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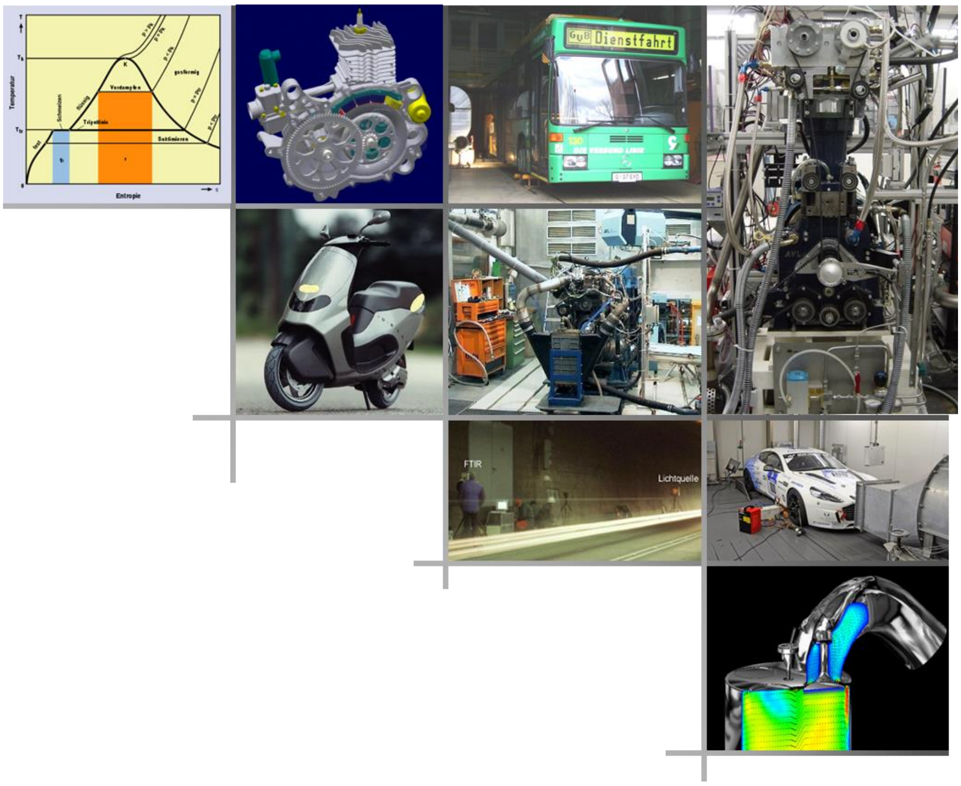

Feasibility assessment regarding the development of VECTO for hybrid heavy-duty vehicles

CLIMA.C.4/ETU/2016/0005LV

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Abbreviations

ACEA	European Automobile Manufacturers Association
AMT	Automated manual transmission, spur-gear design
AT	Automated transmission, hydraulic element & planetary gearbox
avrg	Average
CLCCR	International Association of the Body and Trailer Building Industry
CLEPA	European Association of Automotive Suppliers
CO_2	Carbon dioxide
dyno	Dynamometer
ECU	Electronic control unit
EM	Electrical machine
EPT	Ex-Post Test Procedure; test for validation of VECTO input data related to axle, gear box and engine based on a complete vehicle test
Eta or η	Efficiency, usually defined here as ratio from output work to input work of a component
FC	Fuel consumption, usually ratio of (consumed fuel) to (driven distance)
GEM	Greenhouse Gas Emissions Model, c/o USEPA
GHG	Greenhouse gas
HDH	Heavy-Duty Hybrid vehicle
HDV	Heavy-duty vehicle, maximum permitted vehicle mass > 3.5 t
HEV	Hybrid electrical vehicle
ICE	Internal combustion engine
MT	Manual transmission
no.	Number
OEM	Original Equipment Manufacturer
PHEV	Plug-in hybrid electrical vehicle
RC-element	Resistor–Capacitor element
ReESS	Rechargeable Energy Storage Device
SI	Système international d’unités
SOC	State of charge, energy storage, battery or supercapacitor
SORT	Standardized On-Road Test
UITP	International Association of Public Transport
VECTO	Vehicle Energy Consumption calculation Tool
w/o	without

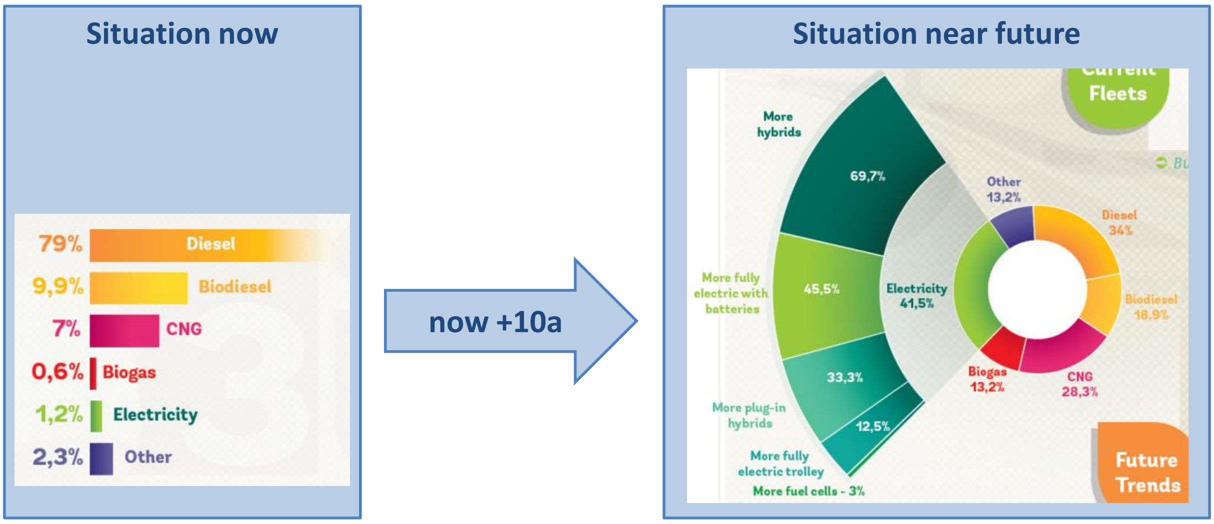
1 Introduction

The computer simulation tool, VECTO, used to calculate CO_2 emissions from new heavy-duty vehicles to be certified, reported and monitored in the European Union mandatory from 1.1.2018 on. In its current version, VECTO does not have the capability to simulate hybrid powertrains. This represents a clear limitation of the entire approach because it would leave a significant and increasing share of new HDVs (see Figure 1), in particular city buses where the technology is more spread, without a certified fuel consumption value. In addition, this could lead to a potential market distortion because if they cannot be compared in a mandatory EU certification procedure with the other HDVs in terms of fuel consumption and CO_2 emissions, the introduction of hybrid powertrains might be disincentivized.

The aim of this study was to assess the current situation and to propose technical solutions for the extension of the HDV CO_2 certification procedure to include hybrid powertrain configurations. Therefore, relevant powertrain configurations to be considered shall be derived from the assessment of hybrid technologies –existing or under development- at OEM level. One obvious strategy is to extend VECTO so as to inherently support hybrids. Independently of assessing the feasibility of extending VECTO, due to the intrinsic complexity of the issue and the potential costs involved, the study should also identify possible alternative approaches beyond the use of VECTO but still showing a good correlation with VECTO results. For the detailed analysis of possible options the following 5 tasks were performed for the purposes of this study:

1) Assessment of the current status regarding hybrid powertrains at OEM level
2) Review of the methodologies and tools used or planned to be used for hybrid HDV certification in other global markets
3) Identification and description of possible options for the extension of VECTO to simulate hybrid HDVs
4) Identification of alternative options for certifying hybrid HDVs
5) Assessment and comparison of all suggested approaches for certifying fuel consumption and CO_2 emissions of hybrid HDVs

Figure 1: Future trends in propulsion systems for buses in urban operation[1]



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[1] UITP 2013

2 Task 1: Assess current status regarding hybrid powertrains at OEM level

Objectives:

- to elaborate, what types of hybrid powertrains and architectures are currently being produced or developed for near future commercial use

Key tasks:

- collect information on the hybrid powertrain options currently produced/being developed by the OEMs
- create a classification of the various hybrid systems with respect to hybrid system type, architecture and specific configurations of each type and architecture based on the information collected
- compile rough estimates on the OEM claims for the fuel-consumption savings of the available powertrain options
- compile estimates on the maturity and penetration level in the market for these systems now and in the next decade
- collect information on how each option could be handled at certification level methodologically and in terms of VECTO adaptation

Outputs:

- Relevant types, architectures and configurations of hybrid systems for CO_2 certification
- OEM estimated fuel saving potential of different hybrid powertrains
- OEM estimated maturity of technology and penetration level in market of different hybrid powertrains
- Possible options to handle hybrid powertrains in the CO_2 certification

2.1 Overview of task 1

The basic idea for collecting a lot of information efficiently and also being able to compile aggregated and structured findings later on was to create a questionnaire. But given the diversity of variants of hybrid powertrains, it was important to develop a broad overview at the beginning of the study for developing some kind of standardization scheme. Thus, in a first step information collection on an informal level (i.e. via existing contact persons at hybrid system OEMs) was performed. TUG has been in contact with engineers from vehicle manufacturers and component suppliers to collect information on existing and future (near future commercial application) hybrid powertrain technologies regarding system types, architecture, technology level and special configurations of these parameters. In parallel to this activity a desk based search of literature regarding existing and future (near future commercial application) hybrid powertrain technologies was performed. Based on the information retrieved during the first step, a structured questionnaire with a standardized classification of hybrid powertrains and corresponding methods used by vehicle manufacturers and suppliers was designed and distributed in a second step.

Since the information asked for in the questionnaire is very sensitive and should not be revealed to competitors, TUG had to sign non-disclosure agreements with all vehicle OEMs and is not allowed to share specific information given by individual OEMs. Thus, an aggregated and structured overview was developed from the feedback received as basis for the work performed in tasks 3 to 5.

Where more detailed information was necessary, interviews were conducted with dedicated hybrid system experts at each manufacturer on demand over the course of the study.

2.2 Information collection for task 1

This section gives a summary of all the organizations that were contacted by TUG over the course of this study and the respective feedback received. Table 1 shows the instruments used for collecting information and also whether feedback was received or not. Expert interviews were conducted with the respective contacts at each institution via e-mail or phone to provide more detailed information where necessary. The questionnaire distributed can be found in the annex of this study.

Table 1: Organizations contacted and instruments used for information collection

		Instruments used			
Organization		Informal collection of information	Questionnaire		Expert interviews
			Distributed	Feedback received	
ACEA			X		
	DAF	X		X	X
	Daimler	X		X	X
	Iveco	X		X	
	MAN	X		X	X
	Scania	X		X	X
	Volvo	X		X	X
CLEPA			X		
CLCCR			X		
UITP			X	X	
ECOCHAMPS		X			

The questionnaire was distributed to manufacturers of hybrid vehicles or component suppliers via the respective umbrella organization which forwarded it to its individual members, which was the agreed way to proceed at the project meeting held in Brussels on 30th of November 2016.

All of the European Automobile Manufacturers Association's (ACEA) members contacted provided feedback to the questionnaire.

The International Association of Public Transport (UITP) provided feedback received from four of their members, one public transport operator and three industry members: BAE Systems (industry), Alexander Dennis (industry), Yutong (industry) and TEC Belgium (operator).

The European Association of Automotive Suppliers (CLEPA) and the International Association of the Body and Trailer Building Industry (CLCCR) provided no feedback to the questionnaire. At the project meeting held in Graz on 3rd of April 2017, Mr. Thorenz as representative of CLEPA stated that no feedback was provided due to high number of suppliers within CLEPA which made it difficult to come to a common position within the given timeframe of the project.

The respective contact person of the ECOCHAMPS project, Mr. Ciuffo from the Joint Research Centre (JRC) of the European Commission, stated that there can be no contribution to this study expected by the ECOCHAMPS project. The project is very much OEM oriented (i.e. usage of OEM specific test methods and simulation tools) with the main goal of developing more efficient hybrid powertrains without significant increase in production costs. The planned activities in the ECOCHAMPS project which could contribute to this feasibility study were put on hold at this point in time.

2.3 Outcome and findings of task 1

In this section the findings of task 1 are summarized under the respective subparagraphs below.

2.3.1 Relevant types, architectures and configurations of hybrid systems for CO_2 certification

Table 2 shows the types, architectures and configurations of hybrid systems identified as relevant for the CO_2 certification based on the feedback to the questionnaire as well as on the results of the desk based search of literature. The subsequent subparagraphs contain detailed definitions and descriptions of the different hybrid systems as well as of all technical terms used. Paragraph 2.3.1.4 describes each of the hybrid systems listed in Table 2 in detail with a schematic diagram.

Table 2: Types, architectures and configurations of hybrid systems identified as relevant for CO_2 certification

System type	Parallel			Serial	Power-split
	Micro	Mild	Full		
Electric	X	X	X	X	X
Hydraulic					
Kinetic					

It seems that for the next years only electric hybrid systems are produced or being developed. Not only the feedback received by vehicle OEMs but also the desk based search of literature lead to the same conclusion regarding this fact. There were concepts of hybrid powertrains identified having other than electric system types, but these systems are either small-scale series, prototypes performing field tests, retrofitting equipment installed in already existing vehicles or are still under development for an initial field testing phase.[2] Therefore other than electric system types are not considered as relevant for CO_2 certification in the near future.

Green Propulsion, as a member of UITP, reported that they have developed a plug-in hybrid motorisation for urban busses which is installed as retrofit equipment in a standard vehicle (i.e. replacement motorisation). Since there is no existing path in the current CO_2 certification scheme how to handle systems installed after certification of the vehicle by the original manufacturer the specific design of this plug-in hybrid system is not considered relevant for the scope of this study. A schematic diagram of this system can be found in paragraph 2.3.1.4.1.

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[2] KIT 2012, 14 pp.; Rexroth 2007; Rexroth 2009; PassengerTransport 2015; JustAuto 2014

2.3.1.1 Definition of hybrid system architecture

The hybrid system architecture defines the way how individual components are arranged and connected in a hybrid powertrain. The basic segmentation between parallel, series and power-split systems is explained in Table 3. The schematics in Figure 3 to Figure 6 show the related configurations to be considered.

Table 3: Basic segmentation of hybrid system architecture

Architecture	Description
Parallel	Both, ICE and alternative energy converter mechanically connected to wheels of vehicle. Propulsion power can be provided by either of them or both simultaneously.
Series	Only alternative energy converter mechanically connected to wheels, not ICE. ICE connected to second alternative energy converter to generate energy that is used to directly power alternative energy converter mechanically connected to wheels or is stored in ReESS.
Power-split	System with ICE and two alternative energy converters connected via planetary gearbox(es), one alternative energy converter is directly connected to the wheels. ICE can be used in variable operation from providing propulsion power to the wheel directly to generating energy or both simultaneously by controlling the second alternative energy converter which is not directly connected to the wheels. The alternative energy converter which is directly connected to the wheels is used for regenerative braking. This system can provide both, parallel and series operation of the hybrid powertrain with operation of the ICE independently of the wheel speed.

2.3.1.2 Definition of technical terms used

Table 4 explains the technical terms used for characterizing hybrid powertrain systems.

Table 4: Definitions of technical terms used

Technical term	Description
Hybrid system type	The type of the hybrid system is defined by the type of alternative energy converter and rechargeable energy storage system that is used in a hybrid powertrain (e.g. electric, hydraulic, flywheel).
Alternative energy converter	A component of the hybrid powertrain other than the internal combustion engine, converting one form of energy into a different one for the primary purpose of vehicle propulsion (e.g. electric machine).
Rechargeable energy storage system	A component of the hybrid powertrain that can store chemical, electrical or mechanical energy and that may also be able to internally convert those energies without being directly used for vehicle propulsion, and which can be refilled or recharged externally and/or internally (e.g. battery).

2.3.1.3 Definition of degree of hybridization

An attribute applicable to parallel hybrids, characterizing the capabilities of the system. The three different degrees of hybridization are explained in Table 5.

Table 5: Definitions for different degrees of hybridization

Degree of hybridization	Regenerative braking only	Regenerative braking and boosting	Charge-depleting mode
	Stored energy can only be used to re-crank the ICE and/or power auxiliaries.	Stored energy can also be used to modestly assist ICE in propulsion.	Significant amount of propulsion power can be provided by alternative energy converter, also driving mode with ICE off is possible.
Micro	Yes	No	No
Mild	Yes	Yes	No
Full	Yes	Yes	Yes

2.3.1.4 Schematic diagram of different generic hybrid systems

The figures in this paragraph describe the types, architectures and configurations of hybrid systems identified as relevant for the CO_2 certification in subparagraph 2.3.1.

Figure 2: Elements for schematic diagrams of hybrid powertrain architecture

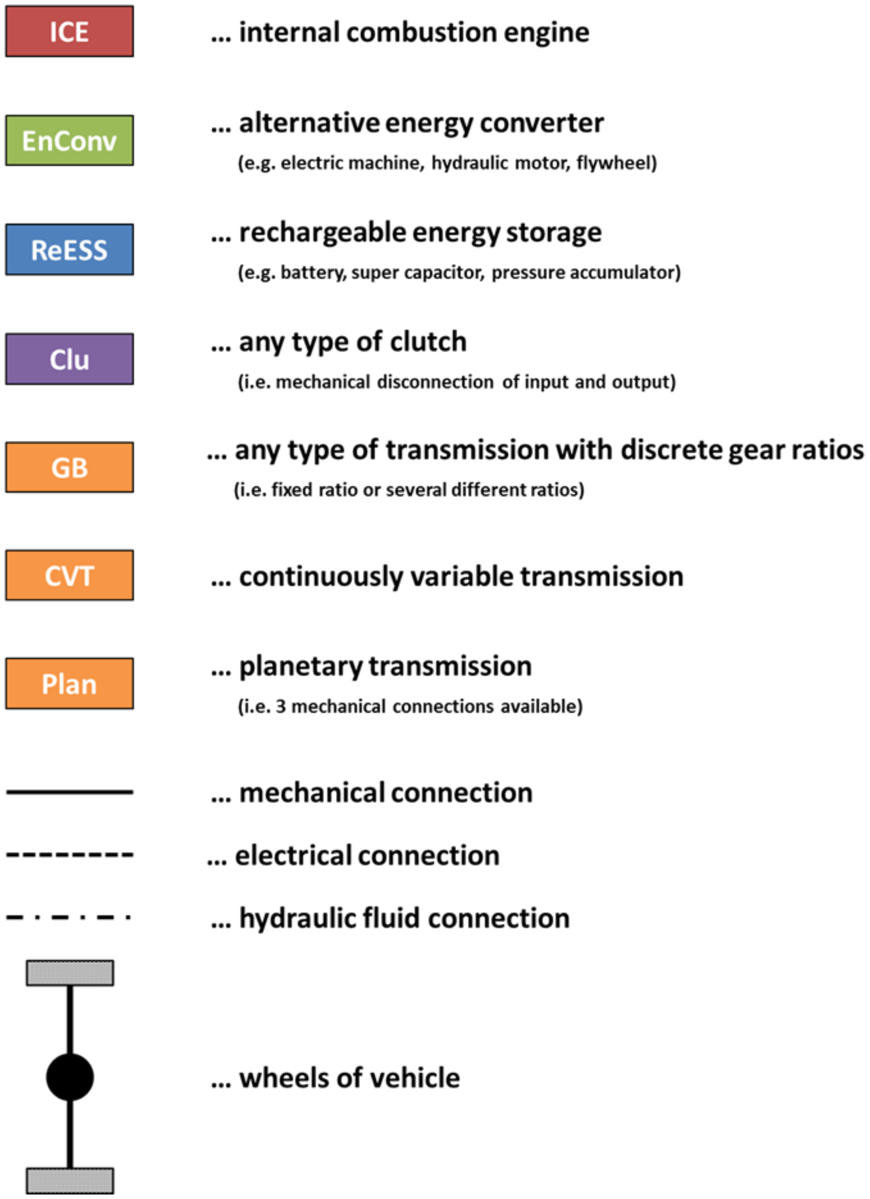


Figure 3: Definition of electric parallel micro hybrid system

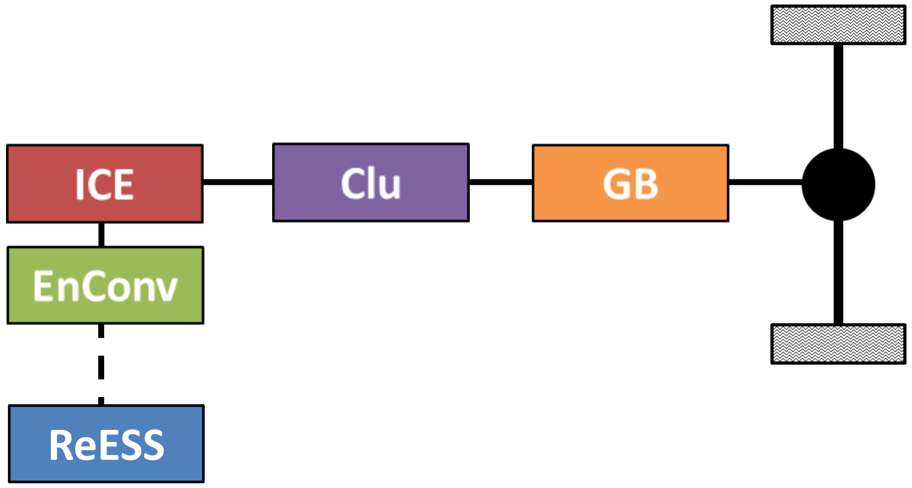


Figure 4: Definition of electric parallel mild/full hybrid system

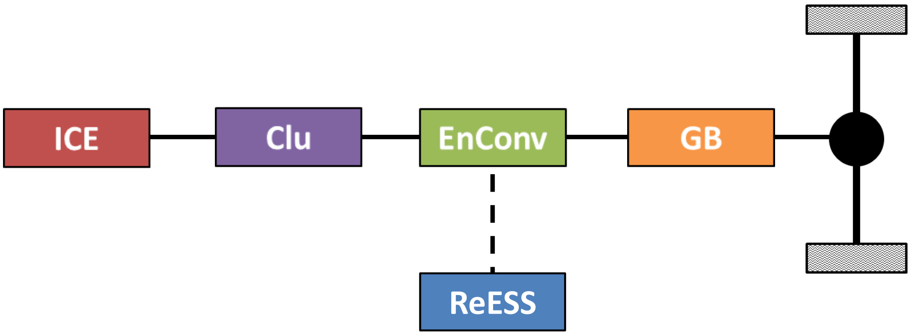


Figure 5: Definition of electric serial hybrid system

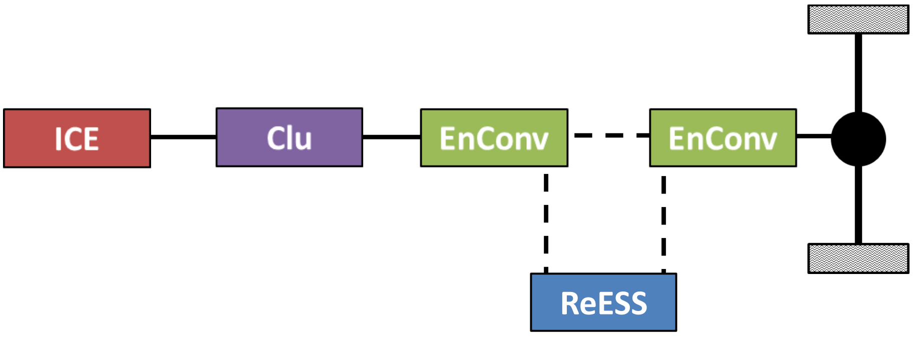
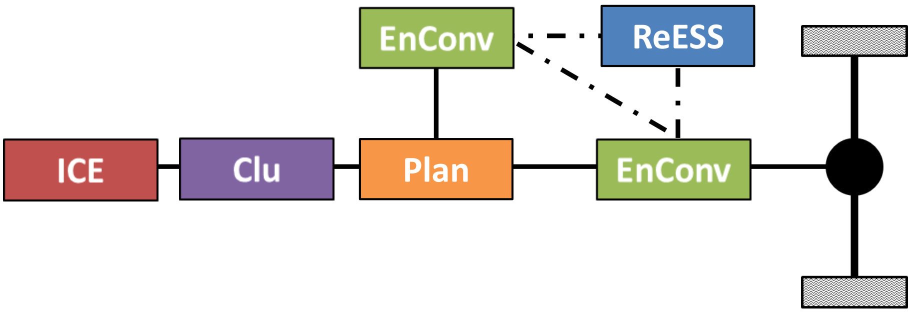


Figure 6: Definition of electric power-split hybrid system

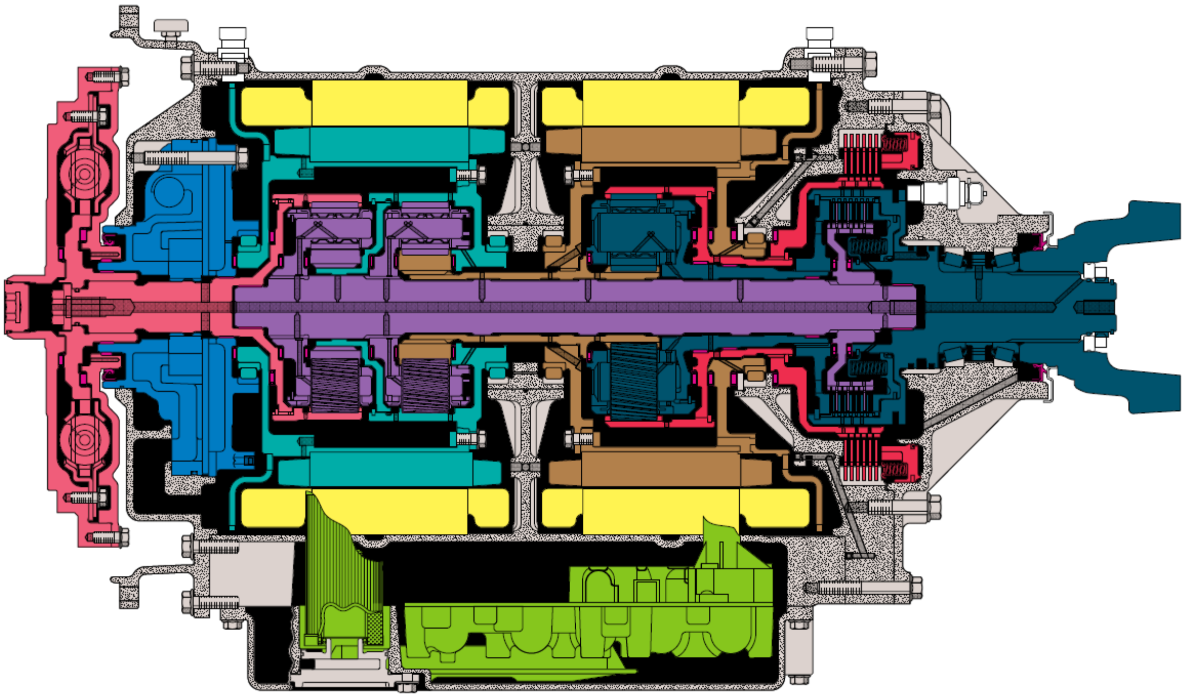


2.3.1.4.1 *Schematic diagram of specific hybrid systems*

In this subchapter two hybrid systems already available on the market are described.

The hybrid transmission by Allison Transmission can be seen as a more complex variant of the hybrid architecture power-split. The Allison system consists of two electric motors, three planetary gear sets and two wet friction clutches (see Figure 7). This system is relevant for the CO_2 certification scheme for hybrids since it is originally installed in the vehicle to be certified.

Figure 7: Allison Transmission power-split hybrid system[3]



The plug-in hybrid system by Green Propulsion consists of an ICE and two electric motors where the generator set (i.e. connected pair of ICE and EM) can be disconnected from the wheels with a

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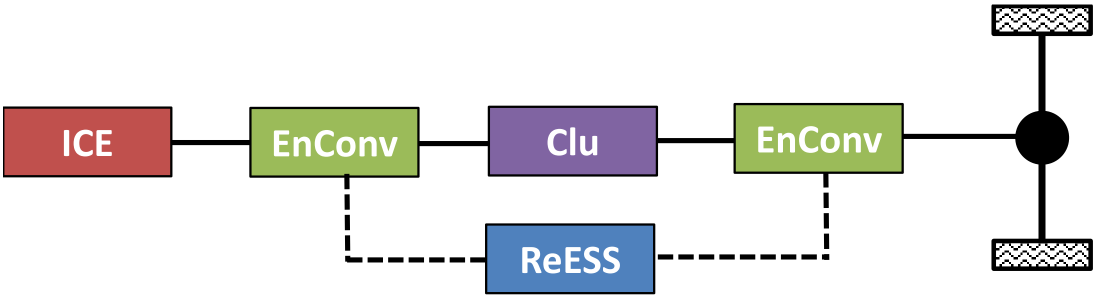
[3] Allison 2011

clutch allowing the operation as either parallel or series architecture. This system is not considered relevant for the scope of this study since it is installed as replacement equipment as explained in paragraph 2.3.1.

Figure 8: Green Propulsion plug-in hybrid system (replacement equipment)



2.3.2 OEM estimated fuel saving potential of different hybrid powertrains

Table 6 shows the estimated fuel saving potential of different hybrid powertrains in percent. The individual OEMs provided estimated values only for the combination of vehicle configurations and duty cycles where they already have or plan to introduce hybrid powertrains on the market and have analysed the saving performance in more detail. Thus the answers of different OEMs were quite inhomogeneously distributed among the given standardized segmentation table. In order not to disclose any confidential information the results have been aggregated to an even higher level of detail when evaluating the feedback to the questionnaire. This leads to the segmentation of four relevant operation scenarios as listed in Table 6 below, which shows the average of the estimates provided by the individual vehicle OEMs as well as the minimum and maximum values reported in parentheses.

Table 6: Estimated fuel saving potential of different hybrid powertrains (in %)

Vehicle operation / duty cycle	Parallel			Serial	Power-split
	Micro	Mild	Full		
Long-Haul	0.8 (0.5 – 2.0)	2.5 (1.0 – 5.0)	5.0 (1.0 – 8.0)	2.5 (0.0 – 5.0)	4.5 (1.0 – 8.0)
Regional	1.4 (0.8 – 2.0)	3.5 (3.0 – 4.0)	7.0 (5.0 – 15.0)	4.0 (4.0 – 4.0)	10.0 (5.0 – 15.0)
Urban	3.3 (1.0 – 4.0)	6.0 (2.0 – 12.0)	15.0 (5.0 – 25.0)	9.5 (2.0 – 12.0)	15.0 (5.0 – 25.0)
City bus	3.7 (2.0 – 6.0)	8.7 (3.0 – 24.0)	22.3 (7.0 – 30.0)	21.8 (8.0 – 30.0)	19.9 (8.0 – 28.3)

2.3.3 OEM estimated maturity of technology and penetration level in market of different hybrid powertrains

This is probably one of the most sensitive information to reveal for OEMs, since this data includes information about the future business strategy of the company. Due to the sensitivity level, not all OEMs provided data on this topic. Also not to disclose the different business strategies pursued, the answers of different OEMs were quite inhomogeneously distributed among the given standardized segmentation table. Due to confidentiality agreements, it is not possible for this question to show detailed replies in this report, but general conclusions can be drawn from the feedback received:

- All hybrid technologies are expected to be developed to high maturity level within the next 10 years
- The penetration level of specific hybrid technologies is expected to be quite high in the respective vehicle class within the next 10 years
- For certain vehicle classes running mainly in urban application a penetration level of more than 30% up to 75% is expected within the next 10 years
- For certain vehicle classes running mainly in long-haul application a penetration level of 15-25% is expected within the next 10 years (up to 70% for micro or mild technologies)

In addition to the above values given by OEMs as replies to the questionnaire sent out for this study, UITP reported numbers for city buses based on the market expectations of OEMs compiled in the ZeEUS project (http://zeeus.eu/): According to this source the market share of hybrid city buses varies from 11-20% depending on the speed of change from ICE based to alternative propulsion systems (forecast for base scenario is 9% in 2020 and 11% in 2025).

It should be noted that the ZeEUS project is focusing on city buses only whereas the figures provided by OEMs include also trucks, which might be a source for the differences. Also, plug-in hybrids were counted as electric vehicle in the ZeEUS project and thus are not included in the forecast numbers of the ZeEUS project – this might pose an additional source for the differences.

2.3.4 Possible options to handle hybrid powertrains in the CO_2 certification

Table 7 shows the possible methods to handle hybrid powertrains in the CO_2 certification and the average rating for each method determined by evaluating the individual feedback provided (by six ACEA members and four UITP members). The valid range for the rating of the options is from 1 to 5, where 1 means not viable at all and 5 means perfectly viable for to handling hybrid powertrains in the CO_2 certification.

The methods listed were already aligned as reasonable standard options during the phase of informal collection of information before creating the questionnaire. Nevertheless, participants in the survey were asked to indicate additional alternative methods which are not present in the standardized table, but no alternative method was reported in the feedback.

Table 7: Assessment of different options for CO_2 certification of hybrid vehicles (overall average)

Item no.	Method	Description of method	Rating (1=poor, 5=best)
1	**Simulation in VECTO**	The hybrid system is simulated within the existing VECTO software by implementing separate models for each relevant component of the hybrid powertrain, the respective architectures of the hybrid powertrain defining how the components are physically connected and a hybrid controller handling the operation of the hybrid system.	3.3
2	**Simple crediting scheme**	Generic savings depending on several parameters (e.g. type of hybrid system, vehicle class, mission profile). The generic values could be defined in a normalized way depending on parameters like vehicle mass, maximum power of alternative energy converter, maximum capacity of ReESS. *This method requires the usage of a conventional reference vehicle to determine the base fuel consumption in VECTO!*	2.1

Item no.	Method	Description of method	Rating (1=poor, 5=best)
3	**Advanced crediting scheme**	Savings calculated in a post-processing step in VECTO taking limited maximum power of alternative energy converter and limited maximum capacity of ReESS over time into account. *This method requires the usage of a conventional reference vehicle to determine the base fuel consumption in VECTO!*	2.7
4	**Powertrain measurement**	Measurement of average efficiency of hybrid system in grams fuel per kWh work performed on a powertrain test bench (e.g. connection at output shaft of transmission or of final drive) over several vehicle cycles, where the remaining part of the vehicle downstream of the connection point as well as the driving resistances need to be simulated in real time. From the measured average efficiency values in g/kWh the total fuel consumption is determined in a second step by running a conventional reference vehicle in VECTO to get the cycle work. *This method requires the usage of a conventional reference vehicle to determine the cycle work in VECTO!*	1.8
5	**Chassis dyno measurement**	a) Either direct measurement of the fuel consumption and CO_2-emissions for each hybrid vehicle on the chassis dyno. b) Or determination of the average efficiency of the hybrid system on the chassis dyno and determination of cycle work with a conventional reference vehicle in VECTO (as described for option 4). *This method requires the usage of a conventional reference vehicle to determine the cycle work in VECTO!*	2.9

Item no.	Method	Description of method	Rating (1=poor, 5=best)
6	**On-road measurement**	Determination of the average efficiency of the hybrid system in grams fuel per kWh work performed on-road by using torque measurement rims and a fuel-flow meter. From the measured average efficiency values in g/kWh the total fuel consumption is determined in a second step by running a conventional reference vehicle in VECTO to get the cycle work. *This method requires the usage of a conventional reference vehicle to determine the cycle work in VECTO!*	2.2

While Table 7 shows the average values over all ten individual replies received, Table 8 compares the view of two different organizations:

From the comments provided by UITP members one can conclude that they are in favor of direct measurement of CO_2 emissions and fuel consumption by a straight forward procedure that can also be repeated by the public transport operators for verification purposes. UITP commented that if simulation in VECTO is used for hybrid buses, it should be done based on the SORT cycles and in combination with an on-road verification test. It was not considered by UITP members that there might be a lot of variants for each vehicle type (e.g. cabins/chassis, axles etc.) in the future, especially for trucks as opposed to buses, which would significantly increase the effort for procedures based on measurement. Also, the SORT cycles were developed for city buses and will not give realistic results for trucks or coaches at all.

Nevertheless, it was stated that in the future the simulation in VECTO could be a very cost efficient method producing accurate results given that specific component data as well as the specific hybrid control strategy would be used.

From an ACEA point of view due to the expected number of variants for each vehicle type a simulation based approach is the only viable method that is future-proof. Also, it is the only method that produces results that correlate with the ones for conventional vehicles since the same basic simulation routine is used.

Table 8: Assessment of different options for CO_2 certification of hybrid vehicles (average by institution)

Item no.	Method	Average rating by ACEA (1=poor, 5=best)	Average rating by UITP (1=poor, 5=best)
1	**Simulation in VECTO**	4.7	1.3
2	**Simple crediting scheme**	2.8	1.0
3	**Advanced crediting scheme**	3.3	1.8
4	**Powertrain measurement**	1.3	2.5
5	**Chassis dyno measurement**	1.9	4.3
6	**On-road measurement**	1.3	3.5

2.3.5 OEM estimates on the effort of the different methods for handling hybrid powertrains in the CO_2 certification

This question addressed the estimation of the effort needed for both implementation and application of the different options presented in paragraph 2.3.4 for handling hybrid powertrains in the CO_2 certification. Two separate assessments were requested by the questionnaire:

- The estimated effort for the company to support in the development of the different test methods identified as well as the target timeline, when the final procedure needs to be in place for certifying hybrid vehicles from an OEM point of view.
- The estimated costs arising for the company to be able to certify a hybrid vehicle according to the different test methods identified. The estimates for the costs should be split up into initial investments in testing infrastructure necessary and the costs per vehicle certified.

Unfortunately, for this question very little feedback was received and the data obtained was deemed implausible during the evaluation process. Thus, estimates for necessary investment costs were gathered from alternative sources at a later stage in the study, the assumptions made are described in the section of task 4.

3 Task 2: Review of the methodologies and tools used or planned to be used for Hybrid HDV certification

Objectives:

- to perform a review of the methods available for hybrid powertrain certification in other global markets (Focus shall be given to type approval oriented simulators and the regulated methodologies to support these simulators)

Key tasks:

- collect information on existing and future type approval methods for hybrid powertrains
- in cases where simulation tools are used: describe their operating characteristics and compare them with VECTO
- in cases where non-simulation based approaches are used: describe the established approach and discuss whether such alternatives would be functional in the European certification scheme

Outputs:

- Overview of approaches for certification of hybrid powertrains in other global markets
- Assessment of applicability of these approaches in the European certification scheme
- Issues that would need to be considered before application of these approaches in the European certification scheme
- List of advantages and disadvantages of these approaches

3.1 Overview of task 2

In a first step information collection on an informal level (i.e. via existing contact persons at governmental bodies, certification authorities and relevant NGOs) was performed. In parallel to this activity a desk based search of literature regarding existing certification methods for hybrid powertrains (or methods currently under development) was performed. Based on the information retrieved during the first step, a round of detailed questioning was performed where necessary due to the quality of the received information or lack of detail. Focus was given to both simulation-based approaches and the corresponding methodologies as well as non-simulation-based approaches. From all feedback received, a structured overview addressing the items listed in the tender specifications for this task was developed as basis for the work performed in tasks 3 to 5 with special focus on the applicability of the identified methods for the European certification approach.

3.2 Information collection for task 2

This section gives a summary of all the organizations that were contacted by TUG over the course of this study. Table 9 shows the contacted organizations and the instruments used for collecting information.

Table 9: Organizations contacted and instruments used for information collection

		Instruments used	
Organization		Informal collection of information	Expert interviews
USA	US EPA		X
	ICCT	X	
Canada	Environment Canada	X	
Japan	JASIC	X	X
Korea	Korea Transportation Safety Authority (TS2020)	X	
China	Chinese Research Institute for Vehicle Regulations (CATARC)	X	

3.3 Outcome and findings of task 2

In this section the most important findings of task 2 are summarized under the respective subparagraphs below.

3.3.1 Overview of approaches for certification of hybrid powertrains in other global markets

Table 10 gives a basic overview of all different approaches for certification of hybrid powertrains established in other global markets and additionally the UNECE HILS approach. All the approaches listed are explained in detail in the subsequent paragraphs and their applicability in the European certification scheme is discussed.

Table 10: Overview of different approaches for certification of hybrid powertrains in other global markets

	Market		
Parameters	**USA + Canada**	**Japan + UNECE HILS**	**China + Korea**
Method	Powertrain testing	HILS simulation	Vehicle cycle on chassis dyno
Simulation-based	mixed	yes	no
Hybrid part simulated	no	yes	no
Hybrid configurations covered	all	all that are available in simulation model	all that can be handled by the chassis dynamometer
Specific hybrid control strategy included	yes	yes	yes
Specific vehicle data used	Mass, driving resistances, drive axle, tires	Engine, transmission, alternative energy converter, ReESS	all
Generic vehicle data used	Engine, transmission*	Mass, driving resistances, drive axle, tires	none
Specific hybrid component data	all	all	all
Generic hybrid component data	none	none	none

** For the conventional reference vehicle, which is used to simulate g/kWh FC generic engine+transmission is used (limited accuracy of results)*

3.3.2 Approach in USA and Canada

The US regulation phase 2 standards, published in August 2016, apply to vehicles from model year 2021 on and will be phased in gradually, reaching full stringency with model year 2027. Canada aligned its regulations with the US standards in the past and the Canadian Department of Environment is also proposing to keep this regulatory alignment also for the phase 2 standards.

In the US regulation separate engine and vehicle standards are defined, but for the purpose of this study only the vehicle standard shall be analysed. For certification of a hybrid system the powertrain procedure in accordance with 40CFR 1037.550[4] has to be used. The powertrain for a hybrid system comprises the whole hardware of the hybrid powertrain (i.e. ICE, all alternative

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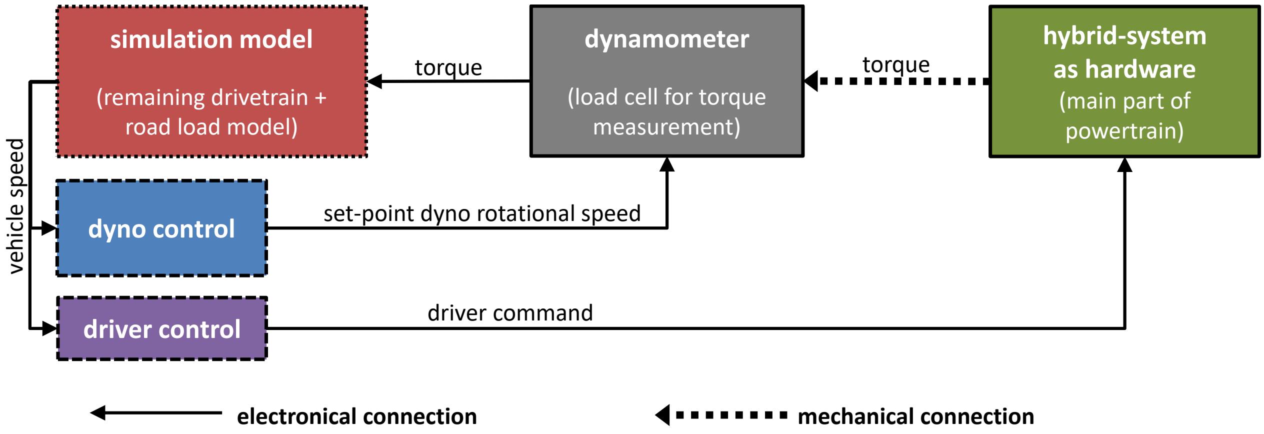
[4] US 2016

energy converters, all ReESSs, all electronic control units necessary to operate the powertrain). The US regulation defines a combined approach for CO_2 certification where in a first step the efficiency of the hybrid system is determined over a set of different cycles on a powertrain testbed and in a second step the conventional (non-hybrid) vehicle simulation model used in the US regulation (GEM) is used to determine the cycle work of the vehicle over the certification duty cycle. The simulation model itself is not analysed in this study since it has no hybrid functionality incorporated but is simply covering conventional ICE powered vehicles. More details on the GEM model can be found in the Regulatory Impact Analysis published by EPA[5].

Powertrain testing is basically similar to engine dynamometer testing. The main differences are where the test article connects to the dynamometer and the software that is used to command the dynamometer and operator demand setpoints. The procedure allows for the dynamometer(s) to be connected to the powertrain either upstream of the drive axle or at the wheel hubs. The output of the transmission is upstream of the drive axle for conventional powertrains. In addition to the transmission, an electric motor in the case of a series hybrid may be located upstream of the drive axle for hybrid powertrains. If optional testing with the wheel hub is used, two or more dynamometers will be needed, one at each hub. Beyond these points, the only other difference between powertrain testing and engine testing is that for powertrains, the dynamometer and throttle setpoints are not set by fixed speed and torque targets prescribed by the cycle, but are calculated in real time by a vehicle model. The powertrain test procedure requires a forward calculating vehicle model, thus the output of the model is the dynamometer speed setpoints. The vehicle model calculates the speed target using the measured torque at the previous time step, the simulated brake force from the driver model, and the vehicle parameters (rolling resistance, air drag, vehicle mass, rotating mass, and axle efficiency). The operator demand that is used to change the propulsion torque from the hybrid system is controlled such that the powertrain follows the vehicle speed target for the cycle instead of being controlled to match the torque or speed setpoints of the cycle. Figure 9 illustrates the principles of powertrain testing.

Figure 9: Basic signal flow of the powertrain method



To limit the amount of testing powertrains are tested in a limited number of simulated vehicles that will cover the range of vehicles in which the powertrain will be used. A matrix of 8 to 9 tests will be needed per certification duty cycle, to enable the use of the powertrain results broadly across all the vehicles in which the powertrain will be installed. The individual tests differ by the vehicle that is being simulated during the test.

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[5] EPA 2016, page 4-3

The results from all the different testruns are then put into the form of fuel mass as a function of n/v (i.e. ratio of rotational speed over the vehicle speed, as defined by the tire radius and drive-axle ratio) and cycle work of the powertrain. Both values rotational speed and cycle work are determined at the location where the powertrain connects to the dynamometer.

GEM uses the results from the powertrain testing instead of the input data required for the powertrain of a conventional vehicle (i.e. engine fuel map, maximum torque curve, motoring curve and transmissions gear ratios) to determine the fuel consumption for the hybrid vehicle over the certification cycle. Since a conventional vehicle model is used, the powertrain in the simulation (engine and transmission) is parameterized using default values fixed for each vehicle class[6]. The remaining parameters are set specific for the hybrid vehicle to be certified and the n/v ratio as well as the cycle work is determined over the certification duty cycle. GEM will then interpolate the fuel consumption from the input matrix determined in the powertrain measurement based on the actual n/v ratio and cycle work of the vehicle being certified.

3.3.2.1 Applicability in the European certification scheme

In principle this method would be applicable in the envisaged European certification scheme. Nevertheless, some issues were identified that would need to be addressed before this approach could be used:

- Typically, the descriptions of the test procedures in the US regulation are not as detailed as in the European legislation, only the basic principle is described. This approach is ok for the US, since there is only a single authority developing the regulations and also monitoring their correct application (by performing selective enforcement audits as well as confirmatory testing in EPA labs)[7] as well as providing information regarding questions on the correct application. Wordings like "*You may perform something consistent with good engineering judgment*", "*You may ask us to …*", "*We may establish specific approval criteria …*" or "*you need to develop your own driver model and vehicle model*" are used throughout the description of the procedure leaving a lot of freedom to the OEM. But this is ok for the US type-approval system, since the OEM is held responsible for the results he produces and EPA is checking input data used as well as results by independent confirmatory testing. Whereas in Europe several type approval authorities exist in parallel, requiring a very strict regulatory framework that leaves as little room for interpretation as possible in order to guarantee comparable test results. Thus, based on the US regulation a modified stricter version would need to be elaborated. Based on the experiences from elaborating the component test procedures for the existing CO_2 certification method, the effort for further developing of a powertrain test procedure would exceed the resources necessary for the previous component tests by far.
- Application of the powertrain method would also require remodelling the existing European VECTO model, since coupling with the testbed control requires a forward-simulation, where the torque represents the forward-path of the calculation and the rotational speed is provided on the backward-path as system response (as illustrated in Figure 9). Additionally, the model would need to run in real-time on the testbed environment. MATLAB Simulink and other similar software are

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[6] EPA 2016, Table 3-27, page 3-81

[7] US 2016, pages 74068-74070

designed for that purpose and there is dedicated rapid prototyping hardware available to create such interactions between different systems. The effort for creating such a system based on open source software is considered very high. It would take several person years to come up with a software like MATLAB Simulink. Thus, an existing commercial software solution would have to be used for this certification method.

- Also a generic driver model would be required that can deal with operating a virtual accelerator and brake pedal in forward-simulation and at the same time is able to follow the VECTO specific target speed cycles without producing too much deviations from the target speed due to overshoots or undershoots of the driver control algorithm (see Figure 10 in paragraph 3.3.3.1 exemplarily) which can be improved by tuning the parameters of the driver controller but cannot be completely eliminated.
- For complex highly integrated control systems in the vehicle several signals of the electronic control units that are not present during the setup on the testbed need to be emulated. In the so-called restbus simulation missing signals need to be modelled in software and provided to the electronic control units present in hardware on the testbed. Since this is a really highly complex setup, it is hard to check whether everything is set up correctly or if some signals are illegally used to optimize the performance of the hybrid system on the testbed. Besides, also tampering with control strategies present in hardware cannot be completely excluded. Thus, a sophisticated procedure for verification of the correct setup and system performance on the testbed would need to be developed to avoid possible loopholes (i.e. special testbed mode of the system).
- The SOC of the ReESS over the whole test cycle has to be neutral in order to ensure a fair, energy-neutral determination of the CO_2 emission value, where all propulsion energy has to be generated and consumed by the hybrid-system during the test cycle. A neutral SOC could be achieved by several repetitions of the testcycle with adjusted start SOC which increases the test effort significantly. Also for some combinations of hybrid system and test cycle a neutral SOC might not be possible to achieve. Thus, a generally applicable correction method would need to be developed to correct the measured CO_2 value to a value representative for a neutral SOC over the testcycle.

The advantages and disadvantages of this approach are summarized below.

Advantages:

- OEM specific control logics can be used (without disclosure)
- No simulation of hybrid system needed

Disadvantages:

- High investment costs for initial testbed installation (estimate 2 million Euros per testbed)
- High effort for setup of hybrid system on testbed (estimated 4-8 weeks, depending on the complexity of the system)
- High time effort and costs for each testrun (needs to run in real-time on testbed)

- Risk that hybrid system on testbed does not exactly perform as in real vehicle
- High effort for system verification on the testbed (ideally required!)
- Much more effort for certification of HDHs compared to conventional HDVs in VECTO

3.3.3 Approach in Japan and UNECE HILS

The UNECE HILS method was developed as amendment to UNECE regulation GTR no. 4 based on an already existing Japanese regulation used for both pollutant emission and CO_2 certification. In 2015 Japan started implementing the updated GTR no. 4 into their national certification framework. The activities for introducing the HILS method from GTR no. 4 are on hold for the moment, but will be continued soon. Despite the fully flexible architecture of the updated simulation model allowing to depict all possible layouts of hybrid powertrains, the current Japanese HILS approach and the updated GTR no. 4 HILS approach are very similar. Thus, in this study only the GTR no. 4 model is described, since it has a much clearer and universal definition of model architecture whereas the current Japanese model uses in fact individual models for each configuration of hybrid system.

The basics of this approach are that a complete vehicle test over a duty cycle is run in simulation where the vehicle with all its powertrain components is modelled and the vehicle’s electronic control units defining the hybrid operation strategy are connected as hardware.

The model is implemented as forward-simulation of vehicle longitudinal dynamics in MATLAB Simulink, where the torque represents the forward-path of the calculation and the rotational speed is provided on the backward-path as system response. It consists of a driver and a vehicle model and makes communication with the hardware control units possible. However, the integration of the control units requires specifying of model structure and signal flow as well as simulation in a real-time environment. The control units are connected to the vehicle model as well as to the driver model via in- and output interfaces, which handle unit conversion of signals between the simulation model and the control unit(s) on a software layer and the physical connection via wiring harness as well as signal transformation or tuning of the digital model outputs on a hardware layer.

The model comes with a completely flexible component library which contains the individual elements for modelling each specific powertrain-architecture. The library is based on the concept of port-based modelling which is characterized by defining physical connections between individual components by the energy flow to and from the component, respectively through a so-called port. For each component two types of interfaces are defined:

- a physical interface to connect different compatible components together physically
- a signal interface to control the component and to output sensor signals

Multiplication of the actual values of the physical forward- and backward-path (e.g. torque and rotational speed of a mechanical component) leads to the power flow to and from the respective component. The torque forwarded via the mechanical interfaces on the forward-path can consequently have both negative and positive values representing demanded or delivered power of the respective component.

The existing library provides models of all core components of a hybrid-system, like for instance the ICE and all common energy converters and storages both electrical and hydraulic/pneumatic as well as mechanical, and also all other drivetrain components. Due to the modular structure and expandability, it is possible to easily incorporate components of future powertrain concepts.

Furthermore, the model has a flexible data bus with a naming convention for all signals present, since the possibility of a fully flexible arrangement of individual components requires the same degree of freedom in signal flow.

The version 3 of the VECTO model was based on the same principles of port-based modelling and also a data bus was implemented in the model during the restructuring performed. In principle VECTO allows also a similar flexible approach in arranging components as the HILS model, but in VECTO the available architectures of the powertrain need to be pre-defined in the source code and cannot be manually changed by the user.

In order to determine the CO_2 value for a vehicle to be certified with the HILS method, a model representing the specific hybrid powertrain to be tested is set up using the individual elements provided by the component library as a first step. All input parameters characterizing the different specific powertrain components (i.e. ICE, alternative energy converter, ReESS) are determined in accordance with standardized component tests by specifically defined measurement procedures (very similar to European CO2 component test procedures). For the transmission, if applicable, the real transmission ratios but a generic efficiency factor is used. Vehicle parameters defining the mass, driving resistances, drive axle, tires are set according to the definition of a generic vehicle for the respective vehicle class certified.

If a specific hybrid-system architecture of the simulation model is used for the first time in the certification process, conformity between real vehicle and simulation model has to be proved. All vehicle parameters which cannot be directly assigned to the hybrid-system (e.g. tire radius, final drive ratio, drivetrain rotational inertias etc.) are set according to the values of the specific vehicle that is used on the test bed for verification of the model during this step and changed back to the generic values again before the official simulation for the certified CO_2 value. The real vehicle is operated in the same test cycle on a chassis dynamometer as the simulation model is for the CO_2 certification. During this measurement several signals like vehicle speed, rotational speeds, torques and power flows of all components of the hybrid-powertrain as well as pedal positions and selected gears are recorded. All the recorded data are compared to the respective simulation outputs by means of linear regression analysis where the vehicle in the simulation is following the velocity profile recorded on the chassis dyno. If the output from the simulation meets the defined tolerances, the HILS model is verified and can be used for the certification process. If the same hybrid system layout has already been certified before and no structural changes are made inside the model or the interface, repeated model verification is not necessary and all model parameters are set according to the component test procedures defined in the regulation.

With the verified simulation model the CO_2 value is then determined by interpolation of fuel consumption out of the recorded engine fuel map for the operation points of the ICE directly in the HIL simulation run.

In the last process step the compliance of the simulation run with defined limits for deviations from the reference vehicle speed is checked. Additionally the criterion of neutral state of charge of the energy storage system over the whole test cycle applies in order to ensure a fair, energy-neutral determination of the emission value where all propulsion energy has to be generated and consumed by the hybrid-system during the test cycle. To avoid unnecessary repetitions of the simulation run, a tolerance threshold of 3% for the difference in stored energy in relation to the delivered work from the ICE over the cycle was defined. If one of the applicable criteria cannot be fulfilled, the driver model can be tuned and the initial state of charge of the energy storage system can be adjusted and the simulation run has to be repeated. If all the boundary conditions mentioned above are fulfilled, the determined CO_2 value is valid.

3.3.3.1 Applicability in the European certification scheme

In principle this method would be applicable in the envisaged European certification scheme. Nevertheless, some issues were identified that would need to be addressed before this approach could be used:

- The verification procedure defined in the regulation would need to be adapted. It works quite well for the simpler Japanese hybrid systems, the more complex HDHs tested during the development of the GTR procedure had difficulties to achieve the pass criteria. Also during the work performed for the GTR procedure it became obvious that a linear regression analysis is not the best option when assessing accuracy of complex simulation models[8]. Even more for the determination of fuel consumption, where model accuracy is more critical than for emission certification, a more sophisticated approach would be needed for verification of the simulation model.
- Simpler verification approach needed for efficient approach. HILS method needs chassis dyno test for each hybrid system.
- The standardized component test procedures would need to be adapted to the accuracy level established in the European CO_2 regulation, which means described in more detail with stricter boundary conditions defined.
- Application of the HILS method would require remodelling the existing European VECTO model, since coupling with an electronic control unit requires a forward-simulation, where the torque represents the forward-path of the calculation and the rotational speed is provided on the backward-path as system response. Additionally, the model would need to run in a real-time environment. This demand is not in line with the demand for very short computation time which is required for handling the large number of HDV calculations expected.
- Also a new driver model would be required that can deal with operating a virtual accelerator and brake pedal in forward-simulation and at the same time is able to follow the VECTO specific target speed cycles without producing too much deviations from the target speed due to overshoots or undershoots of the driver control algorithm. Figure 10 illustrates this typical behaviour of a simpler control algorithm, which can be improved by tuning the parameters of the driver controller but cannot be completely eliminated.
- In Japan the simulation model is run on a computer of the certification authority, thus no tampering with the simulation model is possible. How to ensure that no changes in the completely open simulation model are made would also require the development of some special provisions to be followed in the certification process.

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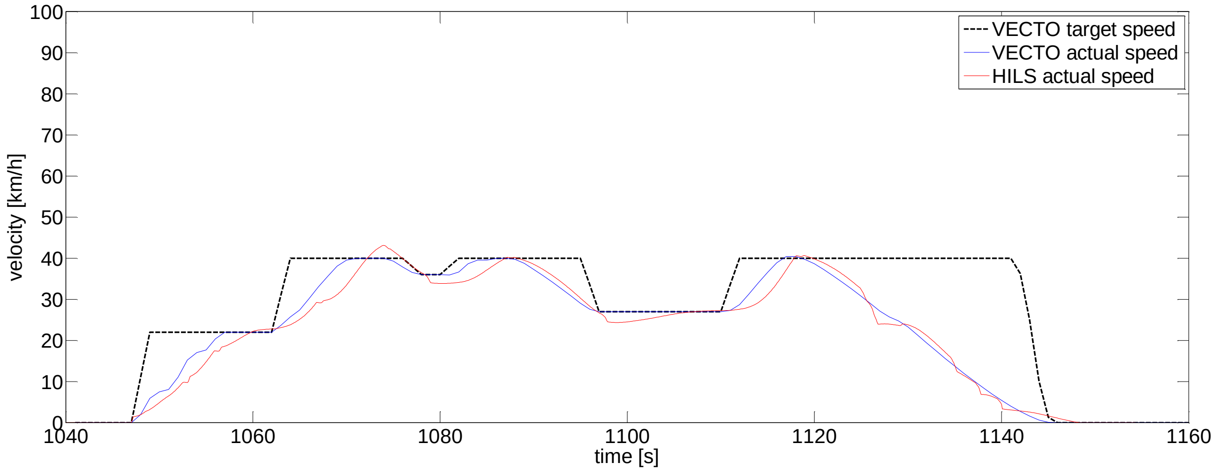
[8] Six 2014

Figure 10: Behaviour of driver controller in forward simulation vs. backward simulation



Standardized interface required for ECUs

The advantages and disadvantages of this approach are summarized below.

Advantages:

- OEM specific control logics can be used (without disclosure), since electronic control units are connected as hardware
- Already verified model can be re-used for similar systems, but this lowers the necessary effort only if a higher number of similar hybrid variants are certified
- Low cost for each testrun compared to powertrain testing. Once the system is set up, since neither an expensive testcell nor lots of trained staff is needed (besides need of chassis dyno for verification tests).
- Low investment costs for equipment

Disadvantages:

- High effort for setup of hybrid system on testbed (estimated 8-12 weeks, depending on the complexity of the system)
- In most cases specific simulation model per vehicle needed (no re-use of already verified models possible)
- Standardized interface to electronic control units needed
- Long simulation time (needs to run in real-time)
- High effort for system verification by use of chassis dyno

3.3.4 Approach in China and Korea

The standards established in China and Korea share the same basic principles. The Chinese standard GB/T 19754 was issued in 2005 and revised in 2013 and applies for heavy-duty vehicles whereas the current Korean standards only apply for light trucks.

In both standards, the fuel consumption of the vehicle is determined over standardized test cycles on a chassis dynamometer. The steps in this approach are quite simple: The vehicle is placed on a chassis dynamometer where the driving resistances are set determined according to existing standards. Then a cycle for preconditioning is run to ensure that both the vehicle and the measurement devices are functioning properly at normal operating temperatures. In a next step the actual certification cycles are run and emissions are sampled and recorded. Fuel economy is then evaluated via an analysis of the recorded CO_2 emission values.

Chassis dynamometer testing has the ability to evaluate a vehicle's performance in a manner that most closely resembles the vehicle's in-use performance, as long as the vehicle does not switch into a special chassis dynamometer operation mode. Nearly all of the fuel efficiency technologies can be evaluated simultaneously on a chassis dynamometer, including the vehicle systems' interactions that depend on the behaviour of the engine, alternative energy converters, ReESS, transmission and vehicle electronic controllers. One challenge associated with the application of wide-spread heavy-duty chassis testing is the small number of heavy-duty chassis test sites that are available. In addition no standards for chassis dyno testing of HDVs exists in the EU.

The biggest disadvantage of this approach is the initial cost of a new test facility which is estimated to be around 3-5 million Euros[9] for installation of the test facilities in an existing building (as reported by the European Commission's JRC). Besides, there can be increased test-to-test variability under chassis dynamometer test conditions due to variations in tire performance, tire temperature and pressure stability as well as variations in human driver performance, in the test facilities' heating, ventilation and air conditioning system affecting emissions aftertreatment performance (e.g. increased fuel consumption to maintain aftertreatment temperature) and engine accessory power (e.g. engine fan clutching). The variation of chassis dynamometer test results is much worse for heavy-duty than for light-duty or passenger cars. For these reasons also EPA discarded this as a viable option in the final development of the phase 2 of their greenhouse gas emission standards.[10]

3.3.4.1 Applicability in the European certification scheme

In principle this method would be applicable in the envisaged European certification scheme. Nevertheless, some issues were identified that would need to be addressed before this approach could be used:

- There is no existing standard for measurement of heavy-duty vehicles on a chassis dynamometer in Europe. Thus such a standard would need to be developed based on existing standards in other global markets.
- The existing VECTO target speed cycles cannot be used for the measurement on the chassis dynamometer directly. Therefore a pre-processing step would be needed in VECTO to convert the target speed cycle to an actual vehicle speed cycle. This would also require to define a separate standard how the hybrid vehicle to be certified should be modelled as conventional vehicle within VECTO. In addition, the length of VECTO cycles (~100km) is not well suited for driving on chassis dyno testbeds.
- The deviations between actual vehicle speed and defined vehicle speed which are inherent in the chassis dynamometer approach would lead to differences in both travelled distance and cycle work between single testruns with the same vehicle.

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[9] US 2016, page 73533; estimated costs for chassis dyno also reported by JRC with around 5 million Euros

[10] US 2016

The repeatability of the results are expected to be within 2% but still there is not the one true CO_2 value as opposed to the approach in VECTO. This issue could be partly addressed by averaging over several runs of the same cycle at the price of increasing test effort even more. But still the reproducibility, meaning comparability of results between different labs or between different measurement series performed at the same lab, is also estimated from existing round robin data to be within 2-10%. From the experiences during the validation tests performed for development of the UNECE HILS approach for GTR no. 4, the variations between single tests were even higher for hybrid vehicles than for conventional ones.[11] The more complex the hybrid system, the more variation occurred between single testruns, even though for the more complex system an automated driving robot was used to eliminate the variations caused by a human driver.

- One concern is that the vehicle could switch into a special chassis dynamometer operation mode. Especially for hybrids this issue is even more relevant, since the braking power is transferred only via one or two driven axles on the chassis dynamometer, which could trigger a different behaviour of the controller than real use resulting in a difference in recuperated energy over the testcycle.
- Heavy-duty chassis dynamometers typically have a single roller, thus articulated vehicles and vehicles with multiple driven axles (e.g. ICE drives one axle, alternative energy converter drives other axle or even several other axles) cannot be handled by this approach unless a special testbed setup with multiple adjustable rollers would be installed.
- The SOC of the ReESS over the whole test cycle has to be neutral in order to ensure a fair, energy-neutral determination of the CO_2 emission value, where all propulsion energy has to be generated and consumed by the hybrid-system during the test cycle. A neutral SOC could be achieved by several repetitions of the testcycle with adjusted start SOC which increases the test effort significantly. Also for some combinations of hybrid system and test cycle a neutral SOC might not be possible to achieve. Thus, a generally applicable correction method would need to be developed to correct the measured CO_2 value to a value representative for a neutral SOC over the testcycle.

The advantages and disadvantages of this approach are summarized below.

Advantages:

- OEM specific control logics can be used (without disclosure), since electronic control units are directly interacting with the components they control
- Vehicle performance close to real-world (as long as no special chassis dynamometer operation mode occurs)
- No simulation of hybrid system needed

Disadvantages:

- High investment costs for initial testbed installation (estimated around 5 million Euros)

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[11] Six 2014

- High time effort and costs for each testrun (duration for simulation of the VECTO cycles is several hours)
- Risk that hybrid system on testbed does not exactly perform as in real vehicle (needs some kind of verification/plausibility check by comparison with real world data)
- Variability in test results is quite high compared to other approaches

4 Overview of approaches for certification of hybrid vehicles identified in task 1 and 2

Table 11 gives an aggregated overview of all approaches for the CO_2 certification of hybrid vehicles identified based on the findings from task 1 and 2 and also shows a first preliminary rating of those approaches.

Based on the issues to be addressed for each approach before introducing it as certification method as well as the disadvantages identified in task 1 and 2, some approaches were discarded in a first step together with experts from the European Commission and industry in the meeting held in Graz on 3rd of April 2017.

If one of the following basic criteria is fulfilled it was suggested to discard the respective option:

- development effort > medium   AND ALSO   accuracy < medium
- accuracy < low
- development effort > high   AND ALSO   investment > high   AND ALSO   effort for certification > high

All methods not discarded in this first step were analysed further in tasks 3 and 4 with the findings described paragraphs 5 and 6.

Chassis dyno testing and on-road testing were added as viable options for assessment as requested by different stakeholders during the project meeting held in Brussels on 19th of July 2017 even though these two option were already discarded earlier in time.

Table 11: Approaches for certification of hybrid vehicles identified in task 1 and 2

Method	Simulation-based	Hybrid part simulated	Effort for development of certification procedure	Capital investment for test facilities	Effort for certification test	Reachable accuracy	Suited for EU
Simulation in VECTO	yes	yes	high	none	low	high	**yes**
Simple crediting scheme	yes	no	low	none	low	very low	**no**
Advanced crediting scheme 1 ***(Post-processing of braking energy)***	yes	no	medium	none	low	low	**yes**
Advanced crediting scheme 2 ***(Complex bonus factors)***	yes	no	high	none	low	medium	**yes**
HILS	yes	yes	very high	low*	very high	very high	**no**
Powertrain measurement	mixed	no	very high	high	high	very high	**yes**
Chassis dyno measurement**	no	no	high	very high	high	medium	**no**
On-road measurement**	no	no	high	low	medium	low	**no**

** very high with chassis dyno model verification*

*** chassis dyno measurement and on-road measurement were considered as viable options again due to the comments received from other stakeholders at a later point in time during the feedback phase after the release of the draft version of the final report (see chapter 7)*

5 Task 3: Identify and describe possible options for the extension of VECTO to simulate hybrid HDVs

Objectives:

- to identify one or more strategies to extend VECTO in order to simulate hybrid powertrain configurations

Key tasks:

- specify and describe all the necessary steps for their implementation in the tool and the accompanying methodology
- list any technical limits or uncertainties that have to be addressed prior to the commencement of the activity
- describe interventions necessary at the type approval level and in the corresponding legislation
- make estimates regarding the implementation time and costs for extending VECTO

Outputs:

- detailed description of the method with a first draft for component models and corresponding parameters
- list of issues that pose a potential risk and would need to be considered before or during implementation
- a detailed estimation of effort and time necessary for the implementation broken down to individual steps
- a summary about the method and a list of advantages identified

5.1 Overview of task 3

Based on the results from task 1 and task 2 possible options were identified to consider HDHs in VECTO. A detailed analysis was performed in order to identify the necessary details to be considered for all items being part of this approach. Based on these findings a list of issues posing a potential risk in the implementation of this approach was created and a detailed list of all steps of the implementation process was developed. Based on this list the estimation of the effort and time necessary for realization of this method for certification was performed. All the results can be found in the following paragraphs.

5.2 Possible options for the extension of VECTO identified

Table 12 lists the possible options identified for the extension of VECTO to be able to simulate hybrid vehicles. The listed options differ in the level of detail of the simulation model, but share the same basic structure of implementation in the VECTO software. This means that the accuracy of the simulation results will increase with each level of detail due to the added details for the performance of components of the hybrid system or a more sophisticated operation strategy.

By considering possible future expandability of the hybrid parts of the simulation model already from the very beginning, the envisaged solution would allow to add more and more vehicle specific information at later stages in the CO_2 certification method without the need to change the structure of the VECTO model itself. Also future architectures and types of hybrid powertrains could be implemented rather easy as long as standardized interfaces between the different components, the control strategy and the driver as well as the remaining non-hybrid components of the powertrain are defined. One simple example is that a generic efficiency factor for a certain component could be replaced by a detailed efficiency map for that component as soon as the respective standardized component test procedure is at a ready-for-certification level. This means that the simplest solution possible could be used for the very first introduction of hybrid vehicles in the CO_2 certification, which only considers specific parameters where absolutely necessary for a reasonable accuracy of the simulation results. This would keep the development effort to a minimum and would at the same time allow adding more complexity step by step in future updates of the procedure. The following paragraph will give a more detailed description of the approach and the corresponding steps for its implementation.

Table 12: Possible options for extension of VECTO to simulate hybrid HDVs

Detail level	Architecture and type of hybrid system	Components of hybrid system		Operation strategy of hybrid system
		properties*	efficiencies	
0	specific	specific	generic	generic
1	specific	specific	specific	generic
2	specific	specific	specific	specific (HiL / SiL)

* Properties such as capacity of ReESS, maximum power of electric machine, usable SOC range of ReESS

5.3 Detailed description of extension of VECTO

Based on the outcome of task 1, only electric hybrids would need to be integrated into VECTO in a first step. Thus, an electric alternative energy converter (i.e. electric machine) and an electric ReESS (i.e. battery and supercapacitor) would need to be modelled in VECTO. The inverter between ReESS and electric machine should be already included in the efficiency of the machine itself, an optional DC-to-DC converter (for supplying energy to the low-voltage electric consumers) could be modelled with a simple efficiency factor or a generic efficiency map as a function of voltage level and current. As with the existing software structure introduced with the new VECTO version 3, all components of the hybrid powertrain would be completely encapsulated and only use standardized in- and output signals for both power flow as well as communication with the remaining simulation model. The concept of port-based modelling should be applied throughout all components introduced into the software. All the component models would be based on physical equations and/or efficiency maps, thus the approach would be fully compatible with the open-source status of the VECTO software. First sketches of applicable component models will be described further below.

All relevant architectures of hybrid powertrains identified in task 1 (see paragraph 2.3.1) would need to be added as new configurations of powertrain layout to the existing VECTO powertrain builder part which selects the corresponding components setup in VECTO according to the user defined vehicle properties (e.g. AT/AMT/MT selection). The models defined for the electric machine and the electric storage could be universally used for all architectures of electric hybrid powertrains. If later on there is the necessity to implement also other types of hybrid systems (e.g. hydraulic, kinetic) then the same design principles should be used throughout all components.

As third item the control strategy of the hybrid powertrain would need to be added, which would also be completely encapsulated and use standardized in- and output signals for the communication with all components of the hybrid powertrain. Here, a separate control strategy for each hybrid architecture is needed in case the control strategy is modelled as generic item. If an OEM specific control strategy would be linked to the simulation model later on, only the standardized interface would be used for communication with the hybrid components.

As last item, also the operation point search, which is part of the driver model of VECTO, would need to be adapted to be able to deal with a hybrid powertrain. This part of the software will get more complex since with a hybrid powertrain there are more degrees of freedom for supplying the demanded propulsion power to the wheels whereas for a conventional vehicle there is only one source of propulsion power.

The necessary input data for the hybrid vehicle will be absolutely the same than for a conventional one, thus all existing standards for deriving the respective parameters stay valid. Only the additional hybrid components would need new standards to be defined on how to derive the respective model parameters. The VECTO input are either generic values or derived by a standardized measurement procedure. An overview of a first draft of input data will be given further below. The data-flow should follow the same principles already established for the components of a conventional vehicle, meaning that either the component supplier or the vehicle manufacturer generate the input parameters for the respective component according to the defined standards. This input data is then structured according to the defined data format and a hash is calculated to ensure data integrity over all steps of the certification process.

For the envisaged ex-post testing (EPT) in the European CO_2 scheme, hybrids could in principle be treated as other regular vehicles. In the EPT the speed and torque at the hubs of the driven wheels of a vehicle is measured and used as target duty cycle for the simulation of this exact vehicle in VECTO. This approach would work also for hybrids, with the exception that some additional boundary conditions and signals to be recorded might need to be defined. Also additional checks might be needed in the validation of the EPT, one important item being the usable range of the SOC of the ReESS[12]. But the EPT procedure for hybrids can only be defined once the envisaged method and the corresponding component models are fixed. If the majority of the values used for parameterizing the model and also the control strategy is generic, it might be a good option to introduce an additional safety factor ≥ 1 applied to the simulation results of the EPT. This factor could be declared by the vehicle manufacturer, in order to avoid failing the EPT due to the effect of generic parameters leading to a lower than realistic fuel consumption figure for the actual vehicle tested. Since the OEM will know the difference between the efficiency of his product and the VECTO result, it should be possible to declare a realistic safety factor if needed.

5.3.1 First draft of component models

The subparagraphs below describe a first draft status of the hybrid component models as well as the respective input data, which was elaborated based on the discussion with hybrid experts from industry and on the experience from TUG staff gained during the development of the UNECE

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[12] Since life time of batteries is reduced with increasing number or intensity of charge/discharge events, the useful SOC range is usually limited to a much smaller energy than the overall capacity.

HILS hybrid simulation model. This shall not be seen as conclusive status, but will need to be further discussed and developed during a potential implementation of this simulation approach.

5.3.1.1 Electric machine

The electric machine could be modelled using efficiency maps to represent the relation between its mechanical and electrical (DC) power, where separate maps should be defined for the positive and negative torque ranges, respectively. The dynamics of the electric machine could be modelled as a first order system with a generic time constant (possibly defined as a function of the rotational inertia or the dimensions of the machine). The efficiency maps could be a function of rotational speed, torque and DC-bus voltage level of the electric machine.

Limitations of the available power could be defined by a maximum (drive mode) and minimum (regeneration mode) torque curve of the electric machine as a function of rotational speed. How the de-rating of the electric machine due to the thermal condition could be modelled would still need to be investigated when this approach should be actually implemented. This could either be done by defining a standardized component test targeting the differences in maximum available power due to thermal conditions or by defining a generic de-rating effect depending on a few design parameters of the component.

In VECTO the physical inputs of the electric machine could be rotational speed and torque, the outputs could be voltage and current to be supplied. The control and sensor signals for the data bus in the model can only be defined during the development of the interface for the hybrid control strategy.

List of input parameters:

- Rotational inertia (generic function possible)
- Time constant for first order dynamics (generic value)
- Maximum torque as function of rotational speed (specific value)
- Minimum torque as function of rotational speed(specific value)
- Efficiency map for drive mode as function of rotational speed, torque and DC-bus voltage level (generic or specific value)
- Efficiency map for regeneration mode as function of rotational speed, torque and DC-bus voltage level (generic or specific value)
- De-rating effect (to be further investigated, how to be handled)

5.3.1.2 Electric ReESS

The electric ReESS could either be a battery or a supercapacitor, depending on the concept of the hybrid vehicle.

5.3.1.2.1 Battery

The battery could be modelled either as simple voltage source with an internal resistance in series or as a more complex model with one resistance in series with a second RC-element. If the more complex model which is able to better reflect the dynamic behaviour of a battery is necessary would need to be investigated during the actual implementation of this approach.

The open-circuit voltage as well as the resistances could be a function of the SOC of the battery and also depend on the direction of the current. The maximum discharge/charge rate of the battery, which limits the current, could be defined as generic value based on the cell chemistry of the battery. The battery could be scalable by providing the number of single cells arranged in series and in parallel as simple design parameter. A generic value could be used for the additional resistance of the connections in the battery pack. The SOC course over the testcycle of the battery could be determined by the method of current counting. If the associated coulombic efficiency is set to 100% or a value smaller than one would still need to be investigated.

List of input parameters:

- Number of cells in parallel (specific)
- Number of cells in series (specific)
- Capacity of single cell (specific)
- open-circuit voltage as function of SOC (generic function or specific)
- Resistances (either R or R_0, R and C) as function of SOC (generic function or specific)
- Maximum discharge/charge rate (generic)
- SOC range allowed (specific)

5.3.1.2.2 Supercapacitor

The supercapacitor could be modelled as a RC-circuit in series. For a supercapacitor modelled as RC system, the SOC is directly proportional to the capacitor voltage. The supercapacitor could be scalable by providing the number of single cells arranged in series and in parallel as simple design parameter. A generic value could be used for the additional resistance of the connections in the whole pack. The minimum and maximum voltage allowed for the supercapacitor could simply be derived from a datasheet of the cell manufacturer.

List of input parameters:

- Number of cells in parallel (specific)
- Number of cells in series (specific)
- Capacitance (specific or generic)
- Resistance (specific or generic)
- Minimum voltage allowed (specific)
- Maximum voltage allowed (specific)

5.4 Issues identified for this approach

Some issues were identified for this approach that would need to be investigated during the implementation phase and could pose a risk regarding timeline or necessary effort for the implementation:

- Gear shift strategy

The current gear shift strategy implemented in VECTO is mainly based on the full-load curve of the ICE. For a parallel hybrid, where the alternative energy converter is located upstream of the gearbox, the combined full-load curve has a higher torque than only the ICE (at least in some speed ranges) but at the same time can be changing dynamically over the cycle due to available energy in the ReESS or de-rating of components. Thus, the current shifting strategy might need to be adapted for parallel hybrids. The necessity to adapt the gear shift strategy would need to be analyzed during the actual implementation of this approach. For other hybrid architectures there might be special gear shift rules necessary as soon as there are shift transmissions installed, but this is typically not the case with current architectures of series and power-split vehicles.

- Power-split architecture
  In task 1 also power-split systems were identified as relevant hybrid architecture for the near future. These systems have a quite high complexity both in mechanical design as well as in their control strategy[13]. In any way it will not be possible to implement these systems without intensive support by the respective manufacturers. An alternative option would be to define standards how these systems could be virtually converted to a parallel hybrid architecture at the price of reduced accuracy of the simulation results. Allison Transmission experts suggested that this system could be modeled as parallel hybrid system whereby the transmission is modeled as a continuous variable transmission. In addition to that a default loss map for this type of system could be derived from a one-time measurement campaign in order to represent the efficiency losses.

- De-rating of electric machine
  As already explained above, the de-rating of the electric machine due to the thermal condition needs to be depicted somehow in the simulation. If this should be done by the results of the component test procedure or as generic function (depending on some design parameters like mass or dimensions of the electric machine) would need to be analyzed during the actual implementation of this approach.

- Usable SOC range
  A crucial parameter when looking at hybrid vehicles is the difference between nominal and usable SOC range of the ReESS, since this defines the amount of energy which can be stored in or drawn from the storage. The usable SOC range is defined by the vehicle manufacturer in the specific hybrid control strategy and cannot easily be determined by a simple component test procedure. In case a generic control strategy is used, this parameter would need to be declared by the vehicle manufacturer upfront for the certification and could then be checked during the EPT when the real vehicle is available. But also the practical applicability of this method would need to be further investigated during the actual implementation of this approach.

- Risk of acceptance of results by vehicle manufacturers
  Since the VECTO result is foreseen as customer information, an accurate ranking between different makes and models of vehicles is regarded as relevant. If the majority of the values used for parameterizing the model and also the control strategy is generic, it might be the

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[13] Allison 2017

case that results from VECTO do not represent the real-world fuel efficiency correctly. Thus, there is the risk that significantly more effort needs to be put into fine-tuning of certain parts of the simulation model with several iteration loops in order for the results to get closer to the real-world ranking of the vehicles and being accepted by all OEMs (as it is the case in the development of the simulation method for AT gearboxes)[14].

- Advanced auxiliaries model
  The advanced auxiliaries model, relevant for certification of buses, in its current implementation is not running directly in the loop but is added as post-processing for each timestep in the simulation.

  Furthermore, the whole model structure is designed only for conventional vehicles and does not provide all technology necessary for HDHs. Since the decision when auxiliaries are operated at which load point is made in the post-processing step, it cannot be influenced by the hybrid control strategy – thus not allowing the hybrid to explore its full potential of energy savings. This would be a crucial feature that should be handled directly inside the simulation loop because the hybrid system would need to optimize the energy flows during recuperative braking. Also the over-run switch for smart auxiliaries triggered in the advanced auxiliaries model uses parameters that do not work with a hybrid system. This could lead to double counting of recuperated brake energy, once in the hybrid part of the software and a second time in the auxiliary part. Besides, the parameterization of the efficiencies of the electric alternator is not compatible with and less detailed than the typical efficiency maps for electric machines used in hybrid vehicles. Also, the whole electric energy inside the advanced auxiliaries model is provided by alternators leading directly to an added portion of fuel consumption, which makes it impossible to install some kind of workaround for hybrid powertrains. Additionally, there is no possibility foreseen to operate the pneumatic system on electrical auxiliaries. Due to the expected arbitrary results in combination with hybrid systems, there would be a huge source of inaccuracy added to the certification results for hybrids.

  These are the most important shortcomings of the advanced auxiliaries model with respect to hybrid vehicles that could be identified. An analysis performed for this study, based on the power consumption values used in declaration mode for VECTO, showed that for city buses the fuel saving potential through electrification of auxiliaries is around 8-10% of the total fuel consumption over the testcycle compared to the current mechanically driven standard technology of auxiliaries. This saving potential equals 33-39% of the fuel consumption of the auxiliaries over the testcycle. These figures underline how important the accurate modelling of this part is for the certification procedure.

  Thus, the strong recommendation would be to redesign the current advanced auxiliaries model by keeping the basic methods but including it directly into the main simulation loop for each timestep and add some small additional adaptions for hybrid vehicles. This redesign could be used also for conventional vehicles and would add an additional benefit, since it would decrease the runtime of the model significantly by avoiding recalculation of various constant values at each call of the advanced auxiliaries model as it is currently implemented. Since ACEA considers a restructuring of the advanced auxiliaries model for application in the certification, these efforts could be combined (compare Bus Board meeting held in Brussels on 28th of June 2017).

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[14] The actual strategy for AT gearboxes is still under discussion in LOT4/SR7

5.5 Effort and time for implementation

The estimated effort necessary for implementation of this approach to a ready-for-certification level are shown in Table 13 - Table 16, the corresponding estimated timeline is shown in Figure 11 (a detailed timeline was only elaborated for this option since for all other options described the underlying assumptions are too uncertain to make a reasonable estimate).

The underlying assumption for deriving these values was that vehicle manufacturers will support the activities with experts participating in the discussions and in the development of methods, internal data for assessment of different options to be implemented and validation of the VECTO hybrid models against their in-house simulation tools. Also the development of different generic hybrid control strategies should be supported by industry (already first activities started within ACEA).

Suggested is to follow a 4-step approach:

1. Adapt existing VECTO and provide release according to level 0 in Table 12
2. Initiate first testing phase by industry and collect feedback
3. Amendments in VECTO according to feedback from step 2 and drafting of technical annex
4. Conduct a pilot phase for HDHs

Table 13: Estimated effort for implementation of the extension of VECTO (Step 1)

Step no.	Item	Sub-item	Effort (person-days)
1	**Architectures**	**Total**	**24**
		Develop architectures to be implemented	2
		Develop method how to handle power-split hybrids	10
		Define new configurations of powertrains in VECTO	3
		Define changes in VECTO powertrain builder	3
		Define changes in VECTO GUI/Command line interface	1
		Implementation of all points above in VECTO	5
2	**Components**	**Total**	**53**
		Develop physical component models	12
		Define component parameters	8
		Define standardized interfaces (physical and signal)	2
		*Analyse where generic values can be used and where component tests are necessary ***	*10*
		Implementation in VECTO	15

		Testing of implementation (EM, ReESS, planetary gearbox)	6
3	**Hybrid control strategy**	**Total**	**58**
		Develop generic hybrid control strategies (parallel + series)	12
		Develop generic hybrid control strategy for power-split or develop alternative workaround	10
		Define information flow and interfaces to components	6
		Implementation in VECTO	18
		Testing of implementation of control strategies in combination with all architectures and components	12
4	**Adaption of driver model**	**Total**	**36**
		Analysis of necessary amendments for driver model	10
		Define standardized information flow and interfaces for operation point search in driver model	8
		Implementation in VECTO	7
		Testing of implementation in combination with all architectures, components and control strategies	11
5	**Adaption of gear shift strategy**	**Total**	**18**
		Analysing effects of existing gear shift strategy with newly implemented hybrid models	5
		Adaption of gear shift strategy if necessary	5
		Testing of implementation in combination with all architectures, components, control strategies and different vehicle properties	8
6	**Adjustment of advanced auxiliaries model**	**Total**	**52**
		Developing new model architecture based on existing basic methods for all auxiliary types	20
		Developing methods for hybrid vehicles	10
		Implementation in VECTO	15
		Testing of implementation	7

Table 14: Estimated effort for implementation of the extension of VECTO (Step 2)

Step no.	Item	Sub-item	Effort (person-days)
7	**External testing by industry**	**Total**	**25**
		Support for external testing and instant bug-fixing in VECTO	15
		Collection of feedback from external testing	3
		Analyse feedback and create open issue list for next step	7

Table 15: Estimated effort for implementation of the extension of VECTO (Step 3)

Step no.	Item	Sub-item	Effort (person-days)
8	**Optimizing hybrid model**	**Total**	**25**
		Processing of open issues identified in step 7	20
		Optimizing of simulation model	5
9	***Drafting of technical annexes*** ***(only if identified as necessary)***	***Total***	***45***
		*Development of component test procedures for hybrid items or rules for determining generic values *** *(maybe not relevant for 1st phase of HDHs in VECTO)*	*30*
		Writing of technical annexes on how to handle HDHs in certification	*15*
10	**Ex-post validation test**	**Total**	**15**
		Adaption of EPT procedure for hybrid vehicles*	15

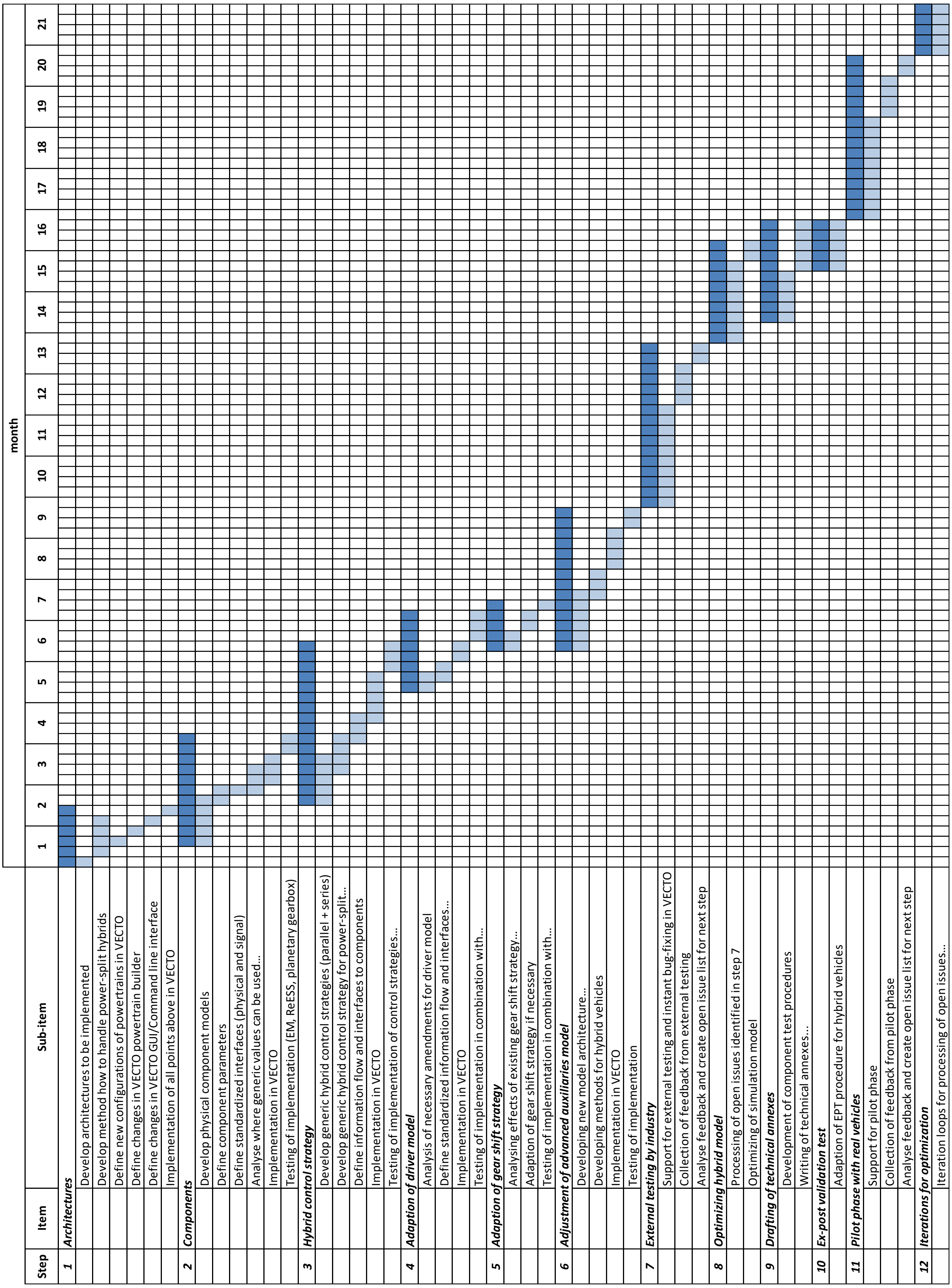
Table 16: Estimated effort for implementation of the extension of VECTO (Step 4)

Step no.	Item	Sub-item	Effort (person-days)
11	**Pilot phase with real vehicles**	**Total**	**21**
		Support for pilot phase	10
		Collection of feedback from pilot phase	5
		Analyse feedback and create open issue list for next step	6
12	**Iterations for optimization**	**Total**	**20**
		Iteration loops for processing of open issues and optimization of simulation model and component test procedures	20
		OVERALL TOTAL	**392**

* Since the torque of EM and ICE needs to be assessed by VECTO in the EPT mode, an extension to the existing method needs to be developed.

** Effort saved if only generic component data supplied by industry is used (i.e. level 0 in Table 12) is implemented in a first stage of legislation (see step number 2 in Table 13 and step number 9 in Table 15)

Figure 11: Estimated timeline for implementation of the extension of VECTO



Step	Item	Sub-item
1	*Architectures*	
		Develop architectures to be implemented
		Develop method how to handle power-split hybrids
		Define new configurations of powertrains in VECTO
		Define changes in VECTO powertrain builder
		Define changes in VECTO GUI/Command line interface
		Implementation of all points above in VECTO
2	*Components*	
		Develop physical component models
		Define component parameters
		Define standardized interfaces (physical and signal)
		Analyse where generic values can be used…
		Implementation in VECTO
		Testing of implementation (EM, ReESS, planetary gearbox)
3	*Hybrid control strategy*	
		Develop generic hybrid control strategies (parallel + series)
		Develop generic hybrid control strategy for power-split…
		Define information flow and interfaces to components
		Implementation in VECTO
		Testing of implementation of control strategies…
4	*Adaption of driver model*	
		Analysis of necessary amendments for driver model
		Define standardized information flow and interfaces…
		Implementation in VECTO
		Testing of implementation in combination with…
5	*Adaption of gear shift strategy*	
		Analysing effects of existing gear shift strategy…
		Adaption of gear shift strategy if necessary
		Testing of implementation in combination with…
6	*Adjustment of advanced auxiliaries model*	
		Developing new model architecture…
		Developing methods for hybrid vehicles
		Implementation in VECTO
		Testing of implementation
7	*External testing by industry*	
		Support for external testing and instant bug-fixing in VECTO
		Collection of feedback from external testing
		Analyse feedback and create open issue list for next step
8	*Optimizing hybrid model*	
		Processing of open issues identified in step 7
		Optimizing of simulation model
9	*Drafting of technical annexes*	
		Development of component test procedures
		Writing of technical annexes…
10	*Ex-post validation test*	
		Adaption of EPT procedure for hybrid vehicles
11	*Pilot phase with real vehicles*	
		Support for pilot phase
		Collection of feedback from pilot phase
		Analyse feedback and create open issue list for next step
12	*Iterations for optimization*	
		Iteration loops for processing of open issues…

5.6 Summary

The basic principles for this approach established in the preceding paragraphs are valid for all levels of detail explained in Table 12. Nevertheless, level 2 is discarded as short-term option being ready within the next few years due to the time needed to develop a complex interface between the VECTO model and an external hybrid controller. The representatives of the European Commission stated in the meeting held in Graz on 3rd of April 2017 that the envisaged timeline for introducing hybrid vehicles into the CO_2 certification is around the year 2020. This would be a too short timeframe for establishing such a complex project, but at least the basic structure of the newly introduced hybrid part could at least foresee already the respective interfaces and signals to be able to implement such a connection to an external hybrid controller as long-term solution.

The preferred option would be to start the approach with hybrid simulation in VECTO without the need for actual component testing, i.e. level 0. This could be achieved by defining generic values for the electric components depending on their technology (e.g. cell chemistry of battery) or by deriving values from a component data sheet which are already determined by a standardized procedure. Avoiding component test procedures in a first stage would keep the effort low for both the development of the hybrid method in the CO_2 certification scheme (around 40 person-days less in estimated effort if only generic component data supplied by industry is used – see step number 2 in Table 13 and step number 9 in Table 15) as well as the vehicle certification for the manufacturer by demanding only the same input data to be measured by dedicated test procedures as for conventional vehicles.

At a later stage, if the new procedure is well established and there are more and more hybrid vehicles on the market helping to gain more experience, component test procedures could be introduced either as optional or mandatory. In any way, as opposed to other approaches based on measurement (e.g. powertrain testing, chassis dyno testing) there is no high investment in test facilities necessary for determining the input parameters to the simulation model for hybrid components (e.g. testing battery cells or electric machines).

Since a generic hybrid controller and also a generic gear shift strategy will be used, the resulting operation point for each component might not be the one optimized to the real (measured) efficiency data of the component. The effect is considered rather small for ReESS but could be relevant for energy converters. This argument also supports the idea of using generic component data in a first phase, whereas component test procedures might be introduced only together with a specific hybrid controller.

Even though a generic hybrid controller will be used, the result will still be quite accurate since the vast majority of the fuel saving potential of a hybrid system is due to the recuperated energy during braking. The amount of recuperated energy is more dependent on the capability of the hybrid components (i.e. storage capacity or peak power of energy converter) than on the hybrid strategy itself. Only a few percentage points of the overall fuel savings result from more sophisticated operation strategies.[15]

The advantages of a simulation approach are:

- Good long term expandability for future hybrid powertrain configurations, since the same basic structure can be used and only new components or architectures have to be added according to the definitions

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[15] VAN REEVEN 2010

- Extremely short calculation time to produce CO_2 result
  Only a few seconds as compared to several hours for options including measurement of the hybrid system or the UNECE HILS method.

- Easy iteration with adjusted start SOC possible to determine CO_2 result for neutral SOC over testcycle

- Compared to simple crediting schemes, the in-the-loop simulation of the hybrid system is the physically correct realization with the advantage that the interference with other concurrent systems targeting at the same recuperative energy (e.g. ADAS systems, smart auxiliaries) will be depicted correctly

- Approach is compatible with stepwise introduction of future features in VECTO (e.g. coupling of OEM specific hybrid control logic or gear shift logic as SIL)

- High accuracy of the CO_2 results
  It was not possible during this study to determine accurate figures for the accuracy of the simulation method envisaged, but ACEA is performing a first internal assessment using OEM in-house simulation tools for a comparison between a simplified generic operation strategy and a complex vehicle specific one.

- Ability to handle high number of variants
  According to the OEMs also for hybrid vehicles a higher number of variants per vehicle type (e.g. different cabins/chassis, axle, EM power rating, ReESS capacity etc.) can be expected in future. The simulation approach would allow to handle a lot of variants with little effort (same component based principle as for conventional vehicles) as opposed to options based on measurement.

6 Task 4: Identify alternative options for certifying hybrid HDVs

Objectives:

- to identify two alternative options to certify hybrid HDVs in Europe beyond the use of VECTO and/or other software for direct simulation of the hybrid system

Key tasks:

- specify and describe all the necessary steps for their implementation in the tool and the accompanying methodology
- list any technical limits or uncertainties that have to be addressed prior to the commencement of the activity
- describe interventions necessary at the type approval level and in the corresponding legislation
- make estimates regarding the implementation time and costs for the different approaches

Outputs:

- detailed description of two different methods
- list of issues that pose an additional source of inaccuracy to this approach
- a detailed estimation of effort and time necessary for the implementation of the two different methods broken down to individual steps
- a summary about the two different methods

6.1 Overview of task 4

Based on the results from task 1 and task 2 possible options were identified to consider HDHs in the European CO_2 certification without direct simulation of the hybrid system in VECTO or any other software tool. The following approaches are analysed here:

- Advanced crediting scheme 1 and 2
- Powertrain method

A detailed analysis was performed in order to identify the necessary details to be considered for all items being part of this approach. In addition sources of inaccuracy to the approaches were analysed. Furthermore, a detailed list of all steps of the implementation process was developed. Based on this list the estimation of the effort and time necessary for realization of this method for certification was performed. All the results can be found in the following paragraphs.

6.2 General issues identified for both approaches

The basic principle of all the alternative approaches identified in Table 11 (i.e. powertrain measurement as well as advanced crediting scheme 1 and 2) is that some kind of efficiency value representative for a specific hybrid system on a certain duty cycle needs to be determined in a first step. This could either be a specific fuel consumption value of the hybrid system expressed in mass of fuel consumed per cycle work performed or a fuel saving potential compared to the respective conventional base vehicle. The actual fuel consumption figure for the hybrid vehicle to be certified is then determined in a second step be applying the appropriate efficiency value from the first step to a result determined for a conventional base vehicle by using VECTO.

The application of the efficiency value means either multiplying the cycle work determined in VECTO by the specific fuel consumption of the hybrid powertrain or multiplying the base fuel consumption determined in VECTO by the fuel saving ratio of the hybrid powertrain. The second step needs to be performed within VECTO in order to keep the consistency with the results for conventional vehicles, since using a different software tool for running the vehicle simulation would result in a deviation also for the exact same vehicle due to the differences in simulation methods and model performance.

For the simulation of the conventional base vehicle in VECTO to determine the base result, the vehicle needs to represent the actual hybrid vehicle to be certified as good as possible. This means that all vehicle specific parameters like mass, rolling resistance, air resistance and rotational inertias of the wheels which are relevant for determining the cycle work at the wheel are set according to the hybrid vehicle. The remaining powertrain upstream of the wheels towards the ICE needs to be modelled as conventional system. This leads to several problems depending on the approach that is selected for the certification method, since in most cases the respective conventional base vehicle without hybrid functionality does not exist as real vehicle. The effects identified are described in more detail in the following paragraphs.

6.2.1 Issues for the advanced crediting scheme 1 and 2

Both of the advanced crediting scheme methods determine a base fuel consumption value over the testcycle which is then corrected by multiplication with a fuel saving rate in percent (e.g. 80% of the fuel consumption of the comparable conventional vehicle).

For setting up the conventional powertrain used for comparison there is a final drive axle, a transmission and an ICE needed. These components would need to be defined as close as possible to the certified hybrid powertrain which is quite reasonably possible for parallel hybrids but requires quite complex standards and definitions for modelling of series or power-split hybrids, since these concepts do not come with a conventional transmission or final drive installed. Also the ICE of these hybrid concepts could be extremely downsized because the alternative energy converter provides additional power to the wheels. Thus, taking only the ICE installed in the hybrid vehicle can lead to a too low available power to propel a conventional vehicle over the testcycle resulting in a very low value for the base fuel consumption or cycle work.

In order to assess the influence of certain vehicle parameters on cycle work and fuel consumption simulations were performed for urban operation for two vehicle classes: a typical 16-ton rigid delivery truck (VECTO class 3) and a typical 12 meter 18-ton city bus. Both vehicles were modelled with an AMT gearbox. The AMT gearbox was used in this analysis even for the city bus, since this is today the only applicable option to be used for modelling a hybrid powertrain as virtual conventional powertrain. An AT gearbox would result in additional effects on driveline torque due to its torque converting characteristics which are not representative for a hybrid system.

All other parameters were set to the standard values used in the declaration mode of VECTO for the respective vehicle class.

In the following sections uncertainties resulting from settings for the virtual powertrain of the base vehicle are analysed. The virtual powertrain full-load is representing the combined full-load curve of ICE and EM for a hybrid vehicle, which needs to be specifically defined and does not simply equal the sum of ICE and EM maximum torque. Besides, the full-load capabilities of a hybrid system are not fixed but can change during the testcycle due to low available energy from the ReESS or thermal overload.

6.2.1.1 Influence of different full-load curves and settings for traction interruption

In this chapter the influence of the full-load curve on the cycle work of the base vehicle is analysed as basis for accuracy assessments.

6.2.1.1.1 Analysis for 16-ton rigid truck

For this analysis three different full-load curves of the ICE were used, the respective gear shift polygons in the model were adapted according to the standards defined for declaration mode in VECTO. The variants v1 to v3 in Figure 12 represent the regular range of ICE power ratings available for this vehicle. With these vehicle configurations the effect of the different ICE power ratings as well as the different settings for the traction interruption time in VECTO on the resulting cycle work both at the wheel and for the ICE was analysed. Therefore the mission profiles were run with a traction interruption of 1 second and without traction interruption.

Figure 12: Variants of ICE full-load curves for 16-ton rigid truck

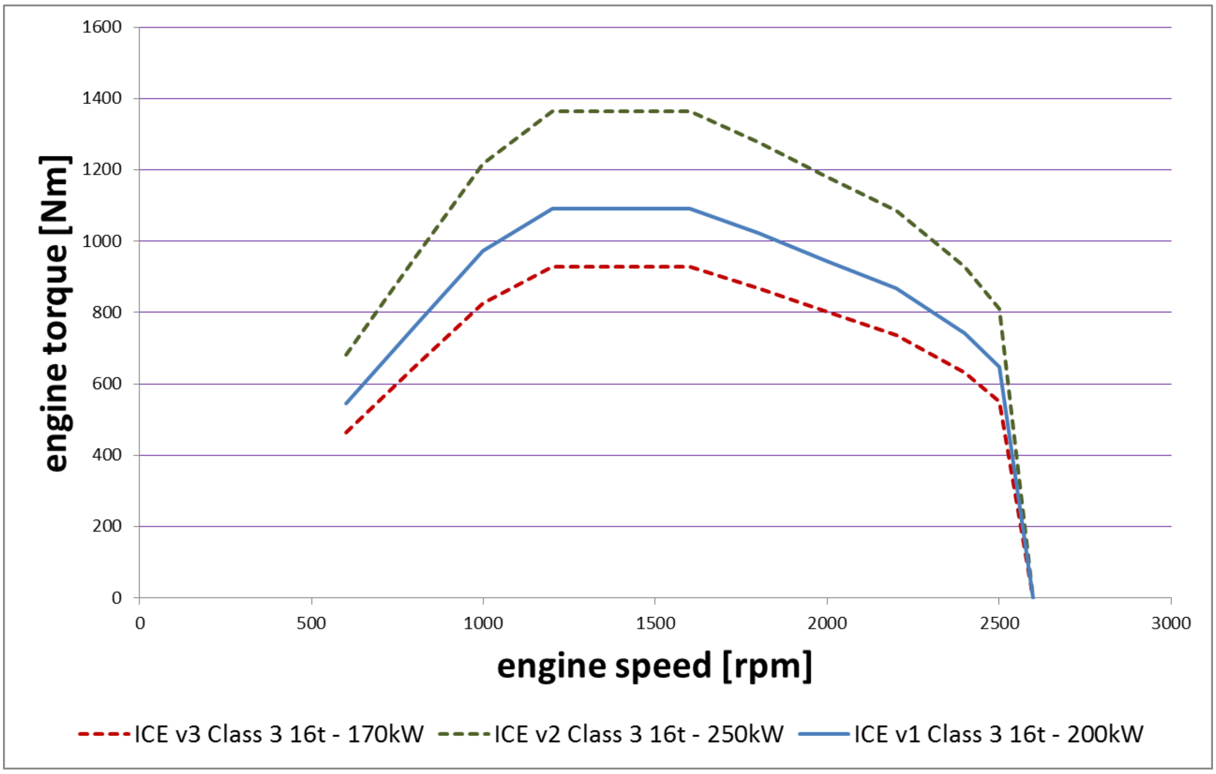


Table 17: Variability of cycle work for 16-ton delivery truck for variations in the full-load curve

CO_2 mission profile	Traction interruption time [s]	Variability of cycle work [%] *(reference is engine v1 with TI=0)*	
		at wheels	at virtual ICE
Urban delivery	0	-0.1 to +0.3	-0.4 to +0.4
	1	-0.8 to -0.5	0.0 to 0.8
Regional delivery	0	-0.3 to +0.2	-0.2 to -0.1
	1	-0.7 to -0.1	-0.7 to -0.4

The results summarized in Table 17 show that the influence of the different power ratings of the ICE on cycle work at the wheels is below 0.5% determined from the results for 0 seconds traction interruption (which could be the basis setting used for simulating the virtual hybrid powertrain in VECTO). The variation in the cycle work at the virtual ICE is below 0.8% for 0 seconds traction interruption. The variation gets a little higher for a traction interruption time of 1 second, but is still around 1%.

6.2.1.1.2 Analysis for 12 meter city bus

For this analysis four different full-load curves of the ICE were used, the respective gear shift polygons in the model were adapted according to the standards defined for declaration mode in VECTO. The variants v1 to v3 in Figure 13 represent the regular range of ICE power ratings available for this vehicle, whereas variant v4 should represent an extremely downsized ICE for a certain hybrid concept. With these vehicle configurations the effect of the different ICE power ratings on the resulting cycle work at the wheels was analysed in VECTO.

Figure 13: Variants of ICE full-load curves for 12m city bus

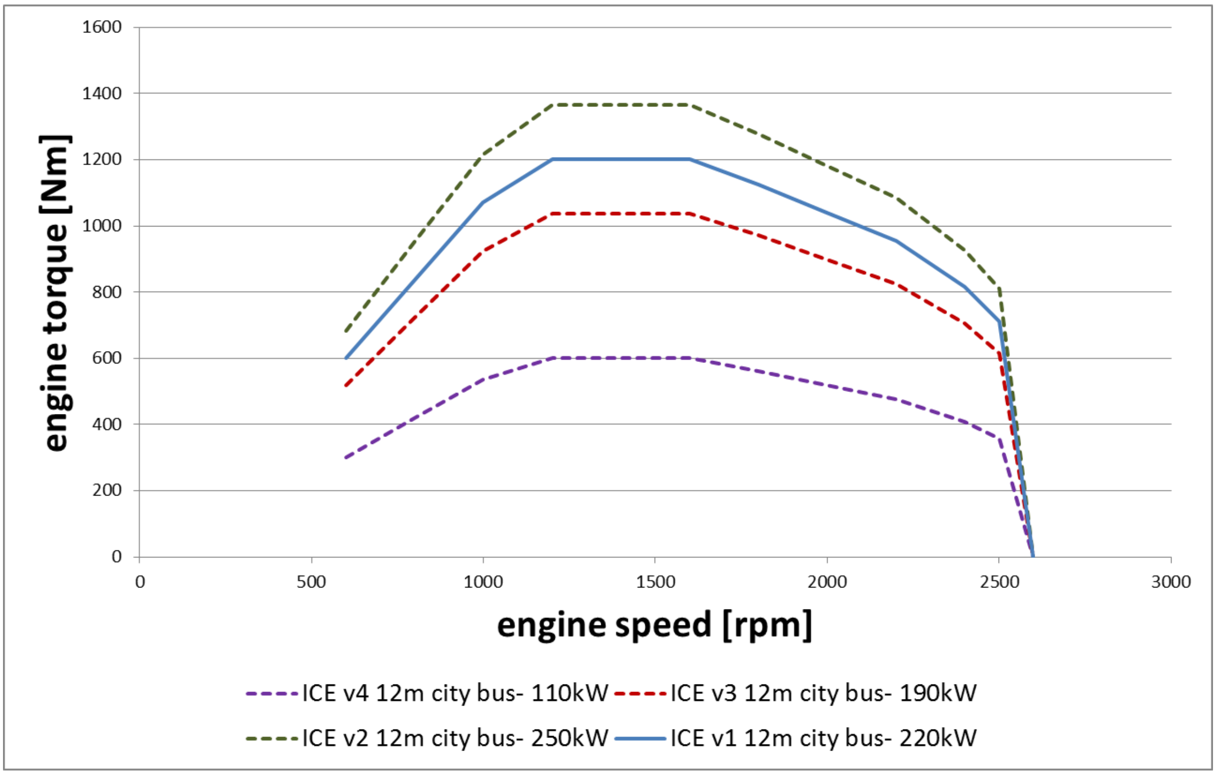


Table 18: Variability of cycle work for 12m city bus for variations in the full-load curve

CO₂ mission profile	Engine variants considered for variability	Variability of cycle work [%] *(reference is engine v1)* at wheels
Heavy urban	v2 and v3	up to +1.5
	v4	-2.6
Urban	v2 and v3	up to +0.8
	v4	-1.8
Suburban	v2 and v3	up to +0.9
	v4	-7.0

The results summarized in Table 18 show that the influence of the different regular power ratings of the ICE (i.e. v1 – v3) on cycle work of up to 1.5% is higher in the city bus cycles as compared to the urban delivery cycle. 1.5% is a magnitude that should not be neglected anymore when defining the reference cycle work.

For the extremely downsized variant 4, the cycle work is between 2-7% lower compared to the standard full-load curve. This indicates that using the ICE full-load curve only and not considering additional power of the alternative energy converters for defining the reference vehicle leads to a huge decrease in accuracy for certain hybrid concepts (e.g. series hybrids). Thus, the engine data of an HDH cannot be applied for the virtual base vehicle and generic reference engines per vehicle class would be needed (full-load curve, fuel map, correction factors).

Summarizing the findings of this analysis, the following can be stated:

- The influence of different power ratings of the ICE on the cycle work is rather small, but not neglectable for parallel hybrids with a low ratio of alternative power to ICE power (as long as the ICE power is within a reasonable range for the respective vehicle class)
- For other than parallel hybrids the influence of different power ratings of the ICE on the cycle work can be up to 7% depending on the concept of the hybrid system as well as the mission profile
- Thus it is important to develop standards how each specific hybrid architecture and type should be converted to a virtual conventional vehicle powered only by an ICE. Therefore, standard procedures how to define all the powertrain specific parameters need to be elaborated (i.e. ICE full-load curve and fuel map, transmission ratios and efficiencies, axle ratios and efficiencies and several model parameters for the gear shift and driver model).

6.2.1.2 Influence of different full-load curves for virtual hybrid powertrain

This analysis was only performed for the 12 meter city bus, since the preceding results showed that the sensitivity for changes in cycle work is higher for the city bus than for the delivery cycles. For this analysis three different full-load curves of the ICE were used, the respective gear shift polygons in the model were adapted according to the standards defined for declaration mode. The variant v1 represents a real ICE that is the standard motorization for the real bus. The hybrid variants Var1 and Var2 represent two realistic full-load curves of a hybrid system (i.e. combined torque of ICE and alternative energy converter) converted to a virtual ICE, where the available torque is increased especially at lower rotational speeds. 600kg of additional mass for the hybrid system was considered in the simulation model as compared to the conventional vehicle powered by the ICE v1.

Figure 14: Variants of full-load curves of virtual hybrid powertrain for 12m city bus

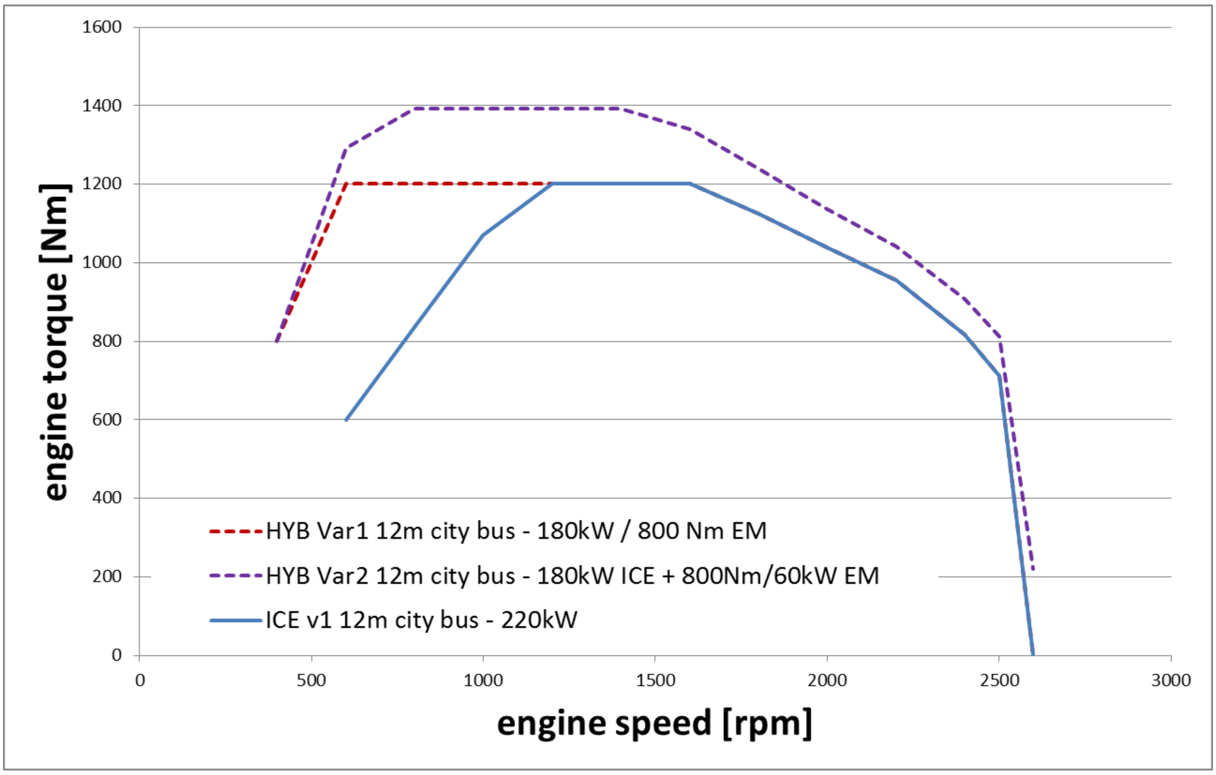


Table 19: Variability of cycle work for 12m city bus with virtual hybrid powertrain

CO_2 mission profile	Variability of cycle work [%] *(reference is ICE v1)* at wheels	at virtual ICE
Heavy urban	+5.0	+2.6
Urban	+4.7	+2.6
Suburban	up to +5.5	up to +4.2

The results summarized in Table 19 show that the cycle work at the wheels is around 5% higher for the hybrid vehicle. The reason for this effect is the slightly higher vehicle mass but mostly the potential for faster accelerations due to the higher propulsion power available. This can be seen from the average cycle speed which is 2-3% higher for the hybrid vehicles than for the conventional one.

The cycle work at the virtual ICE is around 3% higher in the urban cycles and around 4% higher in the suburban cycle, but increases less than the cycle work at the wheels. This effect can be explained by different gear shift behaviour with less gear shift events, lower losses in the drivetrain due to different operation points of the system as well as lower energy consumed by the auxiliaries due to a shorter cycle time.

Summarizing the findings of this analysis, the following can be stated:

- The influence of the hybrid full-load curve modelled as virtual ICE on the cycle work is significant and should not be neglected. Thus, a well-defined method how to obtain the virtual full-load curve has to be developed.
- The power defined by the virtual full-load curve is not constantly available due to limitations in the hybrid system (e.g. low SOC in ReESS, de-rating due to thermal overload). Thus, the available propulsion power is either under- or overestimated depending on the method on how to define the virtual full-load curve. This contributes additional inaccuracy to the simulation results for hybrid vehicles as compared to the simulation in VECTO.

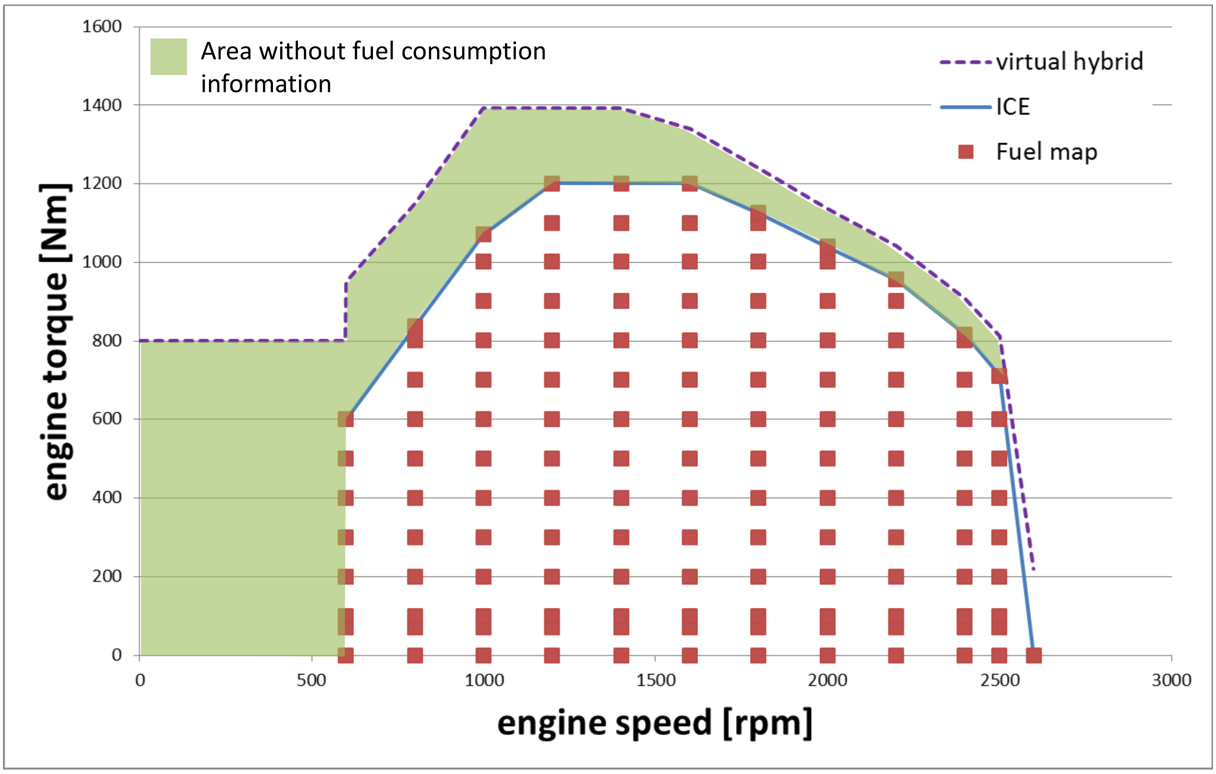
6.2.1.3 Fuel map for virtual ICE

Another issue identified is, that operation points can occur for the hybrid system modelled as virtual ICE and simulated for the base vehicle, where there is no fuel consumption data available. Figure 15 illustrates the principle problem with the respective area marked in green. The fuel map can be recorded only for the actual ICE installed in the vehicle, thus for the area with rotational speeds or torque values located outside the fuel map range there is no data available. But due to the characteristics of a hybrid system, operation points can occur in this area.

Since VECTO does not allow the vehicle to run below idle speed of the engine (i.e. the lowest speed point in the fuel map), the green area located left from the map points might not be that relevant. But due to the restriction of running always above idle speed there is another source of inaccuracy of the results inherently present when using the concept of the virtual ICE. Also the clutch losses determined in VECTO when the vehicle is starting from standstill represent another source of inaccuracy of the results. Both effects mentioned would not occur in a real hybrid vehicle, since an electric machine can provide propulsion torque already at 0 rpm. The effect of these two inaccuracies is estimated with around 1% on urban cycles with a high number of vehicle starts from standstill.

If the real ICE is part of an engine CO_2-family and there is a parent engine existing that covers the green area located above the real ICE of the hybrid system, the fuel map of the parent engine could be used for the simulation of the virtual ICE. If this is not the case, a generic efficiency map would need to be used which adds an additional source of inaccuracy to the final CO_2 results which is estimated with up to 5% depending on the technology of the ICE. The usage of a generic engine fuel map may seem to be the more stable option for the advanced crediting scheme, since for example for series hybrids the ICE may be optimized for a few steady state points only allowing the OEM to use less complex engine technology. Using this simplified engine for the base vehicle would lead to unrealistically high base FC values.

Figure 15: Area in fuel map without information for virtual hybrid powertrain



6.2.2 Issues for the powertrain method

For the powertrain method only the variability in the cycle work at the wheels of the vehicle is relevant, since the whole hybrid powertrain is installed on the testbed and thus engine cycle work and fuel consumption are depicted correctly in this approach. The uncertainty of this influence factor on the final CO_2 result is rather low with around 2-5% (as long as a reasonable ICE power rating is chosen for the respective base vehicle) as explained in paragraphs 6.2.1.1 and 6.2.1.2.

6.3 Advanced crediting scheme

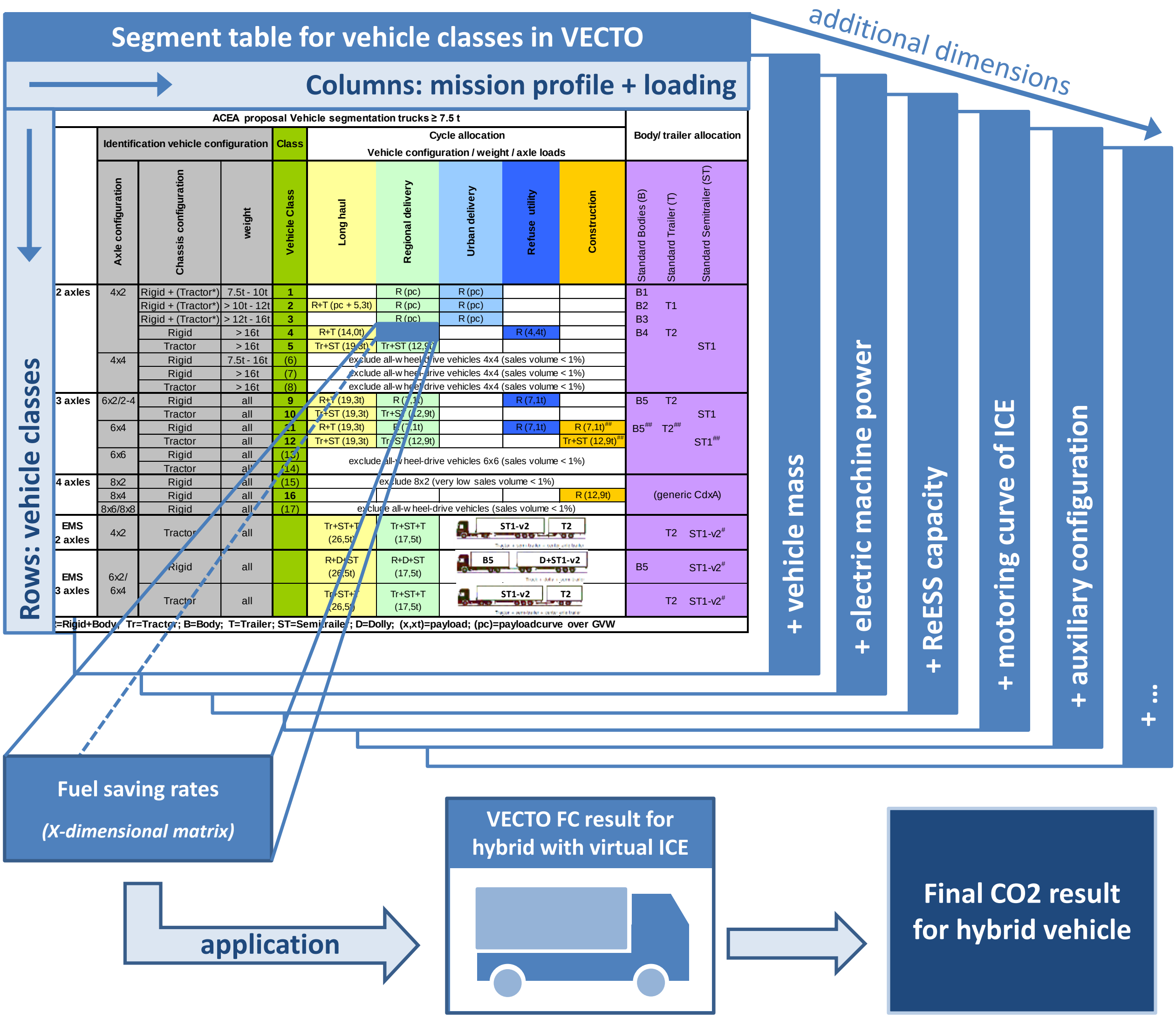
6.3.1 Detailed description of the advanced crediting scheme

There are two principal variants of an advanced crediting scheme which are listed in Table 11. Variant 1 is based on simple post-processing of the VECTO result for the base vehicle simulated with a virtual ICE. In the post-processing energy savings for the hybrid vehicle are assessed by calculating the sum of energy dissipated by braking actions over the testcycle. A certain fraction of this amount of energy could be recuperated by a hybrid system. Thus, the cycle work of the ICE would be corrected for this amount of recuperated energy leading to lower fuel consumption and CO_2 emissions. In addition to all the issues explained in paragraph 6.2 above, a huge source of inaccuracy of this variant 1 would be that the energy to be recuperated is not restricted by the performance limits of the hybrid components (e.g. maximum generator power of electric machine, maximum capacity of ReESS). Thus, the electric power or capacity installed in the vehicle would have no influence on the results. In addition, also other hybrid features that contribute to the fuel savings like pure electric drive at low vehicle speeds or load-point-shifting of the ICE are not depicted in this variant 1.

Variant 1 would be a simpler solution, but during the more detailed analysis of the method the reachable accuracy was considered as too low to produce reasonable CO_2 values for hybrid vehicles. Thus, only variant 2 will be elaborated further in this study.

Variant 2 of the advanced crediting scheme is based on applying fuel saving rates to the base fuel consumption determined in VECTO for a conventional vehicle powered by a virtual ICE representing the power available from the hybrid system. These fuel saving rates need to be pre-defined as a function of several parameters (e.g. vehicle mass, electric machine power, ReESS capacity) that have main influence on the fuel saving potential of the hybrid system. Figure 16 shows the basic principle of this approach.

Figure 16: Basic approach of advanced crediting scheme variant 2



The fuel saving rates need to be determined by comparing the simulated fuel consumption results of a conventional reference vehicle and the respective hybrid vehicle powered by a virtual ICE. The fuel saving rates cannot be determined by comparison of two measured values for the respective vehicle, since the reference vehicle for the base fuel consumption is in most cases non-existing and also there would be too many variations in the measured result due to influence factors (e.g. gearbox settings, driver behavior, auxiliary power demand, etc.) as listed for chassis dyno testing in paragraph 3.3.4.

In the vehicle simulation to determine the fuel saving rates the parameters for mass, rolling resistance, air resistance and tires will be the same for both the hybrid and the conventional reference vehicle. In order to generate the matrix of fuel saving rates the following prerequisites need to be fulfilled:

- A simulation model that can accurately depict hybrid systems of all relevant architectures and types as well as conventional vehicles
- A standardized method how to convert a hybrid powertrain into a virtual conventional powertrain (i.e. rules how to define the ICE, the transmission ratios and efficiencies, the axle ratio and efficiencies for a given hybrid system)
- A standardized method for parameterization of all non-vehicle-specific input data for VECTO (e.g. gearshift model parameters)
- Standardized input parameters for ICE, electric machine, ReESS (e.g. generic efficiency maps, full-load curve, internal resistance of ReESS)
- Generic control strategies for all architectures and types of hybrid systems

In order to produce results with good accuracy, the fuel saving rates need to be calculated for all possible combinations of parameters indicated in Figure 16 for each pair of vehicle class and mission profile. At least the following parameters need to be considered for producing the fuel saving rates and need to be varied within a reasonable range to define the grid for each dimension of the matrix of fuel saving rates:

- Vehicle mass (including loading)
- Electric machine power
- ReESS capacity
- Motoring curve of ICE
- Rolling resistance
- Air resistance
- Auxiliary configuration of vehicle (especially relevant for buses)

When looking at the segment table in Figure 16, there are 12 different vehicle classes defined and 3 additional classes for buses are defined at the moment. For each vehicle class 3 to 4 mission profiles are defined, the two different loadings are covered by the variation of the vehicle mass. This means a total number of around 60 cells, as combination of vehicle class and mission profile, in the segment table. For each of those cells all parameters above will need to be varied. If we assume 10 variation steps for each parameter, this leads to a total number of $60 \times 10^7 = 600\,000\,000$ pairs of conventional and hybrid vehicles to be simulated for determining the fuel saving rates. This produces quite a high effort but offers still only medium accuracy due to the sources of inaccuracy explained in paragraph 6.2.1.

Also, this high number of variations cannot be handled reasonably anymore, neither for data storage and handling as well as for computation of simulation results. There would be a database application necessary to manage and handle the input and outputs of the simulation as well as outsourcing of the simulations to a computing cloud solution. There is the possibility that the necessary variation of parameters or the considered parameters themselves could be reduced by a thorough analysis during the development of the procedure, or that generic patterns emerge that allow to use mathematical functions instead of discrete values for the influence of certain parameters. Nevertheless, this would cause a lot of effort spent for deeper analysis of interrelations of the influence parameters. But even if the set of considered parameters could be reduced to 2 or 3, this would still mean 60 x 10^2 = 6 000 or 60 x 10^3 = 60 000 pairs of conventional and hybrid vehicles to be simulated. But in any case a reduction of detail level in the influence parameters will result in further inaccuracy of the method.

The only approach to avoid that problem would be to agree on estimated bonus factors for each 4-tuple of hybrid architecture, degree of hybridization, vehicle class and mission profile. But this easy solution was already discarded in a first preselection of methods due to the very low accuracy achievable as described in paragraph 4. An expert assessment of bonus factors without a standardized simulation method includes also the big risk, that experts may not reach an agreement (e.g. one OEM may see higher FC reduction rates for series, the other OEM for parallel hybrids). Also EPA discarded the method with simple bonus factors existing for the phase 1 of their greenhouse gas emission standards during the development of the phase 2 of the standards because it was deemed as not able to accurately depict the fuel saving potential of a hybrid system.[16]

6.3.2 Effort and time for implementation

The estimated effort and the time necessary for implementation of this approach to a ready-for-certification level are shown in Table 20. Two options are presented, one detailed option considering the full set of influence parameters on the fuel consumption and one less detailed option considering only the 2 or 3 most important parameters at the price of reduced accuracy of the results.

The underlying assumption for deriving these values was that vehicle manufacturers will support the activities with experts participating in the discussions and in the development of methods, internal data for assessment of different options to be selected and validation results against their in-house simulation tools. Also the development of different generic hybrid control strategies should be supported by industry (already first activities started within ACEA).

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[16] US 2016

Table 20: Estimated effort for implementation of the advanced crediting scheme

Step no.	Item	Sub-item	Effort (person-days) Option 1 "Detailed fuel saving rates"	Option 2 "Only 2-3 parameters considered"
1	**Standardization**	**Total**	**323 OR 201**	**323 OR 201**
		Develop conversion method for hybrid system into conventional vehicle with virtual ICE	16	16
		Develop OR adapt existing simulation model for all hybrid configurations *(* effort for model development taken from estimations in paragraph 5.5 – step 1, 2, 4, 5, 6)*	*182** **OR** 60	*182** **OR** 60
		Develop standardized parameterization for all non-vehicle-specific input data (e.g. gear shift model)	8	8
		Develop standardized maximum drive/generation power and generic efficiency maps for different technologies of alternative energy converters *(if also technology dependent fuel saving rates shall be elaborated)*	12	12
		Develop standardized generic resistances for different technologies of ReESS *(if also technology dependent fuel saving rates shall be elaborated)*	12	12
		Develop generic control strategies for all architectures and types of hybrid systems *(basic hybrid strategy is assumed to exist already in simulation tool)*	20	20
		Implement generic control strategies in simulation tool *(basic hybrid strategy is assumed to exist already in simulation tool)*	10	10

		Testing of implementation of all methods above by comparison with simulation results from other tools or measurement data from OEMs as plausibility check	38	38
		Iteration loop based on feedback from plausibility testing in previous step	25	25
2	**Parameters for variation**	**Total**	**18**	**18**
		Analyse relevant influence parameters on FC of hybrid vehicles for all architectures, types and mission profiles	12	12
		Analyse necessary variation range for each parameter identified	6	6
3	**Determination of fuel saving rates**	**Total**	**1160**	**155**
		Set up all vehicle configurations to be evaluated in the simulation tool (as pair of hybrid and conventional counterpart) ** > 600 000 000 variants for option 1* *need to be handled automatized by a database or similar system*	*120**	40
		Run simulation for all vehicles *Parallelization of simulation tasks necessary;* **estimated additional costs of computing-cloud of 900 000 Euro for 600 000 000 variants with 30 seconds simulation time per variant (according to https://azure.microsoft.com/en-us/pricing/calculator/) assumed as 900 man-days*	*950**	25
		Evaluate results and run automatized plausibility checks on data	50	50
		Possible iteration, bug fixing in simulation tool and fine-tuning of results	30	30
		Create structured matrix with fuel saving rates	10	10
4	**Implementation in VECTO**	**Total**	**20**	**20**
		Implement matrix in VECTO for automatic application of fuel saving rates	15	15

		Testing of correct implementation of fuel saving rates	5	5
5	**Drafting of technical annex**	**Total**	**10**	**10**
		Drafting of technical annex based on all standards to parameterize conventional reference vehicle developed in step 1	10	10
		OVERALL TOTAL	**1531 OR 1409**	**526 OR 404**

6.3.3 Summary

The advanced crediting scheme approach is the one which needs the lowest effort for certification of a vehicle but needs a very high effort for development, since all fuel saving rates need to be pre-calculated by the means of detailed simulation. Even if the number of cases to be simulated would be reduced by 50%, it would still be twice the effort as compared to implementing the simulation directly in VECTO. Basically, this approach needs all steps necessary for the extension of VECTO (except the pilot phase and the adaption of the EPT procedure) and in addition the effort for the determination of the fuel saving rates by simulation. This simulation task, where an estimated 600 000 000 different configurations of vehicle pairs (hybrid and conventional counterpart) would need to be calculated, would take several months of calculation time. The big amount of data and the restrictions of computing resources would require outsourcing of the simulations to a computing cloud solution, to be able to complete the simulations within a few months. This outsourcing of computation tasks causes additional costs of around 900 000 Euros.

The reachable accuracy is estimated to be around 3-9% (depending on the hybrid architecture and mission profile) worse than for the direct simulation of hybrids by extension of VECTO due to the additional sources of inaccuracy explained in paragraph 6.2. Besides, it would work quite well for parallel hybrids but for series and power-split hybrids it will cause limitations of accuracy, since it is not possible to define a conventional powertrain absolutely matching the characteristics and performance of these more complex hybrid systems. Due to the restricted accuracy also applying ex-post verification does not really make sense for this approach, since there will also occur simulation results that are significantly lower than the figures measured for the real vehicle. Furthermore, the interaction with ADAS systems and reduction in rolling and air resistance, which are targeting the same energy (by optimizing the sum of potential and kinetic energy) that is recuperated by the hybrid systems, cannot be depicted by the advanced crediting scheme approach leading to distorted results as soon as these systems are available in hybrid vehicles.

If future powertrain configurations shall be added to this approach, new standards for converting those new hybrid systems into the virtual reference vehicle might need to be elaborated and also the new values for the fuel saving rates need to be determined by simulation these new hybrids in all parameter variations.

The advantages of the advanced crediting scheme are:

- No hybrid simulation is needed in the certification (only for pre-calculation of fuel saving rates)

- No additional input data is needed for certification as compared to conventional vehicles (only selection of architecture, type, configuration and nominal specification of hybrid components necessary to define hybrid powertrain)

- Lowest effort for certification of a vehicle of all options analysed (no measurement, no additional component tests for hybrid components)

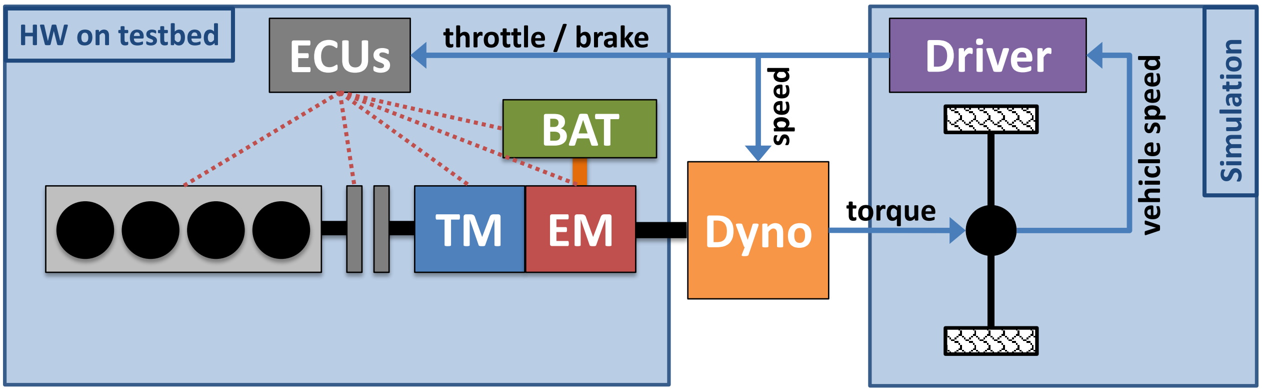
6.4 Powertrain method

6.4.1 Detailed description of the powertrain method

The procedure was already described in detail in paragraph 3.3.2 and is only summarized here again. The powertrain method defines a combined approach for CO_2 certification where in a first step the efficiency of the hybrid system is determined in a measurement procedure over a testcycle on a powertrain testbed and in a second step a conventional vehicle simulation model is used to determine the cycle work of the vehicle over the certification duty cycle. In the vehicle simulation to determine the cycle work all parameters vehicle parameters (i.e. mass, rolling resistance, air resistance and tires; optional: drive axle) will be set for the specific hybrid vehicle to be certified, whereas the engine and transmission will be set as generic data. The value for cycle work determined in kWh is then multiplied by the fuel efficiency value from the testbed defined in grams fuel per kWh in order to calculate the final fuel consumption figure for the hybrid vehicle.

The powertrain for a hybrid system installed on the testbed comprises the whole hardware of the hybrid powertrain (i.e. ICE, all alternative energy converters, all ReESSs, all electronic control units necessary to operate the powertrain). The dynamometer(s) of the testbed are connected to the powertrain either upstream of the drive axle or at the wheel hubs. The dynamometer and throttle setpoints are not set by fixed values prescribed by a cycle, but are calculated in real time by a vehicle and a driver model. The powertrain test procedure requires a forward calculating vehicle model, thus the output of the model is the dynamometer rotational speed setpoints. The vehicle model calculates the speed target using the measured torque at the previous time step, the simulated brake force from the driver model, and the vehicle parameters (rolling resistance, air drag, vehicle mass, rotating mass, and axle efficiency). The operator demand that is used to change the propulsion torque from the hybrid system is controlled by the driver model such that the powertrain follows the vehicle speed target for the cycle. Figure 17 shows the basic principle (for a setup upstream of the drive axle exemplarily) and the signal flow.

Figure 17: Schematic illustration of powertrain method and respective control signals



Hybrid systems are particularly challenging to simulate within a computer program because the powertrain components installed in vehicles today are actively and interactively controlled by their own sophisticated electronic controls. A key advantage of the powertrain test approach is that it directly measures the effectiveness of the engine, the transmission, the hybrid components and the integration of these components. Thus, the OEM specific control logics are included in the procedure without the need to disclose any sensitive information and without simulation of any of the hybrid parts needed.

The main disadvantage of this method are the high costs associated, both for initial investment in test facilities and also for performing the actual testruns. The investment costs for the initial testbed installation in an existing building are estimated with 2 million Euros.[17] The effort for the setup of a hybrid system on a testbed is estimated with 4-8 weeks, depending on the complexity of the system. Since the measurement runs in real-time on the testbed (i.e. several hours for one testcycle), the effort and costs for each testrun are extremely high.[18]

EPA made an estimation for the introduction of the phase 2 of their greenhouse gas emission standards, which states that costs of $150,000 would provide about one month of powertrain testing services. The also estimated that once a powertrain test cell is fully operational, the cost for powertrain installation, testing, and data analysis would be about $70,000 without the investments included.[19]

At the beginning of the European CO_2 certification procedure being introduced as mandatory for hybrids, there will most likely be only one variant of hybrid system per vehicle category at each OEM existing. Thus, the powertrain test could be performed with the specific vehicle data. Later, if there are more variants of hybrid powertrains established, a family concept as available in the US standards could be introduced. This family concept covers the range of vehicles in which the powertrain will be used and limits the amount of testruns necessary by setting all vehicle parameters at several intermediate levels within these ranges. For the final CO_2 value the hybrid system efficiency is the interpolated from a matrix of values determined in the measurement based on the parameters of the vehicle to be certified.

The forward simulating vehicle model and the associated driver model necessary for the powertrain method cannot be developed completely from scratch as open-source solution or adapted based on the existing VECTO. There would be the need to build on already existing

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[17] US 2016 p73533

[18] Environment Canada 2012

[19] US 2016 p73533

solutions which have been established as industry standard for performing tasks where simulation models need to be coupled to a testbed environment (e.g. MATLAB/Simulink in combination with dSpace hardware equipment[20]). For the US approach there is a ready-to-use model in MATLAB/Simulink provided. If this would be compatible with the European regulation would need to be clarified.

Since the setup of the hybrid system on the testbed is quite a complex task, the risk exists that the hybrid system on testbed does not exactly perform as in the real vehicle. In order to check the performance of the system on the testbed, a sophisticated procedure for verification of the correct setup would need to be developed to avoid possible loopholes (i.e. special testbed mode of the system) as described in paragraph 3.3.2.1. This system verification procedure on the testbed would increase the necessary effort for creating powertrain test results even more.

Also, for a neutral SOC to be achieved over the cycle for a fair comparable fuel efficiency value several repetitions of the testcycle with adjusted start SOC can be necessary which again increases the test effort significantly.

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[20] dSpace 2017

6.4.2 Effort and time for implementation

The estimated effort and the time necessary for implementation of this approach to a ready-for-certification level are shown in Table 21 - Table 22. Due to the complexity of this approach and the missing experience with this kind of testing an initial measurement campaign based on the existing US standard as well as two subsequent pilot phases are suggested. If the necessary equipment (powertrain testbed with HIL option in a software supporting VECTO target speed cycles) would be available in time is questionable.

The underlying assumption for deriving these values was that vehicle manufacturers will support the activities with experts participating in the discussions and in the development of methods, internal data for assessment of different options to be selected, intense measurement and testing effort and validation results against their in-house simulation tools.

Due to the novelty of the test method and the lacking experience, it is suggested to follow a 2-step approach for the implementation.

Table 21: Estimated effort for implementation of the powertrain method (Step 1)

Step no.	Item	Sub-item	Effort (person-days)
1	**Evaluation of approach**	**Total**	**24**
		Contact EPA and collect feedback on issues for test procedure based on their experience	6
		Analyse issues, discuss with vehicle OEMs and develop items to be analysed	12
		Develop powertrain test program to be run by OEMs to address all open issues identified *US EPA MATLAB/Simulink models could be used for this activities*	6
2	**Conducting of evaluation test program by OEMs**	**Total**	**41**
		Support during evaluation test program	20
		Collection of feedback from evaluation test program	8
		Analyse feedback and create open issue list for next step	13
3	**Development/adaption of vehicle and driver model**	**Total**	**75**
		Define features for vehicle and driver model based on feedback from previous step and adjust the US EPA model	8
		Perform adaptions to existing simulation models (US EPA model)	55
		SIL testing of new/updated simulation models	12

4	**Development of test procedure**	**Total**	**66**
		Further develop procedure for powertrain testing based on existing US approach and feedback from step 2	35
		Develop conversion method for hybrid system into conventional vehicle with virtual ICE	16
		Writing of first draft technical annex for test procedure	15
5	**Development of method to correct for neutral SOC**	**Total**	**12**
		Development of a method to correct for neutral SOC over testcycle for a fair comparable CO_2 result	9
		Describe correction method in technical annex	3

Table 22: Estimated effort for implementation of the powertrain method (Step 2)

Step no.	Item	Sub-item	Effort (person-days)
6	**Pilot phase 1** **(Testing of simulation model and test procedure by OEMs)**	**Total**	**27**
		Support during testing of new/updated simulation model together with new test procedure	14
		Collection of feedback from pilot phase 1	4
		Analyse feedback and create open issue list for next step	9
7	**Optimization loop**	**Total**	**28**
		Optimizing of simulation and driver model based on feedback from previous step	20
		Optimizing of technical annex based on feedback from previous step	8
8	**Development of verification procedure**	**Total**	**28**
		Develop verification procedure based on experiences collected in steps 1, 2 and 5	19
		Writing of first technical draft for verification procedure	9
9	***Depending on status after pilot phase 1:*** ***Pilot phase 2***	***Total***	***22***
		Support during testing of updated test procedure and simulation model	*12*

	(Testing of simulation model and test procedure by OEMs)	*Collection of feedback from pilot phase 2*	*3*
		Analyse feedback and create open issue list for next step	*7*
10	**Iterations for optimization**	**Total**	**25**
		Max. 4 iteration loops for processing of open issues and optimization of simulation model and test procedure	25
		OVERALL TOTAL	**348**

The main costs during the implementation of this approach are caused at the participating OEMs for setting up powertrain testbeds and performing actual testruns. No testing activities at European Commission or contractors are included here.

6.4.3 Summary

The powertrain approach leads to a quite high accuracy at the price of very high effort for certification of single vehicles as well as investment necessary for installation of the required test facilities. In Europe, powertrain measurement is not as common as in the US, thus only few testbeds are existing and would need to be built especially for the purpose of certification.

In the powertrain method applied for a specific hybrid vehicle, as long as the hybrid system and the corresponding controls are set up correctly on the testbed (which should be ensured by an additional verification test), the only sources of inaccuracy on the test result are the typical measurement uncertainty on the testbed and the variation in cycle work of the virtual conventional vehicle used (see paragraphs 6.2.1.1 and 6.2.1.2). This added inaccuracy of this method to the very basic accuracy of the whole VECTO approach itself is estimated to be within 3-6%. Furthermore, the accuracy is considered to be within the same range as for the direct simulation of hybrids by extension of VECTO.

As soon as a family concept is introduced to limit the amount of test burden, the accuracy might get worse due to the interpolation of the efficiency factor from a matrix of values determined for a set of standard vehicles covering the range of vehicles in which the powertrain will be used typically. The added inaccuracy due to the family concept cannot be assessed without performing a thorough test campaign. Besides, introducing a family concept only makes sense if a certain hybrid powertrain is installed in a larger number of vehicle variants which is typically not the case at the moment. Thus, it would be suggested to apply this method by measuring the efficiency factor directly for the hybrid vehicle to be certified in the first phase of the procedure. This would also allow to gain more experience with this method.

Also a standardized method how to convert a hybrid powertrain into a virtual conventional powertrain (i.e. rules how to define the ICE, the transmission ratios and efficiencies, the optional axle ratio and efficiencies for a given hybrid system) is needed to derive the cycle work by simulation in step 2 of the powertrain method.

The advantages of the powertrain method are:

- No hybrid simulation is needed in the certification
- No additional input data is needed for certification as compared to conventional vehicles (only the g/kWh efficiency values from the powertrain test)
- OEM specific control logics can be used without disclosure of sensitive information

7 Task 5: Assess and compare all suggested approaches for certifying fuel consumption and CO_2 emissions of hybrid HDVs

Objectives:

- to identify the two best options for certifying fuel consumption and CO_2 emissions of hybrid HDVs
- to describe in detail a pathway for their implementation in the certification scheme

Key tasks:

- perform a preliminary assessment of the approaches identified in tasks 3 and 4
- determine the two best options by evaluation of the results
- describe in detail a pathway for their implementation in the certification scheme

Outputs:

- detailed pathways for the implementation in the certification scheme for the two best options
- summary and list of recommendations

7.1 Overview of task 5

In this paragraph the approaches described in task 3 and 4 are assessed according to certain criteria and recommendations for further steps are given.

7.2 Assessment of options

Table 23 shows the assessment of the viable options identified in task 3 and 4 according to different relevant criteria performed by the authors of this study, where 5 is the best and 1 the worst rating. Thus, the method with the highest score is the best. Also a weighting of the single criteria is introduced which is applied multiplicative to each single rating before summing up the weighted total. More detailed information for each option assessed as well as the degree of meeting the single criteria can be found in the description of each option in paragraphs 5 and 6. Also the detailed pathways for the implementation of the different options have already been sketched in those paragraphs.

Chassis dyno testing and on-road testing were added to the original table as options for assessment as requested by different stakeholders during the project meeting held in Brussels on 19th of July 2017 even though these two option were already discarded earlier in time (see chapter 4). All stakeholders were asked to provide their individual view on the different options by a separate rating table.

In order to reflect the individual views of different stakeholders, Table 24 shows the alternative total ratings submitted by the European Commission’s JRC, CLEPA and IVECO. Finally, Table 25 gives a comparison of the average of all alternative ratings to the assessment by the authors of this study. The complete rating tables for each stakeholder including all comments can be found in the annex of this study.

Table 23: Assessment of different options analyzed performed by the authors of this study

Method	Simulation in VECTO	Advanced crediting scheme – Variant 2	Powertrain method	Chassis dyno testing**	On-road testing**	Weighting (3=high, 1= low importance)
Effort needed for implementation in certification scheme	3	1	3	3	3	2
Timeline for implementation	4	3	2	3	3	2
Complexity of the method	4	5	2	3	3	1
Additional input data necessary	4	5	4	4	4	1
Fleet coverage for hybrids	4	4	5	4	5	3
Technologies covered	4	4	5	5	5	3
Practical feasibility	5	4	3	3	2	3
Compatibility with current VECTO	5	1	4	4	1	2
Needs for extension of the tool	2	5	5	5	4	1
Adaptability to existing certification framework	5	4	3	3	3	2
Investment necessary for testing facilities/equipment	5	5	2	2	4	2
Effort for certification per vehicle	5	5	2	2	2	3
Ex-post testing possible	4	1	4	4	4	2
Reachable accuracy	4	2	4	4	3	3
TOTAL not weighted	***58***	***49***	***48***	***49***	***46***	
TOTAL weighted	**128**	**102**	**104**	**104**	**98**	

*** added to the original table at a later point in time even though these two option were already discarded earlier in time (see chapter 4)*

Table 24: Assessment of different options analyzed performed by other stakeholders

Institution	Method	Simulation in VECTO	Advanced crediting scheme – Variant 2	Powertrain method	Chassis dyno testing**	On-road testing**
JRC	*TOTAL not weighted*	55	48	40	44	52
	TOTAL weighted	124	101	88	99	118
CLEPA	*TOTAL not weighted*	46	51	48	51	53
	TOTAL weighted	101	105	104	110	113
IVECO	*TOTAL not weighted*	55	52	47	51	48
	TOTAL weighted	121	108	101	111	102

*** added to the original table at a later point in time even though these two option were already discarded earlier in time (see chapter 4)*

ACEA did not provide a separate assessment table, but instead stated that “the overall ranking of the methods as shown in the table is very much in agreement of the perception of the ACEA Task Force”. Thus, the assessment of the authors of this study was applied as assessment of ACEA for determination of the average values of other stakeholders in Table 25.

UITP did not provide a separate assessment table, but instead stated that “they support the outcome of the JRC’s assessment”. Thus, the assessment of the JRC was applied as assessment of UITP for determination of the average values of other stakeholders in Table 25.

Table 25: Comparison of assessment results by other stakeholders vs. authors of this study

Institution	Method	Simulation in VECTO	Advanced crediting scheme – Variant 2	Powertrain method	Chassis dyno testing**	On-road testing**
Authors of this study	TOTAL weighted	128	102	104	104	98
Average of other stakeholders	TOTAL weighted	120	103	97	105	110

*** added to the original table at a later point in time even though these two option were already discarded earlier in time (see chapter 4)*

Table 25 shows clearly that simulation in VECTO is the preferred option for both, the authors of this study as well as other stakeholders on average. The differences in the figures are mainly resulting from requirements of the various stakeholders: For example, CLEPA prefers measurement based methods of the whole hybrid system performed by the vehicle manufacturer over simulation since the suppliers would like to avoid the investment costs and effort for component measurement (which would be necessary for the simulation method).

Besides, all stakeholders see the powertrain method as least favorable measurement based option since it is much more complex, requires much higher effort than the other two measurement options and the expected accuracy is regarded to be lower due to the simplifications made on the testbed as well as involvement of simulation parts coupled with the hardware.

Furthermore, all stakeholders agree that the advanced crediting scheme poses no viable option since it needs huge effort for its development (based on simulation or measurements) but due to a lot of simplifications offers only low accuracy.

8 Additional feedback received after distribution of the draft final report

The following paragraphs list additional feedback received from stakeholders after the distribution of the draft version of the final report. These inputs should shine a light on different aspects of different certification options relevant to certain stakeholders

8.1 Feedback received from ACEA

ACEA stated some general comments regarding the findings and conclusions of this study:

- We fully agree with the conclusion that direct simulation by extension of VECTO is the overall best solution
- We also agree with the recommendation to elaborate the direct simulation method and start as simple as possible with generic control models and generic component efficiencies.
- We support the implementation plan. The members of the working group are prepared to give support for the implementation activities and will also continue in supporting the development of the generic control strategies.
- As already earlier stated: for ACEA it is a prerequisite that hybrid technologies are included in the VECTO procedure from the very beginning of the mandatory CO_2 declaration of buses. As a consequence, we insist on having only one pilot phase for buses incorporating both the conventional and hybrid vehicles. So we do not like to have a separate pilot phase for hybrids (see step 11 in Table 16) but one integral pilot phase for buses in which step 11 is included.
- In view of the former point and looking to experiences with the former pilot phase we think that the estimate of the throughput time of 4 months for the pilot phase as proposed in Figure 11 might be to short.

ACEA also stated some additional remarks regarding certain assessment criteria in Table 23:

- *Fleet coverage:*

  If all hybrid architectures are included in the simulation approach the fleet coverage for the simulation method can be as high as the powertrain and the on-road testing.

- *Technologies covered:*

  Interactions with other control technologies or vehicle parameters like air drag, weight etc. as well as controlled electrical auxiliaries are very difficult to incorporate in the test methods. Extensive vehicle verifications are required for powertrain and chassis dynamometer test methods.

- *Practical feasibility and effort for certification per vehicle:*

  Here the trade-off between high number of vehicle configurations on one side and simplifications in measurement based methods on the other side gives high preference for simulation above physical testing.

- *Reachable accuracy:*

  The ranking is correct for one vehicle variant value. But the accuracy for the total fleet by simulation is higher than by using measurement based methods.

8.2 Feedback received from IVECO

IVECO stated that from past experience for the powertrain methods installation on the testbed is much more complex and it is difficult to ensure reliable powertrain control between systems simulated and physically tested. They expressed their doubt about whether the hybrid control software behavior would be real during a powertrain test (same issue as for SIL or HIL based full simulation).

Additionally, powertrain testing is more costly in engineering hours for installation, checking and testruns for certification.

From their point of view the chassis dyno is more cost effective (as less check need to be done on the test bench and it is a more straight forward method) and the method will ensure that the real driveline efficiency is certified – of course still with some deviations against real life because some parts in the energy flow are still simulated (driving resistances, driver behavior, etc. and also ambient and cooling conditions can deviate from real world).

8.3 Feedback received from UITP

UITP provided feedback on several points of this study:

- *Fuel saving potential of various types of hybrids (see paragraph 2.3.2):*

  The numbers seem to be within a realistic range. One UITP member commented that the figures for full parallel and series hybrid should be more equal. Another member stated that the figures for micro hybrids should be slightly higher. Also, the fuel saving potential of a power-split hybrid is considered to be higher than for parallel and series in the urban transportation operation according to one UITP member.

- *Rating of certification options*

  The OEMs who are member of UITP prefer detailed simulation in VECTO with specific hybrid component data and the specific hybrid control strategy. Simulation with generic values for both, efficiencies of hybrid components and operation strategy of hybrid systems, is not considered accurate enough to compare vehicles and promote technological progress.
  The preferred option for public transport operators is SORT testing since they are used to this easy, cost-effective and straightforward method. Also, on-road testing in general, as the preferred option, gives public transport operators the ability to verify the certification results independently. As an alternative, they suggest chassis dyno testing which, from their point of view, delivers more realistic results than on-road testing but is also more expensive.
  The industry members of UITP prefer chassis dyno measurements since this is more controlled and repeatable than on-road testing and at the same time evaluates the real hardware as well as the real hybrid control strategy of the vehicle.

  The powertrain method is rejected as too complex, not cost-efficient and also too inaccurate due to a lot of simplifications on the testbed. Also the advanced crediting schemes are rejected because the fuel savings provided by a hybrid drivetrain are considered not to be directly attributable to the system hardware parameters – they are considered to be far more influenced by the system control algorithms. In the advanced crediting scheme, no credit or penalty would be given for good or bad control.

- *Generic data for components*

  Some industry members are concerned about using generic component data and a generic control strategy because that would produce inaccurate results that are unrepresentative of the actual vehicle system. Another industry representative thinks that generic data could be possible for a start, but sees it as important to gradually increase the measurements of individual components to ensure the accuracy of data.

- *Sharing of intellectual property*

  Generally, one industry member is concerned that, while the VECTO simulation would be a nice solution, in order to provide a true result, it would involve the sharing of certain industry's proprietary system control algorithms with external parties. This is something that could be problematic for hybrid system suppliers.

- *On-road validation of values*

  The general UITP comment on VECTO is that, if VECTO is used, the VECTO process should include an on-road validation of the results. Having a full vehicle driving validation on-road is essential for UITP, since this would pose a compromise combining simulation and real-world driving. Moreover, according to UITP the simulation should be based on the SORT cycles in order to allow independent on-road comparisons by operators.

- *Accuracy tests by OEMs*

  UITP suggests to simulate both, the standardized VECTO certification cycles and the SORT cycles, and to compare the results for conventional as well as for hybrid buses.

During the project meeting held in Brussels on 19th of July 2017 Ms. Stienen from UITP requested that UITP would prefer a measurement of the complete hybrid vehicle in the SORT cycle instead of simulation.[21] Therefore, some general comments regarding the application of the SORT procedure for CO2 certification were added by the authors of this study in the following paragraph 8.4.

8.4 General comments regarding the SORT procedure

The SORT procedure was developed to establish comparability of fuel consumption results of different vehicles for public transport operators, since there was no other official independent methodology available. But the SORT methodology has the following weak spots when applied for CO_2 certification of HDHs:

- *Applicability for all vehicle classes*

  The SORT procedure is designed for bus operation in urban areas and thus not suitable for other vehicle categories.

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[21] UITP 2014

- *Energy consumption of auxiliaries*

  Auxiliaries are to be switched off during testing and thus are not considered in the measurement results.

- *Road gradient*

  The test have to be performed on a level surface, thus no road gradient is present during testing leading to unrealistic fuel consumption figures. Additionally, for hybrids the absence of a road gradient also influences the amount of braking energy to be recuperated which leads to a further distortion of the final results.

- *Accuracy of fuel flow measurement*

  The accuracy of fuel flow requirement is much lower for SORT testing (±2.0%) than for the VECTO component test (±0.6%) also leading to a higher inaccuracy.

- *External influence factors*

  For on-road testing there are a lot of external influence factors on the result like driver behavior, weather conditions (temperature influence on performance of electric ReESS, wind), preconditioning cycle of the hybrid system or road surface properties. All these influence factors lead to a poor repeatability of the procedure which is required to be below ±3.0% for one single measurement series for one vehicle.

- *Special vehicle operation mode*

  There is also the risk that the hybrid control strategy as well as the gear shift strategy could be designed with a special SORT mode that would be activated as soon as the vehicle recognizes the characteristical test profile leading to unrealistically low fuel consumption values.

Interestingly, Green Propulsion – a UITP member supporting the development of the SORT methodology for hybrid vehicles, who gave individual feedback to the authors of this study – stated that they don’t see SORT as the preferred method for CO_2 certification.

But in order to allow independent on-road comparisons by public transport operators, the VECTO simulation could easily produce results for the SORT cycles in the certification process in addition to the regular CO_2 test cycles, so that the respective reference values for SORT testing would be available.

8.5 Feedback received from MAN

MAN stated an additional comment regarding the request of UITP to use the SORT cycles for CO2 certification (see paragraph 8.3):

“MAN Truck & Bus as member of ACEA and UITP recommends only to use the truck and bus cycles in VECTO which have been developed for the CO_2 *legislation process. It is strictly recommended not to include any other cycles such as SORT in order not to mix up completely different procedures. For vehicle on-road testing an ex-post verification procedure is being developed allowing all external parties to verify the VECTO results with own measurements and reasonable effort.”*

8.6 Feedback received from Volvo

Volvo stated an additional comment regarding plug-in hybrid vehicles:

“As the plug-in feature on hybrid vehicle will be developed quite heavily in a near future we think its implementation should be taken into account at the same time as for Hybrid vehicles. Indeed if the current proposal is applied to PHEV vehicles (i.e. without charging function), it will surely provide worse CO_2 values than for HEV vehicles as the PHEV might have lower battery capacity due to chargeability feature. Then it will not show the real CO_2 reduction that is definitively achieved by PHEV vehicles!

There could be several options for its implementation:

a) *Hybrid simulation in VECTO + simple crediting scheme for external charging: It could be a % of CO_2 saving depending on cycles, vehicle weight, battery capacities …*
b) *Hybrid simulation in VECTO with fully charged battery at the beginning of the cycle*
c) *Hybrid simulation in VECTO with specific virtual charging stations on each cycle that allow instantaneous battery charging to SOC max. It could be based on market analysis.”*

8.7 Feedback received from CLEPA

CLEPA stated an additional comment regarding the different levels of detail for the simulation of HDHs in VECTO as shown in Table 12:

“Detail level 0 is seen as a feasible option to determine CO_2-emission of HEV’s. Generic values should not reflect the worst case but realistic conditions. This concept has the potential for inclusion in the first step of the CO_2-emission legislation for busses.

Detail level 2 is seen as a good solution from the technical point of view under the assumption that VECTO will be chosen for CO_2-determination. If all input values of the simulation are based on specific properties of the simulated vehicle a good accuracy will be reached.

The intermediate step (detail level 1) is a mix of some specific input data and ongoing generic input. Especially the control strategy of the hybrid system will not be specific. We believe that the control strategy parameters will have a greater impact on CO_2-emission as the specific efficiency data of the components.

Therefore we propose to cancel ‘detail level1’ and to go to ‘detail level 2’ immediately after ‘level 0’.

In case that this is not possible CLEPA strongly recommends an in-depth impact analysis of the contribution of control strategy and component efficiency values on CO_2-emissions. This should be done before starting any work on detail level 1.”

8.9 Feedback received from BAE Systems

During the discussion in the final project meeting held in Graz on 18th of October 2017, the representative of BAE Systems requested a statement about the handling of confidentiality issues for component input data to be made in this report. Therefore, the following statement was added by the authors of this study as a short explanation:

The component input data of hybrid system components used for the vehicle simulation in VECTO would be treated as any other component data in the existing VECTO procedure. This means it is assumed that vehicle manufacturers sign a non-disclosure agreement in order to receive the respective component data required from their suppliers. This agreement obliges them to use the component data only within the VECTO process and not to share any component data with third parties.

9 Summary and recommendations

Based on the existing analysis done, the following recommendations can be made:

The integration of the hybrid simulation into VECTO is considered to be the best overall option.

The main advantages of this approach are:

- Future-proof option
    - high number of vehicle variants can be handled with low effort
    - can later be extended towards SIL or HIL
    - more complex functionality or more detailed component data can be introduced stepwise leading to improved accuracy
- Reasonable accuracy (realistic results)
- No investments in expensive new test facilities necessary in a first step
- Similar effort for certification of HDHs compared to conventional HDVs
- Other fuel saving technologies are depicted correctly in combination with hybrids
- Coherent with existing approach for conventional HDVs (no inherent offset in the results generated by a different procedure for hybrids)

The main disadvantages are the effort for developing the method and implementing it in VECTO and also to get agreement between all involved stakeholders on a generic controller for use in the first phase. Additionally, supplier industry will have to carry the potential additional costs for necessary component testing.

This recommendation is also supported by the feedback of other stakeholders involved in the project. Despite the reservations and weaknesses of the chassis dyno method presented in paragraph 3.3.4 and also the quite low score reached in paragraph 7.2, most of the other stakeholders consider chassis dyno testing as a reasonable alternative option.

The drawback with all pure measurement based methods is that they don’t work well for a larger number of vehicle variants – which was also the main reason for following the component based approach for conventional HDVs. As soon as a higher number of vehicle variants are available, chassis dyno testing would require a family concept for transferring one measurement result to other variants within one vehicle type. Also this transfer of results would lead to further reduced accuracy of the final CO_2 values.

Nevertheless, chassis dyno testing could pose an interesting opportunity as fallback solution for new technologies that cannot be immediately simulated in VECTO (due to the lack of component models or operation strategy) or to depict the fuel savings of more complex hybrid features that are not implemented in the VECTO tool. Thus, basic investigations for such a fallback method based on chassis dyno measurements could be performed in parallel (with synergy effects) during the development of the regular hybrid simulation model in VECTO since model development work requires also chassis dyno measurements for validation.

The development of an optional chassis dyno test procedure would require additional resources since there is no existing chassis dyno standard for HDVs in Europe. In addition, defining a potential family concept for chassis dyno testing seems to be a complicated and challenging task.

Powertrain testing can be discarded as option based on the feedback received from stakeholders in paragraph 8. This approach is considered as too complex with too high effort for system setup for certification purposes. Also, due to a lot of simplifications and the interaction of the hardware with a simulation model part it is considered too inaccurate and would require extensive verification to be accepted.

Also a crediting scheme can rather be discarded as option due to the limited future expandability and low accuracy that can be reached.

On-road testing can also rather be discarded due to the poor repeatability caused by a lot of external influence factors and also most stakeholders prefer chassis dyno testing over on-road testing.

The option “integration into VECTO” could meet a timeline, where a method for CO_2 certification of HDHs is ready in 2020, early enough for the envisaged introduction of buses into the certification scheme. For integration in VECTO the development phase may need approximately 17 months to be followed by a pilot phase of around 4 months with a subsequent final iteration loop for optimization of the procedure. Sufficient test stand availability of HDV chassis dynos as well as hybrid vehicles for testing could pose a problem to the envisaged timeline for development of the procedure. An additional main uncertainty is the acceptance of rankings between hybrid configurations by all OEMs. As learned from other components (e.g. AT gearboxes), since the results are intended as customer information also, the correct ranking of different makes and models is of high competitive relevance for each OEM (as opposed to USA, Japan, China where only a limit value has to be met for certification). Thus, some percent uncertainty may not be accepted by all OEMs and could cause much longer development phases than assumed in the assessments performed for this study. However, such a development process seems to be unavoidable for a fair certification scheme.

In a project for a possible extension of VECTO also the open issues for gear shift models may be included since gear shift rules will have to be elaborated and validated for hybrids also. The approach shall certainly cover also mild hybrids based on 48V technology and possibly plug-in HEVs (PHEVs) as well as pure battery electric vehicles (BEVs). The additional potential for reduction in CO_2 emissions of PHEVs could be taken into account by defining virtual recharging stations in the VECTO mission profiles. Consequently, the vehicle could be simulated once starting with a full ReESS (i.e. charge-depleting mode) and once again in charge-sustaining mode. Finally, a weighting factor could be applied to these two results to determine the final CO_2 figure (similar as the concept for CO2 emissions of PHEV passenger cars).

Since buses are a main target for hybridization, also an adjustment of the advanced auxiliary model for buses is recommended in the course of the hybrid development process to better cover electric driven auxiliaries and to solve open issues for other auxiliary types.

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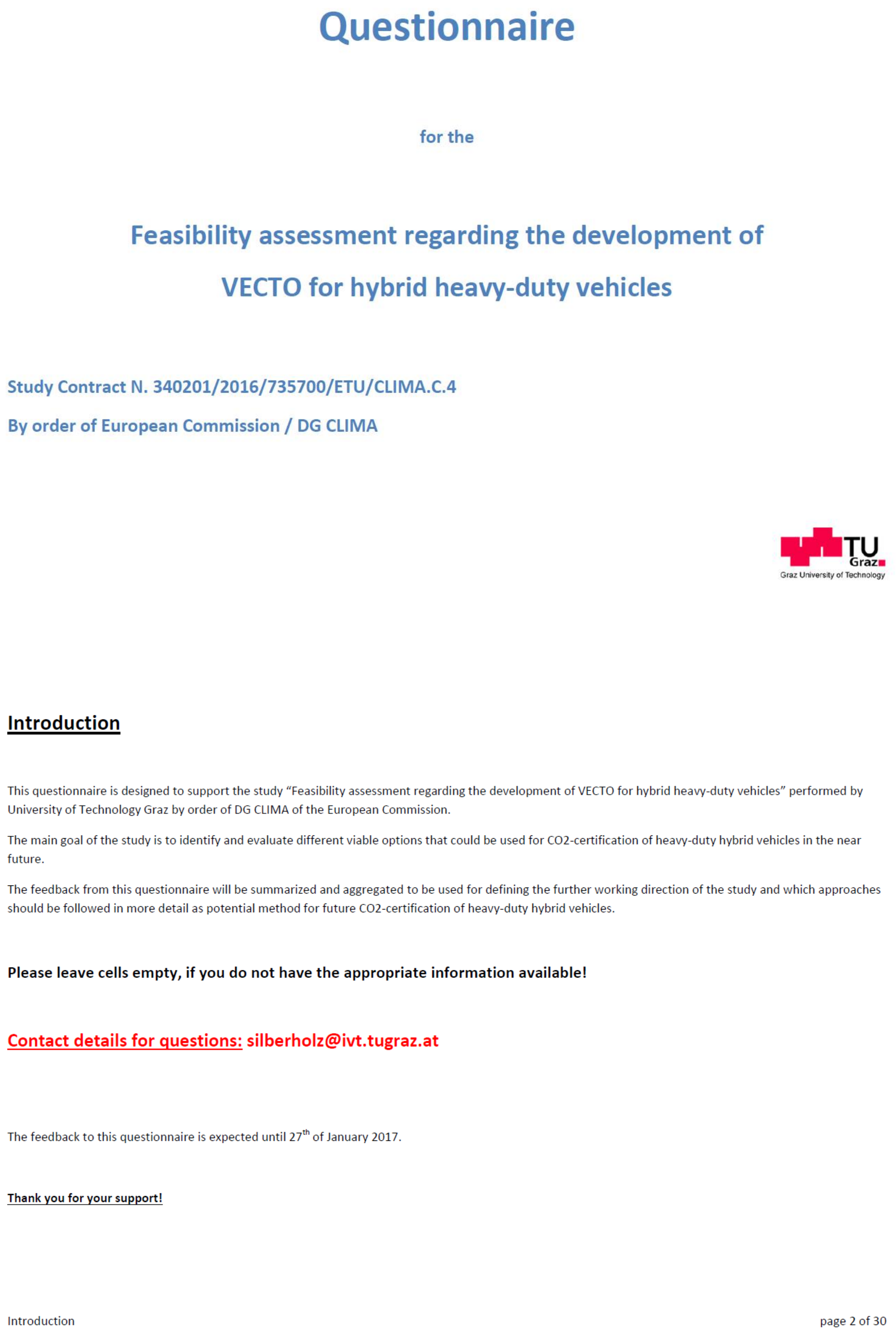
Annexes

1. **Questionnaire distributed for this study**

2. **Individual rating tables from stakeholders**

Annex 1

Questionnaire distributed for this study



Questionnaire

for the

Feasibility assessment regarding the development of VECTO for hybrid heavy-duty vehicles

Study Contract N. 340201/2016/735700/ETU/CLIMA.C.4

By order of European Commission / DG CLIMA

TU Graz
Graz University of Technology

Introduction

This questionnaire is designed to support the study “Feasibility assessment regarding the development of VECTO for hybrid heavy-duty vehicles” performed by University of Technology Graz by order of DG CLIMA of the European Commission.

The main goal of the study is to identify and evaluate different viable options that could be used for CO2-certification of heavy-duty hybrid vehicles in the near future.

The feedback from this questionnaire will be summarized and aggregated to be used for defining the further working direction of the study and which approaches should be followed in more detail as potential method for future CO2-certification of heavy-duty hybrid vehicles.

Please leave cells empty, if you do not have the appropriate information available!

Contact details for questions: silberholz@ivt.tugraz.at

The feedback to this questionnaire is expected until 27th of January 2017.

Thank you for your support!

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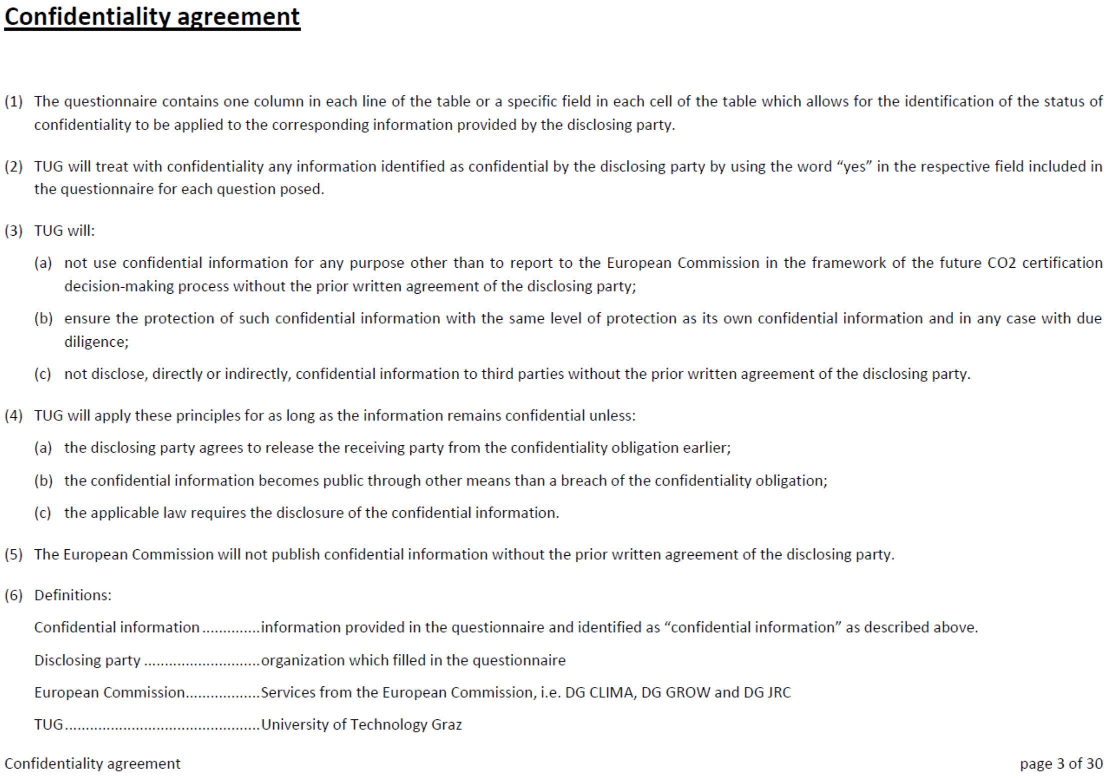


Confidentiality agreement

(1) The questionnaire contains one column in each line of the table or a specific field in each cell of the table which allows for the identification of the status of confidentiality to be applied to the corresponding information provided by the disclosing party.

(2) TUG will treat with confidentiality any information identified as confidential by the disclosing party by using the word "yes" in the respective field included in the questionnaire for each question posed.

(3) TUG will:

(a) not use confidential information for any purpose other than to report to the European Commission in the framework of the future CO2 certification decision-making process without the prior written agreement of the disclosing party;

(b) ensure the protection of such confidential information with the same level of protection as its own confidential information and in any case with due diligence;

(c) not disclose, directly or indirectly, confidential information to third parties without the prior written agreement of the disclosing party.

(4) TUG will apply these principles for as long as the information remains confidential unless:

(a) the disclosing party agrees to release the receiving party from the confidentiality obligation earlier;

(b) the confidential information becomes public through other means than a breach of the confidentiality obligation;

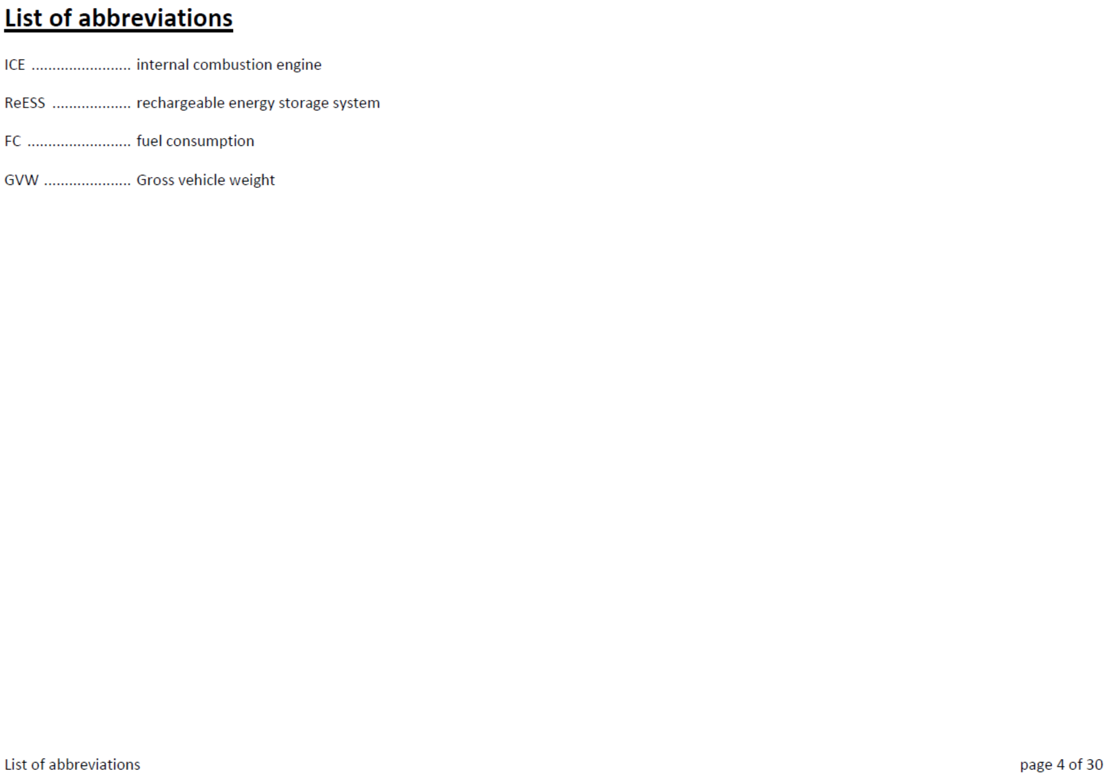
(c) the applicable law requires the disclosure of the confidential information.

(5) The European Commission will not publish confidential information without the prior written agreement of the disclosing party.

(6) Definitions:

Confidential information	information provided in the questionnaire and identified as "confidential information" as described above.
Disclosing party	organization which filled in the questionnaire
European Commission	Services from the European Commission, i.e. DG CLIMA, DG GROW and DG JRC
TUG	University of Technology Graz

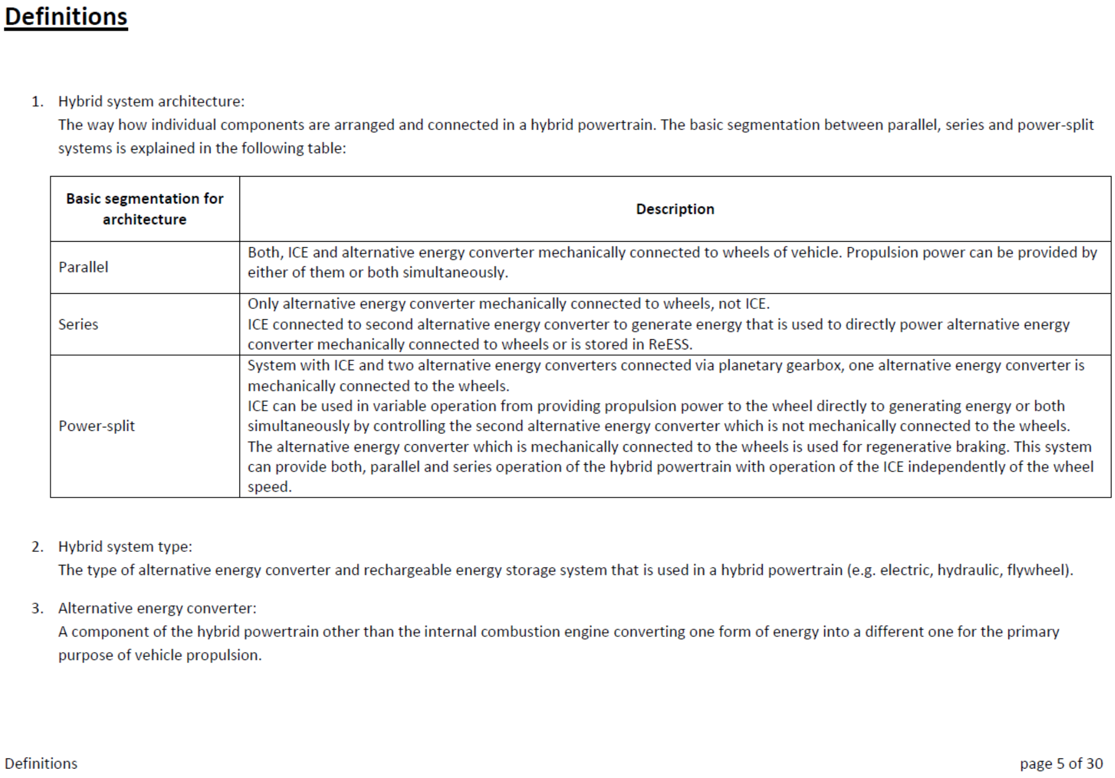
Confidentiality agreement page 3 of 30



List of abbreviations

ICE	internal combustion engine
ReESS	rechargeable energy storage system
FC	fuel consumption
GVW	Gross vehicle weight

List of abbreviations page 4 of 30

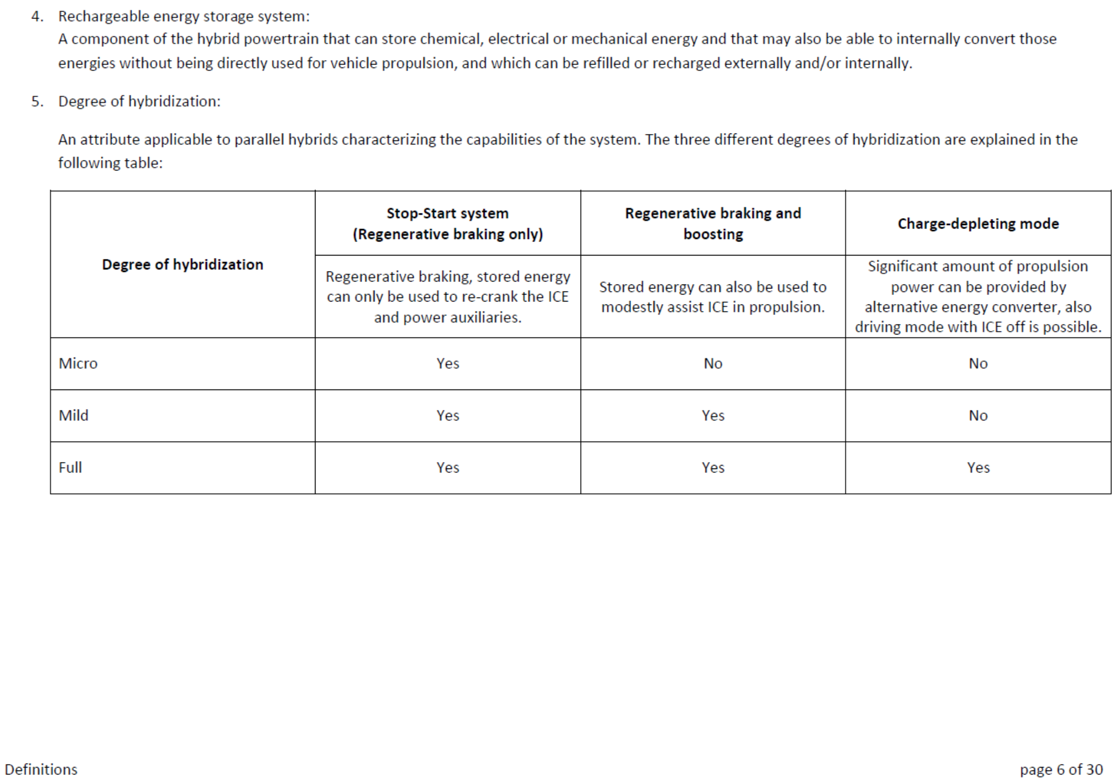


Definitions

1. Hybrid system architecture:
   The way how individual components are arranged and connected in a hybrid powertrain. The basic segmentation between parallel, series and power-split systems is explained in the following table:

Basic segmentation for architecture	**Description**
Parallel	Both, ICE and alternative energy converter mechanically connected to wheels of vehicle. Propulsion power can be provided by either of them or both simultaneously.
Series	Only alternative energy converter mechanically connected to wheels, not ICE. ICE connected to second alternative energy converter to generate energy that is used to directly power alternative energy converter mechanically connected to wheels or is stored in ReESS.
Power-split	System with ICE and two alternative energy converters connected via planetary gearbox, one alternative energy converter is mechanically connected to the wheels. ICE can be used in variable operation from providing propulsion power to the wheel directly to generating energy or both simultaneously by controlling the second alternative energy converter which is not mechanically connected to the wheels. The alternative energy converter which is mechanically connected to the wheels is used for regenerative braking. This system can provide both, parallel and series operation of the hybrid powertrain with operation of the ICE independently of the wheel speed.

2. Hybrid system type:
   The type of alternative energy converter and rechargeable energy storage system that is used in a hybrid powertrain (e.g. electric, hydraulic, flywheel).
3. Alternative energy converter:
   A component of the hybrid powertrain other than the internal combustion engine converting one form of energy into a different one for the primary purpose of vehicle propulsion.



4. Rechargeable energy storage system:
   A component of the hybrid powertrain that can store chemical, electrical or mechanical energy and that may also be able to internally convert those energies without being directly used for vehicle propulsion, and which can be refilled or recharged externally and/or internally.
5. Degree of hybridization:

   An attribute applicable to parallel hybrids characterizing the capabilities of the system. The three different degrees of hybridization are explained in the following table:

Degree of hybridization	**Stop-Start system (Regenerative braking only)**	**Regenerative braking and boosting**	**Charge-depleting mode**
	Regenerative braking, stored energy can only be used to re-crank the ICE and power auxiliaries.	Stored energy can also be used to modestly assist ICE in propulsion.	Significant amount of propulsion power can be provided by alternative energy converter, also driving mode with ICE off is possible.
Micro	Yes	No	No
Mild	Yes	Yes	No
Full	Yes	Yes	Yes

Question 1

This question is relevant only for vehicle manufacturers, body and trailer building industry and suppliers of hybrid systems or components.

What types of hybrid powertrains and architectures are currently being produced or developed for near future commercial use?

a) **Please indicate in the respective cells of Table 1 which types and architectures of hybrid powertrains are currently being produced or developed for near future commercial use by your company and its associations worldwide.**

For each possible type and architecture of a hybrid system a corresponding cell exists in the table which should be filled out as follows:

Relevant:	Indicate here with „yes“ or „no“ if this specific hybrid system is currently being produced or developed for near future commercial use by your company or its associations worldwide.
Confidential:	Indicate here with „yes“ or „no“ if the information given about this specific hybrid system is confidential or not.
Variant number:	Assign a variant number as unique identifier to this specific hybrid system, which should be composed of the letter “V” followed by two digits (e.g. “V07”). This number is needed as identifier in Table 2.

b) **Please indicate in the respective cells of Table 2 the architecture of the hybrid powertrains identified as relevant in question (a)/Table 1 by using the elements listed in Figure 1 to generate a diagram describing the architecture.**

Figure 2 and Figure 3 give examples of how to arrange the individual elements to depict a specific hybrid powertrain.
In case the elements listed in Figure 1 do not cover a specific component needed, please feel free to add the respective component together with some additional description.
The fields of Table 2 should be filled out as follows:

Variant number	Refer here to the respective variant number indicated in Table 1 (e.g. “V07”).
Confidential	Indicate here with „yes“ or „no“ if the information given about this specific hybrid system is confidential or not.
Diagram of powertrain architecture	Describe the powertrain architecture of the specific hybrid system with a diagram by using the elements listed in Figure 1. Add elements together with some additional description if necessary.

Figure 1: elements for simplified diagrams of hybrid powertrain architecture

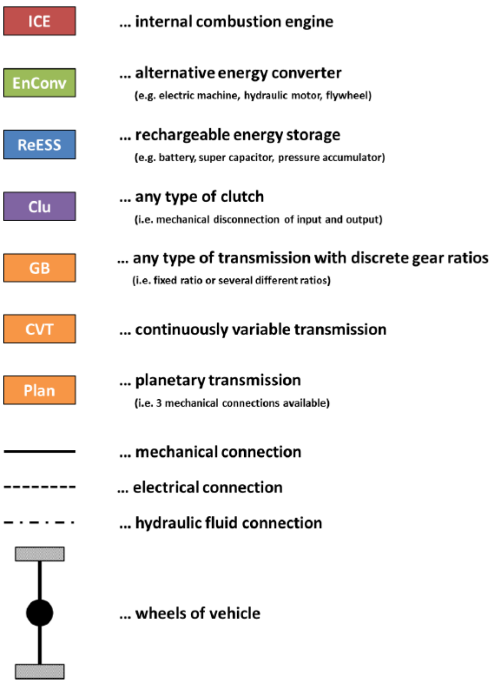


Figure 2: Example diagram of pre-transmission parallel hydraulic hybrid powertrain

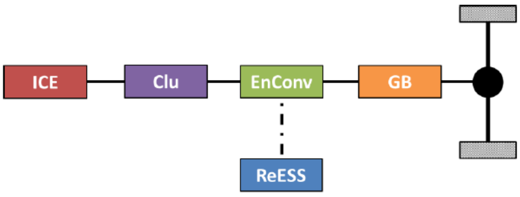
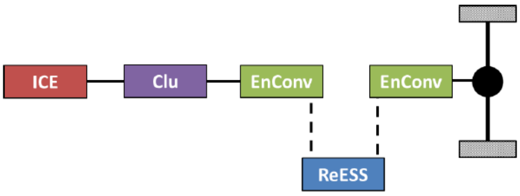


Figure 3: Example diagram of series electric hybrid powertrain



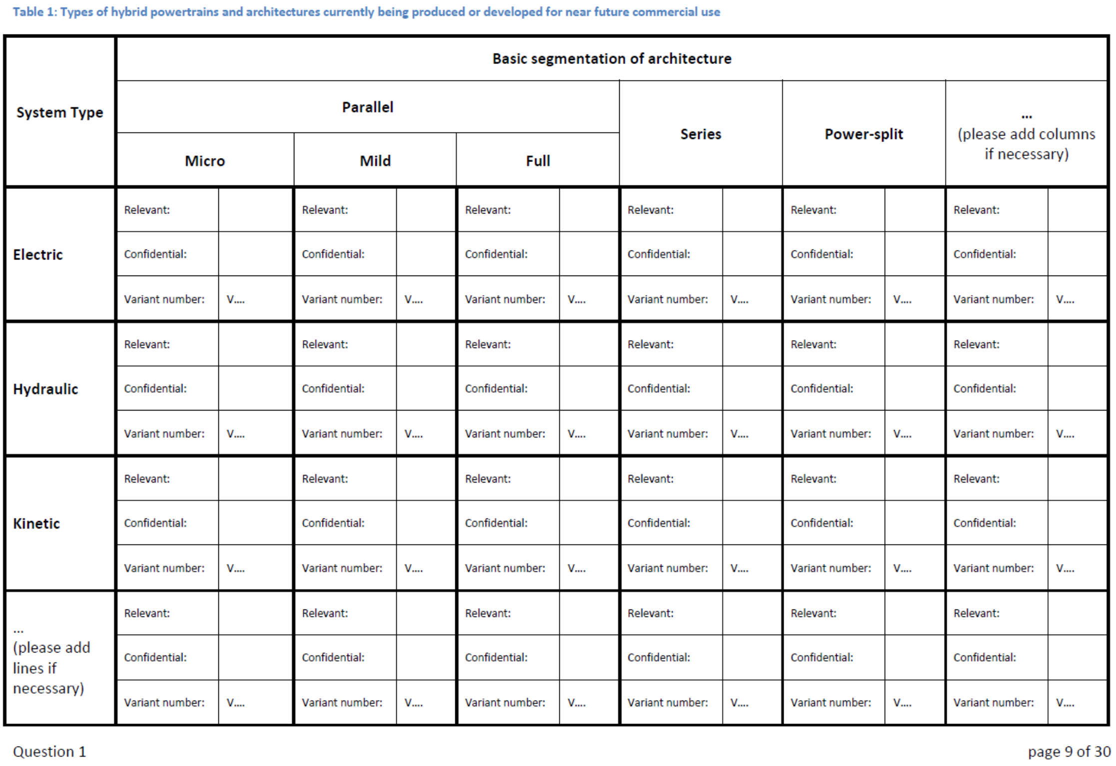


Table 1: Types of hybrid powertrains and architectures currently being produced or developed for near future commercial use

System Type	Basic segmentation of architecture											
	Parallel						Series		Power-split		… (please add columns if necessary)	
	Micro		Mild		Full							
Electric	Relevant:		Relevant:		Relevant:		Relevant:		Relevant:		Relevant:	
	Confidential:		Confidential:		Confidential:		Confidential:		Confidential:		Confidential:	
	Variant number:	V….	Variant number:	V….	Variant number:	V….	Variant number:	V….	Variant number:	V….	Variant number:	V….
Hydraulic	Relevant:		Relevant:		Relevant:		Relevant:		Relevant:		Relevant:	
	Confidential:		Confidential:		Confidential:		Confidential:		Confidential:		Confidential:	
	Variant number:	V….	Variant number:	V….	Variant number:	V….	Variant number:	V….	Variant number:	V….	Variant number:	V….
Kinetic	Relevant:		Relevant:		Relevant:		Relevant:		Relevant:		Relevant:	
	Confidential:		Confidential:		Confidential:		Confidential:		Confidential:		Confidential:	
	Variant number:	V….	Variant number:	V….	Variant number:	V….	Variant number:	V….	Variant number:	V….	Variant number:	V….
… (please add lines if necessary)	Relevant:		Relevant:		Relevant:		Relevant:		Relevant:		Relevant:	
	Confidential:		Confidential:		Confidential:		Confidential:		Confidential:		Confidential:	
	Variant number:	V….	Variant number:	V….	Variant number:	V….	Variant number:	V….	Variant number:	V….	Variant number:	V….

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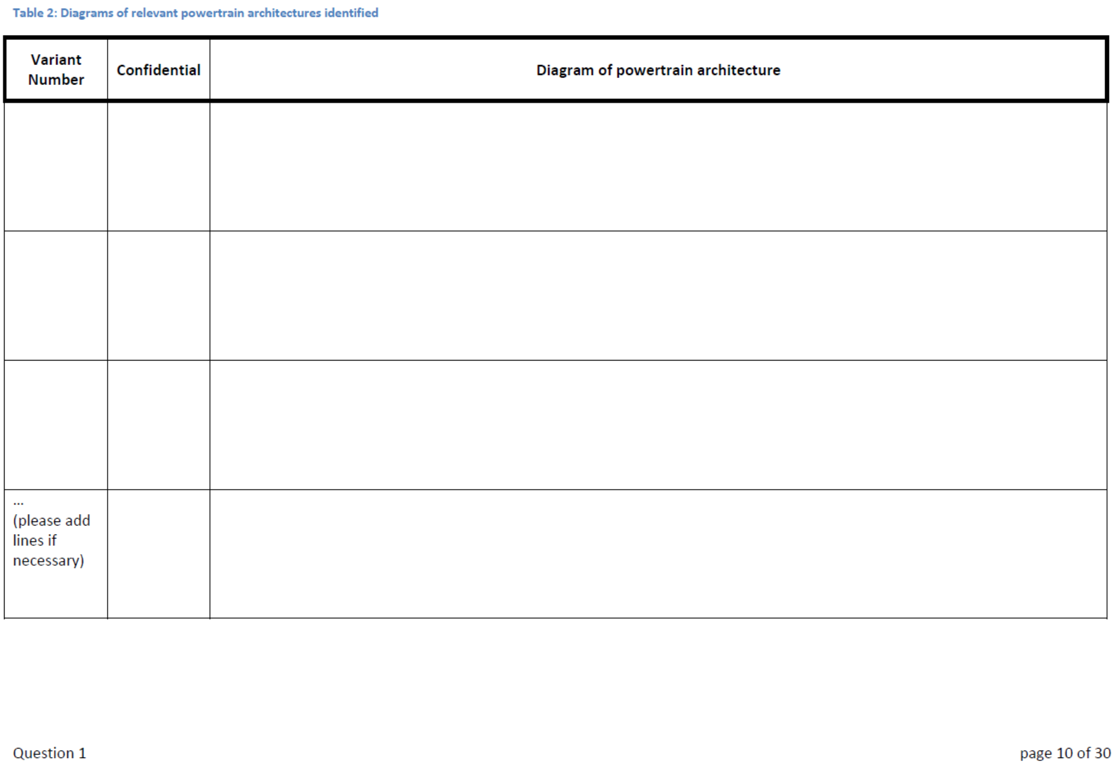

Table 2: Diagrams of relevant powertrain architectures identified

Variant Number	Confidential	Diagram of powertrain architecture
… (please add lines if necessary)		

Question 1 page 10 of 30

Question 2

What are the estimates on the fuel-consumption savings of the different hybrid powertrains?

Please indicate in the respective cells of Table 3 **OR** Table 4 **OR** Table 5**.** the estimated fuel consumption savings of different hybrid systems in %.

Please leave cells empty if no appropriate data is available!

The following abbreviations for the mission profiles used in the CO2-certification in VECTO are used in the tables:

LH .... Long haul
RD ...... Regional delivery
UD ...... Urban delivery
MU ..... Municipal utility
CO ...... Construction
HU ...... Heavy urban
UR ...... Urban
SU .... Suburban
IU .... Interurban
CA .... Coach

Depending on the depth of detail of the available data, please choose one of the following options:

a) Table 3 for generic estimated fuel consumption savings for different hybrid system architectures on different mission profiles.

For each possible combination of hybrid system architecture (lines of the table) and mission profile (columns of the table) the generic estimated fuel consumption savings in % should be indicated in the respective cell.

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Indicate in the column marked with “Confidential” with „yes“ or „no“ if the information given about a specific hybrid system architecture is confidential or not.

b) Table 4 for OEM specific estimated fuel consumption savings for each hybrid system variant identified in Question 1 broken down to mission profiles.

For each combination of hybrid system variants identified in Question 1 (lines of the table) and relevant mission profile (columns of the table) the estimated fuel consumption savings in % should be indicated in the respective cell.

Please refer here to the respective variant number indicated in Table 1 (e.g. “V07”).

Indicate in the column marked with “Confidential” with „yes“ or „no“ if the information given about a specific hybrid system variant is confidential or not.

c) Table 5 for OEM specific estimated fuel consumption savings for each hybrid system variant identified in Question 1 broken down to vehicle classes and mission profiles.

For each combination of hybrid system variants identified in Question 1 (lines of the table) and relevant vehicle class with its corresponding mission profiles (columns of the table) the estimated fuel consumption savings in % should be indicated in the respective cell.

Please refer here to the respective variant number indicated in Table 1 (e.g. “V07”).

Indicate in the column marked with “Confidential” with „yes“ or „no“ if the information given about a specific hybrid system variant is confidential or not.

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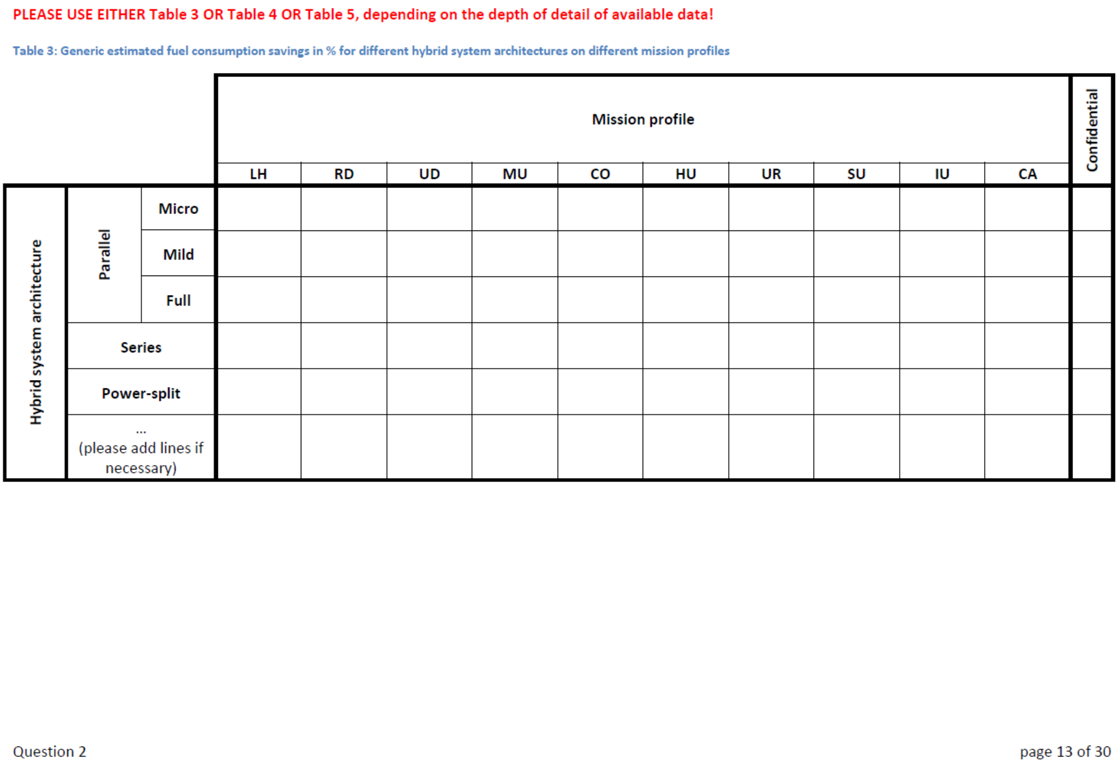

PLEASE USE EITHER Table 3 OR Table 4 OR Table 5, depending on the depth of detail of available data!

Table 3: Generic estimated fuel consumption savings in % for different hybrid system architectures on different mission profiles

			Mission profile										Confidential
			LH	RD	UD	MU	CO	HU	UR	SU	IU	CA	
Hybrid system architecture	Parallel	Micro											
		Mild											
		Full											
	Series												
	Power-split												
	… (please add lines if necessary)												

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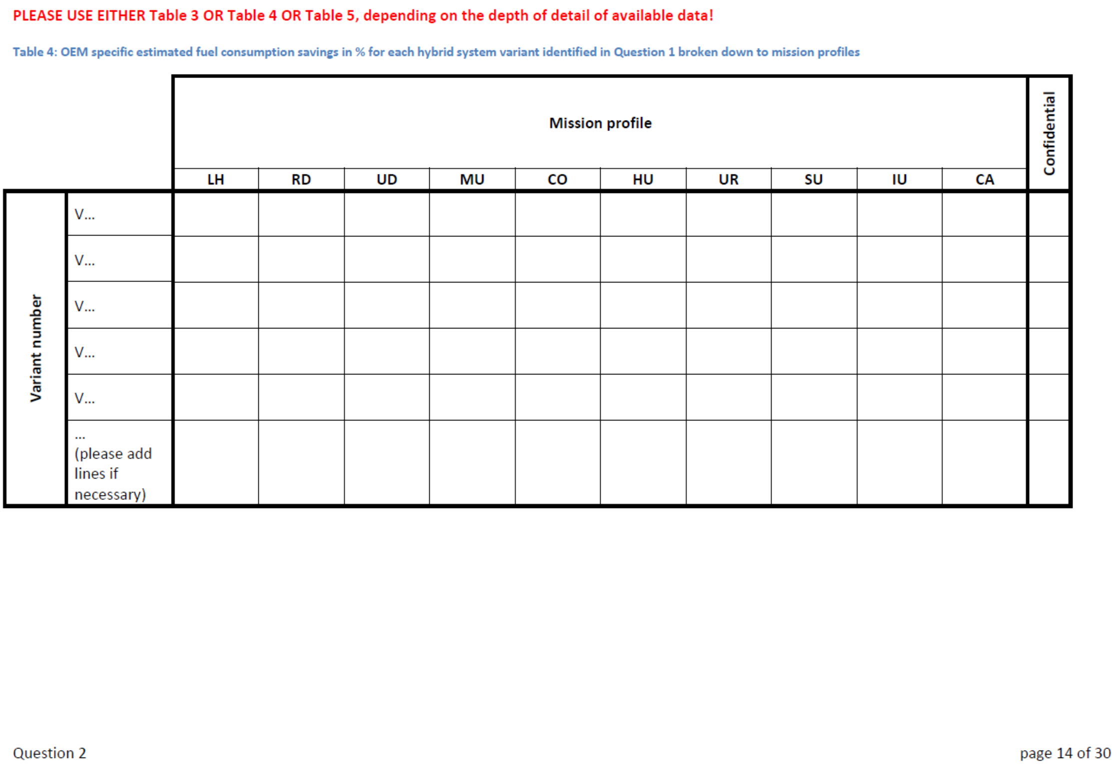

PLEASE USE EITHER Table 3 OR Table 4 OR Table 5, depending on the depth of detail of available data!

Table 4: OEM specific estimated fuel consumption savings in % for each hybrid system variant identified in Question 1 broken down to mission profiles

		Mission profile										Confidential
		LH	RD	UD	MU	CO	HU	UR	SU	IU	CA	
Variant number	V…											
	V…											
	V…											
	V…											
	V…											
	… (please add lines if necessary)											

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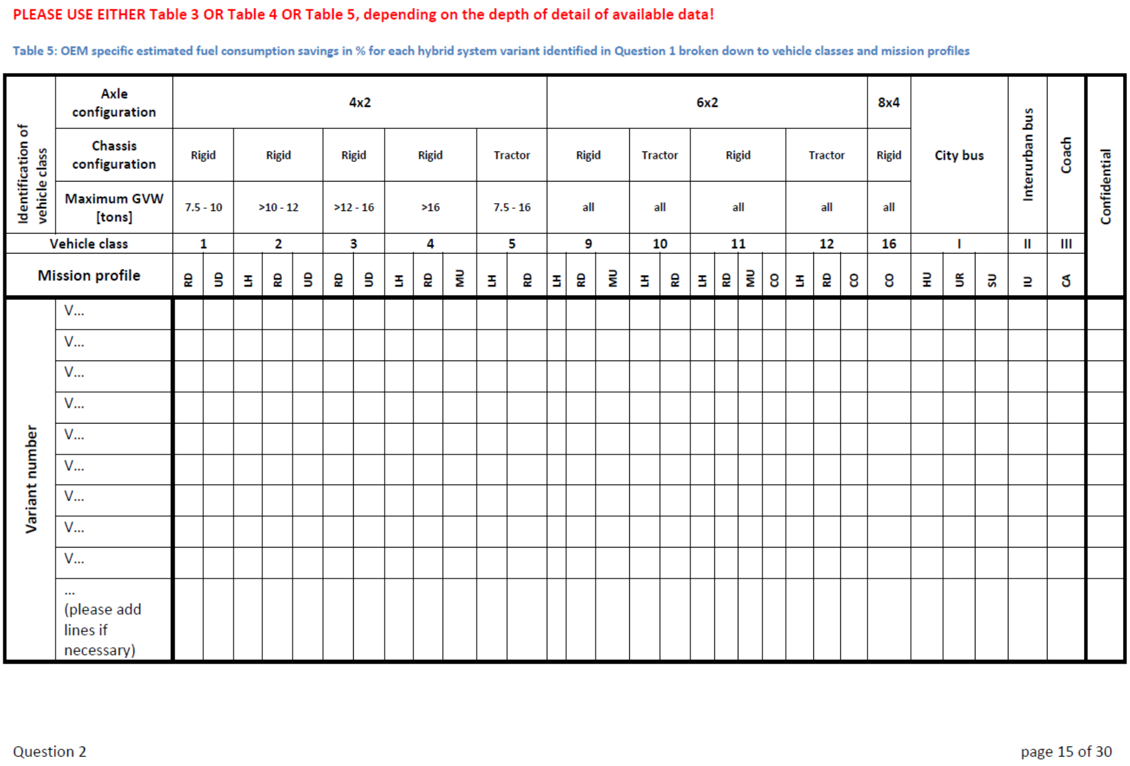

PLEASE USE EITHER Table 3 OR Table 4 OR Table 5, depending on the depth of detail of available data!

Table 5: OEM specific estimated fuel consumption savings in % for each hybrid system variant identified in Question 1 broken down to vehicle classes and mission profiles

Identification of vehicle class	Axle configuration	4x2												6x2												8x4	City bus			Interurban bus	Coach	Confidential
	Chassis configuration	Rigid		Rigid			Rigid		Rigid			Tractor		Rigid			Tractor		Rigid				Tractor			Rigid						
	Maximum GVW [tons]	7.5 - 10		>10 - 12			>12 - 16		>16			7.5 - 16		all			all		all				all			all						
Vehicle class		1		2			3		4			5		9			10		11				12			16	I			II	III	
Mission profile		RD	UD	LH	RD	UD	RD	UD	LH	RD	MU	LH	RD	LH	RD	MU	LH	RD	LH	RD	MU	CO	LH	RD	CO	CO	HU	UR	SU	IU	CA	
Variant number	V…																															
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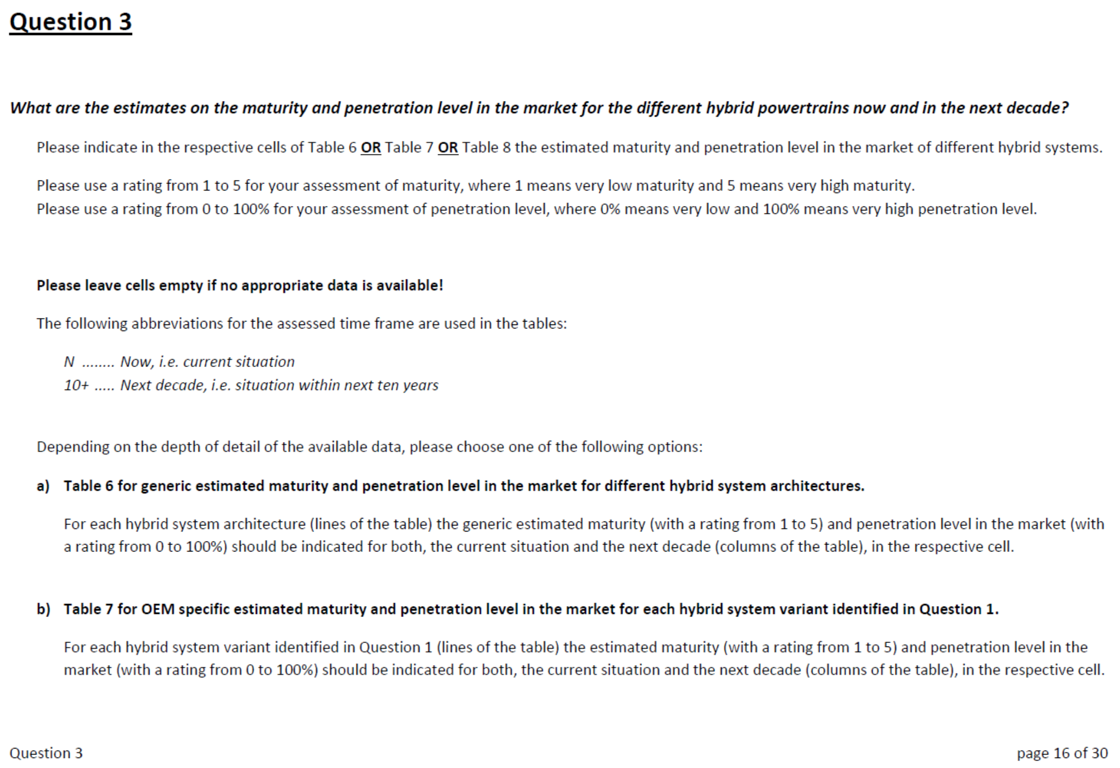

Question 3

What are the estimates on the maturity and penetration level in the market for the different hybrid powertrains now and in the next decade?

Please indicate in the respective cells of Table 6 **OR** Table 7 **OR** Table 8 the estimated maturity and penetration level in the market of different hybrid systems.

Please use a rating from 1 to 5 for your assessment of maturity, where 1 means very low maturity and 5 means very high maturity.
Please use a rating from 0 to 100% for your assessment of penetration level, where 0% means very low and 100% means very high penetration level.

Please leave cells empty if no appropriate data is available!

The following abbreviations for the assessed time frame are used in the tables:

N .... Now, i.e. current situation
10+ ..... Next decade, i.e. situation within next ten years

Depending on the depth of detail of the available data, please choose one of the following options:

a) Table 6 for generic estimated maturity and penetration level in the market for different hybrid system architectures.

For each hybrid system architecture (lines of the table) the generic estimated maturity (with a rating from 1 to 5) and penetration level in the market (with a rating from 0 to 100%) should be indicated for both, the current situation and the next decade (columns of the table), in the respective cell.

b) Table 7 for OEM specific estimated maturity and penetration level in the market for each hybrid system variant identified in Question 1.

For each hybrid system variant identified in Question 1 (lines of the table) the estimated maturity (with a rating from 1 to 5) and penetration level in the market (with a rating from 0 to 100%) should be indicated for both, the current situation and the next decade (columns of the table), in the respective cell.

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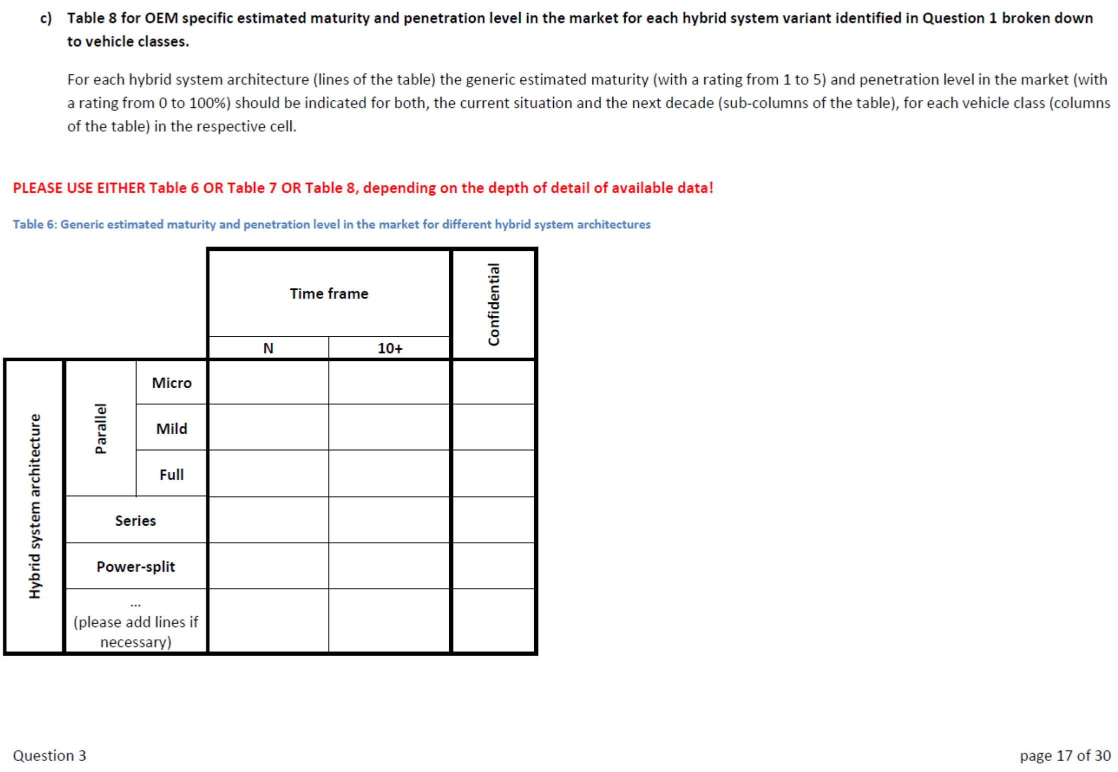


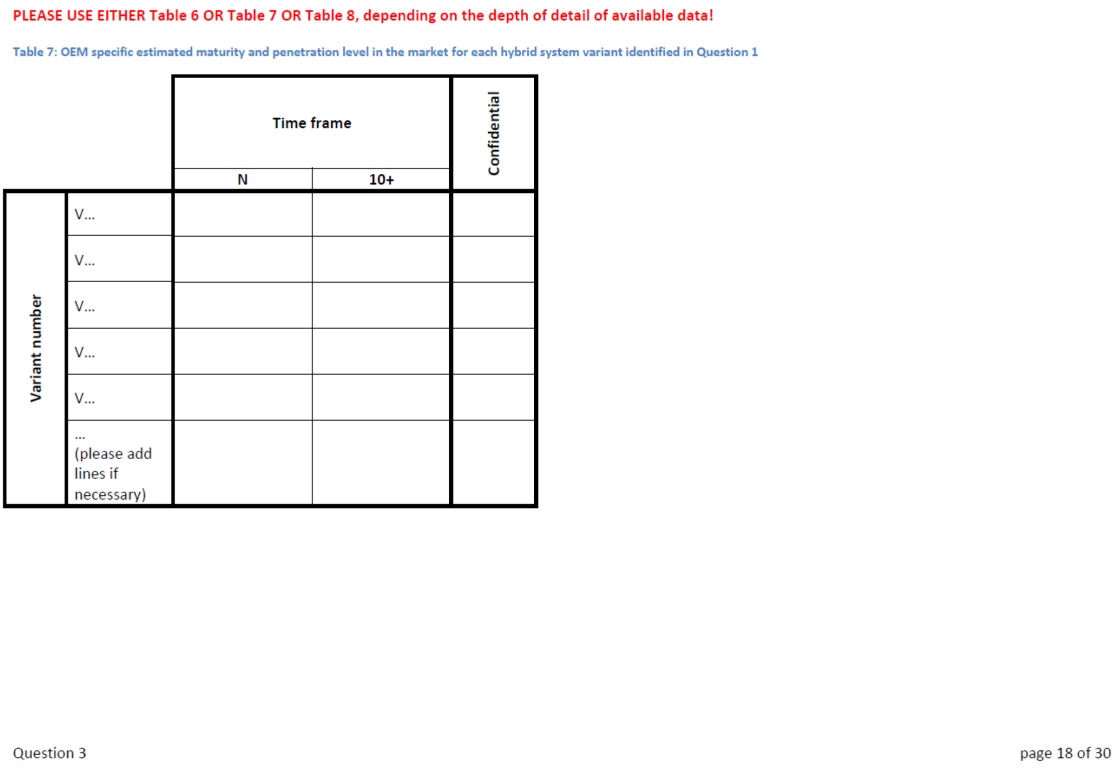
c) **Table 8 for OEM specific estimated maturity and penetration level in the market for each hybrid system variant identified in Question 1 broken down to vehicle classes.**

For each hybrid system architecture (lines of the table) the generic estimated maturity (with a rating from 1 to 5) and penetration level in the market (with a rating from 0 to 100%) should be indicated for both, the current situation and the next decade (sub-columns of the table), for each vehicle class (columns of the table) in the respective cell.

PLEASE USE EITHER Table 6 OR Table 7 OR Table 8, depending on the depth of detail of available data!

Table 6: Generic estimated maturity and penetration level in the market for different hybrid system architectures

			Time frame		Confidential
			N	10+	
Hybrid system architecture	Parallel	Micro			
		Mild			
		Full			
	Series				
	Power-split				
	... (please add lines if necessary)				



PLEASE USE EITHER Table 6 OR Table 7 OR Table 8, depending on the depth of detail of available data!

Table 7: OEM specific estimated maturity and penetration level in the market for each hybrid system variant identified in Question 1

		Time frame		Confidential
		N	10+	
Variant number	V...			
	V...			
	V...			
	V...			
	V...			
	... (please add lines if necessary)			

PLEASE USE EITHER Table 6 OR Table 7 OR Table 8, depending on the depth of detail of available data!

Table 8: OEM specific estimated maturity and penetration level in the market for each hybrid system variant identified in Question 1 broken down to vehicle classes

Identification of vehicle class	Axle configuration	4x2										6x2								8x4		City bus		Interurban bus		Coach		Confidential
	Chassis configuration	Rigid		Rigid		Rigid		Rigid		Tractor		Rigid		Tractor		Rigid		Tractor		Rigid								
	Maximum GVW [tons]	7.5 - 10		>10 - 12		>12 - 16		>16		7.5 - 16		all		all		all		all		all								
Vehicle class		1		2		3		4		5		9		10		11		12		16		I		II		III		
Time frame		N	10+	N	10+	N	10+	N	10+	N	10+	N	10+	N	10+	N	10+	N	10+	N	10+	N	10+	N	10+	N	10+	
Variant number	V…																											
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	V…																											
	… (please add lines if necessary)																											

Question 4

Which components of a hybrid system require dedicated test procedures to determine input parameters for the simulation model?

Please indicate in the respective cells with the header “Ranking” of Table 9 the assessment if a specific component of a hybrid system requires dedicated test procedures to determine its input parameters for the simulation model.

Please use a rating from 1 to 5 for your assessment, where 1 means no component testing necessary and 5 means component testing absolutely necessary.

Please add a short description characterizing the type of component to be considered in the column “Types of component to be considered” (e.g. Li-Ion Battery, hydraulic accumulator with compressed Nitrogen). Add your additional comments in the respective column if necessary (e.g. voltage level of battery, pressure range of hydraulic accumulator etc.).

Table 9: Assessment of necessity of dedicated test procedures to determine input parameters for components of a hybrid system

Component		Rating	Types of component to be considered	Additional comments	Confidential
Electric	**Alternative energy converter**				
	ReESS				
	… (please add lines if necessary)				
Hydraulic	**Alternative energy converter**				
	ReESS				
	… (please add lines if necessary)				
Kinetic	**Alternative energy converter**				
	ReESS				
	… (please add lines if necessary)				
… (please add lines if necessary)	Alternative energy converter				
	ReESS				
	… (please add lines if necessary)				

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Question 5

Which special operation modes of the hybrid system should be considered for CO2-certification of heavy-duty hybrid vehicles?

Please indicate in the respective cells of Table 10 which special operation modes of the hybrid system should be considered for CO2-certification of heavy-duty hybrid vehicles (e.g. last mile electric drive, pure electric mode or ICE-off mode for other types, boosting etc.).

Please add your additional comments in the respective column if necessary (e.g. limitations or boundary conditions for the respective mode).

Table 10: Special operation modes of the hybrid system to be considered for CO2-certification of heavy-duty hybrid vehicles

Special operation mode to be considered	Additional comments	Confidential

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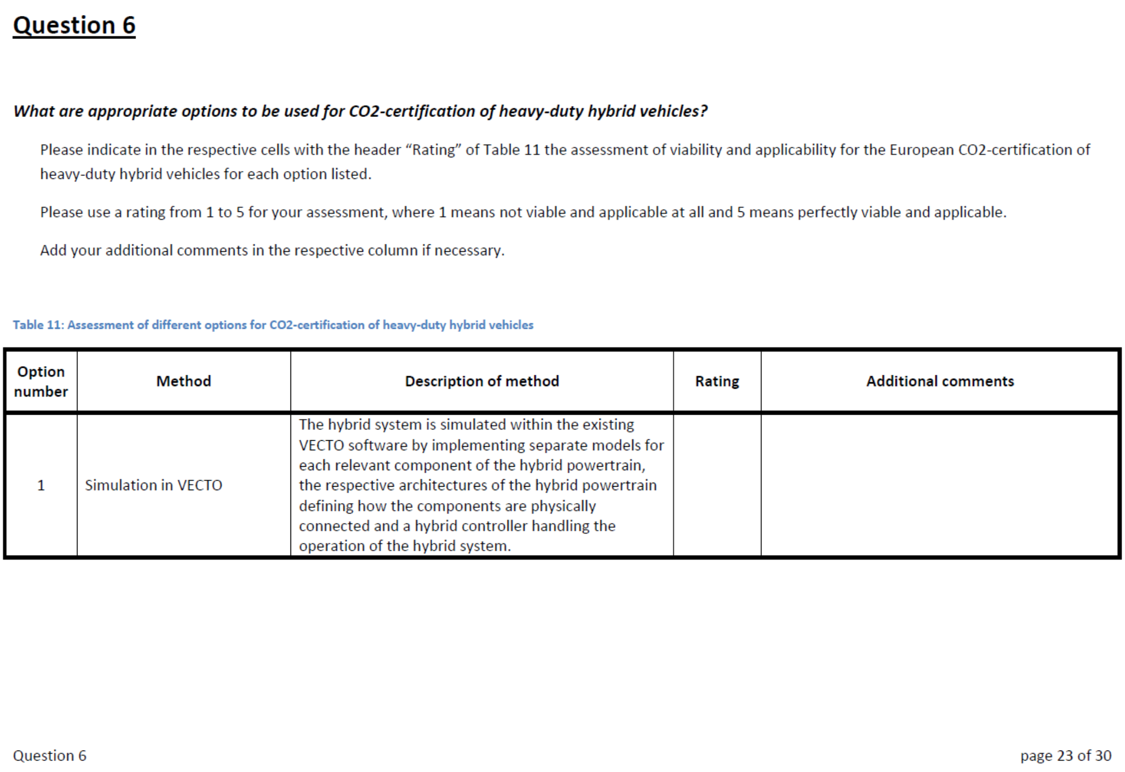

Question 6

What are appropriate options to be used for CO2-certification of heavy-duty hybrid vehicles?

Please indicate in the respective cells with the header “Rating” of Table 11 the assessment of viability and applicability for the European CO2-certification of heavy-duty hybrid vehicles for each option listed.

Please use a rating from 1 to 5 for your assessment, where 1 means not viable and applicable at all and 5 means perfectly viable and applicable.

Add your additional comments in the respective column if necessary.

Table 11: Assessment of different options for CO2-certification of heavy-duty hybrid vehicles

Option number	Method	Description of method	Rating	Additional comments
1	Simulation in VECTO	The hybrid system is simulated within the existing VECTO software by implementing separate models for each relevant component of the hybrid powertrain, the respective architectures of the hybrid powertrain defining how the components are physically connected and a hybrid controller handling the operation of the hybrid system.		

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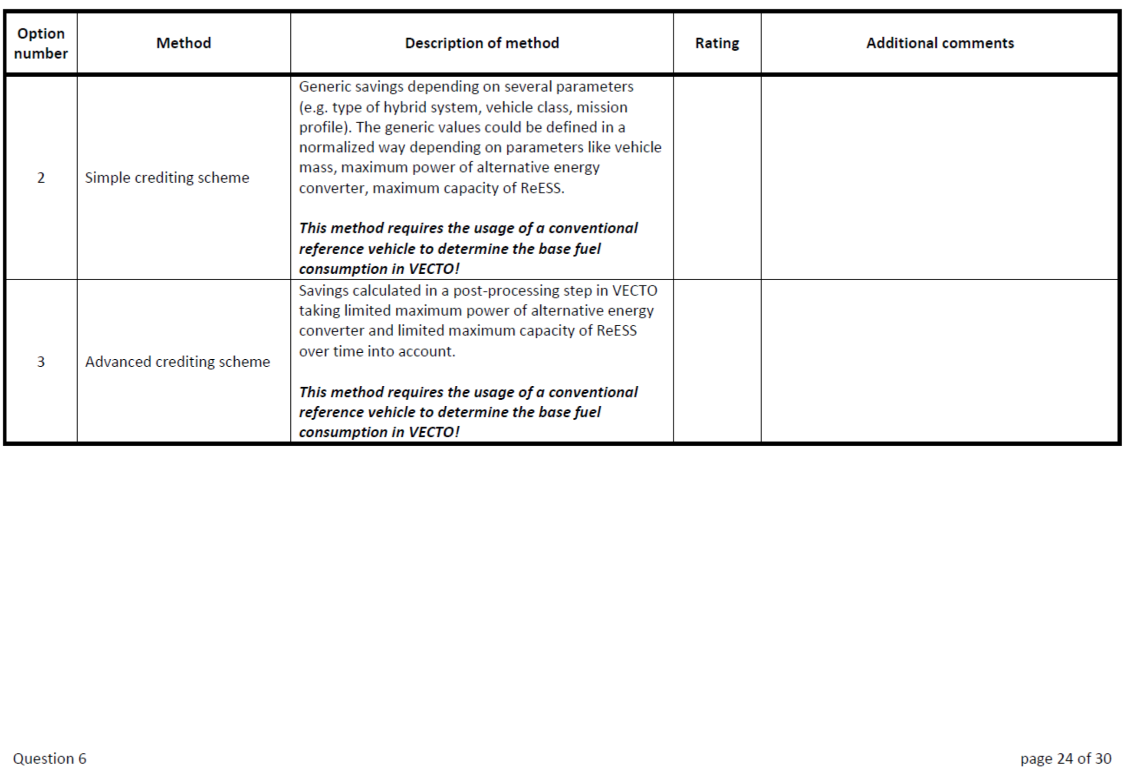

Option number	Method	Description of method	Rating	Additional comments
2	Simple crediting scheme	Generic savings depending on several parameters (e.g. type of hybrid system, vehicle class, mission profile). The generic values could be defined in a normalized way depending on parameters like vehicle mass, maximum power of alternative energy converter, maximum capacity of ReESS. ***This method requires the usage of a conventional reference vehicle to determine the base fuel consumption in VECTO!***		
3	Advanced crediting scheme	Savings calculated in a post-processing step in VECTO taking limited maximum power of alternative energy converter and limited maximum capacity of ReESS over time into account. ***This method requires the usage of a conventional reference vehicle to determine the base fuel consumption in VECTO!***		

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Option number	Method	Description of method	Rating	Additional comments
4	Powertrain measurement	Measurement of average efficiency of hybrid system in grams fuel per kWh work performed on a powertrain test bench (e.g. connection at output shaft of transmission or of final drive) over several vehicle cycles, where the remaining part of the vehicle as well as the driving resistances need to be simulated in real time. From the measured average efficiency values in g/kWh the total fuel consumption is determined in a second step by running a conventional reference vehicle in VECTO to get the cycle work. ***This method requires the usage of a conventional reference vehicle to determine the cycle work in VECTO!***		
5	Chassis dyno measurement	a) Either direct measurement of the fuel consumption and CO2-emissions for each hybrid vehicle on the chassis dyno. b) Or determination of the average efficiency of the hybrid system on the chassis dyno and determination of cycle work with a conventional reference vehicle in VECTO (as described for option 4). This method requires the usage of a conventional reference vehicle to determine the cycle work in VECTO!		

Question 6

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Option number	Method	Description of method	Rating	Additional comments
6	On-road measurement	Determination of the average efficiency of the hybrid system in grams fuel per kWh work performed on-road by using torque measurement rims and a fuel-flow meter. From the measured average efficiency values in g/kWh the total fuel consumption is determined in a second step by running a conventional reference vehicle in VECTO to get the cycle work. ***This method requires the usage of a conventional reference vehicle to determine the cycle work in VECTO!***		

Question 6

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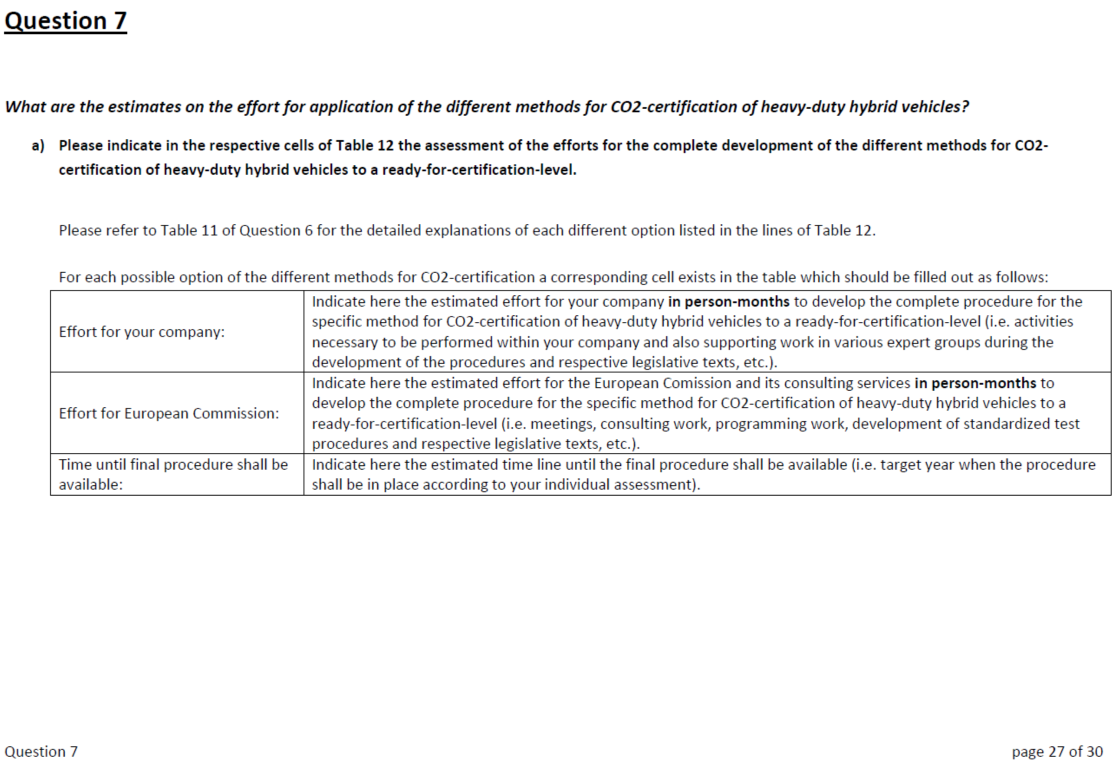


Question 7

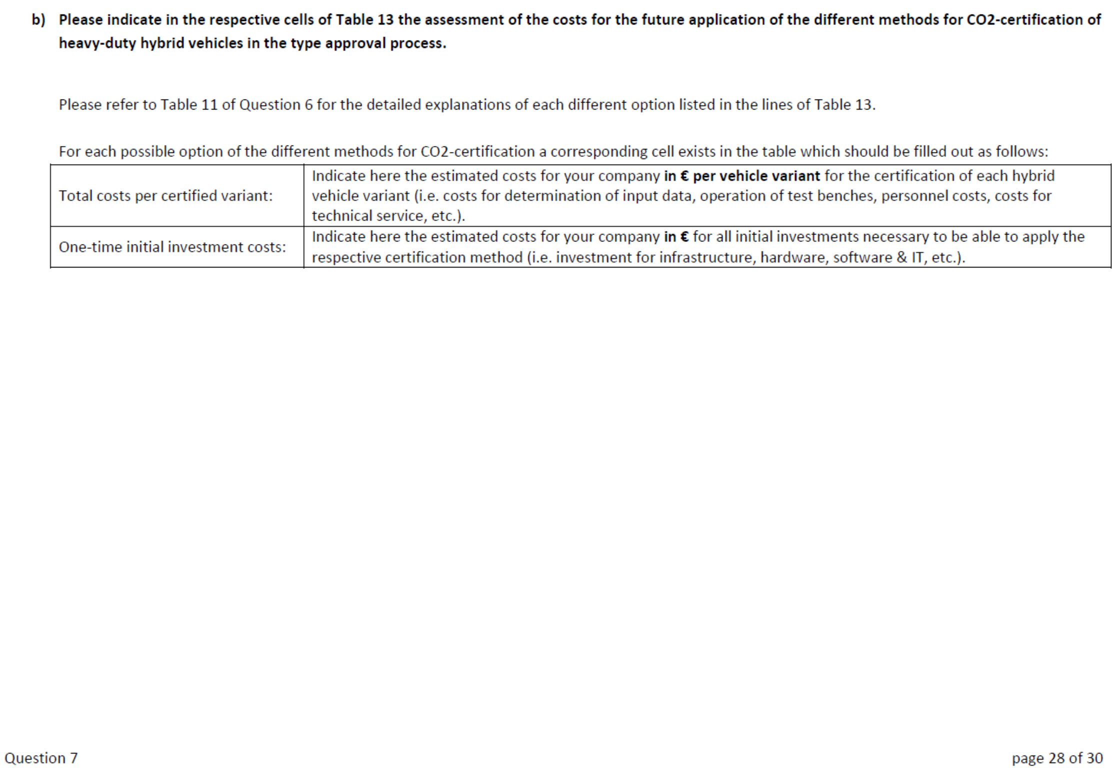
What are the estimates on the effort for application of the different methods for CO2-certification of heavy-duty hybrid vehicles?

a) Please indicate in the respective cells of Table 12 the assessment of the efforts for the complete development of the different methods for CO2-certification of heavy-duty hybrid vehicles to a ready-for-certification-level.

Please refer to Table 11 of Question 6 for the detailed explanations of each different option listed in the lines of Table 12.

For each possible option of the different methods for CO2-certification a corresponding cell exists in the table which should be filled out as follows:

Effort for your company:	Indicate here the estimated effort for your company **in person-months** to develop the complete procedure for the specific method for CO2-certification of heavy-duty hybrid vehicles to a ready-for-certification-level (i.e. activities necessary to be performed within your company and also supporting work in various expert groups during the development of the procedures and respective legislative texts, etc.).
Effort for European Commission:	Indicate here the estimated effort for the European Comission and its consulting services **in person-months** to develop the complete procedure for the specific method for CO2-certification of heavy-duty hybrid vehicles to a ready-for-certification-level (i.e. meetings, consulting work, programming work, development of standardized test procedures and respective legislative texts, etc.).
Time until final procedure shall be available:	Indicate here the estimated time line until the final procedure shall be available (i.e. target year when the procedure shall be in place according to your individual assessment).



b) Please indicate in the respective cells of Table 13 the assessment of the costs for the future application of the different methods for CO2-certification of heavy-duty hybrid vehicles in the type approval process.

Please refer to Table 11 of Question 6 for the detailed explanations of each different option listed in the lines of Table 13.

For each possible option of the different methods for CO2-certification a corresponding cell exists in the table which should be filled out as follows:

Total costs per certified variant:	Indicate here the estimated costs for your company **in € per vehicle variant** for the certification of each hybrid vehicle variant (i.e. costs for determination of input data, operation of test benches, personnel costs, costs for technical service, etc.).
One-time initial investment costs:	Indicate here the estimated costs for your company **in €** for all initial investments necessary to be able to apply the respective certification method (i.e. investment for infrastructure, hardware, software & IT, etc.).

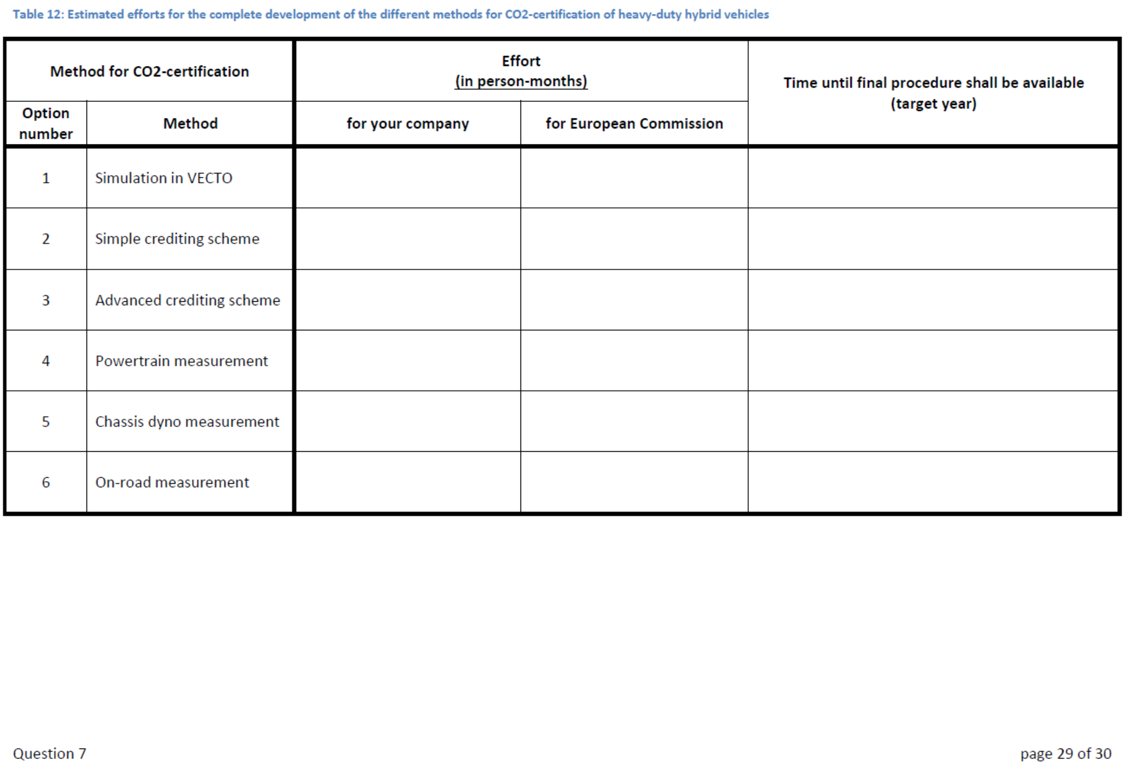


Table 12: Estimated efforts for the complete development of the different methods for CO2-certification of heavy-duty hybrid vehicles

Method for CO2-certification		Effort (in person-months)		Time until final procedure shall be available (target year)
Option number	Method	for your company	for European Commission	
1	Simulation in VECTO			
2	Simple crediting scheme			
3	Advanced crediting scheme			
4	Powertrain measurement			
5	Chassis dyno measurement			
6	On-road measurement			

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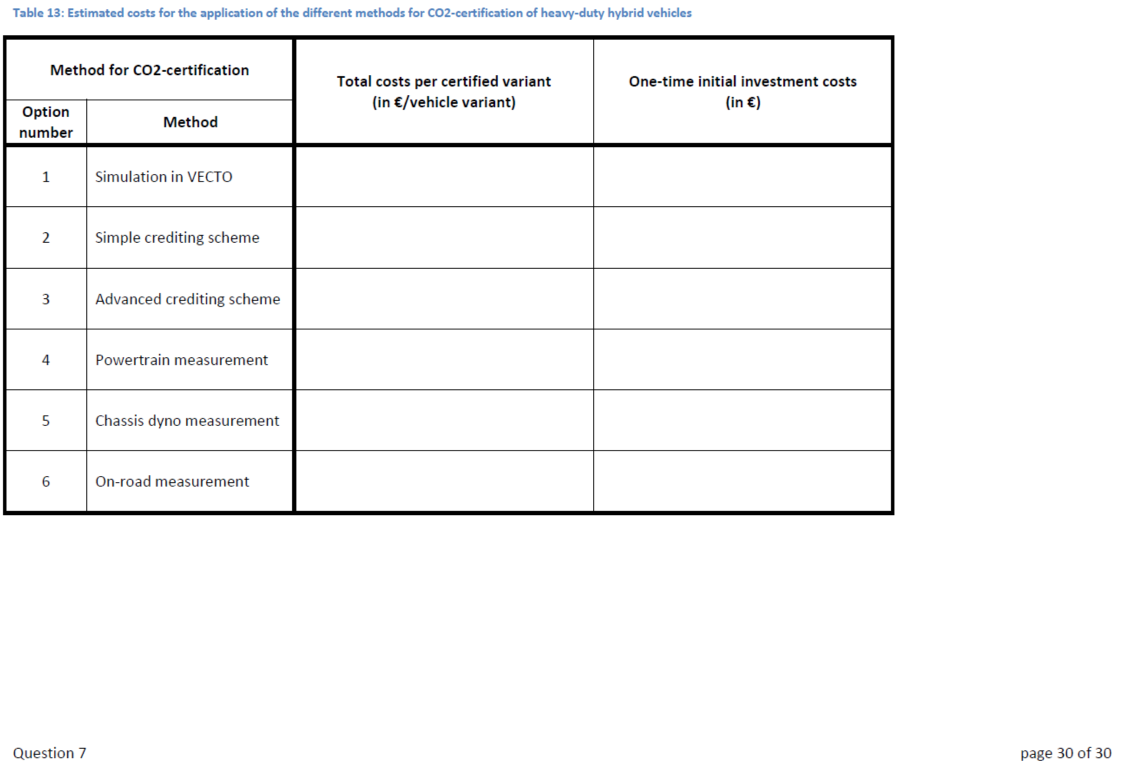

Table 13: Estimated costs for the application of the different methods for CO2-certification of heavy-duty hybrid vehicles

Method for CO2-certification		Total costs per certified variant (in €/vehicle variant)	One-time initial investment costs (in €)
Option number	Method		
1	Simulation in VECTO		
2	Simple crediting scheme		
3	Advanced crediting scheme		
4	Powertrain measurement		
5	Chassis dyno measurement		
6	On-road measurement		

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Annex 2

Individual rating tables from stakeholders

Assessment provided by JRC (Fontaras Georgios, Grigoratos Theodoros, Tansini Alessandro)

Method	Simulation in VECTO	Advanced crediting scheme – Variant 2	Powertrain method	Chassis dyno testing	On-road testing	Weighting (3=high 1= low importance)	Considering all HDV classes.
Effort needed for implementation in certification scheme	4	3	3	4	4	2	
Timeline for implementation	4	2	1	3	3	2	Considering all HDV classes.
Complexity of the method	3	5	2	3	3	1	
Additional input data necessary	3	5	3	4	4	2	
Fleet coverage for hybrids	3	3	4	4	5	3	
Technologies covered	4	3	4	5	5	3	
Practical feasibility	5	4	2	2	3	3	
Compatibility with current VECTO	5	3	4	2	3	1	This is irrelevant for other methodologies rather than VECTO itself therefore the weighting shall be lower
Needs for extension of the tool	2	5	5	4	4	1	family concept for chassis dyno and on road tests necessary if test burdens shall be limited --> some add ons in VECTO necessary to transfer test results to all single HDH certified in future
Adaptability to existing certification framework	5	3	1	2	3	2	
Investment necessary for testing facilities/equipment	5	4	2	2	4	2	
Effort for certification per vehicle	4	5	2	1	2	3	
Ex-post testing possible	4	1	3	4	5	3	In my opinion the ex-post testing is equally imortant to the certification itself. It gives added value to the whole procedure and closes any window for doubts
Reachable accuracy	4	2	4	4	4	3	I see no future for crediting scheme, huge effort for its development with permanent doubts on its accuracy.
TOTAL not weighted	**55**	**48**	**40**	**44**	**52**		
TOTAL weighted	**124**	**101**	**88**	**99**	**118**		

Assessment provided by IVECO BUS

Method	Simulation in VECTO	Advanced crediting scheme – Variant 2	Powertrain method	Chassis dyno testing	On-road testing	Weighting (3=high 1= low importance)	Comments
Effort needed for implementation in certification scheme	3	1	3	3	3	2	
Timeline for implementation	4	3	2	3	3	2	
Complexity of the method	4	5	2	4	4	1	
Additional input data necessary	4	5	4	4	4	1	
Fleet coverage for hybrids	4	4	5	4	5	3	
Technologies covered	4	3	4	5	5	3	advanced crediting sheme will has to show a disadvantage regarding technology coverage because results will come either from simulation or testing simplification of powertrain test bench should show disadvantage comapred to chassis dyno
Practical feasibility	5	5	3	4	2	3	
Compatibility with current VECTO	5	3	4	2	1	2	
Needs for extension of the tool	2	5	5	4	4	1	family concept for chassis dyno and on road tests necessary if test burdens shall be limited --> some add ons in VECTO necessary to transfer test results to all single HDH certified in future
Adaptability to existing certification framework	5	5	3	3	3	2	
Investment necessary for testing facilities/equipment	3	5	2	3	4	2	in our opinion, simulation requires also investment on testing method and cost to obtain relevant component efficiency data if existing a chassis dyno then investement could be less than powetrain method that should require more maintenance to be adpated to HEV config diversity , while not the case for chassis dyno
Effort for certification per vehicle	4	5	2	4	3	3	if considering just the effort for one vehicle certification despite the diversity or cost issues, simulation should require as much effort than passing vehicle on chassis dyno in order to obtain good data of each component and control to simulate correclty
Ex-post testing possible	4	1	4	4	4	2	
Reachable accuracy	4	2	4	4	3	3	
TOTAL not weighted	**55**	**52**	**47**	**51**	**48**		
TOTAL not weighted	**121**	**108**	**101**	**111**	**102**		

Assessment provided by CLEPA

	1	2	3	4	5		
Method	**Simulation in VECTO**	**Advanced crediting scheme – Variant 2**	**Powertrain method**	**Chassis dyno testing**	**On-road testing**	**Weighting (3=high 1= low importance)**	**Comments**
Effort needed for implementation in certification scheme	3	1	3	3	3	2	
Timeline for implementation	4	3	2	4	4	2	1: effort: VECTO-development + pre-tests (chassis dyno, on-road) 4+5: effort: development test procedure (given cycles, adoption of test equipment) + pre-tests
Complexity of the method	3	5	2	4	4	1	1: complexitiy of VECTO tool might increase to cover the hybrid control strategy 4. complexity not so high: minor modifications of vehicle TCU and installation of test equipment, driving by roboter 5:complexitiy not so high; no vehicle modifications, only proper pre-conditioning (SOC, temperature..), installation of test equipment
Additional input data necessary	2	5	4	4	5	1	1: additional **component** input data necessary (generic or specific) 5: real driving needs no additional input data (compared with VECTO)
Fleet coverage for hybrids	4	4	5	5	5	3	4: existing hybrid systems could be measured; same rating as for on-road testing
Technologies covered	~~2~~	3	5	5	5	3	1: relevant control strategies (OE-dependent, **big influence on CO2-emmission**) not covered; generic approach; Powersplit hard to implement 3: credting for control functions hard to define
Practical feasibility	5	5	3	3	~~4~~	3	3: power train test benches state of the art at many OEM and gearbox manufacturers; hybrid modifications feasible 4: on-road-test state of the art -> **test procedure for SORT cycles defined and practiced**
Compatibility with current VECTO	5	3	4	2	1	2	IS WEIGHTING CORECT ? IS COMPATIBILITY WITH VECTO SUCH IMPORTANT ?
Needs for extension of the tool	2	5	5	4	4	1	*family concept for chassis dyno and on road tests necessary if test burdens shall be limited --> some add ons in VECTO necessary to transfer test results to all single HDH certified in future*
Adaptability to existing certification framework	5	5	3	3	3	2	
Investment necessary for testing facilities/equipment	3	5	2	~~3~~	4	2	1: high investment on **suppliers side**; e.g. test bench for efficiency maps of electric axles 4: use of exisiting chassis dynos needs few investment
Effort for certification per vehicle	3	5	2	2	2	3	1: effort for **component testing** on suppliers side 3: one powertrain normally used for several vehicles (smart family concept to be developed) 4: effort for chassis dyno not so high; assumption: initial test needs 5 days on dyno (= 8 T€ for preparation, 20 T€ fo testing); follow-up tests about 20 T€ / based on actual fuel consumption tests on chassis dyno in Germany
Ex-post testing possible	3	1	4	4	5	2	1: ex-post testing possible; but same problems as for conventional vehicles and even more problems because of battery behavior depency on temperatures. 5: same test procedure as for certification possible (this procedure is already in use for busses /SORT)
Reachable accuracy	2	1	4	5	4	3	1: accuracy low due to generic control strategies 4: highest possible accuracy by using driver robots; all control functions included 5. less accuracy due to human driver and external impact (temperatur, wind...) but all control functions included
TOTAL not weighted	**46**	**51**	**48**	**51**	**53**		
TOTAL not weighted	**101**	**105**	**104**	**110**	**113**		