUISE and derived from the fuel consumption results through the fuel specific CO_2 emission factors. CH_4 and N_2O emissions are assessed based on the legislation limits for Euro 5 and Euro 6 employed in case of 2010 and 2020+ vehicle configurations, respectively. The defined percentages of

[8] Issues related to fuel production and provision is covered in the Well-to-Tank report (WTT) of the study.

the N_2O over the total NO_x emission limit and the CH_4 over the Total Hydro Carbon (THC) emission limit, respectively, are reported in ***Table 4-1***[9]. The resulting CO_2 equivalent emissions of Methane (CH_4) and Nitrous Oxide (N_2O) are derived based on their Global Warming Potential (GWP) factor, which is the parameter that considers the GHG effect of the specific gas. This factor is equal to 25 for Methane and 298 for Nitrous Oxide[10]. The following equations are evaluated in ***Table 4-1*** for the CO_2-equivalent emissions due to N_2O and CH_4 contributions:

$$CO_{2eq}(CH_4)[gCO_{2eq}/km] = THC_{EL} \bullet CH_4\text{-}\% \bullet GWP_{CH4}$$

$$CO_{2eq}(N_2O)[gCO_{2eq}/km] = NOx_{EL} \bullet N_2O\text{-}\% \bullet GWP_{N2O}$$

where:

NOx_{EL}, THC_{EL}: EURO 5 & 6 legislation limits in terms of NO_x and THC emissions

N_2O-%: percentages of N_2O from the total NO_x emission limit

CH_4-%: percentages of CH_4 from the total THC emission limit

GWPx: Global Warming Potential factor of molecule x

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

2010		EURO 5 limit THC or NOx [mg/km]	Percentage (N_2O or CH_4)	GWP [-]	$CO_{2\text{-}eq}$ GHGs [g/km]	2020+		EURO 6 limit THC or NOx [mg/km]	Percentage (N_2O or CH_4)	GWP [-]	$CO_{2\text{-}eq}$ GHGs [g/km]
CH4	Gasoline	100	10%	25	0.25	CH4	Gasoline	100	10%	25	0.25
	LPG	100	10%	25	0.25		LPG	100	10%	25	0.25
	CNG	100	60%	25	1.50		CNG	100	45%	25	1.13
	Diesel	50	10%	25	0.13		Diesel	90	10%	25	0.23
N2O	Gasoline	60	2%	298	0.36	N2O	Gasoline	60	3%	298	0.54
	LPG	60	2%	298	0.36		LPG	60	3%	298	0.54
	CNG	60	2%	298	0.36		CNG	60	3%	298	0.54
	Diesel	180	2%	298	1.07		Diesel	80	5%	298	1.19

In case of fully electrified vehicles (BEV, FCEV and REEV FC), no CO_2, Methane or Nitrous Oxide is released. In case of xEV configurations 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, the following weighting equation is used therefore:

$$CO_{2,eq} = \frac{D_e \cdot CO_{2,eq,CD} + 25 \cdot CO_{2,eq,CS}}{D_e + 25}$$

where:

$CO_{2,eqCD}$: CO_2 equivalent emissions in Charge Depleting

$CO_{2,eqCS}$: CO_2 equivalent emissions in Charge Sustaining

D_e: All Electric Range

[9] Data for the GHG evaluations are partially taken from the "INGAS" project: http://www.ingas-eu.org

[10] 2007 IPCC Fourth Assessment Report (AR4): the activities of the Working Group 1 (WG1) and Chapter 2 of that report (Changes in Atmospheric Constituents and Radiative Forcing) http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf

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 e.g. vehicle mass, driving resistance or performance criteria are not considered to have any impact to the estimated errors. Due to the complexity of the analyzed systems, the chosen approach of error assessment is to isolate the subsystems responsible for the total Tank-to-Wheel CO_2 emissions, which in case of conventional vehicles lead to:

$$CO_2\left[\frac{g_{CO2}}{km}\right] = EF \cdot \int \frac{P_{veh} \cdot BSFC}{\varepsilon_{dr}} dt$$

where:

CO_2: Tank-to-Wheels CO_2 emissions

EF: Specific CO_2 Emission Factor

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 of the Tank-to-Wheel CO_2 emissions are defined by the following equation for conventional configurations:

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

where:

$Err(P_{VEH})$: 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 configurations (HEV, PHEV, REEV, BEV, FCEV and REEV FC) derives:

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

where:

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

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

c_{xx}: Weighting factors of the different driving phases

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

- 2020+ configurations are characterized by an increased error (3 – 6%) with respect to 2010 configurations, due to the uncertain forecast of the technological development

- In conventional vehicles the main inaccuracy is due to 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 3.5 – 5% for 2010 configurations, and 5.8 – 9.8% for 2020+ configurations.

- Partially electrified vehicles (HEV, PHEV and REEV) are characterized, on average, by higher uncertainty due to their higher complexity. The resulting overall error is in the range of 5.2 – 6.7% for 2010 configurations, and 9.1 – 12.9% for 2020+ configurations.

- The considered Battery Electric Vehicles are lean systems (unique power source and single gear transmission) and the components are characterized by a high-level simulation approach. A good confidence follows in the case of the 2010 configuration (3% of error). 2020+ configurations are characterized by a higher error (7.2%) due to the uncertain evolution of future Li-Ion battery technology development.

- The FCEV and, even more, the REEV FC show a lower technological maturity. The resulting errors are high in both 2010 (6.5%) and 2020+ configurations (10.1 – 11.9%)

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

5 2010 Vehicle Configurations & Results

5.1 Vehicle configurations

In the following the 2010 conventional as well as electrified vehicle configurations are described in detail regarding their main component specifications. In terms of definition of the components technologies for 2010 a range from approximately 2008 up to 2012 is considered to represent today's state of the art in automotive industry in a more general way. 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 are given in chapter 3.

5.1.1 Simulation parameter & main data

Table 5-1: Mass balance for "ICE only" configurations 2010

Mass balance for "ICE only" Variants 2010		PISI			DISI			DICI	
		Gasoline[1]	LPG (bi-fuel)	CNG (mono-fuel)	Gasoline[1]	LPG (bi-fuel)	CNG (mono-fuel)	Diesel[2]	DME (bi-fuel)
Powertrain									
ICE mass	kg	135	135	135	145	145	145	165	165
Transmission mass	kg	50	50	50	50	50	50	50	50
Powertrain mass change	*kg*	*Reference*	*0*	*0*	*Reference*	*0*	*0*	*Reference*	*0*
Storage System									
Fuel Tank Capacity	L	55	80 + 55	150 + 14	55	80 + 55	150 + 14	55	80 + 55
Tank System mass	kg	15	50	160	15	50	160	15	50
Fuel mass	kg	41	76	36	41	76	36	46	89
Storage System mass change	*kg*	*Reference*	*+70*	*+140*	*Reference*	*+70*	*+140*	*Reference*	*+78*
Vehicle									
Curb weight (incl. driver, 90% fuel)	**kg**	**1300**	**1370**	**1440**	**1310**	**1380**	**1450**	**1370**	**1448**
Reference mass for ITW	kg	1325	1395	1465	1335	1405	1475	1395	1473
ITW Class	kg	1360	1360	1470	1360	1360	1470	1360	1470
Performance mass	**kg**	**1425**	**1495**	**1565**	**1435**	**1505**	**1575**	**1495**	**1573**
Payload	kg	600	530	460	590	520	450	530	452
Gross vehicle mass	**kg**	**1900**	**1900**	**1900**	**1900**	**1900**	**1900**	**1900**	**1900**

1) Same vehicle mass is assumed for the different fuel variants Gasoline, Gasoline E10 market bl., Gasoline E20 High RON & E85.
2) Same vehicle mass is assumed for the different fuel variants Diesel, Diesel B7 market blend, FAME, FT-Diesel & HVO.

Table 5-2: Mass balance for xEV Configurations 2010

Mass balance for xEV Variants 2010		**DISI ("ICE only")**	**Hybrid DISI**	**PHEV20 DISI**	**REEV80 SI**	**BEV**	**FCEV**	**DICI ("ICE only")**	**Hybrid DICI**	**PHEV20 DICI**
		Gasoline[1]	Gasoline[1]	Gasoline[1]	Gasoline[1]	Electricity	Hydrogen[3]	Diesel[2]	Diesel[2]	Diesel[2]
Powertrain										
ICE mass	kg	145	145	145	135	0	0	165	165	165
Transmission mass	kg	50	80	80	10	10	10	50	80	80
Powertrain mass change	*kg*	*Reference*	*+30*	*+30*	*-50*	*-185*	*-185*	*Reference*	*+30*	*+30*
Fuel Cell										
Fuel cell module mass[5]	kg	#	#	#	#	#	167	#	#	#
Electric Components										
eMachine mass[4]	kg	#	32	44	76	76	72	#	32	44
Generator (2nd eMachine) mass[4]	kg	#	#	#	42	#	#	#	#	#
Battery mass[4]	kg	#	34	80	165	200	34	#	34	80
xEV wiring harness mass	kg	#	11	15	20	20	20	#	11	15
eComponents mass change	kg	*Reference*	*+77*	*+139*	*+303*	*+296*	*+126*	*Reference*	*+77*	*+139*
Storage System										
Fuel Tank Capacity	L	55	55	55	35	0	#	55	55	55
Tank System mass	kg	15	15	15	15	0	92	15	15	15
Fuel mass	kg	41	41	41	26	0	4	46	46	46
Storage System mass change	*kg*	*Reference*	*0*	*0*	*-15*	*-56*	*+40*	*Reference*	*0*	*0*
Vehicle										
Curb weight (incl. driver, 90% fuel)	**kg**	**1310**	**1417**	**1479**	**1548**	**1365**	**1458**	**1370**	**1477**	**1539**
Reference mass for ITW	kg	1335	1442	1504	1573	1390	1483	1395	1502	1564
ITW Class	kg	1360	1470	1470	1590	1360	1470	1360	1470	1590
Performance mass	**kg**	**1435**	**1542**	**1604**	**1673**	**1490**	**1583**	**1495**	**1602**	**1664**
Payload	kg	590	483	421	352	535	442	530	423	361
Gross vehicle mass	**kg**	**1900**	**1900**	**1900**	**1900**	**1900**	**1900**	**1900**	**1900**	**1900**

1) Same vehicle mass is assumed for the different fuel variants Gasoline, Gasoline E10 market bl., Gasoline E20 High RON & E85.
2) Same vehicle mass is assumed for the different fuel variants Diesel, Diesel B7 market blend, FAME, FT-Diesel & HVO.
3) Same vehicle mass is assumed for both Hydrogen Variants (CGH2 & cCGH2).
4) Masses for e-components include housing, power electronics and cooling system.
5) Mass of Fuel Cell module includes the whole system.

A DC/DC converter for LV power supply is included in all relevant xEV components masses in terms of weight; however DC/DC losses are omitted in the system efficiency chain for all xEV configurations due to negligible impact on results.

Auxiliaries – status of electrification 2010:

- Steering Pump: HPS (Hydraulic Power Steering) for Conventional ("ICE only") configurations, EHPS (Electro-Hydraulic Power Steering) for xEV configurations
- Brake Vacuum Pump: Mechanical for conventional configurations (for PISI not required), electrified for xEV configurations
- Water Pump: Mechanical (not controlled) for conventional configurations, electrified for xEV configurations
- (ICE) Oil Pump: Mechanical for all configurations
- (Transmission) Oil Pump: Only needed for xEV Configurations (due to AT), electrified

5.1.2 ICE specifications

The RON for the Gasoline blends and CN for Diesel B7 are defined in the fuel properties table (***Table 3-1***). However in market fuels these numbers could vary in a certain range of a few numbers. Such RON / CN variations for fuels (e.g. Gasoline E20 RON range of 99-102) 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 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 2010 configurations comply with the legislative emissions standards for EURO 5. In addition, electrification is considered as an Add-On technology for 2010 xEV configurations in general, therefore no adaptions (e.g. ICE downsizing) are made for the 2010 xEV ICEs in relation to the conventional ICE definitions.

Table 5-3: Gasoline ICE specifications for 2010 configurations with (standard) gasoline fuel

AVL Gasoline ICE Variants Specifications by AVL		Gasoline ICE Variants 2010				
		PISI ("ICE only")	DISI ("ICE only")	Hybrid DISI	PHEV20 DISI	REEV80 SI
ICE Type / Technology	---	- MPI - NA	- TGDI ICE - IVVT			- NA - High-expansion Atkinson Cycle - VVT-i - Cooled EGR
Displacement	L	1.4	1.4			1.4
No. of Cylinders	---	IL4	IL4			IL4
Specific power	kW / L	~64	~64			~39
Maximum Power	kW @ rpm	90 @ 5750	90 @ 4300			55 @ 5500
Maximum Torque	Nm @ rpm	158 @ 3500	200 @ 1750 - 4000			110 @ 4000
Maximum Speed	rpm	6250	4800			6000
Idle Speed	rpm	700	750			800
BSFC @ 2000 rpm / 2 bar	g/kWh	380 - 385	370 - 375			~350
BSFC minimum	g/kWh	240	235			~235

Table 5-4: Diesel ICE specifications for 2010 configurations with (standard) diesel fuel

AVL Diesel ICE Variants Specifications by AVL		Diesel ICE Variants 2010			
		DICI ("ICE only")	Hybrid DICI	PHEV20 DICI	REEV80 CI
ICE Type / Technology	---	- Common Rail with1800 bar, solenoid injector - High pressure EGR - VGT Turbocharger - Closed coupled DOC-DPF			No REEV80 CI Variant for 2010
Displacement	L	1.6			
No. of Cylinders	---	4			
Specific power	kW / L	~55			
Maximum Power	kW @ rpm	88 @ 4000			
Maximum Torque	Nm @ rpm	285 @ 1750 –2750			
Maximum Speed	rpm	4500			
Idle Speed	rpm	780			
BSFC @ 2000 rpm / 2 bar	g/kWh	280 - 285			
BSFC minimum	g/kWh	205			

Table 5-5: PISI ICE specifications for 2010 configurations with alternative fuels

AVL Gasoline ICE Variants Specifications by AVL		PISI ICE 2010 for "ICE only" Variants				
		Gasoline	E20 high RON	E85	LPG	CNG
ICE Type / Technology	---	- MPI - NA			LPG ICE - MPI - NA	CNG ICE - MPI - NA
Displacement	L	1.4			1.46	1.72
No. of Cylinders	---	IL4				
Specific power	kW / L	~64			~64	~57
Maximum Power	kW @ rpm	90 @ 5750			94 @ 5750	99 @ 5750
Maximum Torque	Nm @ rpm	158 @ 3500			160 @ 3500	170 @ 3500
Maximum Speed	rpm	6250				
Idle Speed	rpm	700				
BSFC @ 2000 rpm / 2 bar	g/kWh	380 - 385	414	560	357 ≙ ~375 Gasoline equivalent	355 ≙ ~375 Gasoline equivalent
BSFC minimum	g/kWh	240	251	340	217 ≙ ~231 Gasoline equivalent	216 ≙ ~228 Gasoline equivalent

Table 5-6: DISI ICE specifications for 2010 configurations with alternative fuels

AVL Gasoline ICE Variants Specifications by AVL		DISI ICE 2010 for "ICE only", Hybrid & PHEV20 Variants				
		Gasoline	E20 high RON	E85	LPG[1]	CNG[1]
ICE Type / Technology	---	- TGDI ICE - IVVT			LPG ICE - Turbo - MPI - IVVT	CNG ICE - Turbo - MPI - IVVT
Displacement	L	1.4			1.46	1.55
No. of Cylinders	---	IL4				
Specific power	kW / L	~64			~64	~64
Maximum Power	kW @ rpm	90 @ 4300			94 @ 4300	99 @ 4300
Maximum Torque	Nm @ rpm	200 @ 1750 - 4000			210 @ 1750 - 4000	220 @ 1750 - 4000
Maximum Speed	rpm	4800				
Idle Speed	rpm	750				
BSFC @ 2000 rpm / 2 bar	g/kWh	370 - 375	401	540	346 ≙ ~369 Gasoline equivalent	344 ≙ ~363 Gasoline equivalent
BSFC minimum	g/kWh	235	239	322	210 ≙ ~224 Gasoline equivalent	205 ≙ ~215 Gasoline equivalent
1) LPG & CNG fuel is only used for the "ICE only" variant.						

5.1.3 xEV specifications

Table 5-7: xEV components' specifications: overview of xEV 2010 configurations

Variant	Component	Specific	Unit	Requirements to meet the performance criteria	Value*
HEV	Electric Machine	Power	kW	*Complete regenerative braking during the NEDC*	**24** (12)
		Torque	Nm	*Complete regenerative braking during the NEDC*	**160** (80)
	Li-Ion Battery Pack	Power	kW	*Required electric power from/to the electric machine*	**30**
		Energy	kWh	*Along the NEDC, complete regenerative braking and a lifetime of at least 160000 km*	**1.4** (0.4)
PHEV	Electric Machine	Power	kW	*Electric drive up to 100 km/h: continuously, during the NEDC (continuous P and Tq) occasionally, during high demanding transients (peak P & Tq): Artemis Cycles as driving reference*	**40** (20)
		Torque	Nm		**190** (100)
	Li-Ion Battery Pack	Power	kW	*Required electric power from/to the electric machine*	**50**
		Energy	kWh	*Along the NEDC, 20 km of All Electric Range and a lifetime of at least 160000 km*	**3.7** (2.1)
REEV	Electric Machine	Power	kW	*Maximum Speed => Continuous Power Acceleration and Elasticity => Peak Power Gradeability 20% => Continuous Torque Gradeability 30% => Peak Torque*	**90** (45)
		Torque	Nm		**280** (180)
	Generator	Power	kW	*Guarantees the continous power required by the electric machine*	**57** (57)
		Torque	Nm	*Suitable coupling with the ICE*	**114** (114)
	Li-Ion Battery Pack	Power	kW	*Required electric power from/to the electric machine during charge depleting and high demanding transients of charge sustaining*	**100**
		Energy	kWh	*Along the NEDC, 80 km of All Electric Range and a lifetime of at least 160000 km*	**14.9** (11.2)
BEV	Electric Machine	Power	kW	*Maximum Speed => Continuous Power Acceleration and Elasticity => Peak Power Gradeability 20% => Continuous Torque Gradeability 30% => Peak Torque*	**90** (45)
		Torque	Nm		**280** (180)
	Li-Ion Battery Pack	Power	kW	*Required electric power from/to the electric machine*	**> 100**
		Energy	kWh	*Along the NEDC, 120 km (2010) or 200 km (2020) of All Electric Range and a lifetime of at least 160000 km*	**17.8** (14.2)
FCEV	Electric Machine	Power	kW	*Maximum Speed => Continuous Power Acceleration and Elasticity => Peak Power Gradeability 20% => Continuous Torque Gradeability 30% => Peak Torque*	**85** (60)
		Torque	Nm		**280** (195)
	Fuel Cell System	Power	kW	*To supply the required power to the electric machine. Demanding transients require the battery support (top speed: 180 km/h)*	**70**
	Li-Ion Battery Pack	Power	kW	*Required electric power from/to the electric machine*	**30**
		Energy	kWh	*Along the NEDC, complete regenerative braking and a lifetime of at least 160000 km*	**1.4** (0.6)

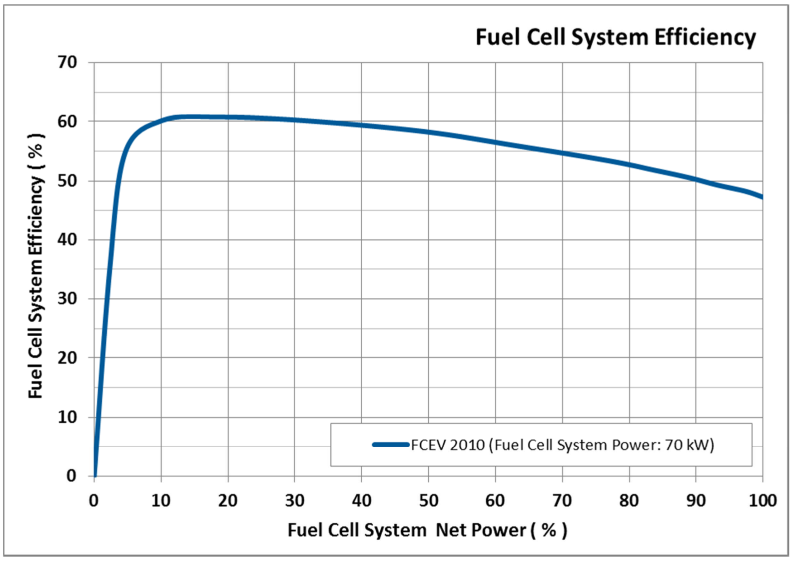
**) Electric Machine, Generator, Fuel Cell System: The values show the peak and (in parenthesis) the continuous power and torque; Li-Ion Battery Pack: The values show the total and (in parenthesis) the available energy*

The xEV components specifications of the 2010 configurations were designed and optimized in correlation to the given boundary conditions and vehicle minimum performance criteria of the current TTW study.

Table 5-7 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 available energy (in parenthesis) is outlined.

Figure 5-1 shows the Fuel Cell System Efficiency characteristic for the FCEV configuration 2010. The efficiency was obtained by input from several EUCAR members based on available technologies used in demonstration vehicles. For better comparability of the FC characteristic with 2020+ configurations the characteristic is given in percent of the Fuel Cell System maximum power.

Figure 5-1: Fuel Cell System Efficiency of FCEV Configuration 2010



Impacts of FC cooling pump losses and other FC related ancillaries are included in the FC system efficiencies. For 2010 the FC system is assumed to have its own cooling system (showing a slightly reduced FC system efficiency), whereas for 2020+ the FC system cooling is integrated into the cooling system of the vehicle. The FC module in the FCEV and REEV FC (for 2020+ configurations) 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.

The 2010 BEV E-Machine is oversized in comparison to the 2010 FCEV due to the fact, that for a production related system design xEV components are maintained for different configurations as much as possible; therefore, based on similar performance criteria, REEV80 (SI) and BEV use the same E-Machine, whereas the FCEV needs a different E-Machine due to its different maximum driving velocity criterion (180km/h instead of 130km/h for REEV80 and BEV).

5.2 Simulation results

5.2.1 Results for conventional ("ICE only") configurations

Table 5-8: Simulation results for "ICE only" configurations 2010

2010 VARIANTS	Curb Weight	Fuel Tank Capacity	Fuel Consumption[1]			El. Energy Consumption[1]		GHG emissions[1]			
						w/o charging losses	with charging losses	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L	MJ/100km	l/100km	kg/100km	kWh/100km	kWh/100km	g CO_2 /km	g CO_2 eq/km	g CO_2 eq/km	g CO_2 eq/km
PISI ("ICE only") 2010, MT5											
Gasoline	**1300**	**55**	**211.3**	**6.57**	**4.89**	**#**	**#**	**155.1**	**0.3**	**0.4**	**155.8**
Gasoline E10 market blend	**1300**	**55**	**211.3**	**6.80**	**5.10**	**#**	**#**	**154.8**	**0.3**	**0.4**	**155.5**
Gasoline E20 high RON	**1300**	**55**	**208.6**	**6.95**	**5.25**	**#**	**#**	**152.5**	**0.3**	**0.4**	**153.2**
LPG[2]	**1370**	**80**	**215.7**	**8.53**	**4.69**	**#**	**#**	**141.8**	**0.3**	**0.4**	**142.5**
CNG[3]	**1440**	**150** (25 kg)	**232.3**	**#**	**5.15**	**#**	**#**	**130.7**	**1.5**	**0.4**	**132.6**
E85	**1300**	**55**	**207.1**	**9.04**	**7.10**	**#**	**#**	**148.2**	**0.3**	**0.4**	**148.9**
DISI ("ICE only") 2010, MT6											
Gasoline	**1310**	**55**	**203.8**	**6.33**	**4.72**	**#**	**#**	**149.6**	**0.3**	**0.4**	**150.3**
Gasoline E10 market blend	**1310**	**55**	**203.8**	**6.56**	**4.92**	**#**	**#**	**149.3**	**0.3**	**0.4**	**150.0**
Gasoline E20 high RON	**1310**	**55**	**201.3**	**6.71**	**5.07**	**#**	**#**	**147.2**	**0.3**	**0.4**	**147.9**
LPG[2]	**1380**	**80**	**207.8**	**8.22**	**4.52**	**#**	**#**	**136.6**	**0.3**	**0.4**	**137.3**
CNG[3]	**1450**	**150** (25 kg)	**211.8**	**#**	**4.70**	**#**	**#**	**119.1**	**1.5**	**0.4**	**121.0**
E85	**1310**	**55**	**198.6**	**8.67**	**6.81**	**#**	**#**	**142.1**	**0.3**	**0.4**	**142.8**
DICI ("ICE only") 2010, MT6											
Diesel	**1370**	**55**	**162.5**	**4.53**	**3.77**	**#**	**#**	**119.0**	**0.1**	**1.1**	**120.2**
Diesel B7 market blend	**1370**	**55**	**162.5**	**4.55**	**3.81**	**#**	**#**	**119.3**	**0.1**	**1.1**	**120.5**
FAME	**1370**	**55**	**162.5**	**4.91**	**4.37**	**#**	**#**	**123.8**	**0.1**	**1.1**	**125.0**
DME[4]	**1448**	**80**	**171.8**	**9.02**	**6.04**	**#**	**#**	**115.6**	**0.1**	**1.1**	**116.8**
FT-Diesel	**1370**	**55**	**162.5**	**4.73**	**3.69**	**#**	**#**	**115.1**	**0.1**	**1.1**	**116.3**
HVO	**1370**	**55**	**162.5**	**4.73**	**3.69**	**#**	**#**	**115.1**	**0.1**	**1.1**	**116.3**

1) NEDC Cycle results for cold start condition; Vehicle Test Mass = Curb weight incl. Driver, 90% fuel
2) Bi-valent LPG Vehicle; MPI ICE; ICE Displacement increased to compensate additonal vehicle weight;
3) Mono-valent CNG Vehicle; MPI ICE; ICE Displacement increased to compensate reduced ICE volumetric efficiency & additional vehicle weight;
4) Only theoretical consideration of Bi-valent DME Vehicle - DME is currently not used for PC applications; ICE Displacement increased to compensate add. vehicle weight;

Compared to the results of correlating 2010+ configurations in the Version 3c report the results of 2010 PISI, DISI and DICI conventional configurations in the current study show some specific differences in fuel consumption; these differences are given by the higher ITW class of the C-segment reference vehicle of 1360kg (adding 3.4g CO_2/km relative to the 1250kg ITW class), the different and in general more stringent minimum vehicle performance targets (11s instead of 13s in the Version 3c report), and finally the Start-Stop functionality, which was included in the 2010 conventional vehicle configurations in Version 3c report, but is not considered in the current report. With respect to use of E20 high RON in PISI and DISI, which has not been simulated in the Version 3c report, a benefit of 1% to 2% CO_2 saved compared to Gasoline in PISI/DISI can be observed. This is a conservative result compared to other sources [Thewes 2010][11]. The study identifies a 3.1 % reduction in CO2 emissions for E20 Splash Blend compared to a RON 95 as a consequence of leveraging the higher knock resistance of an E20 Splash Blend (RON 102).

However, all vehicle parameters were chosen in correlation to the current market situation. Additionally the 2010 EU C-segment average is well reflected by the actual results.

[11] M. Thewes et al.: Future Fuels for Modern DISI Engines, in proceedings of the 19th Aachen Colloquium 2010, October 2010, Aachen

5.2.2 Results for xEV configurations

In the following result tables the results for electric energy consumption in case of configurations including a Plug-In feature are always given both with and without consideration of Battery charging losses. In general the legislative regulations in UNECE R101 define, that charging losses are to be included in reference values of electric energy consumption for all Plug-In features vehicle configurations.

5.2.2.1 HEV

Table 5-9: Simulation results for HEV configurations 2010

2010 VARIANTS	Curb Weight	Fuel Tank Capacity	Fuel Consumption[1]			El. Energy Consumption[1]		GHG emissions[1]			
						w/o charging losses	with charging losses	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L	MJ/100km	l/100km	kg/100km	kWh/100km	kWh/100km	g CO_2 /km	g CO_2 eq/km	g CO_2 eq/km	g CO_2 eq/km
Hybrid DISI 2010 (AT6 + TCC)											
Gasoline	**1417**	**55**	**141.7**	**4.44**	**3.28**	**#**	**#**	**104.9**	**0.3**	**0.4**	**105.6**
Gasoline E10 market blend	**1417**	**55**	**141.7**	**4.56**	**3.42**	**#**	**#**	**104.7**	**0.3**	**0.4**	**105.4**
Gasoline E20 high RON	**1417**	**55**	**139.9**	**4.66**	**3.52**	**#**	**#**	**103.1**	**0.3**	**0.4**	**103.8**
LPG	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**
CNG	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**
E85	**1417**	**55**	**138.1**	**6.03**	**4.74**	**#**	**#**	**99.6**	**0.3**	**0.4**	**100.3**
Hybrid DICI 2010 (AT6 + TCC)											
Diesel	**1477**	**55**	**128.0**	**3.60**	**2.97**	**#**	**#**	**94.4**	**0.1**	**1.1**	**95.6**
Diesel B7 market blend	**1477**	**55**	**128.0**	**3.59**	**3.00**	**#**	**#**	**94.6**	**0.1**	**1.1**	**95.8**
FAME	**1477**	**55**	**128.0**	**3.87**	**3.44**	**#**	**#**	**98.2**	**0.1**	**1.1**	**99.4**
DME	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**
FT-Diesel	**1477**	**55**	**128.0**	**3.73**	**2.91**	**#**	**#**	**91.3**	**0.1**	**1.1**	**92.5**
HVO	**1477**	**55**	**128.0**	**3.73**	**2.91**	**#**	**#**	**91.3**	**0.1**	**1.1**	**92.5**

1) NEDC Cycle results for cold start condition; Vehicle Test Mass = Curb weight incl. Driver, 90% fuel

5.2.2.2 PHEV

Table 5-10: Simulation results for PHEV configurations 2010 (according to ECE 101 regulation)

2010 VARIANTS	Curb Weight	Fuel Tank Capacity	Fuel Consumption[1]			El. Energy Consumption[1]		GHG emissions[1]			
						w/o charging losses	with charging losses[2]	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L	MJ/100km	l/100km	kg/100km	kWh/100km	kWh/100km	g CO_2 /km	g CO_2 eq/km	g CO_2 eq/km	g CO_2 eq/km
PHEV20 DISI 2010 (AT6 + TCC)											
Gasoline	**1479**	**55**	**101.2**	**3.17**	**2.34**	**3.12**	**4.07**	**75.0**	**0.1**	**0.2**	**75.3**
Gasoline E10 market blend	**1479**	**55**	**101.2**	**3.25**	**2.44**	**3.12**	**4.07**	**74.9**	**0.1**	**0.2**	**75.2**
Gasoline E20 high RON	**1479**	**55**	**99.8**	**3.33**	**2.51**	**3.12**	**4.07**	**73.7**	**0.1**	**0.2**	**74.0**
LPG	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**
CNG	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**
E85	**1479**	**55**	**98.6**	**4.30**	**3.38**	**3.12**	**4.07**	**71.3**	**0.1**	**0.2**	**71.6**
PHEV20 DICI 2010 (AT6 + TCC)											
Diesel	**1539**	**55**	**91.6**	**2.57**	**2.12**	**3.17**	**4.14**	**67.4**	**0.1**	**0.6**	**68.1**
Diesel B7 market blend	**1539**	**55**	**91.6**	**2.57**	**2.15**	**3.17**	**4.14**	**67.8**	**0.1**	**0.6**	**68.5**
FAME	**1539**	**55**	**91.6**	**2.77**	**2.46**	**3.17**	**4.14**	**70.2**	**0.1**	**0.6**	**70.9**
DME	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**	**#**
FT-Diesel	**1539**	**55**	**91.6**	**2.67**	**2.08**	**3.17**	**4.14**	**65.3**	**0.1**	**0.6**	**66.0**
HVO	**1539**	**55**	**91.6**	**2.67**	**2.08**	**3.17**	**4.14**	**65.3**	**0.1**	**0.6**	**66.0**

1) NEDC Cycle results for cold start condition according to ECE 101 regulation; Vehicle Test Mass = Curb weight incl. Driver, 90% fuel
2) Charging losses based on the Charger Type 3.x kW (1x 16A)

5.2.2.3 REEV

Table 5-11: Simulation results for REEV SI configuration 2010 (according to ECE 101 regulation)

2010 VARIANTS	Curb Weight	Fuel Tank Capacity	Fuel Consumption[1]			El. Energy Consumption[1]		GHG emissions[1]			
						w/o charging losses	with charging losses[2]	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L	MJ/100km	l/100km	kg/100km	kWh/100km	kWh/100km	g CO_2 /km	g CO_2 eq/km	g CO_2 eq/km	g CO_2 eq/km
REEV80 SI 2010 (Single Stage Transmission)											
Gasoline	1548	35	34.9	1.09	0.81	9.12	11.58	25.7	0.1	0.1	25.9
Gasoline E10 market blend	1548	35	34.9	1.12	0.84	9.12	11.58	25.5	0.1	0.1	25.7
Gasoline E20 high RON	1548	35	34.4	1.15	0.86	9.12	11.58	25.0	0.1	0.1	25.2
LPG	#	#	#	#	#	#	#	#	#	#	#
CNG	#	#	#	#	#	#	#	#	#	#	#
E85	1548	35	33.9	1.48	1.16	9.12	11.58	24.2	0.1	0.1	24.4

1) NEDC Cycle results for cold start condition according to ECE 101 regulation; Vehicle Test Mass = Curb weight incl. Driver, 90% fuel
2) Charging losses based on the Charger Type 3.x kW (1x 16A)

5.2.2.4 BEV

Table 5-12: Simulation results for BEV configuration 2010

2010 VARIANTS	Curb Weight	Fuel Tank Capacity	Fuel Consumption[1]			El. Energy Consumption[1]		GHG emissions[1]			
						w/o charging losses	with charging losses[2]	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L	MJ/100km	l/100km	kg/100km	kWh/100km	kWh/100km	g CO_2 /km	g CO_2 eq/km	g CO_2 eq/km	g CO_2 eq/km
BEV 2010 (Single Stage Transmission)											
Electricity	1365	#	#	#	#	11.38	14.49	0.0	0.0	0.0	0.0

1) NEDC Cycle results for cold start condition; Vehicle Test Mass = Curb weight incl. Driver, 90% fuel
2) Charging losses based on the Charger Type 3.x kW (1x 16A)

For better comparability the BEV electric energy consumption is additionally given in MJ/100km, resulting in 40.97 MJ/100km w/o charging losses and 52.16 MJ/100km with charging losses.

5.2.2.5 FCEV

Table 5-13: Simulation results for FCEV configuration 2010

2010 VARIANTS	Curb Weight	Fuel Tank Capacity	Fuel Consumption[1]			El. Energy Consumption[1]		GHG emissions[1]			
						w/o charging losses	with charging losses	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L	MJ/100km	l/100km	kg/100km	kWh/100km	kWh/100km	g CO_2 /km	g CO_2 eq/km	g CO_2 eq/km	g CO_2 eq/km
FCEV 2010 (Single Stage Transmission)											
Hydrogen (CGH2)	1458	4	74.99	#	0.624	#	#	0.0	0.0	0.0	0.0
Hydrogen (cCGH2)	1458	4	74.99	#	0.624	#	#	0.0	0.0	0.0	0.0

1) NEDC Cycle results for cold start condition; Vehicle Test Mass = Curb weight incl. Driver, 90% fuel

FCEV simulation results for 2010 show a distinctively lower Hydrogen fuel consumption than currently available Fuel Cell Electric Vehicles like the Honda FCX Clarity or the Mercedes Benz B-class FC configuration. Such lower 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 2020+ Vehicle Configurations & Results

6.1 Vehicle configurations

In the following the 2020+ conventional as well as electrified vehicle configurations are described in detail regarding their main component specifications. Definition of the components technologies for 2020+ is assessed based upon the likely technology development foreseen 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 are given in chapter 3.

6.1.1 Simulation parameter & main data

Table 6-1: Mass balance for "ICE only" configurations 2020+

Mass balance for "ICE only" Variants 2020+		PISI			DISI			DICI	
		Gasoline[1]	LPG (mono-fuel)	CNG (mono-fuel)	Gasoline[1]	LPG (mono-fuel)	CNG (mono-fuel)	Diesel[2]	DME (mono-fuel)
Powertrain									
ICE mass	kg	135	135	135	135	135	135	165	165
Transmission mass	kg	50	50	50	50	50	50	50	50
Powertrain mass change	*kg*	*Reference*	*0*	*0*	*Reference*	*0*	*0*	*Reference*	*0*
Storage System									
Fuel Tank Capacity	L	35	60 + 14	100 + 14	35	60 + 14	100 + 14	35	60 + 14
Tank System mass	kg	15	40	60	15	40	60	15	40
Fuel mass	kg	26	37	27	26	37	27	29	44
Storage System mass change	*kg*	*Reference*	*+36*	*+46*	*Reference*	*+36*	*+46*	*Reference*	*+40*
Vehicle									
Curb weight (incl. driver, 90% fuel)	**kg**	**1190**	**1226**	**1236**	**1200**	**1236**	**1246**	**1260**	**1300**
Reference mass for ITW	kg	1215	1251	1261	1225	1261	1271	1285	1325
ITW Class	kg	1250	1250	1250	1250	1250	1250	1250	1360
Performance mass	**kg**	**1315**	**1351**	**1361**	**1325**	**1361**	**1371**	**1385**	**1425**
Payload	kg	550	550	550	550	550	550	550	550
Gross vehicle mass	**kg**	**1740**	**1776**	**1786**	**1750**	**1786**	**1796**	**1810**	**1850**

1) Same vehicle mass is assumed for the different fuel variants Gasoline, Gasoline E10 market bl., Gasoline E20 High RON & E85.
2) Same vehicle mass is assumed for the different fuel variants Diesel, Diesel B7 market blend, FAME, FT-Diesel & HVO.

Table 6-2: Mass balance for xEV configurations 2020+ in relation to the DISI ("ICE only")

Mass balance for xEV Variants 2020+		DISI ("ICE only")	Hybrid DISI	PHEV20 DISI	REEV80 SI	REEV80 FC	BEV	FCEV
		Gasoline[1]	Gasoline[1]	Gasoline[1]	Gasoline[1]	Hydrogen[2]	Electricity	Hydrogen[2]
Powertrain								
ICE mass	kg	135	135	135	130	0	0	0
Transmission mass	kg	50	80	80	10	10	10	10
Powertrain mass change	*kg*	*Reference*	*+30*	*+30*	*-45*	*-175*	*-175*	*-175*
Fuel Cell								
Fuel cell module mass[4]	kg	#	#	#	#	79	#	109
Electric Components								
eMachine mass[3]	kg	#	28	36	58	55	51	55
Generator (2nd eMachine) mass[3]	kg	#	#	#	35	#	#	#
Battery mass[3]	kg	#	26	59	95	90	175	26
xEV wiring harness mass	kg	#	11	15	20	20	20	20
eComponents mass change	kg	*Reference*	*+65*	*+110*	*+208*	*+165*	*+246*	*+101*
Storage System								
Fuel Tank Capacity	L	35	25	25	25	#	0	#
Tank System mass	kg	15	15	15	15	80	0	80
Fuel mass	kg	26	19	19	19	4	0	4
Storage System mass change	*kg*	*Reference*	*-7*	*-7*	*-7*	*+43*	*-41*	*+43*
Vehicle								
Curb weight (incl. driver, 90% fuel)	**kg**	**1200**	**1288**	**1333**	**1356**	**1312**	**1230**	**1278**
Reference mass for ITW	kg	1225	1313	1358	1381	1337	1255	1303
ITW Class	kg	1250	1360	1360	1360	1360	1250	1250
Performance mass	**kg**	**1325**	**1413**	**1458**	**1481**	**1437**	**1355**	**1403**
Payload	kg	550	550	550	550	550	550	550
Gross vehicle mass	**kg**	**1750**	**1838**	**1883**	**1906**	**1862**	**1780**	**1828**

1) Same vehicle mass is assumed for the different fuel variants Gasoline, Gasoline E10 market bl., Gasoline E20 High RON & E85.
2) Same vehicle mass is assumed for both Hydrogen Variants (CGH2 & cCGH2).
3) Masses for e-components include housing, power electronics and cooling system.
4) Mass of Fuel Cell module includes the whole system.

Table 6-3: Mass balance for xEV configurations 2020+ in relation to the DICI ("ICE only")

Mass balance for xEV Variants 2020+		DICI ("ICE only")	Hybrid DICI	PHEV20 DICI	REEV80 CI (Variant 1)	REEV80 CI (Variant 2)
		Diesel[1]	Diesel[1]	Diesel[1]	Diesel[1]	Diesel[1]
Powertrain						
ICE mass	kg	165	165	165	145	115
Transmission mass	kg	50	80	80	10	10
Powertrain mass change	*kg*	*Reference*	*+30*	*+30*	*-60*	*-90*
Electric Components						
eMachine mass[2]	kg	#	28	36	58	58
Generator (2nd eMachine) mass[2]	kg	#	#	#	40	35
Battery mass[2]	kg	#	26	59	95	95
xEV wiring harness mass	kg	#	11	15	20	20
eComponents mass change	kg	*Reference*	*+65*	*+110*	*+213*	*+208*
Storage System						
Fuel Tank Capacity	L	35	25	25	25	25
Tank System mass	kg	15	15	15	15	15
Fuel mass	kg	29	21	21	21	21
Storage System mass change	*kg*	*Reference*	*-8*	*-8*	*-8*	*-8*
Vehicle						
Curb weight (incl. driver, 90% fuel)	**kg**	**1260**	**1347**	**1392**	**1405**	**1370**
Reference mass for ITW	kg	1285	1372	1417	1430	1395
ITW Class	kg	1250	1360	1360	1470	1360
Performance mass	**kg**	**1385**	**1472**	**1517**	**1530**	**1495**
Payload	kg	550	550	550	550	550
Gross vehicle mass	**kg**	**1810**	**1897**	**1942**	**1955**	**1920**

1) Same vehicle mass is assumed for the different fuel variants Diesel, Diesel B7, FAME, FT-Diesel & HVO.
2) Masses for e-components include housing, power electronics and cooling system.

A DC/DC converter for LV power supply is included in all relevant xEV components masses in terms of weight; however DC/DC losses are omitted in the system efficiency chain for all xEV configurations due to negligible impact on results. For the 2020+ conventional configurations a completely electrified oil pump to support a quick Start-Stop functionality is not necessary, as a hydraulic oil pressure storage unit similar to the technology used in some automatic transmissions is considered.

Auxiliaries – status of electrification 2020+:

- Steering Pump: EPS for all Configurations 2020+ (ICE only & xEV)
- Brake Vacuum Pump: Mechanical for conventional configurations, electrified for xEV configurations
- Water Pump: Controllable mechanical for conventional configurations, electrified for xEV configurations
- (ICE) Oil Pump: Partly electrified for all configurations
- (Transmission) Oil Pump: Only needed for xEV Configurations (due to AT), electrified

6.1.2 ICE Specifications

The RON for the Gasoline blends and CN for Diesel B7 are defined in the fuel properties table (***Table 3-1***). However in market fuels these numbers usually vary in a certain range of a few numbers. In this simulation work, such RON / CN changes for fuels (e.g. Gasoline E20 RON range of 99-102) do not require ICE map adaptions in this simulation study, 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) are not evaluated in detail in the current TTW analysis. However, all vehicle simulations of the 2020+ configurations comply with the legislative emissions standards for EURO 6, which is the currently known emission standard for 2020+.

In contrast to 2010 the definition of 2020+ ICE specifications is adapted to the degree of electrification of xEV configurations: Electrification is not just seen as an Add-On technology like in 2010, 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 nor downrated to prevent complex NOx after-treatment systems. For this study, it is not assumed that the representative Diesel engines are operated in HCCI/PCCI mode in the 2020+ timeframe. Both Gasoline and Diesel ICEs are improved in terms of technology (e.g. friction reduction) for electrified configurations.

Table 6-4: Gasoline ICE specification for configurations 2020+ with (standard) gasoline fuel

AVL Gasoline ICE Variants Specifications by AVL		Gasoline ICE Variants 2020+				
		PISI ("ICE only")	DISI ("ICE only")	Hybrid DISI	PHEV20 DISI	REEV80 SI
ICE Type / Technology	---	- MPI - Electr. Supercharged - Optimized Friction - CDA	- TGDI - Miller Cycle - Dual VVT - Increased Compression - Cooled EGR & manifold			- NA - High-expansion Atkinson Cycle - Cooled EGR - Increased Compression
Displacement	L	1.4	1.2	1.0		1.2
No. of Cylinders	---	IL4	IL3			IL3
Specific power	kW / L	~54	~71	~70		~39
Maximum Power	kW @ rpm	75 @ 5500	85 @ 5500	70 @ 5500		47 @ 5000
Maximum Torque	Nm @ rpm	175 @ 2500	185 @ 1500 - 4000	150 @ 1750 - 4000		95 @ 4000
Maximum Speed	rpm	6000	6000			5500
Idle Speed	rpm	750	750			750
BSFC @ 2000 rpm / 2 bar	g/kWh	~340	~365	~360		~345
BSFC minimum	g/kWh	~240	~225	~220		~220

Table 6-5: Diesel ICE specification for configurations 2020+ with (standard) diesel fuel

Diesel ICE Variants Specifications by AVL		Diesel ICE Variants 2020+				
		DICI	Hybrid DICI	PHEV20 DICI	REEV80 CI - Variant 1	REEV80 CI - Variant 2
ICE Type / Technology	---	- Derating - LNT & DPF - Reduced low-end-torque - Waste Gate Loader instead of VGT - Optimized / Reduced Friction			- Derating - **LNT** - DPF - Reduced low-end-torque	- Derating - **(Advanced) LNT** - DPF - Reduced low-end-torque
Displacement	L	1.6			1.2	0.9
No. of Cylinders	---	IL4			IL3	IL2
Specific power	kW / L	~53			~52	~51
Maximum Power	kW @ rpm	85 @ 4000			63 @ 4000	46 @ 4000
Maximum Torque	Nm @ rpm	285 @ 1750 - 2500			205 @ 2000 - 2500	150 @ 2000 - 2500
Maximum Speed	rpm	4500			4500	4500
Idle Speed	rpm	750			750	750
BSFC @ 2000 rpm / 2 bar	g/kWh	~260	~250		~315	~320
BSFC minimum	g/kWh	~202	~200		~210	~210

Table 6-6: PISI ICE specification for ("ICE only") configurations 2020+ with alternative fuels

Gasoline ICE Variants Specifications by AVL		PISI ICE 2020+ for "ICE only" Variants				
		Gasoline	E20 high RON	E85	LPG	CNG
ICE Type / Technology	---	- MPI - Electr. Supercharged - Optimized Friction - CDA			LPG ICE - MPI - Electr. Supercharged - Optimized Friction - CDA	CNG ICE - MPI - Electr. Supercharged - Optimized Friction - CDA
Displacement	L	1.4			1.44	1.6
No. of Cylinders	---	IL4				
Specific power	kW / L	~54			~54	~48
Maximum Power	kW @ rpm	75 @ 5500			77 @ 5500	77 @ 5500
Maximum Torque	Nm @ rpm	175 @ 2500			180 @ 2500	180 @ 2500
Maximum Speed	rpm	6000				
Idle Speed	rpm	750				
BSFC @ 2000 rpm / 2 bar	g/kWh	~340	368	498	314 ≙ *~334 Gasoline equivalent*	312 ≙ *~326 Gasoline equivalent*
BSFC minimum	g/kWh	~240	245	331	209 ≙ *~223 Gasoline equivalent*	205 ≙ *~215 Gasoline equivalent*

Table 6-7: DISI ICE specification for ("ICE only") configurations 2020+ with alternative fuels

Gasoline ICE Variants Specifications by AVL		DISI ICE 2020+ for "ICE only" Variants				
		Gasoline	E20 high RON	E85	LPG	CNG
ICE Type / Technology	---	- TGDI - Miller Cycle - Dual VVT - Increased Compression - Cooled EGR & manifold			LPG ICE - Turbo DI - Miller Cycle - Dual VVT - Increased Compression - Cooled EGR & manifold	CNG ICE - Turbo MPI - Miller Cycle - Dual VVT - Increased Compression - Cooled EGR & manifold
Displacement	L	1.2			1.23	1.32
No. of Cylinders	---	IL3				
Specific power	kW / L	~71			~71	~66
Maximum Power	kW @ rpm	85 @ 5500			87 @ 5500	87 @ 5500
Maximum Torque	Nm @ rpm	185 @ 1500 - 4000			190 @ 1500 - 4000	191 @ 2000 - 3000
Maximum Speed	rpm	6000				
Idle Speed	rpm	750				
BSFC @ 2000 rpm / 2 bar	g/kWh	~365	389	524	336 ≙ ~357 Gasoline equivalent	335 ≙ ~347 Gasoline equivalent
BSFC minimum	g/kWh	~225	231	311	199 ≙ ~212 Gasoline equivalent	198 ≙ ~206 Gasoline equivalent

6.1.3 xEV specifications

The xEV components specifications of the 2020+ configurations were designed and optimized in correlation to the given boundary conditions and vehicle minimum performance criteria of the current TTW study.

Table 6-8: xEV components' specifications: overview of xEV 2020+ configurations

Variant	Component	Specific	Unit	Requirements to meet the performance criteria	Value*
HEV	Electric Machine	Power	kW	*Complete regenerative braking during the NEDC*	**24** (12)
		Torque	Nm	*Complete regenerative braking during the NEDC*	**140** (70)
	Li-Ion Battery Pack	Power	kW	*Required electric power from/to the electric machine*	**30**
		Energy	kWh	*Along the NEDC, complete regenerative braking and a lifetime of at least 160000 km*	**1.0** (0.4)
PHEV	Electric Machine	Power	kW	*Electric drive up to 100 km/h: continuously, during the NEDC (continuous P and Tq) occasionally, during high demanding transients (peak P & Tq): Artemis Cycles as driving reference*	**38** (19)
		Torque	Nm		**155** (65)
	Li-Ion Battery Pack	Power	kW	*Required electric power from/to the electric machine*	**50**
		Energy	kWh	*Along the NEDC, 20 km of All Electric Range and a lifetime of at least 160000 km*	**2.7** (1.8)
REEV	Electric Machine	Power	kW	*Maximum Speed => Continuous Power Acceleration and Elasticity => Peak Power Gradeability 20% => Continuous Torque Gradeability 30% => Peak Torque*	**75** (38)
		Torque	Nm		**270** (180)
	Generator	Power	kW	*Guarantees the continous power required by the electric machine*	**50** (50)
		Torque	Nm	*Suitable coupling with the ICE*	**105** (105)
	Li-Ion Battery Pack	Power	kW	*Required electric power from/to the electric machine during charge depleting and high demanding transients of charge sustaining*	**> 90**
		Energy	kWh	*Along the NEDC, 80 km of All Electric Range and a lifetime of at least 160000 km*	**11.8** (9.1)
BEV	Electric Machine	Power	kW	*Maximum Speed => Continuous Power Acceleration and Elasticity => Peak Power Gradeability 20% => Continuous Torque Gradeability 30% => Peak Torque*	**70** (37)
		Torque	Nm		**235** (160)
	Li-Ion Battery Pack	Power	kW	*Required electric power from/to the electric machine*	**> 90**
		Energy	kWh	*Along the NEDC, 120 km (2010) or 200 km (2020) of All Electric Range and a lifetime of at least 160000 km*	**22.1** (18.4)
FCEV	Electric Machine	Power	kW	*Maximum Speed => Continuous Power Acceleration and Elasticity => Peak Power Gradeability 20% => Continuous Torque Gradeability 30% => Peak Torque*	**70** (45)
		Torque	Nm		**270** (185)
	Fuel Cell System	Power	kW	*To supply the required power to the electric machine. Demanding transients require the battery support (top speed: 180 km/h)*	**55**
	Li-Ion Battery Pack	Power	kW	*Required electric power from/to the electric machine*	**30**
		Energy	kWh	*Along the NEDC, complete regenerative braking and a lifetime of at least 160000 km*	**1** (0.5)
REEV FC	Electric Machine	Power	kW	*Maximum Speed => Continuous Power Acceleration and Elasticity => Peak Power Gradeability 20% => Continuous Torque Gradeability 30% => Peak Torque*	**72** (36)
		Torque	Nm		**250** (170)
	Fuel Cell System	Power	kW	*To supply the required power to the electric machine. Demanding transients require the battery support (top speed: 130 km/h)*	**30**
	Li-Ion Battery Pack	Power	kW	*Required electric power from/to the electric machine*	**> 90**
		Energy	kWh	*Along the NEDC, 80 km of All Electric Range and a lifetime of at least 160000 km*	**10.7** (8.2)

**) Electric Machine, Generator, Fuel Cell System: 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 available energy*

Table 6-8 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 available energy (in parenthesis) is outlined.

Figure 6-1 shows the Fuel Cell System Efficiency characteristics for the 2020+ configurations in comparison to the 2010 FCEV characteristic, given in percent of the Fuel Cell System maximum power. 2020+ efficiencies are defined by the EUCAR working group and are based on current research and development projects (see also footnote 3).

Figure 6-1: Fuel cell system efficiency of 2020+ configurations

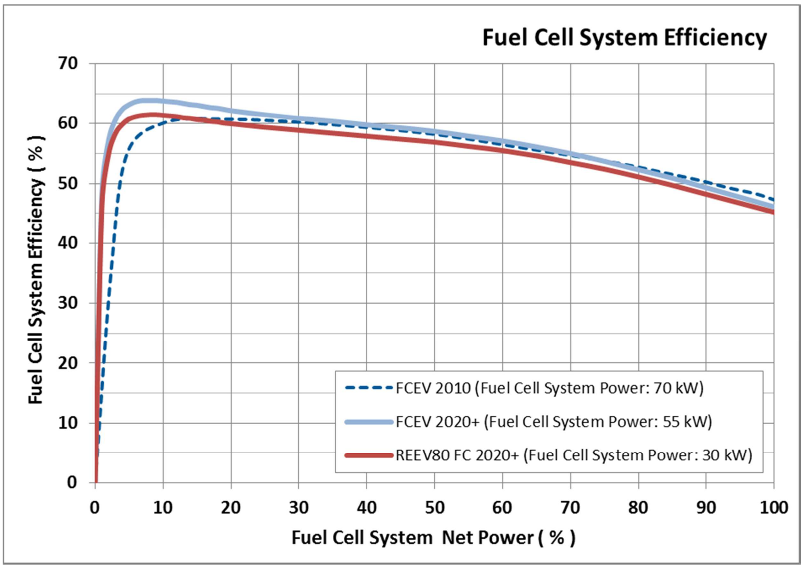


Figure 6-2 and ***Figure 6-3*** show the schematics of the electric system layout of the configurations featuring a Fuel Cell, the FCEV and the REEV FC. Besides the Plug-In feature, the only difference between the two layouts is the positioning of the DC/DC converter, which for each layout is optimized towards the most efficient power supply for driving: In the case of the FCEV (mainly operating via the Fuel Cell) the DC/DC converter is directly connected to the HV battery. In the case of the REEV FC (mainly operating via the HV battery) the DC/DC converter is directly connected to the Fuel Cell. Therefore the Fuel Cell System efficiency of the REEV FC (including a DC/DC converter) is slightly reduced in comparison to the efficiency of the FCEV.

Figure 6-2: Electric system layout of the FCEV

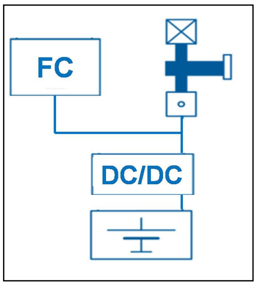
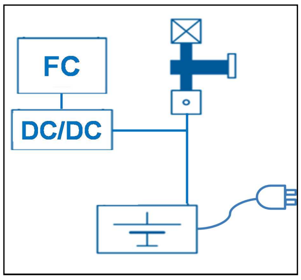


Figure 6-3: Electric system layout of the REEV FC



Impacts of FC cooling pump losses and other FC related ancillaries are included in the FC system efficiencies. For 2010 the FC system is assumed to have its own cooling system (showing a slightly reduced FC system efficiency), whereas for 2020+ the FC system cooling is integrated into the cooling system of the vehicle. The FC module in the FCEV and REEV FC (for 2020+ configurations) 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.

6.2 Simulation results

2020+ simulation results include additionally a so-called “Technology Walk”, which shows in detail the foreseen improvements in xEV technology development in comparison to the 2010 configurations, as they were assessed by EUCAR and AVL experts to their best knowledge.

6.2.1 Results for conventional (“ICE only”) configurations

Table 6-9: Simulation results for “ICE only” configurations 2020+

2020+ VARIANTS	Curb Weight	Fuel Tank Capacity	Fuel Consumption[1]			El. Energy Consumption[1] w/o charging losses	El. Energy Consumption[1] with charging losses	GHG emissions[1] as CO_2	GHG emissions[1] as CH_4	GHG emissions[1] as N_2O	GHG emissions[1] TOTAL
	kg	L	MJ/100km	l/100km	kg/100km	kWh/100km	kWh/100km	g CO_2 /km	g CO_2 eq/km	g CO_2 eq/km	g CO_2 eq/km
PISI ("ICE only") 2020+, MT6											
Gasoline	**1190**	**35**	**150.1**	**4.67**	**3.48**	**#**	**#**	**110.2**	**0.3**	**0.5**	**111.0**
Gasoline E10 market blend	**1190**	**35**	**150.1**	**4.83**	**3.62**	**#**	**#**	**110.0**	**0.3**	**0.5**	**110.8**
Gasoline E20 high RON	**1190**	**35**	**146.6**	**4.89**	**3.69**	**#**	**#**	**107.2**	**0.3**	**0.5**	**108.0**
LPG[2]	**1226**	**60**	**148.5**	**5.87**	**3.23**	**#**	**#**	**97.6**	**0.3**	**0.5**	**98.4**
CNG[3]	**1236**	**100** (17 kg)	**152.5**	**#**	**3.38**	**#**	**#**	**85.8**	**1.1**	**0.5**	**87.4**
E85	**1190**	**35**	**145.5**	**6.35**	**4.99**	**#**	**#**	**104.1**	**0.3**	**0.5**	**104.9**
DISI ("ICE only") 2020+, MT6											
Gasoline	**1200**	**35**	**142.4**	**4.43**	**3.30**	**#**	**#**	**104.5**	**0.3**	**0.5**	**105.3**
Gasoline E10 market blend	**1200**	**35**	**142.4**	**4.58**	**3.43**	**#**	**#**	**104.3**	**0.3**	**0.5**	**105.1**
Gasoline E20 high RON	**1200**	**35**	**140.7**	**4.69**	**3.54**	**#**	**#**	**102.9**	**0.3**	**0.5**	**103.7**
LPG[2]	**1236**	**60**	**143.2**	**5.66**	**3.11**	**#**	**#**	**94.1**	**0.3**	**0.5**	**94.9**
CNG[3]	**1246**	**100** (17 kg)	**145.1**	**#**	**3.22**	**#**	**#**	**81.6**	**1.1**	**0.5**	**83.2**
E85	**1200**	**35**	**138.6**	**6.05**	**4.75**	**#**	**#**	**99.1**	**0.3**	**0.5**	**99.9**
DICI ("ICE only") 2020+, MT6											
Diesel	**1260**	**35**	**118.5**	**3.30**	**2.75**	**#**	**#**	**86.8**	**0.2**	**1.2**	**88.2**
Diesel B7 market blend	**1260**	**35**	**118.5**	**3.32**	**2.78**	**#**	**#**	**87.0**	**0.2**	**1.2**	**88.4**
FAME	**1260**	**35**	**118.5**	**3.58**	**3.19**	**#**	**#**	**90.3**	**0.2**	**1.2**	**91.7**
DME[4]	**1300**	**60**	**122.3**	**6.42**	**4.30**	**#**	**#**	**82.3**	**0.2**	**1.2**	**83.7**
FT-Diesel	**1260**	**35**	**118.5**	**3.45**	**2.69**	**#**	**#**	**83.9**	**0.2**	**1.2**	**85.3**
HVO	**1260**	**35**	**118.5**	**3.45**	**2.69**	**#**	**#**	**83.9**	**0.2**	**1.2**	**85.3**

1) NEDC Cycle results for cold start condition; Vehicle Test Mass = Curb weight incl. Driver, 90% fuel
2) Mono-valent LPG Vehicle; PISI ICE as MPI / DISI ICE as DI; ICE Displacement increased to compensate additonal vehicle weight;
3) Mono-valent CNG Vehicle; MPI ICE (PISI & DISI Variants); ICE Displacement increased to compensate reduced ICE volumetric efficiency & additional vehicle weight;
4) Only theoretical consideration of Mono-valent DME Vehicle - DME currently not used for PC applications; ICE Displacement increased to compensate add. vehicle weight;

Table 6-9 shows the results of the vehicle simulations for “ICE only” vehicles. For 2020+, it has been assumed that the alternative powertrain configurations are taking advantage of component optimization and improved system integration. For example, the relative GHG reduction of CNG vehicles compared to gasoline powered vehicle is more pronounced than for the 2010 configurations. The E20 high RON in PISI and DISI configuration is assumed to deliver a GHG-emission reduction of approx. 3% compared to Gasoline in PISI/DISI. This is comparable to recent research results [Thewes 2010].

Table 6-10: Technology walk for “ICE only” configurations (PISI, DISI, DICI) 2010 → 2020+

Technology Walk for "ICE only" Powertrain Variant (without consideration of GHG)		PISI with Gasoline Fuel		DISI with Gasoline Fuel		DICI with Diesel Fuel	
		NEDC[1] CO_2-Emissions	Technology dependent CO_2-Reduction	NEDC[1] CO_2-Emissions	Technology dependent CO_2-Reduction	NEDC[1] CO_2-Emissions	Technology dependent CO_2-Reduction
		g/km	%	g/km	%	g/km	%
"ICE only" Variant 2010		155.1	Reference	149.6	Reference	119.0	Reference
Transmission	Transmission Measures[2]	148.2	4.4%	145.4	2.8%	114.2	4.0%
ICE	New ICE for 2020+	133.4	9.5%	125.6	13.2%	105.4	7.4%
	Improved Auxiliaries	129.8	2.3%	122.1	2.3%	102.2	2.7%
Start & Stop		122.4	4.8%	116.0	4.1%	98.0	3.5%
Vehicle Measures	Weight Reduction	118.7	2.3%	112.6	2.3%	94.6	2.8%
	Improved aerodynamics	113.9	3.1%	108.0	3.0%	90.4	3.5%
	Improved rolling resistance	110.2	2.4%	104.5	2.3%	86.8	3.0%
"ICE only" Variant 2020+		110.2	28.9%	104.5	30.1%	86.8	27.1%

1) NEDC Cycle results for cold start condition; Vehicle Test Mass = Curb weight incl. Driver, 90% fuel
2) For PISI: New 6-Speed Manual Transmission (MT5 is replaced); For DISI & DICI: Downspeeding & Improved Efficiency of 6-Speed Manual Transmission

6.2.2 Results for xEV configurations

The following tables show the results for electric energy consumption always for both with and without consideration of Battery charging losses, where applicable. In general legislative regulations (UN ECE R101) define, that charging losses are to be included in reference values of electric energy consumption for all Plug-In features vehicle configurations.

6.2.2.1 HEV

Table 6-11: Simulation results for HEV configurations 2020+

2020+ VARIANTS	Curb Weight	Fuel Tank Capacity	Fuel Consumption[1]			El. Energy Consumption[1]		GHG emissions[1]			
						w/o charging losses	with charging losses	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L	MJ/100km	l/100km	kg/100km	kWh/100km	kWh/100km	g CO_2 /km	g CO_2 eq/km	g CO_2 eq/km	g CO_2 eq/km
Hybrid DISI 2020+ (AT8 + LC)											
Gasoline	1288	25	93.4	2.92	2.16	#	#	69.0	0.3	0.5	69.8
Gasoline E10 market blend	1288	25	93.4	3.00	2.25	#	#	68.9	0.3	0.5	69.7
Gasoline E20 high RON	1288	25	92.2	3.07	2.32	#	#	67.9	0.3	0.5	68.7
LPG	#	#	#	#	#	#	#	#	#	#	#
CNG	#	#	#	#	#	#	#	#	#	#	#
E85	1288	25	90.8	3.96	3.11	#	#	65.4	0.3	0.5	66.2
Hybrid DICI 2020+ (AT8 + LC)											
Diesel	1347	25	87.5	2.46	2.03	#	#	64.5	0.2	1.2	65.9
Diesel B7 market blend	1347	25	87.5	2.45	2.05	#	#	64.7	0.2	1.2	66.1
FAME	1347	25	87.5	2.64	2.35	#	#	67.1	0.2	1.2	68.5
DME	#	#	#	#	#	#	#	#	#	#	#
FT-Diesel	1347	25	87.5	2.55	1.99	#	#	62.4	0.2	1.2	63.8
HVO	1347	25	87.5	2.55	1.99	#	#	62.4	0.2	1.2	63.8

1) NEDC Cycle results for cold start condition; Vehicle Test Mass = Curb weight incl. Driver, 90% fuel

Table 6-12: Technology walk for hybrid configurations (DISI, DICI) 2010 → 2020+

Technology Walk for HEV Powertrain Variants (without consideration of GHG)		Hybrid DISI with Gasoline Fuel		Hybrid DICI with Diesel Fuel	
		NEDC[1] CO_2-Emissions	Technology dependent CO_2-Reduction	NEDC[1] CO_2-Emissions	Technology dependent CO_2-Reduction
		g/km	%	g/km	%
Hybrid Variant 2010		104.9	Reference	94.4	Reference
Transmission	New 8-Gear Automatic Transmission	98.6	6.0%	88.5	6.3%
ICE	New ICE²	86.5	11.5%	80.9	8.1%
Electric Machine	New 24 kW Brushless Permanent Magnet EM	84.4	2.0%	78.4	2.6%
Battery	New 1.0 kWh High Power Density Li-Ion Battery	84.0	0.4%	78.2	0.2%
Auxiliaries	Improved Auxiliaries	81.9	2.0%	76.3	2.0%
Vehicle	Improved vehicle weight, aereodynamics & rolling resistance	69.0	12.3%	64.5	12.5%
Hybrid Variant 2020+		69.0	34.2%	64.5	31.7%

1) NEDC Cycle results for cold start condition; Vehicle Test Mass = Curb weight incl. Driver, 90% fuel
2) For Hybrid DISI new 70 kW ICE; For Hybrid DICI new 85 kW ICE

6.2.2.2 PHEV

Table 6-13: Simulation results for PHEV configurations 2020+ (according to ECE101 regulation)

2020+ VARIANTS	Curb Weight	Fuel Tank Capacity	Fuel Consumption[1]			El. Energy Consumption[1]		GHG emissions[1]			
						w/o charging losses	with charging losses[2]	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L	MJ/100km	l/100km	kg/100km	kWh/100km	kWh/100km	g CO_2 /km	g CO_2 eq/km	g CO_2 eq/km	g CO_2 eq/km
PHEV20 DISI 2020+ (AT8 + LC)											
Gasoline	1333	25	67.4	2.11	1.56	2.21	2.70	49.9	0.1	0.3	50.3
Gasoline E10 market blend	1333	25	67.4	2.17	1.62	2.21	2.70	49.6	0.1	0.3	50.0
Gasoline E20 high RON	1333	25	66.5	2.22	1.67	2.21	2.70	49.0	0.1	0.3	49.4
LPG	#	#	#	#	#	#	#	#	#	#	#
CNG	#	#	#	#	#	#	#	#	#	#	#
E85	1333	25	65.5	2.86	2.25	2.21	2.70	47.4	0.1	0.3	47.8
PHEV20 DICI 2020+ (AT8 + LC)											
Diesel	1392	25	63.2	1.77	1.46	2.28	2.79	46.4	0.1	0.7	47.2
Diesel B7 market blend	1392	25	63.2	1.77	1.48	2.28	2.79	46.7	0.1	0.7	47.5
FAME	1392	25	63.2	1.91	1.70	2.28	2.79	48.5	0.1	0.7	49.3
DME	#	#	#	#	#	#	#	#	#	#	#
FT-Diesel	1392	25	63.2	1.84	1.44	2.28	2.79	45.2	0.1	0.7	46.0
HVO	1392	25	63.2	1.84	1.44	2.28	2.79	45.2	0.1	0.7	46.0

Table 6-14: Technology walk for PHEV20 configurations (DISI, DICI) 2010 → 2020+

Technology Walk for PHEV20 Powertrain Variants (without consideration of GHG)		PHEV20 DISI with Gasoline Fuel		PHEV20 DICI with Diesel Fuel	
		NEDC[1] CO_2-Emissions	Technology dependent CO_2-Reduction	NEDC[1] CO_2-Emissions	Technology dependent CO_2-Reduction
		g/km	%	g/km	%
PHEV20 Variant 2010		75.0	Reference	67.4	Reference
Transmission	New 8-Gear Automatic Transmission	70.1	6.5%	62.9	6.7%
ICE	New ICE²	62.3	10.4%	57.4	8.2%
Electric Machine	New 38 kW Brushless Permanent Magnet EM	60.7	2.1%	55.9	2.2%
Battery	New 1.0 kWh High Power Density Li-Ion Battery	63.0	-3.1%	58.4	-3.7%
Auxiliaries	Improved Auxiliaries	61.4	2.1%	57.2	1.8%
Vehicle	Improved vehicle weight, aereodynamics & rolling resistance	49.9	15.3%	46.4	16.0%
PHEV20 Variant 2020+		49.9	33.5%	46.4	31.2%

1) NEDC Cycle results for cold start condition according to ECE101 regulation; Vehicle Test Mass = Curb weight incl. Driver, 90% fuel
2) For PHEV20 DISI new 70 kW ICE; For PHEV20 DICI new 85 kW ICE

6.2.2.3 REEV

Table 6-15: Simulation results for REEV configurations 2020+ (according to ECE101 regulation)

2020+ VARIANTS	Curb Weight	Fuel Tank Capacity	Fuel Consumption[1]			El. Energy Consumption[1] w/o charging losses	El. Energy Consumption[1] with charging losses[2]	GHG emissions[1] as CO_2	GHG emissions[1] as CH_4	GHG emissions[1] as N_2O	GHG emissions[1] TOTAL
	kg	L	MJ/100km	l/100km	kg/100km	kWh/100km	kWh/100km	g CO_2 /km	g CO_2 eq/km	g CO_2 eq/km	g CO_2 eq/km
REEV80 SI 2020+ (Single Stage Transmission)											
Gasoline	1356	25	27.0	0.85	0.63	7.63	9.12	20.1	0.1	0.1	20.3
Gasoline E10 market blend	1356	25	27.0	0.87	0.65	7.63	9.12	19.9	0.1	0.1	20.1
Gasoline E20 high RON	1356	25	26.7	0.89	0.67	7.63	9.12	19.6	0.1	0.1	19.8
LPG	#	#	#	#	#	#	#	#	#	#	#
CNG	#	#	#	#	#	#	#	#	#	#	#
E85	1356	25	26.3	1.15	0.90	7.63	9.12	18.9	0.1	0.1	19.1
REEV80 CI 2020+ "Variant 1" (3-Cylinder with LNT, Single Stage Transmission)											
Diesel	1405	25	27.1	0.76	0.63	7.71	9.25	19.9	0.1	0.3	20.3
Diesel B7 market blend	1405	25	27.1	0.76	0.63	7.71	9.25	19.7	0.1	0.3	20.1
FAME	1405	25	27.1	0.82	0.73	7.71	9.25	20.7	0.1	0.3	21.1
DME	#	#	#	#	#	#	#	#	#	#	#
FT-Diesel	1405	25	27.1	0.79	0.62	7.71	9.25	19.3	0.1	0.3	19.7
HVO	1405	25	27.1	0.79	0.62	7.71	9.25	19.3	0.1	0.3	19.7
REEV80 CI 2020+ "Variant 2" (2-Cylinder with advanced LNT, Single Stage Transmission)											
Diesel	1370	25	26.3	0.74	0.61	7.66	9.17	19.4	0.1	0.3	19.8
Diesel B7 market blend	1370	25	26.3	0.74	0.62	7.66	9.17	19.6	0.1	0.3	20.0
FAME	1370	25	26.3	0.79	0.71	7.66	9.17	20.3	0.1	0.3	20.7
DME	#	#	#	#	#	#	#	#	#	#	#
FT-Diesel	1370	25	26.3	0.77	0.60	7.66	9.17	18.8	0.1	0.3	19.2
HVO	1370	25	26.3	0.77	0.60	7.66	9.17	18.8	0.1	0.3	19.2

1) NEDC Cycle results for cold start condition according to ECE 101 regulation; Vehicle Test Mass = Curb weight incl. Driver, 90% fuel
2) Charging losses based on the Charger Type 3.x kW (1x 16A)

Table 6-16: Technology walk for REEV80 SI configuration 2010 → 2020+

Technology Walk for REEV80 SI Powertrain Variant (without consideration of GHG)		NEDC[1] CO_2-Emissions	Technology dependent CO_2-Reduction
		g/km	%
REEV80 SI 2010, Gasoline Fuel, Single Stage Transmission		25.7	Reference
ICE	New 47 kW ICE	24.3	5.4%
Generator	New 50 kW Brushless Permanent Magnet EM	23.6	2.7%
Electric Machine	New 75 kW Brushless Permanent Magnet EM	22.6	3.9%
Battery	New 11.8 kWh High Power Density Li-Ion Battery	26.0	-13.2%
Auxiliaries	Improved Auxiliaries	25.1	3.5%
Vehicle	Improved vehicle weight, aeerodynamics & rolling resistance	20.1	19.5%
REEV80 SI 2020+, Gasoline Fuel, Single Stage Transmission		20.1	21.8%

1) NEDC Cycle results for cold start condition according to ECE101 regulation; Vehicle Test Mass = Curb weight incl. Driver, 90% fuel

6.2.2.4 BEV

Table 6-17: Simulation results for BEV configuration 2020+

2020+ VARIANTS	Curb Weight	Fuel Tank Capacity	Fuel Consumption[1]			El. Energy Consumption[1] w/o charging losses	El. Energy Consumption[1] with charging losses[2]	GHG emissions[1] as CO_2	GHG emissions[1] as CH_4	GHG emissions[1] as N_2O	GHG emissions[1] TOTAL
	kg	L	MJ/100km	l/100km	kg/100km	kWh/100km	kWh/100km	g CO_2 /km	g CO_2 eq/km	g CO_2 eq/km	g CO_2 eq/km
BEV 2020+ (Single Stage Transmission)											
Electricity	1230	#	#	#	#	8.89	10.59	0.0	0.0	0.0	0.0

1) NEDC Cycle results for cold start condition; Vehicle Test Mass = Curb weight incl. Driver, 90% fuel
2) Charging losses based on the Charger Type 3.x kW (1x 16A)

For better comparability the BEV electric energy consumption is additionally given in MJ/100km, resulting in 32.00 MJ/100km w/o charging losses and 38.12 MJ/100km with charging losses.

Table 6-18: Technology walk for BEV configuration 2010 → 2020+

Technology Walk for BEV Powertrain Variant		NEDC[1] Electric Energy Consumption	Technology dependent Energy-Reduction
		kWh/100km	%
BEV 2010, Single Stage Transmission		**11.38**	Reference
Electric Machine	New 70 kW Brushless Permanent Magnet EM	**11.15**	**2.0%**
Battery	New 23 kWh High Power Density Li-Ion Battery	**11.10**	**0.4%**
Auxiliaries	Improved Auxiliaries	**10.84**	**2.3%**
Vehicle	Improved vehicle weight, aereodynamics & rolling resistance	**8.89**	**17.1%**
BEV 2020+, Single Stage Transmission		**8.89**	**21.9%**

1) NEDC Cycle results for cold start condition; Vehicle Test Mass = Curb weight incl. Driver, 90% fuel

6.2.2.5 FCEV & REEV FC

Table 6-19: Simulation results for FCEV & REEV FC 2020+

2020+ VARIANTS	Curb Weight	Fuel Tank Capacity	Fuel Consumption[1]			El. Energy Consumption[1]		GHG emissions[1]			
						w/o charging losses	with charging losses[2]	as CO_2	as CH_4	as N_2O	TOTAL
	kg	L	MJ/100km	l/100km	kg/100km	kWh/100km	kWh/100km	g CO_2 /km	g CO_2 eq/km	g CO_2 eq/km	g CO_2 eq/km
FCEV 2020+ (Single Stage Transmission)											
Hydrogen (CGH2)	**1278**	**4**	**53.85**	**#**	**0.448**	**#**	**#**	**0.0**	**0.0**	**0.0**	**0.0**
Hydrogen (cCGH2)	**1278**	**4**	**53.85**	**#**	**0.448**	**#**	**#**	**0.0**	**0.0**	**0.0**	**0.0**
REEV FC 2020+ (Single Stage Transmission)[3]											
Hydrogen (CGH2)	**1312**	**4**	**13.43**	**#**	**0.110**	**6.94**	**8.28**	**0.0**	**0.0**	**0.0**	**0.0**
Hydrogen (cCGH2)	**1312**	**4**	**13.43**	**#**	**0.110**	**6.94**	**8.28**	**0.0**	**0.0**	**0.0**	**0.0**

1) NEDC Cycle results for cold start condition; Vehicle Test Mass = Curb weight incl. Driver, 90% fuel
2) Charging losses based on the Charger Type 3.x kW (1x 16A)
3) Results according to ECE 101 regulation

Table 6-20: Technology walk for FCEV configuration 2010 → 2020+

Technology Walk for FCEV Powertrain Variant		NEDC[1] H_2 Consumption	Technology dependent H_2-Reduction
		kg/100km	%
FCEV 2010, Single Stage Transmission		**0.624**	Reference
Electric Machine	New 70 kW Brushless Permanent Magnet EM	**0.597**	**4.3%**
Battery	New 1.0 kWh High Power Density Li-Ion Battery	**0.592**	**0.8%**
Fuel Cell System	New 55kW Fuel Cell System	**0.580**	**1.9%**
Auxiliaries	Improved Auxiliaries	**0.556**	**3.8%**
Vehicle	Improved vehicle weight, aereodynamics & rolling resistance	**0.448**	**17.3%**
FCEV 2020+, Single Stage Transmission		**0.448**	**28.2%**

1) NEDC Cycle results for cold start condition; Vehicle Test Mass = Curb weight incl. Driver, 90% fuel

7 Summary

In this summary an overview of all results for the considered fuel-powertrain combinations including error estimations is given. The figures below show CO_2 equivalent emission (***Figure 7-1*** to ***Figure 7-4***) as well as energy consumption (***Figure 7-5*** to ***Figure 7-8***) for both conventional and electrified configurations. Diagrams are split for SI and CI ICEs and for 2010 and 2020+ configurations, for Plug-In electrified configurations the electric energy consumption is additionally included. Finally the pure electric configurations 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 a specific color-code throughout all diagrams and result tables. Detailed explanations of the results are given in the chapter 5 for the 2010 and in chapter 6 for the 2020+ configurations. In the results the DISI CNG configuration represents an exception, as the CNG fuel is port injected, but the gasoline fuel is directly injected (see also the description in chapter 3.3.1.2 a)).

Figure 7-1: Summary of CO_2 equivalent emission results for SI ICE Configurations 2010

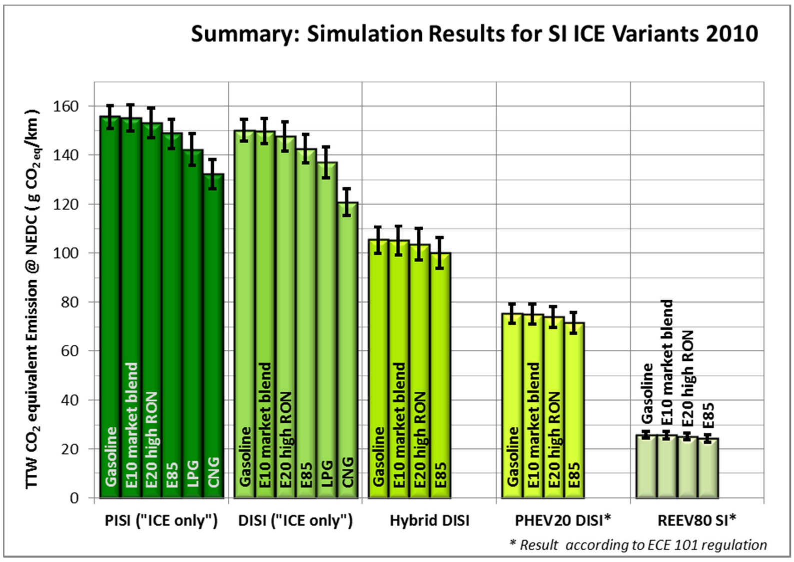


Figure 7-2: Summary of CO_2 equivalent emission results for CI ICE Configurations 2010

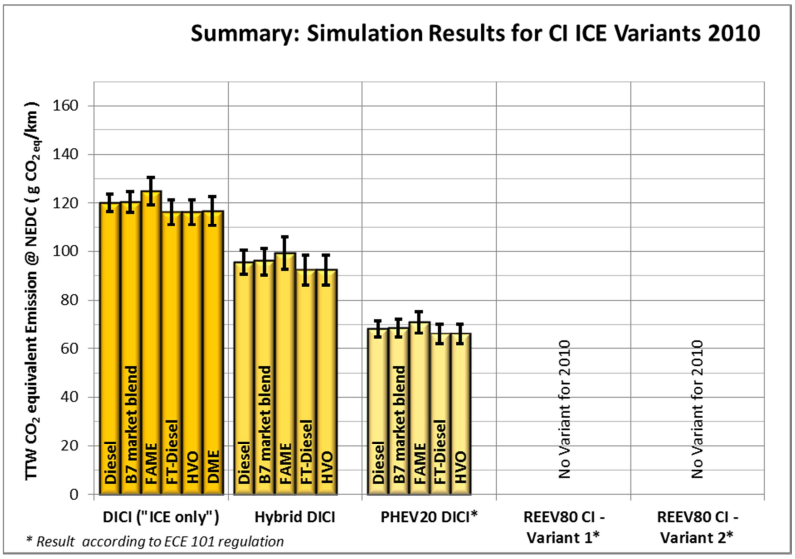


Figure 7-3: Summary of CO_2 equivalent emission results for SI ICE Configurations 2020+

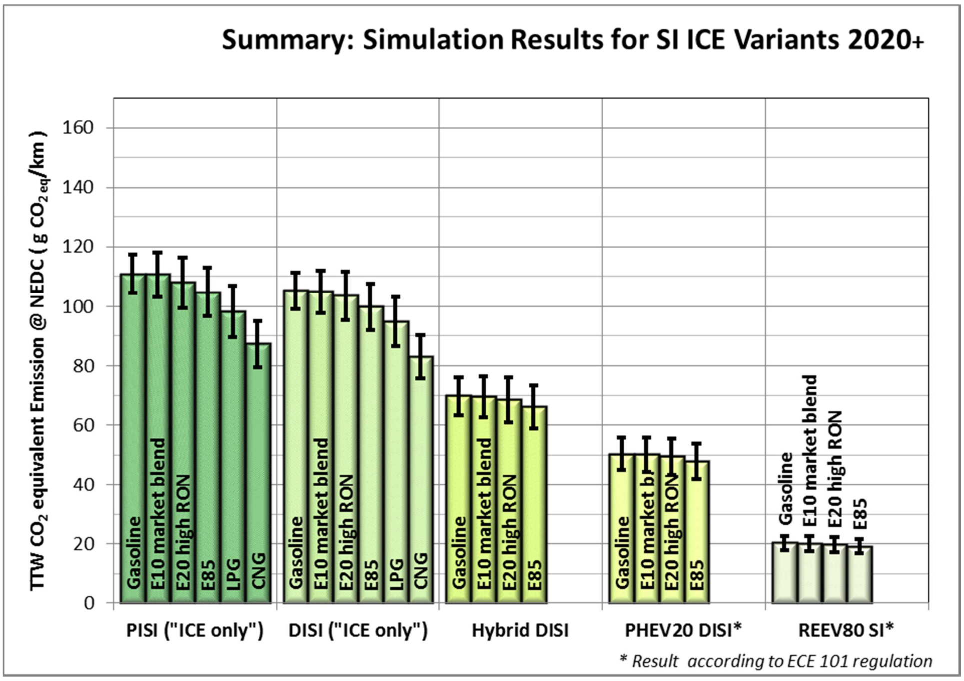


Figure 7-4: Summary of CO_2 equivalent emission results for CI ICE Configurations 2020+

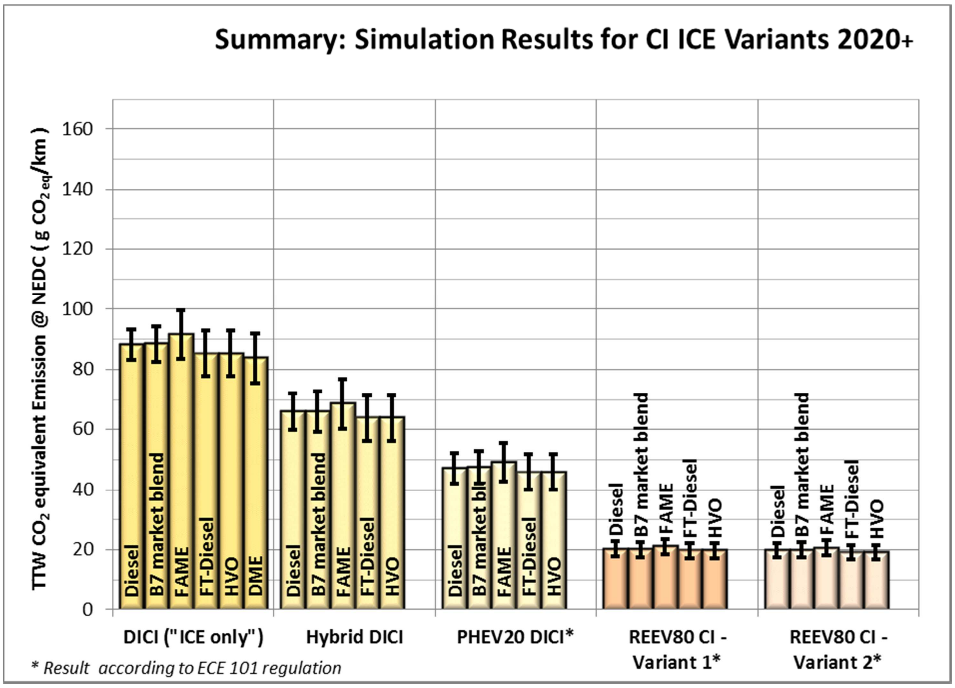


Figure 7-5: Summary of energy consumption results for SI ICE Configurations 2010

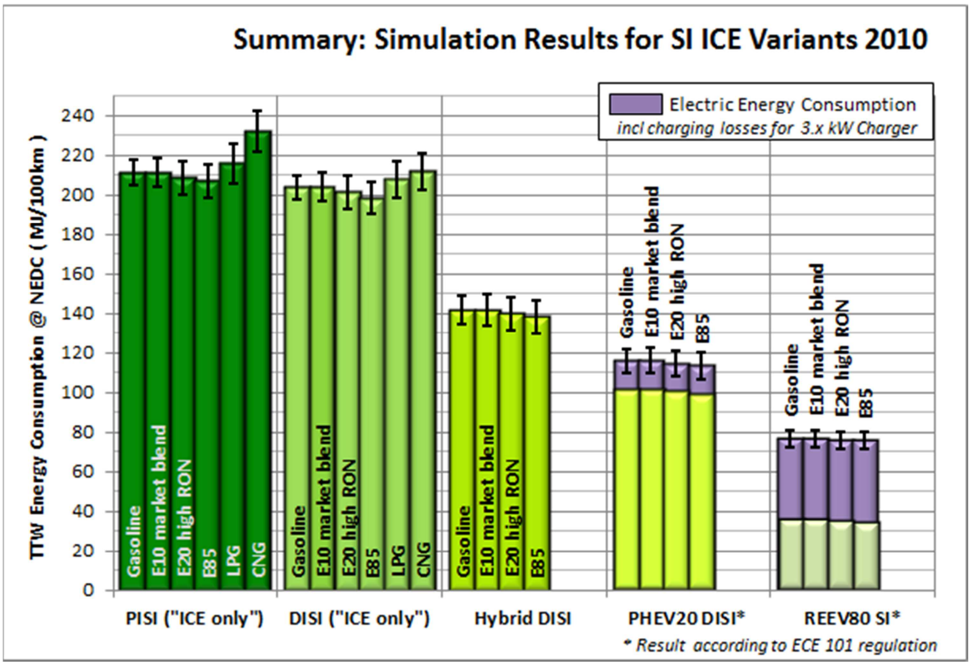


Figure 7-6: Summary of energy consumption results for CI ICE Configurations 2010

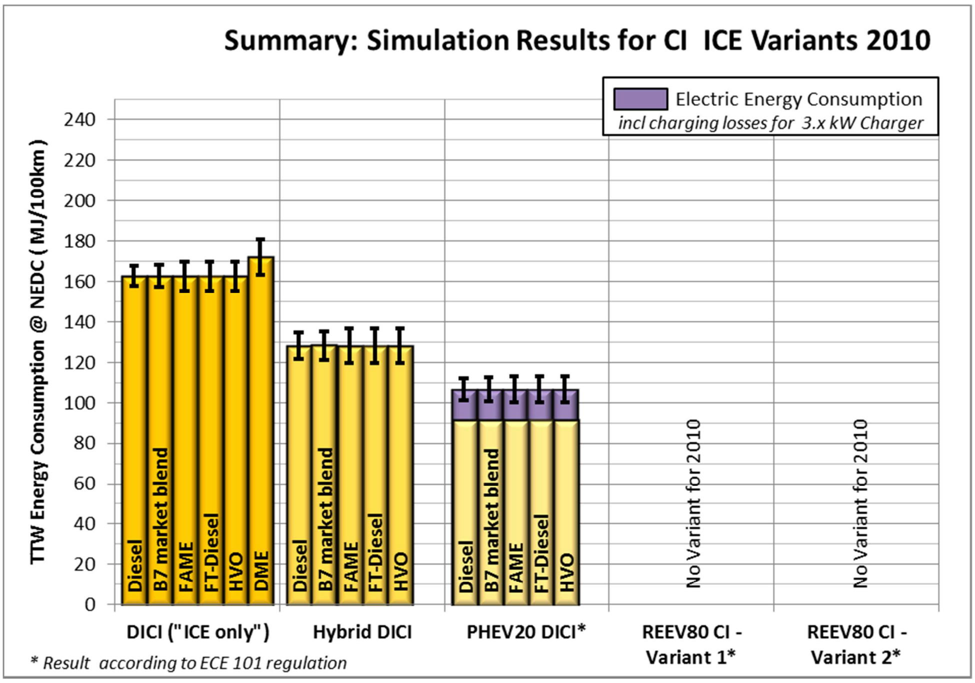


Figure 7-7: Summary of energy consumption results for SI ICE Configurations 2020+

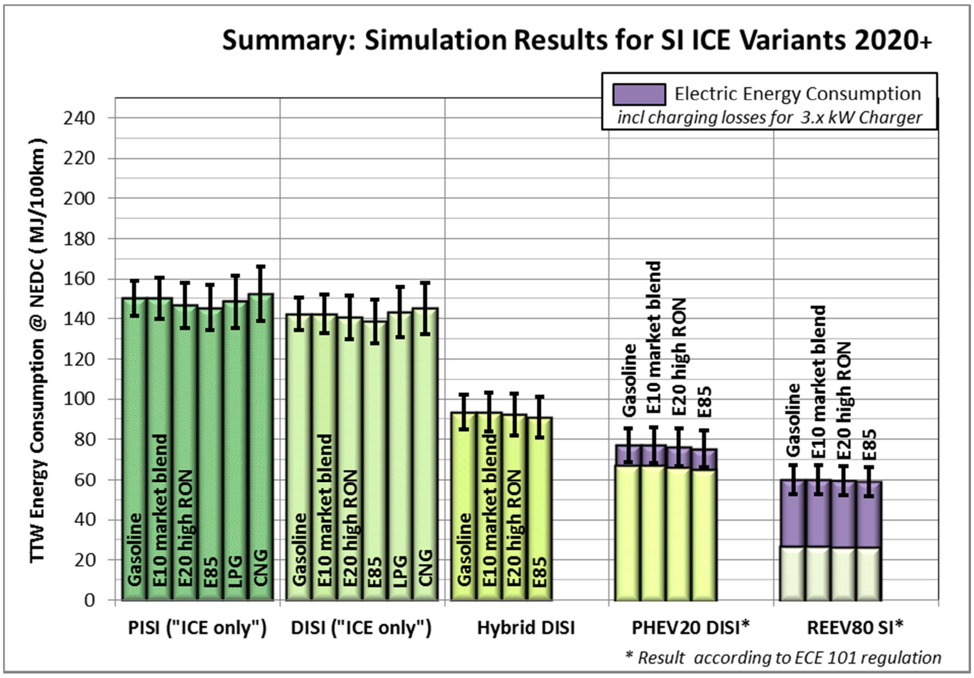


Figure 7-8: Summary of energy consumption results for CI ICE Configurations 2020+

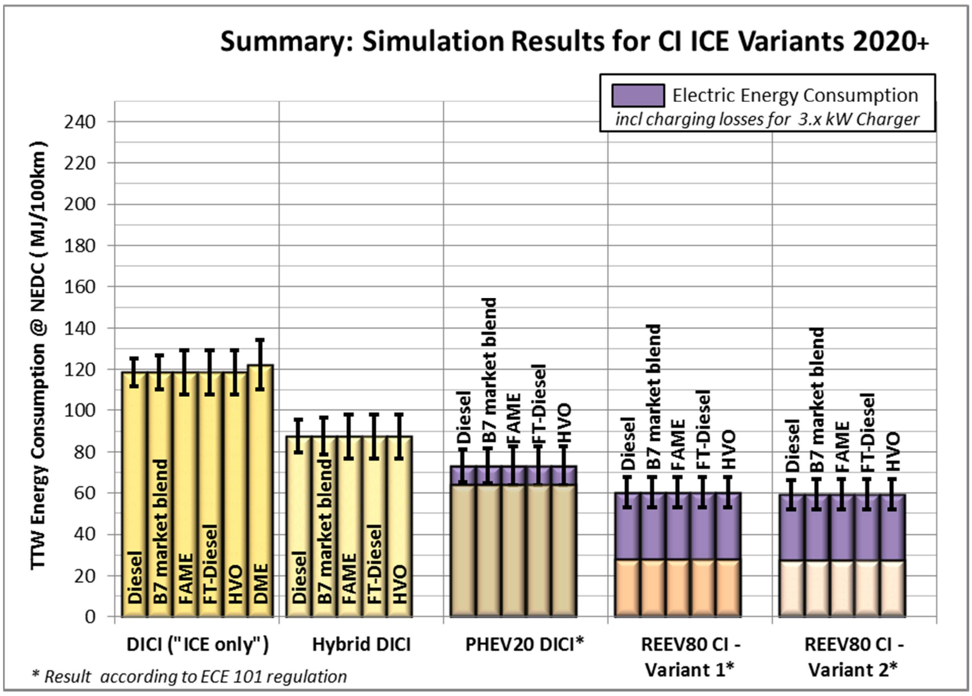
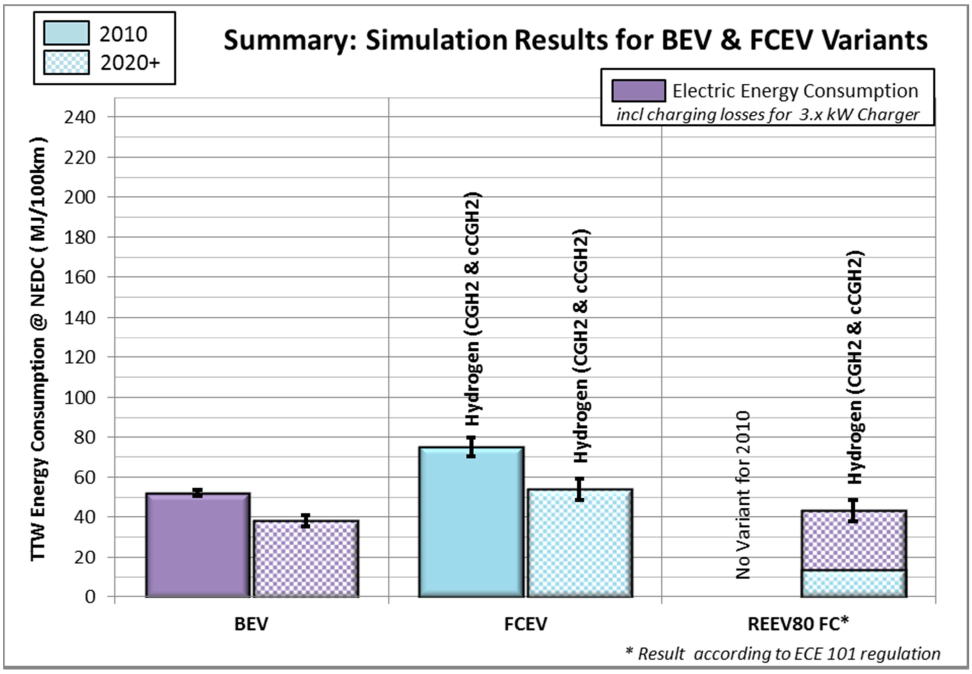


Figure 7-9: Summary of energy consumption results for BEV & FCEV Configurations 2010 & 2020+

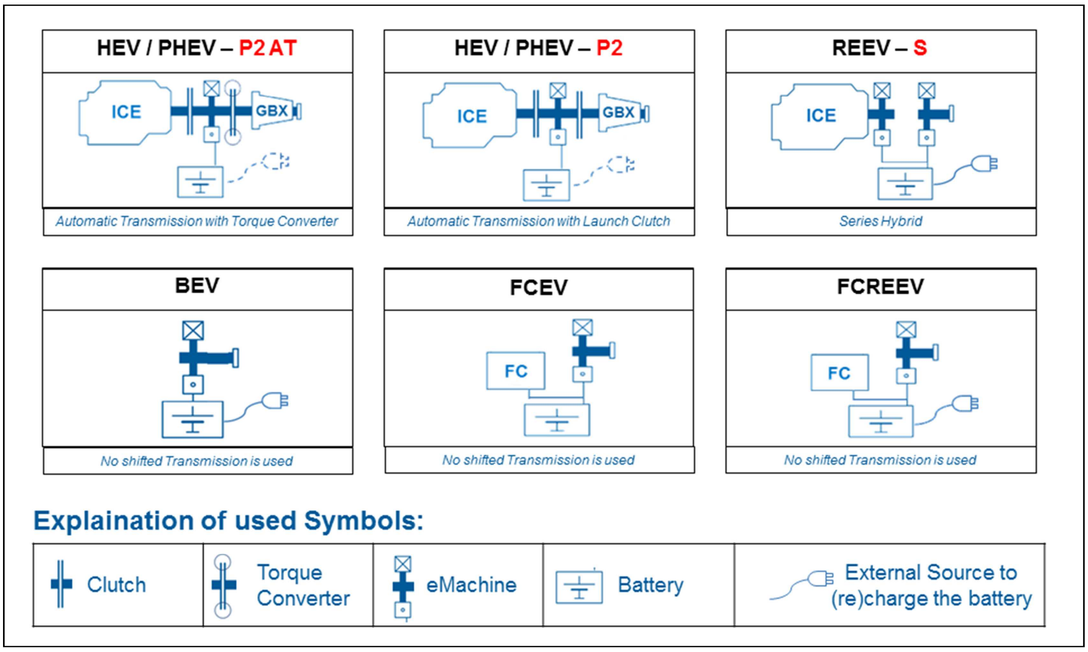


8 Acronyms & Abbreviations used in the TTW study

APP	Acceleration Pedal Position
AT	Automatic Transmission
B7	Diesel fuel with up to 7% v/v FAME, according to EN590
BEV	Battery Electric Vehicle
$cCGH_2$	cryo Compressed Gaseous Hydrogen (also known e.g. as CcH_2)
CGH_2	Compressed Gaseous Hydrogen
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
DICI	Direct Injection Compression Ignition
DISI	Direct Injection Spark Ignition
DME	Di-Methyl-Ether
E10	Gasoline fuel with up to 10% v/v Ethanol (or 3.7 wt% oxygen content), according to EN228
E20	Gasoline fuel with up to 20% v/v Ethanol or up to 7.4 wt% oxygen content
E85	Gasoline fuel with 85% v/v Ethanol
ECE	Economic Commission for Europe
EHPS	Electro-Hydraulic Power Steering
EPS	Electric Power Steering
EUCAR	European Council for Automotive Research and Development
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
FT	Fischer-Tropsch, the process named after its original inventors that converts syngas to hydrocarbon chains
FWD	Front Wheel Drive
GHG	Greenhouse Gas
GVW	Gross Vehicle Weight
HC	Hydro Carbons, as a regulated pollutant
HEV	Hybrid Electric Vehicle
HPS	Hydraulic Power Steering

HV	High Voltage
HVO	Hydro-treated Vegetable Oil
ICE	Internal Combustion Engine
ITW	Inertia Test Weight
JRC	Joint Research Centre (of the EU Commission)
LHV	Lower Heating Value ('Lower" indicates that the heat of condensation of water is not included)
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gases
LPM	Load Point Moving (in ICE operation)
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
PEM	Proton Exchange Membrane, a Fuel Cell technology
PHEV	Plug-In Hybrid Electric Vehicle
PISI	Port Injection Spark Ignition
REEV	Range Extender Electric Vehicle
REEV FC	Fuel Cell driven Range Extender Electric Vehicle
RON	Research Octane Number
SI	Spark Ignition
SOC	State Of Charge (of a Battery)
THC	Total Hydrocarbon
TTW	Tank-To-Wheels, description of the burning of a fuel in a vehicle
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 configurations

Figure 8-1: Powertrain layouts, explanations of used symbols



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