Institute for Powertrains
& Automotive Technology
Getreidemarkt 9
A-1060 Vienna
http://www.ifa.tuwien.ac.at

Univ.-Prof. Dr. Dipl.-Ing.
Bernhard GERINGER
Head of the Institute
phone: +43-1/ 58801-31500
fax: +43-1/ 58801-31599
info@ifa.tuwien.ac.at

Final Report of the Institutes

Development of an exhaust emission and CO_2 measurement test procedure for heavy-duty hybrids (HDH)

Date	Monday, 27 October 2014
Author(s)	Christoph Six - Vienna University of Technology, Institute for Powertrains & Automotive Technology Gérard Silberholz - Graz University of Technology, Institute for Internal Combustion Engines and Thermodynamics Jonas Fredriksson - Chalmers University of Technology, Department of Signals and Systems Bernhard Geringer - Vienna University of Technology, Institute for Powertrains & Automotive Technology Stefan Hausberger – Graz University of Technology, Institute for Internal Combustion Engines and Thermodynamics
Number of pages	118 (incl. appendices)
Sponsor	ACEA – European Automobile Manufacturers Association
Project references	11.10(HILS) & 12.02(HILS)
Project name	“Development of an exhaust emission and CO_2 measurement test procedure for heavy-duty hybrids (HDH)” performed to support the development of amendment 3 to gtr No.4
Internal report	B14030

Abstract

The work described in this report was performed to support the development of amendment 3 to gtr No.4 within the UNECE mandate of the Heavy Duty Hybrids (HDH) working group under GRPE. The amendment aims to include special test provisions for engines installed in heavy duty hybrid vehicles for emission type approval or certification in gtr No.4 and is partially based on the Japanese regulation Kokujikan No.281 [1].

For engines installed in hybrid vehicles, the hybrid system offers a wide and rather specific engine operation range since the engine not necessarily delivers the power needed for propelling the vehicle directly. Applying the WHTC engine test cycle for emission certification and type approval, which is proven to be representative for conventional heavy duty operation, for hybrid engine applications as well is thus hardly justifiable. To meet the requirement of an engine test cycle representative of real-world engine operation also in a hybrid vehicle, the entire vehicle and its control systems need to be considered for the engine certification.

This document presents two test procedures considering the entire hybrid vehicle setup:

- Hardware in the loop simulation (HiLS method) and
- Hybrid powertrain testing (Powertrain method)

Both aim to reflect a vehicle chassis dyno test to derive the in-vehicle engine operation pattern for the emission certification.

To nevertheless ensure the comparability between hybrid and conventional vehicles in terms of emissions and to allow to keep the existing emission limit values also for engines installed in hybrid vehicles, extensive complementary measures needed to be taken and can be summarized as follows:

- The WHVC vehicle and the WHTC engine schedule were aligned in terms of power and cycle work demand
- A method to account for the propulsion work delivered by the entire hybrid system was developed, which defines the basis for calculation of specific emissions in g/kWh of hybrid propulsion systems
- A procedure to determine a representative power rating for a hybrid system with variable power capabilities during operation was developed
- Generic vehicle parameters were established which in first place enable the alignment of conventional and hybrid vehicle testing and allow a test procedure with moderate effort simultaneously
- A hybrid family concept similar to the engine family concept in gtr No. 4 [2] was introduced

However, due to the complexity and novelty of the developed procedures, further development may be needed when the methods have been applied by a higher number of stakeholders.

Accompanying the development of amendment 3 to gtr No.4 a validation test program of the proposed procedures was performed where three European OEMs provided hybrid vehicles and heavily supported the research activates of the group.

Even if indicated in the title of the document, CO_2 determination procedures had to be left out of scope of the performed work.

Abbreviations

ABS	Anti-Lock Breaking System
CD	Chassis dynamometer
ECU	Electronic Control Unit
ELR	European Load Response Test
EPA	United States Environmental Protection Agency
EVE	Electric Vehicles and the Environment
GRPE	UNECE Working Party on Pollution and Energy
gtr	Global technical regulation
HCU	Hybrid Control Unit
HDH	Heavy Duty Hybrids
HDV	Heavy Duty Vehicle
HEC	Hybrid engine cycle, output of the HiLS model
HiLS	Hardware in the loop system
ICE	Internal combustion engine
JRC	Joint Research Centre of the European Commission
MiLS	Model in the loop system
NTSEL	National Traffic Safety and Environment Lab., Japan
OEM	Original Equipment Manufacturer
SiLS	Software in the loop system
SOC	State of charge
UNECE	United Nations Economic Commission for Europe
VECTO	Vehicle Energy consumption Calculation Tool
VTP2	Validation test program 2 of the HDH informal working group of GRPE
WHSC	Wold Harmonized Stationary Cycle for heavy duty engines
WHTC	World Harmonized Transient Cycle for heavy duty engines
WHVC	World Harmonized Vehicle Cycle

List of figures

List of tables

Table of content

Appendices

A Reference WHTC
B Sections of inversed road gradients

1. Introduction

The work described in this report was performed to support the development of amendment 3 to gtr No.4 within the UNECE mandate of the Heavy Duty Hybrids (HDH) working group under GRPE. The amendment aims to include special test provisions for engines installed in heavy duty hybrid vehicles for emission type approval or certification in gtr No.4 and is partially based on the Japanese regulation Kokujikan No.281 [1]. This report shall serve to conclude the rationales and decisions taken during the development.

The application of gtr No.4 to engines installed in conventional vehicles can be characterized as a vehicle independent certification procedure. When developing the WHDC test procedure, world-wide operation patterns of heavy duty vehicles were used for creating a representative vehicle cycle (WHVC). The engine test cycles WHTC and WHSC derived from the WHVC are vehicle independent and are designed to represent typical, average driving conditions in Europe, the United States of America, Japan and Australia.

For engines installed in hybrid vehicles, the hybrid system offers a wider and rather specific engine operation since the engine not necessarily delivers the power needed for propelling the vehicle directly. Thus, no representative engine cycle can be derived from a world-wide pattern of hybrid vehicles. Furthermore, the entire vehicle needs to be considered for the engine certification to meet the requirement of an engine test cycle representative for real-world engine operation in a hybrid vehicle.

Consequently, the consideration of the entire vehicle results in a less vehicle independent certification as for engines installed in conventional heavy duty vehicles. However, a fully vehicle dependent certification as performed for passenger cars is also not appropriate for heavy duty vehicles due to the high number of vehicle derivatives and the resulting high test burden. Chassis dyno testing is therefore not considered a desirable certification or type-approval procedure, and two alternative test procedures considering the entire hybrid vehicle setup either by simulation or in hardware have been developed (chapter 1 and 3). In order to lower test burden and to avoid the introduction of world-wide harmonized vehicle classes, the required vehicle parameters (chapter 4) have been made a function of the rated power (chapter 7) of the hybrid system. Data of conventional vehicles was used to establish this approach.

Even though the WHTC engine dynamometer schedule is not considered representative for engines installed in hybrid vehicles directly, the WHVC vehicle schedule was modified (chapter 5) to be closely linked to the propulsion power demands of the WHTC. This was made possible by introducing the vehicle parameters as a function of hybrid rated power and will result in comparable system loads between conventional and hybrid vehicles. Thus emission limit values in place for engines installed in conventional vehicles are considered to remain valid for hybrids as well.

The test procedures developed are specified in Annex 9 and 10 of gtr No.4 [3], respectively. In order to reflect the engine behaviour during real world operation, both aim to reflect a vehicle chassis dyno test to derive the engine operation pattern for emission certification whereby

- for the HiLS method (chapter 1) the vehicle and its components are simulated and the simulation model is connected to actual ECU(s) of the vehicle to derive the engine operation pattern for an emission test on the engine test bed and
- for the powertrain test (chapter 3) all components are present in hardware and just missing components downstream of the powertrain (e.g. final drive, tires, chassis) are

simulated by the test bed control to derive the engine operation pattern for the type approval or certification.

For a fair comparison of emissions produced by conventional and hybrid vehicles the test methods developed have been aligned with conventional engine testing and allow the emission evaluation independent of the powertrain layout or hybrid topology. This is possible especially with regard to the system work concept (chapter 6), the WHVC vehicle schedule (chapter 5), the generic vehicle parameter (chapter 4) and the hybrid rated power determination procedure (chapter 7) which are all interrelated and cannot be changed or easily modified separately.

Accompanying the development of amendment 3 to gtr No.4 a validation test program of the proposed procedures, mainly focusing on the HiLS method, has been performed (chapter 9). The powertrain method could not be tested within the validation test program but test runs reflecting parts of the procedure have been processed by contracting parties internally.

Even though CO_2 was part of the initially agreed work program, it was later amended by the HDH informal working group and the focus was laid on pollutant emissions only (chapter 10).

2. The HiLS Method

For engines installed in hybrid vehicles, the hybrid system offers a wider operation range for the engine, since the engine not necessarily delivers the power needed for propelling the vehicle directly and thus can (at least partly) be operated independently of the propulsion power demand. Therefore the existing engine test cycles used in type approval (WHTC and WHSC) are not representative of the real operation pattern of engines installed in most hybrid vehicles.

In order to properly reflect the in-use engine operation for engines installed in hybrid vehicles at type approval, the main goal of the HiLS method is to transfer a vehicle speed cycle into an engine test cycle which is representative of the application in a specific hybrid system. The specific engine cycle generated out of the vehicle speed cycle by usage of the HiLS system is then used for evaluating the pollutant emissions on the engine test bench in the same way as it is done for a conventional engine. This transformation process simulates a vehicle following a given speed trace on a chassis dyno and recording the resulting engine operation pattern.

In order to align the type approval test cycles for conventional engines and hybrid systems the WHVC, a representative vehicle speed cycle used as intermediate step in the generation of the WHTC engine cycle was chosen as common basis in the development of the HiLS method [4]. A vehicle speed cycle is a very stable reference basis that does not change much with evolution or new development of drivetrain technologies and is thus a valid reference for both conventional and hybrid vehicles. More details about the alignment of the new test cycle for hybrid systems with the existing type approval test cycles for conventional engines can be found in chapters 4 to 7.

For conventional engines the transformation of the vehicle speed cycle into a specific engine test cycle was done by developing the WHTC as an approximation of representative average engine operation in a conventional vehicle in the underlying vehicle speed cycle. This approximated engine operation pattern was found to be only dependent on the full-load curve of the engine and thus no complex transformation process is needed. In case of a hybrid vehicle the operation of the engine is highly dependent on the specific powertrain layout and the manufacturers' proprietary hybrid control strategies. These control strategies are implemented in the vehicle's electronic hybrid control unit(s) (HCU). Since the hybrid control strategy is the competitive edge as the decisive influence factor on energy consumption, it is not desirable for manufacturers to disclose the proprietary software logics inside the HCU. To be still able to include these control strategies in the transformation process, the HCU is included as hardware part and is connected to a vehicle simulation model, which is run in real-time. This process is called 'hardware in the loop simulation' (HiLS).

In this chapter the basic principle of the HiLS method, i.e. the transformation of a vehicle speed cycle into a specific engine test cycle, as well as the structure of the applied simulation model and its signals are described. Also the determination of characteristic input data for the parameterization of models for the different powertrain components and the verification of the simulation model by means of chassis dyno testing are explained. Furthermore the handling of cold start testing is described.

2.1. General description of the HiLS method

The HiLS method developed for gtr No.4 [3] is based on the Japanese regulation Kokujikan No.281 [1]. Following the existing Japanese HiLS method, the approach was to develop a procedure starting with a vehicle speed cycle as input and simulating a hybrid vehicle driving this transient vehicle speed cycle. By using a simulation model consisting of sub-models for the driving resistances, the different powertrain components and the driver together with the real vehicle control units connected as hardware, the vehicle speed cycle should be transformed into a specific load cycle for the combustion engine that reflects the manufacturer specific operating strategy like it is applied in the real vehicle.

2.1.1. Individual steps of the transformation process

In general, the transformation process from the vehicle speed cycle to the specific engine test cycle can be divided into several steps which are explained as follows:

1. Selection of the hybrid powertrain to be tested

   First the hybrid system to be tested has to be defined by the manufacturer together with the type approval authority. The term hybrid system only refers to the powertrain of a vehicle and not the vehicle itself. The characteristics of a specific vehicle (e.g. mass, vehicle body, etc.) have no influence on the type approval test and if the same hybrid powertrain is used in multiple vehicles only one type approval test is needed. If several versions of one hybrid powertrain that share the same system layout and control strategy but vary in system power or storage capacity exist, they can be grouped into a hybrid powertrain family [3] in order to reduce the number of type approval tests as it is done for engines installed in conventional vehicles.

2. Build and verification of HiLS system setup

   In order to test the hardware that runs the vehicle model, a verification simulation run of a predefined standardized vehicle model with predefined input parameters and a generic control strategy is done as a pre-check. Following a set of given command signals for the driver (i.e. pedal position over time) the resulting model output should match the reference values within certain tolerances.

3. Build of specific hybrid vehicle model

   A vehicle model representing the specific hybrid powertrain to be tested as defined in step 1 is built using the component models available in the model library (see section 2.2). All input parameters characterising the different specific powertrain components (e.g. combustion engine, electric machines, energy storage etc.) are determined according to the defined component test procedures (see section 2.3) or provisions in the regulation. All parameters characterising the generic vehicle (e.g. vehicle mass, rolling resistance coefficient, air drag coefficient, frontal area etc.) are set according to the definition of the generic vehicle dependent on the rated power of the hybrid system (see chapters 4 and 7). All parameters characterising the specific vehicle (e.g. tire radius, final drive ratio, drivetrain inertias) are set according to the values corresponding to the vehicle that is used on the test bench for verification of the model in step 4.

4. Verification of specific hybrid vehicle model

   Before the creation of the specific engine cycle can be performed, conformity between the real vehicle and the simulation model has to be ensured. Therefore the real vehicle is operated in the type approval test cycle on a chassis dynamometer where several signals like vehicle speed, rotational speeds, torques and power flows within the hybrid powertrain as well as pedal positions and selected gears are recorded. There is also the possibility to perform the verification by running parts of the hybrid powertrain in hardware on a powertrain test bench where at least the complete hybrid system consisting of all energy converters, all energy storage systems and all corresponding control units has to be present in hardware whereas the rest of the powertrain is simulated. In both cases all the recorded data are compared to simulation results produced by the vehicle model driving the same test cycle. If the output from the simulation meets the defined tolerances, the HiLS model is verified and can be used for the type approval process. If the same hybrid system layout has already been type approved before and no structural changes are made inside the model or the interface, repeated model verification is not necessary.

5. Determination of the hybrid system rated power

   Generic vehicle parameters have been introduced to keep the type approval process of hybrid systems vehicle independent as it was already the case for engines installed in conventional vehicles. These generic vehicle parameters (i.e. vehicle mass, rolling resistance coefficient, air drag coefficient and frontal area) are dependent on the rated power of a hybrid system (see chapter 4). Due to this concept an intermediate step is required before the creation of the specific engine cycle with the simulation model can be performed. Since the rated power of the hybrid system to be tested is already needed in the preceding step of verification of the vehicle model, the determination of the hybrid system rated power is designed as an iterative process. The vehicle manufacturer declares a value in advance and this declared value is used for calculating the parameters used in the verification of the vehicle model. Then the verified vehicle model is used to check the declared value with a special procedure which is a set of simulations of full load accelerations with different starting conditions. If the newly identified value is close to the declared value the transformation process is continued, otherwise the two consecutive steps of verification of the hybrid model and determination of the hybrid system rated power have to be repeated until the declared and determined value converge.

6. Creation of the hybrid engine cycle

   This is the central part of the HiLS method where a chassis dyno run of a hybrid vehicle on the type approval test cycle with vehicle specific adapted road gradients (see chapter 5) is simulated with the vehicle model parameterized according to step 3, except for the vehicle specific parameters which are set to generic values (i.e. tire radius, final drive ratio, drivetrain inertias and efficiencies). In this simulation run the resulting load cycle of the combustion engine (i.e. speed and torque over time) is recorded. Figure 2.1 pictures the interrelations.

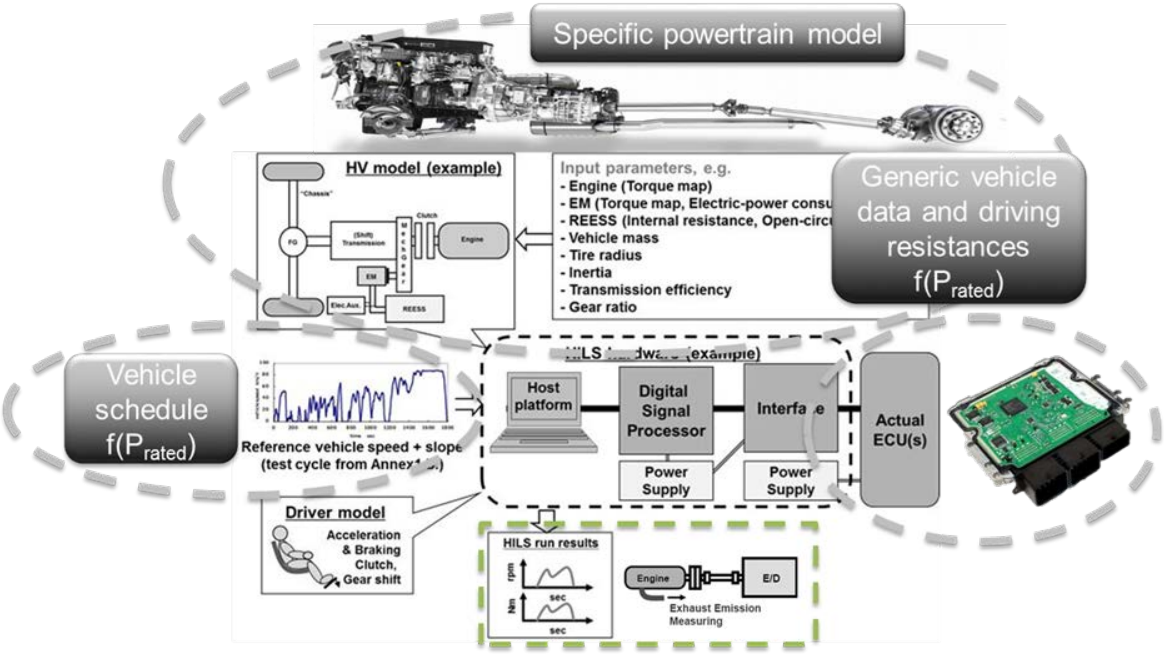


Figure 2.1 HEC creation scheme

After the test cycle is completed 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 comparison where all propulsion energy has to be generated and consumed by the hybrid system during the test cycle and cannot be drawn from or stored in the energy storage system. If these two limits 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 HiL-simulation has to be repeated.

The specific engine load cycle recorded during the HiLS run is then used as dynamometer set points for the exhaust emissions test run on an engine test bench. The engine test is carried out as defined for heavy-duty engines installed in conventional vehicles, only with a different test cycle.

2.1.2. General structure of the simulation model for gtr No.4

To perform the basic task of simulating a vehicle chassis dyno test under defined boundary conditions with certain standardized parts of the simulation model and at the same time allow full flexibility in creating a model of a specific hybrid powertrain and also integrate real hardware control units, the HiLS model has to be set up in a certain structure which is shown in Figure 2.2.

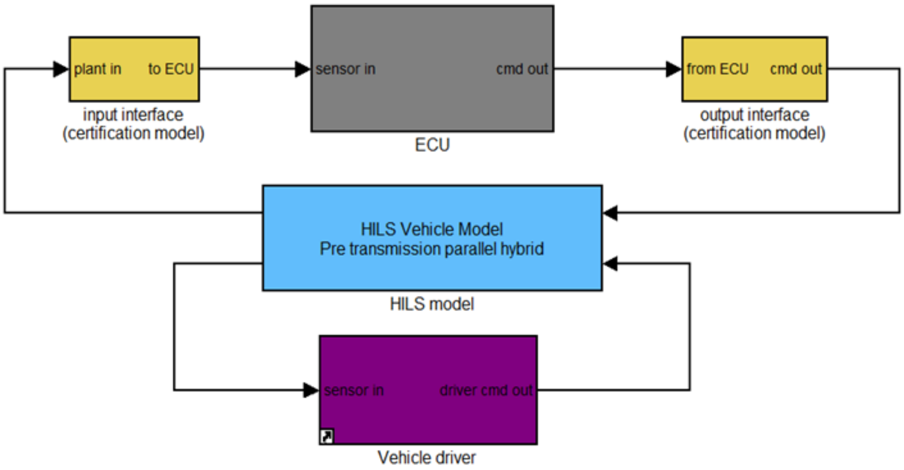


Figure 2.2 General HiLS model structure

The blue box in Figure 2.2 is the centerpiece that contains the vehicle model representing all relevant physical characteristics of the hybrid vehicle. A model of the whole hybrid powertrain is set up using individual components from the model library and connecting them via the standardized interfaces. The total propulsion torque generated by the hybrid powertrain is fed into the standardized chassis model which is the final component block downstream of the hybrid powertrain. There the driving resistances (i.e. rolling resistance, air resistance, road gradients) are applied like it would be done by the chassis dyno control in a real vehicle test. The resulting difference of generated propulsion torque and adverse driving resistances is then accelerating (or decelerating) the vehicle which leads to a new vehicle speed value for each time step in the simulation. Figure 2.3 shows an example vehicle model with an electrical parallel hybrid powertrain where each box represents an individual component of the hybrid powertrain and the blue box on the very right represents the standardized chassis model. The chassis model delivers the standardized output signals for the calculation of the system work over the test cycle (see chapter 6) that is needed for calculation of the specific emissions in g/kWh.

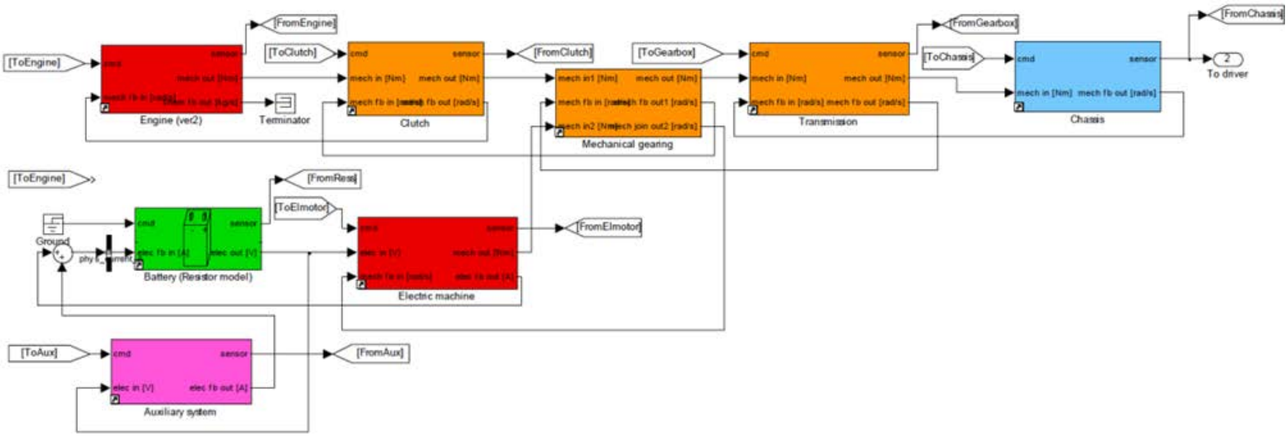


Figure 2.3 Example vehicle model

The purple box in Figure 2.2 contains the driver model that performs all required tasks to drive the vehicle model over the test cycle and typically includes accelerator and brake pedal operation as well as operation of clutch and selection of gear position in case of a manual shift transmission. The intention was to keep the driver model as simple as possible in order to be able to operate the whole variety of hybrid vehicles. Therefore it was decided that the driver model should only perform the necessary tasks to drive a vehicle over a cycle (i.e. accelerator and brake pedal and optional clutch pedal and gear selection) and all very vehicle specific options like setting of levers and switches for e.g. auxiliary braking systems or cruise control should not be handled by the driver model. The applied reference driving cycle is also part of the driver model which tries to track the given reference speed value as well as possible.

The grey box in Figure 2.2 represents the control unit(s) of the hybrid powertrain connected with the vehicle and the driver model. These control unit(s) perform the distribution of propulsion power demand, the switching between different operation modes and the amount of regenerative braking according to the implemented control strategy. In case the functionalities of the hybrid system are performed by multiple control units, those controllers may be integrated via software emulation in the interface block. However, the key hybrid functionalities (i.e. energy management) shall be included as hardware control unit(s) as part of the HiLS system setup.

When running a HiLS system consisting of a vehicle simulation model linked with control units of the real vehicle as hardware parts, it is essential to provide all sensor signals that affect operation of the hybrid system to the control units. This ensures that the simulated system operates equally to the real vehicle and keeps the control units from changing into a failure operation mode which is not representative of real life operation. The need of signal availability throughout the whole model structure led to the introduction of a flexible signal bus where every user is allowed to add or remove signals needed to run the HiLS model, respectively the actual control units connected. Default signals that are needed to run the provided component models from the model library are specified for each component model according to a standardized signal naming convention.

The yellow boxes in Figure 2.2 represent the input and output interfaces to and from the hardware control unit(s). These interfaces are the functional connection between the vehicle and driver model to the HiLS hardware. For these interfaces, a hardware and a software layer exist. The hardware layer handles the physical connection via wiring harness to the hardware control unit(s) and signal transformation or tuning from the digital signal as output from the simulation model to the corresponding signal format needed for the transfer via the wiring harness. The software layer can handle several tasks: For example providing dummy values for signals where no real sensor value is available to the control units in order to avoid unrealistic operation of the hybrid system by control unit(s) switching to error mode due to a missing sensor signal. Additionally control units that are not present in hardware can be emulated as software inside the interface (e.g. ABS control, control units of a high voltage system that should not be present at the test bed, etc.) to allow correct functional operation of the actual hardware control unit(s). Furthermore unit conversion of signals between the simulation model and the control unit(s) can be handled (e.g. rotational speed in rad/s to rpm).

2.1.3. Changes from the original Japanese model to the final model for gtr No.4

The existing Japanese simulation model was successfully used in the type approval process of several vehicles in Japan. These vehicles had standard parallel and series hybrid powertrains with electric systems only and the Japanese simulation model was originally developed to cover these standard powertrain layouts. There were two basic vehicle models available, one for a parallel and one for a series hybrid electric vehicle. The different components of the hybrid drivetrain in the model could be parameterized to fit their characteristics to a specific hybrid system, but the model did not allow any changes in system layout. Also the reference point for the determination of the delivered propulsion work over the driving cycle (see chapter 6), that is needed to calculate the specific emission values in g/kWh, was defined at a fixed position for both the parallel and the series layout. For the interaction between simulation model and connected HCU a standardized interface of exchanged signals was defined in the Japanese model.

The Japanese type approval authority was responsible for adapting the models if necessary. But such an approach was considered not feasible for implementation in a gtr since there is no permanent institution for maintaining or adapting the simulation models. Thus the gtr simulation model should be able to handle a variety of different hybrid systems and also more complex hybrid system layouts. Already for the selected vehicles in the validation test program (see chapter 9) extensive changes of the existing simulation models would have been needed. Furthermore there was the demand to include also non-electric powertrain components into the simulation model to cover possible future hybrid powertrain layouts.

For these reasons it was decided in the informal working group that the simulation model structure should be switched to a completely new and fully flexible component-based structure instead of putting effort into adapting the existing Japanese model to the selected vehicles in validation test program 2 (see chapter 9). Based on this decision a new model structure and a corresponding signal naming convention was developed. This new approach allows to link individual components of a hybrid powertrain fully flexibly in order to set up each specific hybrid system layout according to the real vehicle to be simulated. Defined standardized interfaces for each component and the standard signal naming make it possible to cover also future powertrains and to set up a flexible data-bus which makes every important physical value as well as control signal available throughout the whole model. With the newly implemented data-bus also a standardized interface between simulation model and connected HCU was no longer required which is a huge benefit for vehicle manufacturers, since such a standardized interface could prevent innovations due to the constraints it would pose for the architecture of ECUs. Additionally a common reference point for the determination of the delivered propulsion work over the driving cycle that is valid for all powertrain layouts could be defined in the new model structure (see chapter 6). The new model structure is explained in section 2.2 in more detail.

When implementing the new model structure, the basic physical principle behind the individual hybrid system components were adopted from the original Japanese version. However, some components were adapted according to the demands that were raised during discussions with manufacturers and inside the informal working group or during the validation test program.

For the driver model the original concept of a PID-controller was kept but the driver model was split up into three different options depending on the specific application: one model which is no closed-loop controller but only using recorded driver data (e.g. pedal positions) over time, the second model which handles only accelerator and brake pedal for vehicles without a transmission or any kind of automatized transmission where the gear shifting is handled by the transmission control units, the third model which additionally handles also clutch pedal and gear shifting for vehicles with a manual transmission. The shift algorithm used is based on the method developed for the European CO_2 simulation tool VECTO [5]. The shift algorithm implemented in the final release of the HiLS model library was developed and tested using the existing, simplified SiLS example vehicle models only, but no actual vehicle or powertrain tests were performed for validation of the shift algorithm. A detailed description of the shift algorithm can be found in [3].

The internal combustion engine model was amended by a new torque build-up part that uses two first-order systems. The first one is representing the fast dynamics for instant torque build-up, the second first-order system is representing the slower dynamics corresponding to turbo charger effects and boost pressure build-up.

The simple resistor based battery model was amended by an additional resistor–capacitor circuit in series in order to add time dependence to the current-voltage behaviour of the battery system which allows more accurate simulation of the battery thus leading to better estimation of the power losses of the battery system.

Models of the following components were newly implemented: electrical DC/DC converter, hydraulic machine as energy converter, hydraulic accumulator as energy storage, continuously variable transmission, retarder, torque converter and flywheel.

With the implemented changes it should be possible to model each specific hybrid system layout due to the flexibility in model structure and the component library should also cover new developments in hybrid systems technology in the near future due to the newly introduced component models (e.g. non-electrical hybrid systems). A detailed description of the specific powertrain components is available in Annex 9 of [3].

2.1.4. Summary

Type approval of heavy-duty hybrid vehicles with the HiLS method reduces complexity and effort of the type approval process due to the possibility of testing the hybrid powertrain independently of a specific vehicle but within a simulation environment representing a generic vehicle. Simulation reduces the effort for varying the vehicle parameters as well as the starting conditions of the test cycle compared to testing of the real vehicle. Nevertheless, the performance of the hybrid powertrain is very close to real world operation due to the hybrid control strategy which is integrated into the simulation model via connection of the control units as hardware. The result of the HiLS method is a hybrid system specific engine cycle that is used as reference cycle for exhaust emission testing similar to the procedure for conventional heavy-duty engines but with a cycle more appropriate for the respective hybrid system.

Once a model of a specific hybrid system layout is verified and valid for type approval, the same model can be used for a different hybrid system (e.g. different power level of energy converters, different energy storage capacity, different amount of gears in shift transmission, etc.) as long as the system layout and the interface model is not changed. Therefore it is important that the interface model is set up by the vehicle manufacturer in a way so that it is easy to parameterize or scalable and needs only adaption of numerical values or tables for a new hybrid powertrain with the same basic system layout. Nevertheless, fundamental changes in the interface model need to trigger a new verification process of the altered simulation model.

Based on the Japanese simulation models, extensive changes were made to the model structure and the signal handling inside the simulation model. With the flexibility provided by the standardized component library and signal bus it is possible to model each specific hybrid powertrain layout with just a limited number of standardized components that can be used in different powertrain configurations. Additionally the signal bus allows placing of control unit(s) not containing key hybrid functionalities in the software interface (e.g. avoid safety issues with control units of high voltage systems at the HiLS test bed) as well as adding additional manufacturer specific control signals. Furthermore, the flexible structure and signal bus does not put up constraints for future developments of hybrid control systems since new powertrain components can be added to the library easily without having to change any existing structures of models and also new signals can be added easily to the interface between simulation model and control units.

2.2. HiLS model library

For complete vehicle simulation it is preferable that the component models can be connected together in a straightforward manner to form a complete vehicle model. In Figure 2.4 an idea of a HiLS/SiLS simulation model structure is presented.

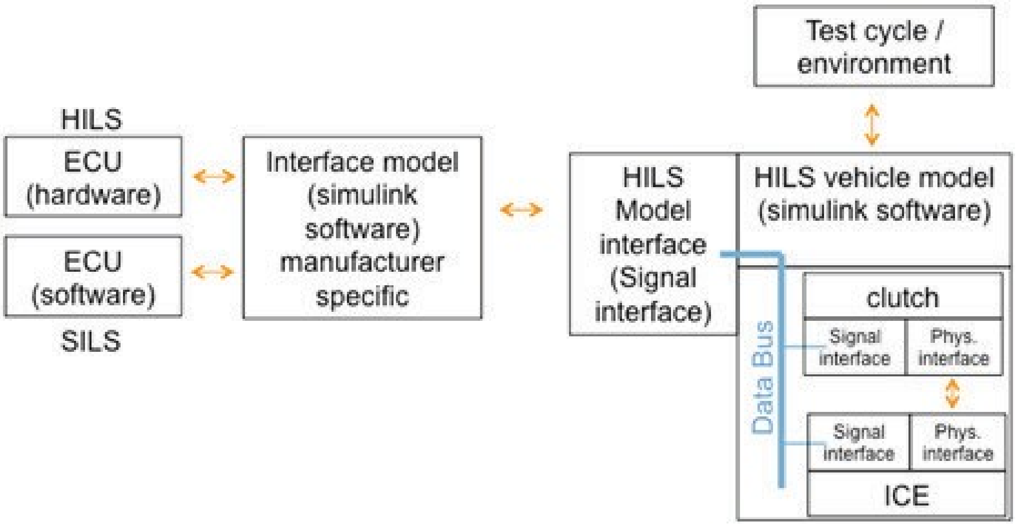


Figure 2.4 HiLS certification model schematically (not entire powertrain shown)

The modelling philosophy that is suitable for HiLS/SiLS applications is called forwarding, which means that the powertrain is described by models described by differential equations. This makes it possible to take into account dynamic effects such as engine speed-up and vehicle inertia etc. The other alternative, called backwarding, is usually based on quasi-static models. Such descriptions can be simulated much faster, but the result does not describe transient effect. Furthermore, in backwarding feedback control cannot be used.

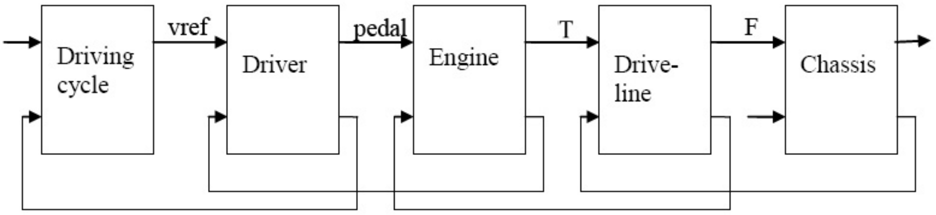


Figure 2.5 Model structure for a powertrain model using forwarding

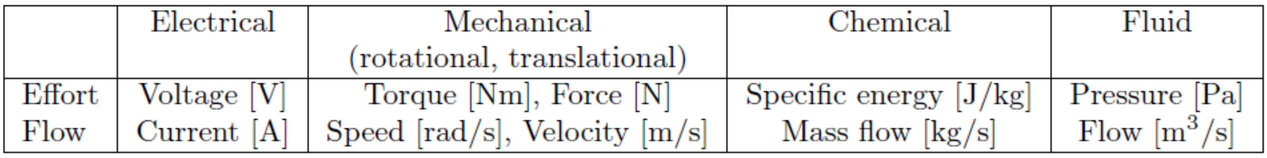
Dynamic simulation or forwarding is outlined in Figure 2.5, this idea is also used, more or less, in the open-source models. The name forwarding comes from the fact that the current subsystem is using information determined in subsystems in front of the current subsystem. The idea is to use a driving cycle, to set the desired vehicle velocity for the driver. The driver utilizes the desired velocity and the current velocity in order to command the vehicle by using the pedals, very similar to what the driver does in a chassis dynamometer setup in reality. The driver is usually represented by some sort of control system. In turn, the engine uses command signals from the driver and a control system and feedback signals from the driveline in order to calculate the current engine states, and so on. In order to achieve this, the model interfaces between the powertrain components needs to be determined.

Two types of interfaces are needed:

- The physical interface is related to how different components are connected together physically
- The signal interface is related to control/sensor signals needed to control the components for an ECU

It is important to define good interfaces capturing all necessary information shared by the different objects. The idea is to use a port-based modelling paradigm. The communication signals between the different components are physical signals, like electric wires, mechanical joints etc. The interfaces or connectors (physical interfaces) are based on energy flow to and from the component or through a port. A port is characterized by an across and a through variable, also known as flow and effort variables in Bond Graph modelling. The interfaces are a key to exchangeability of component models.

For automotive powertrains, four (five) different physical interfaces are necessary, the interfaces are: electrical, mechanical (rotational and translational), chemical and fluid. The table below shows a proposal for physical interface signals.



	Electrical	Mechanical (rotational, translational)	Chemical	Fluid
Effort	Voltage [V]	Torque [Nm], Force [N]	Specific energy [J/kg]	Pressure [Pa]
Flow	Current [A]	Speed [rad/s], Velocity [m/s]	Mass flow [kg/s]	Flow [m^3/s]

Table 2.1 Physical model interface (electrical)

The physical interface proposed is based on best-practice from a number of vehicle powertrain simulation tools, Autonomi, ADVANCE, Dymola (Powertrain library), CAPSim, VSIM, TruckSim.

The port-based modelling paradigm is complemented with a signal interface, for making it possible to control each component.

2.2.1. Naming convention

The following naming convention for the physical interface signals is used:

- Physical interface: phys_description_Unit

where phys is fixed to indicate that it is a physical signal, description is a description of the signal (e.g. torque, voltage) and Unit is the unit of the signal in SI-units (e.g. Nm, V, A etc.). An example: phys_torque_Nm, which is the physical torque in a component model.

For the signal interface, the naming convention follows the AUTOSAR [6] standard as far as possible:

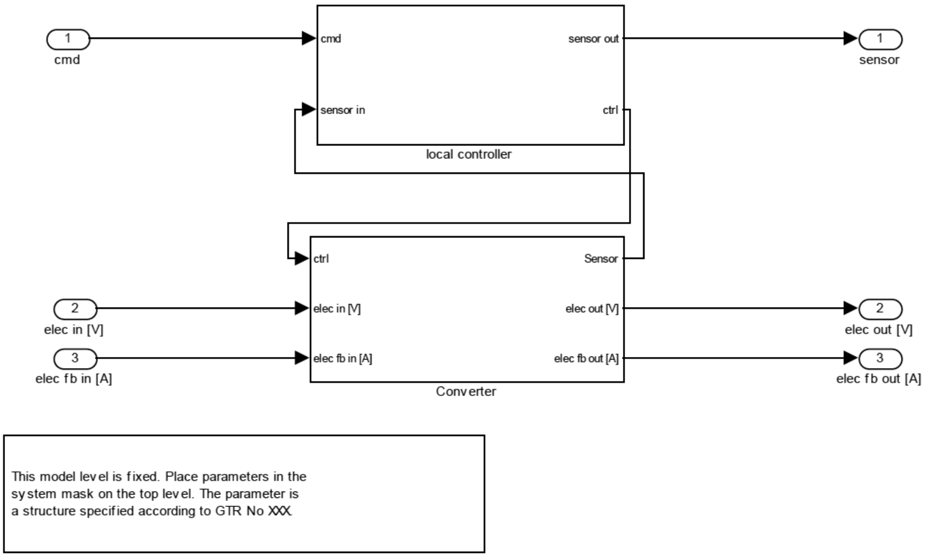
- Signal interface: Component_description_Unit

where Component is the component short name (e.g. Clu, Engine, ElecMac etc.), description is a description of the signal (e.g. actual torque tqAct, voltage u) and Unit is the unit of the signal in SI-units (e.g. Nm, V, A, rad/s etc.). An example: ElecMac_nAct_radps, which is the actual rotational speed of an electric machine in rad/s.

The physical interface and the signal interface for all powertrain component models are available in Annex 9 of GTR no4.

2.2.2. Component model structure in Simulink

The following model structure is proposed, see Figure 2.6. The model structure has been presented at several HDH meetings and it has been accepted for use.



This model level is fixed. Place parameters in the system mask on the top level. The parameter is a structure specified according to GTR No XXX.

Figure 2.6 Model structure (example)

All component models except the driver use the proposed model structure. The model structure is divided into two parts, the physical model and the local controller. Every model includes a local controller, which converts the control signals from the control system (if existing) into local control signals. This block also sends sensor signal values to the control system, i.e. it handles the communication between the control system (ECU) and the physical model. The physical model block should include the implementation of the model equations.

In the Simulink implementation of the physical interfaces for the mechanical components, the inertia or the mass of the component is also transferred between the components in the ’torque’ interface, see table below.

Node	Name	Variable name	Description	Unit
Electrical	elec in [V]	phys_voltage_V	voltage	V
	elec fb in [A]	phys_current_A	current	A
Mechanical	mech in [Nm]	phys_torque_Nm	torque	Nm
		phys_inertia_kgm2	inertia	kgm^2
	mech fb in [rad/s]	phys_speed_radps	speed	rad/s
Mechanical	mech in [N]	phys_force_N	force	N
		phys_mass_kg	mass	kg
	mech fb in [m/s]	phys_velocity_mps	velocity	m/s
Chemical	chem in [J/kg]	phys_specenergy_Jpkg	specific energy	J/kg
	chem fb in [kg/s]	phys_massflow_kgps	mass flow	kg/s
Fluid	fluid in [Pa]	phys_pressure_Pa	pressure	J/kg
	fuid fb in [m3/s]	phys_flow_m3ps	volume flow	m^3/s

Table 2.2 Physical model interfaces

As forwarding is used, feedback signals that go into a block come from the block in front of the current component block. This means that from an energy perspective the energy that goes into a component block is given as the product of the input signal and the feedback output signal. Similarly, the energy that goes out from a component block is given as the product of the output signal and the feedback input signal. As an illustrative example, consider the model in Figure 3.3. The incoming energy (energy flow = power) is determined as Pin = elec in [V] × elec fb out [A] and the outgoing energy is given as Pout = elec out [V] × elec fb in [A].

2.2.3. Vehicle top level model structure

The top level for all vehicle topologies looks the same. It includes a driver model, an ECU model block and its corresponding input/output interface block for converting ECU signals into the proposed signal interface and the powertrain block, see Figure 2.7.

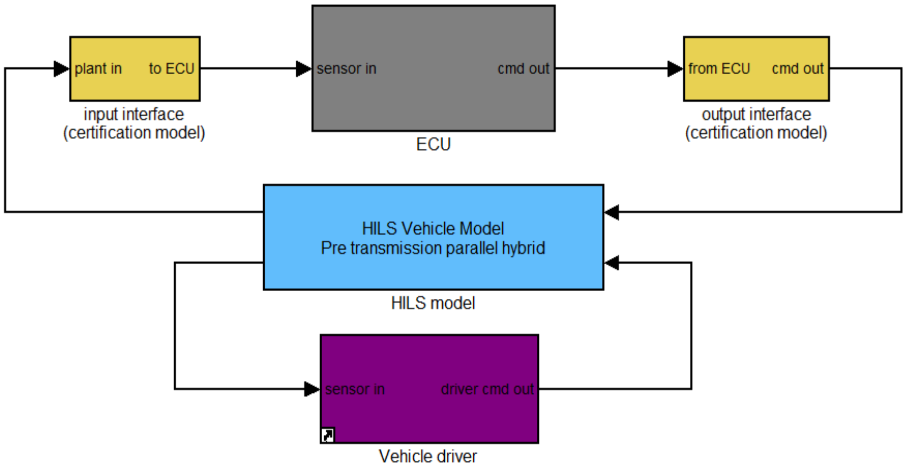


Figure 2.7 Vehicle top level model

The ECU block is replaced by the real ECU when performing a HiLS simulation. The input interface block is modified in order to convert HiLS model signals into desired/needed ECU signals in order to be able to run the ECU. The output interface block is modified in order to convert the ECU signals into signals required by the HiLS model in order to be able to run. See Annex 9 of GTR no4 for signals available from the HiLS model and signals required for the HiLS model.

2.2.4. Model library

Based on the proposed new model structure, which offers flexibility and exchangeability, the open source models are remodelled as separate component models and implemented into a model library, the documentation of the component models is available in Annex 9 of gtr No4 [3].

The component models are categorized into different categories as follows:

- Auxiliary system
- Chassis
- Driver
- Electrical components
- Energy converters
- Mechanical components
- Rechargeable energy storage systems

Each category contains component models related to that specific category. The model library is part of a toolbox. The toolbox is organized as shown below:

```
HILS_GTR............................... The main folder
|--> Documentation..................... Model documentation is located here
|--> DrivingCycles..................... Data of the different driving cycles
|--> Library........................... The model library is located here
   |--> ParameterFiles................. Template parameter files for all
                                         models (copy if used)
|--> Misc.............................. All additional files for the
                                         HILS model library are stored here
|--> Vehicles.......................... Vehicle models are stored here
   |--> Parallel....................... Models for parallel hybrid vehicles
      |--> PreTransmission............. Pre transmission hybrid powertrains
         |--> ExampleVehicle........... Example vehicle ()
            |--> ParameterData......... Data for the different component models
            |--> SimResults............ Simulation results
   |--> ReferenceHybridVehicleModel.... Reference Hybrid Vehicle Model
         |--> ParameterData............ Data for the different component models
         |--> SimResults............... Simulation results
   |--> Series......................... Series hybrid powertrains
      |--> ExampleVehicle.............. Example vehicle ()
         |--> ParameterData............ Data for the different component models
         |--> SimResults............... Simulation results
```

Table 2.3 HiLS toolbox structure

The different directories contain files important for the toolbox and library to work. The library is developed for MATLAB 2012a, but is available for MATLAB 2008a under general files of the UNECE homepage of the GRPE workgroup for HDH [7].

2.2.4.1. Documentation

A directory containing the documentation, the modelling philosophy and examples.

2.2.4.2. Driving Cycles

A directory containing different driving cycles that can be used in the toolbox. The driving cycles are implemented as a vehicle velocity profile as function of time. The driving cycles are saved as mat-files and can be loaded into MATLAB's workspace using the load function.

2.2.4.3. Library

The model library is located in this directory. The component models are categorized into different categories as mentioned earlier. In each category, different component models are available. The main reason for using a model library is that modifications can easily be broadcast to all powertrain models using the library, this secures that all powertrain models are up-to-date.

2.2.4.4. Parameter files

For each component model in the library there is a corresponding parameter file associated to the model. The parameter file contains all parameters that need to be inputted in order to simulate the model. If a component model is included in a powertrain model, it is a good idea to copy the corresponding parameter file and modify the parameters according to the component modeled.

2.2.4.5. Misc

This folder contains functions used for pre or post processing of data and/or simulation results.

2.2.4.6. Vehicles

This folder contains example powertrain models; modeled using the model library. It contains one series hybrid powertrain model and two parallel hybrid powertrain models, one pre-transmission parallel hybrid powertrain model and one post-transmission parallel powertrain model.

2.2.5. Summary

A new model structure has been proposed and implemented. Also a new model library has been developed based on the model structure. Component models build up the model library. Using a component-based modelling philosophy offers flexibility for different hybrid systems and makes it easy to include new or future hybrid systems. The component models in the library are based on the Japanese component models presented in Kokujikan No. 281 [1], with modifications to fit the proposed model structure. The complete model descriptions are available in Annex 9 of gtr No4 [3].

2.3. Component test procedures

To be able to properly set up and parameterize a HiLS model, component data and parameters need to be determined from actual component tests. The described procedures in Annex 9 of gtr No.4 [3] were developed based on state of the art procedures or already existing regulatory standards and comply with generally accepted industry guidelines to provide data for the energy converters and storage devices present in the development process of this gtr amendment. Due to the great variety and the degree of novelty of components used in hybrid vehicles it was not considered as reasonable to prescribe additional test procedures for components not widely used in hybrid systems at the time of completing the amendment to the regulation. The validity of test procedures and determined input data used for model parameterization where no specific test procedure is described in the regulation needs to be assessed by the respective type approval or certification authority.

In general it was the intention to keep all component tests as simple as possible regarding required measurement equipment, design of the test procedure and measurement duration but still accurate enough to represent realistic characteristics of the respective hybrid powertrain component. If a special hybrid system requires higher accuracy, the defined number and allocation of standard sampling points and thus the measurement effort can always be increased. In case of a defined test procedure being not representative for a special type of hybrid system component, the regulation allows also a modification of a standard test procedure in co-ordination with the type approval or certification authority.

Component test procedures were defined for all hybrid system components commonly used in heavy-duty hybrid vehicles presently. For the remaining parts of the powertrain (e.g. clutch, transmission, final drive, etc.) no standard test procedures were defined since these values can be easily derived from data sheets or simple calculations by the vehicle manufacturer (e.g. gear ratios, rotational inertias, efficiencies etc.) and small inaccuracies there do not have a big influence on the overall behaviour of the hybrid system and the resulting combustion engine load cycle. In addition to that the vehicle specific values for rotational inertias and efficiencies are only used for the verification of the specific vehicle simulation model when measured signals from a chassis dyno test run are compared to the respective outputs from the simulation model. Hence the parameterized values are verified implicitly during the model verification. For the creation of the specific engine test cycle in the type approval simulation run all of these values are set to generic values to represent an average vehicle in order to keep the type approval test of a hybrid powertrain vehicle independent.

Also for the vehicle related parameters – i.e. mass, rolling resistance coefficient, air drag coefficient and frontal area – no test procedures are necessary since these values are determined by equations (see chapter 4). These values are used in the HiLS method for both steps, the verification of the vehicle model as well as the creation of the specific engine load cycle.

In the following paragraphs only the basic idea of the component test procedures and the structure of the derived parameters are explained for each specific component, more detailed descriptions can be found in [3].

2.3.1. Internal combustion engine

The combustion engine is modelled in a way that a torque request delivers an actual value of torque output dependent on the current rotational speed. The actual amount of torque delivered is absolutely, statically limited by the maximum (i.e. full load) and motoring (i.e. friction) torque curve of the engine. Additionally, the dynamic response to a change in torque request is modelled by maps for the applicable time response for torque build-up. The dynamic torque build-up of the engine is depicted by using two first order models. The first shall account for almost direct torque build-up representing the fast dynamics. The second first-order system shall account for the slower dynamics corresponding to turbo charger effects and boost pressure build-up.

The parameters for the maximum and minimum limits of the static engine torque are determined by a standard full load (i.e. 100% load) and motoring torque (i.e. 0% load) measurement over the whole engine speed range from idle speed up to the maximum engine speed where the torque drops below zero again. This is the same standard procedure as used for generating the required engine data to calculate the WHTC test cycle. With this measurement the limit for positive engine torque characteristics are defined by maximum torque as function of engine speed and the limit for negative engine torque characteristics by motoring torque as function of engine speed. If applicable also the engine auxiliary brake torque characteristics can be measured in a second iteration of the measurement procedure for motoring torque with the auxiliary brake fully applied.

The parameters for the dynamic torque build-up are determined by an engine load-change test that is based on the procedure of the ELR test. In this test the engine is stabilized for a constant speed point at a very low load and then the load request is immediately changed to 100% and held at that load until speed and torque have stabilized again. This is done for several set-points of engine speeds and the time constants are derived from the measured torque response curve of the engine. The instant torque as function of engine speed is defined as the torque that can be delivered by the engine after a certain short time span. The boost-pressure dynamics are defined by a time constant as function of engine speed calculated by the time when the engine already delivered a defined large portion of the stabilized maximum torque in the respective load step.

2.3.2. Electric machine

The electric machine is modelled in a way that a torque request delivers an actual value of torque output dependent on the current rotational speed. The actual amount of torque delivered is absolutely, statically limited by the maximum (i.e. full motor demand) and minimum (i.e. full generator demand) torque curve. Since the response time of an electric machine is quite fast compared to the one of an internal combustion engine, the dynamic response to a torque request does not need a special test procedure but the time constant can be parameterized by the manufacturer due to low impact on overall hybrid system behaviour. The efficiency values of the electric machine over the operating range are modelled using maps to represent the relation between its mechanical and electrical power. For easier handling of the input data the efficiency values are separated into two individual maps, one for motor mode and one for generator mode.

All parameters are determined by measuring electrical values of voltage and current as well as the mechanical value of torque for a minimum number of defined and equally distributed set-points for speed and load in the whole operating range. From these values the efficiency maps for motor and generator mode are derived as electric power consumed or delivered as a function of the three parameters rotational speed, torque and voltage.

2.3.3. Battery

The battery is modelled as system consisting of an internal resistance and a resistor-capacitor parallel circuit in series. This allows reproducing a more accurate time dependent current-voltage behaviour as response of the voltage value to a current pulse instead of only a static change in battery voltage. The open-circuit voltage, the single internal resistance as well as the resistor-capacitor resistance and capacitance are dependent of the actual energy state of the battery and are modelled using tabulated values in maps. The resistances and the capacitance also have two separate current directional dependent maps.

The parameters for the open circuit voltage of the battery are determined by a test procedure where a fully charged and preconditioned battery is discharged with a very low current in small SOC steps based on the nominal capacity declared by the manufacturer. Each time the next lower level of SOC is reached the discharging is interrupted and the battery is soaked for a defined time span before the corresponding open circuit voltage is measured at the end of the soak time. The last open circuit voltage value corresponds to an empty battery. With the recorded discharging current over time the actual capacity of the battery is calculated and each measured open circuit voltage value can then be assigned to the respective actual SOC value calculated based on the actual capacity of the battery. With this measurement the open circuit voltage is defined as a function of SOC.

The parameters for both resistances and the capacitance are determined by a test procedure where the battery is alternatingly charged and discharged in steps of raising current values at a fixed SOC value. By recording the voltage response with a high time resolution the parameters for the two resistances and the capacitance can be calculated by performing a more complex data analysis. The procedure is repeated for several SOC levels over the whole battery operation range. With this measurement the single internal resistance as well as the resistance and capacitance in the resistor-capacitor parallel circuit are defined as functions of SOC separately for charging and discharging of the battery.

2.3.4. Capacitor

The capacitor is modelled as capacitance in series with an internal resistance. This represents the characteristics of a capacitor as current integrator with a corresponding voltage drop due to the power loss in the internal resistance.

The parameters are determined in a simple test procedure where the preconditioned empty capacitor is fully charged and discharged with a constant current in one continuous cycle with defined waiting periods in between. The maximum and minimum operating voltages that occur in that test cycle are defined by the manufacturer of the capacitor in a data sheet. With the recorded voltage and current values over the test cycle, the approximated linear current-voltage characteristics dependent on the capacitance as well as the internal resistance can be calculated by following the defined data analysis procedure. With this measurement the capacitance and internal resistance are defined as two single parameter values.

2.3.5. Summary

Component test procedures were defined for all hybrid system components commonly used in heavy-duty hybrid vehicles at this time and where reasonable measurement standards as well as experience with measurement procedures existed. In particular for new parts and components that are not used on a broad basis generally valid test procedures can hardly be defined without taking the risk of generating inaccurate or unrepresentative parameter data. Once specific components become commonly used in heavy-duty hybrid vehicles, standardized component tests could be added for these systems based on industry standards in the future.

The existing component test procedures were defined in a way that they are as simple as possible but still accurate enough to represent realistic characteristics of the respective hybrid powertrain component. Especially the test procedures for the electric storage systems are based on a best practice approach using the experience gained in measuring a lot of different types of batteries as well as super capacitors in a lab at the participating universities. These test procedures do not necessarily match the ones used by manufacturers of one specific type of electric storage system but are designed in a way that they fit for a broad range of types of a specific component and deliver parameters which are more realistic for the in-vehicle application of the component.

2.4. Model verification by chassis dyno testing

As explained in section 0 the verification of the specific vehicle simulation model is one important step in the HiLS procedure which ensures the conformity between the real vehicle and the simulation model. That means if a specific vehicle model is used for the first time or after structural changes have been made to an already verified vehicle model, it needs to be checked if the simulation model is able to represent the behaviour of the real vehicle as accurately as necessary. For this check a real chassis dyno test run and a simulation of the exact same chassis dyno test run are compared regarding several signals like vehicle speed, engine operation points, operation points of the secondary energy converter and alike.

2.4.1. Model verification process

Basically the verification process is performed by running a vehicle equipped with the hybrid powertrain to be tested in the applicable vehicle cycle (i.e. WHVC cycle including specifically calculated road gradients) on a chassis dyno. The road load (i.e. rolling resistance, air drag resistance, road gradients) and the mass inertia simulated by the chassis dyno are defined dependent on the rated power of the hybrid system (see chapter 4). The vehicle simulation model is then run over the cycle consisting of the actual measured vehicle speed on the chassis dyno where the chassis model simulates the same road loads as were set on the chassis dyno. The simulation model is parameterized for this case using the input data generated by the component tests for the hybrid system (see section 2.3) and all other parameters according to the actual vehicle as specified by the manufacturer for the remaining powertrain. For the verification simulation run the tire radius, final drive ratio, rotational inertias and efficiencies have to be parameterized according to the values of the actual vehicle in order for the measurement to match the simulation output. If only one drive axle of the vehicle is operated on a single roller chassis dyno then also the rotational inertia values in the simulation model have to be reduced accordingly. For the creation of the specific engine test cycle for type approval at a later stage in the HiLS process the vehicle specific values for tire radius, final drive ratio, rotational inertias and efficiencies are changed to generic values representing an average vehicle.

For the verification of the correlation between simulation model and real vehicle, several characteristic signals have to be recorded that describe the power flows in the hybrid system and vehicle drivetrain. In both test runs, chassis dyno and simulation, at least vehicle speed, speed and torque operation points of all energy converters, power and operation point of the energy storage system as well as the actual energy content have to be logged either directly by using dedicated measurement equipment or indirectly by using signals from ECUs over the vehicle CAN bus. If recorded CAN signals are used, post processing is necessary to transform the logged signal to a value that can be considered as actually measured data. For this post processing method a data pair of rotational speed and a respective command value (e.g. torque request, fuel injection amount, etc.) is used together with the characteristic parameter map that was derived for the specific component through component testing. The CAN signal of torque command is then transferred to the actually measured value of torque by interpolating the corresponding data point from the characteristic component map dependent on rotational speed and the command value using Hermite interpolation procedure.

The comparison of the corresponding particular signals is carried out in a two-step approach. First a short part of the test cycle is compared where both signal types (i.e. measurement and simulation) have to match very accurately. Based on the Japanese regulation and on the experience gained during the validation test program (see chapter 9) the first 140 seconds of the applicable WHVC test run were defined as the short cycle part for the verification. This section consists of two driving events of acceleration with directly consequent deceleration and standstill between the two events. Since it also starts and ends with vehicle standstill, this section poses a good compromise of dynamic vehicle operation and stabilized conditions at the beginning and the end of the section which is important due to the sensitivity of the hybrid system to small changes in the boundary conditions. In this first short part of the model verification, the vehicle model is controlled by using driver command signals that have been recorded during the chassis dyno test. Pedal positions for accelerator and brake pedal as well as clutch pedal position and gear shift timing for manual transmissions are fed into the simulation model and actuate the vehicle model. With this approach the consistency of the entire control system including ECUs between real vehicle and simulation model is checked. For the short part verification requirements for the matching of vehicle speed, torque and power of both energy converters and power of the storage device are defined. Thus, the operation of the different hybrid components and the power flows in the hybrid system have to match very accurately in this short part.

In the second step of the two-step verification approach, the matching of vehicle speed as well as the power and work of the combustion engine are verified. Since a hybrid system is quite sensitive to small changes, a small deviation in the simulation can lead to a different decision of the control logics. Once a different decision has occurred, the error between simulation and real test will propagate and get bigger and bigger with progressing simulation time due to more and more different decisions in the control logics. Thus it is not reasonable and not even possible to apply the same stringent criteria as defined for the first short part over the whole 1800 seconds of the test cycle. Also the data produced in the validation test program showed that an exact reproduction of the hybrid system behaviour is not possible over the whole cycle. Therefore, following the original Japanese regulation, the chosen approach was to define requirements for the matching of the combustion engine operation since this is the component which has to perform the exhaust emission test cycle at a later stage in the procedure. With the vehicle speed, engine torque and the ratio of positive engine work between simulation and measurement as required criteria to match, it is ensured that the operation of the combustion engine is depicted accurately enough for the generation of the specific engine test cycle with the simulation model. So the aim of the simulation model is only to produce a good approximation of the engine operation since the real engine operation behaviour will anyway be tested in the exhaust emission test on the engine test bed. Also the WHTC test for conventional engines is only an approximation of the operation behaviour of the engine installed in the vehicle and not necessarily representative of a specific combination of the engine with an individual transmission and drivetrain. Due to the fact that the specific transmission is included in the HiLS method, the resulting load cycle of the combustion engine should be much closer to real-world operation than the WHTC for a specific vehicle.

One additional boundary condition that has to be fulfilled for a valid simulation model is the net energy change of the energy storage system over the test cycle. This criterion ensures that the difference in stored energy between start and end of the test cycle is matching between measurement and simulation. This poses an additional check of the correctness of energy flows in the hybrid system since the vehicle has to drive at the same speed in the simulation as in the measurement which requires the same demand of propulsion energy that has to be provided by the hybrid system.

One exception from the application of the matching criteria is defined for gear shifting periods. It is hardly possible to match speed and torque values during the actuation of clutches and parts of the transmission during changing of a gear where high gradients in rotational speed and torque occur due to interruption of the driveline torque and transitional phases with frictional effects. These high gradients lead to high deviations during gear shifting periods and would thus artificially worsen the correlation coefficient of measurement and simulation. For that reason points from beginning to the end of clutch actuation (or similar provision for automatized gear boxes) are omitted from the data analysis for calculation of the regression coefficient. But in terms of produced propulsion energy, which is an integrated value instead of a difference between two values, these points are not omitted for the calculation since otherwise the positive engine work over the cycle would be wrong.

2.4.2. Chassis dyno measurement

As explained in the preceding paragraphs, a chassis dyno test is required for the verification of the specific vehicle simulation model. Since there is no existing gtr covering chassis dyno testing of heavy-duty vehicles to refer to, and gtr No. 4 is a regulation specifically for engine testing, it was decided within the HDH informal working group that only specific particularities applying to the HiLS method should be described in the regulation. Writing a comprehensive chassis dyno regulation would not have been possible due to the context of gtr No. 4 and of the mandate given to the HDH informal working group. Furthermore, there is no measurement of exhaust emissions performed on the chassis dyno directly but the recorded data from the chassis dyno is only used for comparison with the output of the simulation model and thus a very accurate definition of the whole test procedure is not necessary. Besides, also the correct setting of the chassis dyno is checked implicitly during the model verification. If both, chassis dyno and simulation model, apply the same correct road load at a certain vehicle speed, the resulting propulsion power demand of the vehicle has to match. If a deviation occurred there, the behaviour of the hybrid system would be completely different and the defined limits for the correlation between measurement and simulation could not be satisfied.

Compared with regular chassis dyno testing no on-road coast-down test is required to determine the respective road load values to be simulated by the test bed controller but these values are defined as equations in the regulation. In order to set the desired target road load values, the chassis dynamometer has to be capable of performing a coast-down procedure to determine and set the correct road load values. Also, in contrary to regular chassis dyno testing, no correction for rotational inertias of vehicle axles which are not operated on the test bed is made in the dynamometer load settings. This is not necessary since the purpose of the chassis dyno test is not to reproduce the exact behaviour of the vehicle driving on-road but only to generate data for comparison with the simulation model. But it is important that the inertia settings in the simulation model correspond to the setup of the real vehicle on the chassis dyno. Furthermore, all modifications or signals required to operate the hybrid vehicle on the chassis dynamometer (e.g. dummy signals for wheel speed of non-operated axles) should be documented and handled in the same way in the simulation model or the interface to the connected ECUs.

Since the applicable test cycle (see chapter 5) was designed so that the propulsion power demand over time is closely linked to that of the WHTC test, it is also important that the chassis dyno test is conducted as a time-based test (i.e. velocity as a function of test time). Unlike following a predefined route where the respective reference distances have to be kept, it is important for the HiLS method that the target velocity is defined over time and thus a target propulsion power demand over time is defined in combination with the specified road gradients. For that reason the “artificial” road gradient of the test cycle should not be fed into the vehicle’s ECUs as an input signal or an existing inclination sensor should be disabled in order to pretend a level ground position of the vehicle. The “artificial” road gradient should only adjust the propulsion power demand and not cause different decisions of the ECUs as well as different behaviour of the hybrid system (e.g. different gear shifting, different recuperation strategy, etc.) due to detection of “real” road gradients instead of a level road.

For the creation of the specific engine test cycle with the simulation model at a later stage in the HiLS procedure no additional loads for auxiliary systems are demanded from the engine as it is defined for testing of heavy-duty engines installed in conventional vehicles. For that reason all auxiliary systems should already be turned off during the chassis dyno test or the respective power consumption measured if deactivation is not possible. This additional power consumption, either electrical or mechanical, over time is then used as input for the auxiliary load models in the vehicle simulation to match the power demand between measurement and simulation.

The beginning of the test cycle is defined as setting the vehicle into driving mode to be consistent with the WHTC test where the engine cranking defines the beginning of the test cycle. For a hybrid system the engine does not necessarily need to be started from the beginning, so the system status of changing from non-driving mode (i.e. no propulsion power delivered by the hybrid system) into driving mode was defined as a corresponding marker for the test start.

The experience gained during the validation test program showed that following the target vehicle speed within very small tolerances is not that easy, especially with vehicles with higher power and thus higher test mass. Again, since there is no direct measurement performed on the chassis dyno but the recorded data from the chassis dyno is only used for comparison with the output of the simulation model, a very accurate tracking of the target cycle speed is not necessary. For the verification step the simulation model will anyway try to follow the actual measured vehicle speed from the chassis dyno test. For that reason the speed tolerances were widened only for the chassis dyno test and the allowable errors in speed and time were changed to ±4.0 km/h in speed and ±2.0 second in time. In addition, these provisions shall not apply in case the demanded accelerations and speeds are not obtained even though the accelerator pedal is fully depressed and maximum performance is requested from the hybrid powertrain. This exception is important since some sections of the test cycle demand very high accelerations which cannot be followed by all vehicles. This exception is also necessary for vehicles with limited maximum speed that cannot follow the target speed in the high-speed part at the end of the cycle.

Phases of deceleration require also some special provisions in some cases. In a standard setup with a single roller chassis dyno the total amount of braking power is applied over one vehicle axle. For heavier vehicles braking over only one axle instead of multiple axles in real-world could lead to too low deceleration values due to limited braking capacity and thus the vehicle would not be able to follow the target speed during phases of deceleration. For that reason the chassis dynamometer may assist in decelerating the vehicle by switching to higher simulated road loads only during phases of deceleration (e.g. by modification of the applied road gradient during decelerations). This arrangement is of course reducing the available energy for recuperation but there is no other option available for these special cases on the chassis dyno. Braking performance of a hybrid system on a chassis dyno test bed will be anyway different from on-road performance in some cases and over- or underestimate the real potential for recuperation of energy due to different behaviour of the system when braking only over several instead of all vehicle axles. But for these cases that is an inherent problem of operating not all axles in a chassis dyno test. Besides, the capacity for both, acceleration and deceleration, of the operated drive axles can be improved by generating sufficient axle load by applying ballast or lashing systems on the chassis dyno test bed.

2.4.3. Summary

For the model verification the correlation between real vehicle and simulation model has to be proven. For that purpose a data set of several signals like vehicle speed, engine operation points, operation points of the secondary energy converter and alike is recorded during a test run of a real vehicle on the chassis dynamometer. The simulation model is then operated over the exact same vehicle speed cycle from the measurement and has to deliver the same behaviour of the hybrid system over time as output. Some specific particularities apply for chassis dyno testing as part of the HiLS method and also for hybrid vehicles in general.

The same basic procedure could theoretically also be applied for powertrain testing where one hybrid system is used for verification of a corresponding simulation model and the verified simulation model is then used to create the specific engine test cycle for several variants of hybrid systems with the same powertrain architecture (e.g. different power of second energy converter, different capacity of energy storage, etc.).

2.5. Consideration of cold start

As cold start is part of the certification and type approval procedure for engines installed in conventional vehicles it was agreed that this scenario should also be applied on hybrid powertrains. Since the cold start temperature is set to 25°C for these test procedures and in order to avoid an unjustifiable effort where component data would need to be derived dependent on temperature, it is assumed that 25°C cold start temperature will not have a negative influence on the detached performance of the hybrid powertrain components. Nevertheless, single system temperatures could influence the operation strategy of the hybrid powertrain which would lead to a different combustion engine operation for warm and cold start operation (see Figure 2.8 where the electric motor is increasing the combustion engine load for a faster exhaust system heat up).

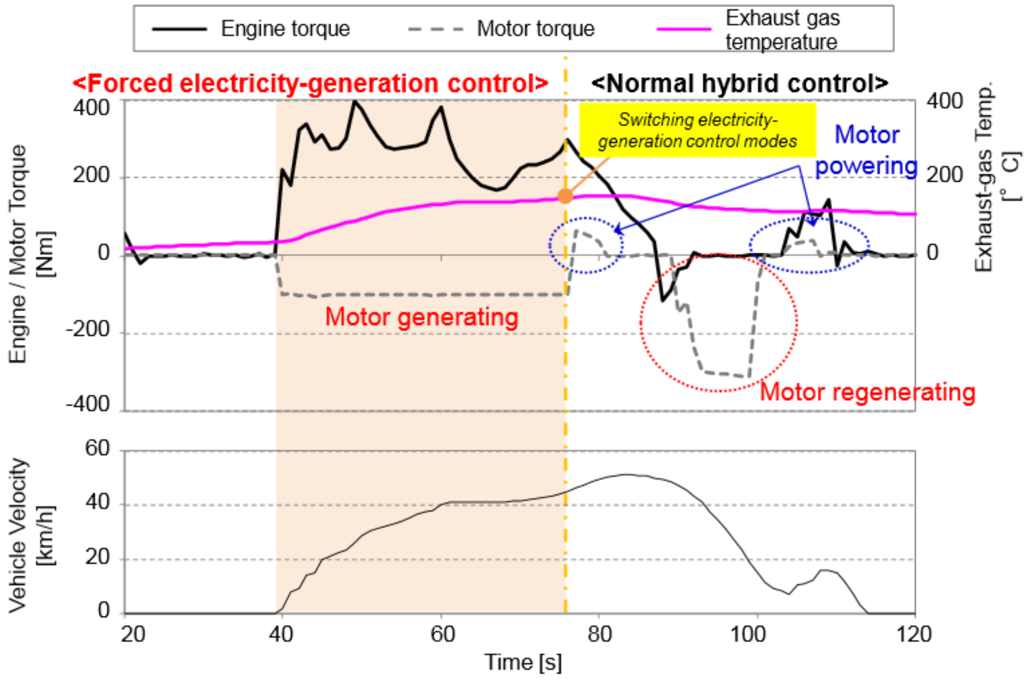


Figure 2.8 Application of hybrid cold start strategy [8]

If this is the case and to be able to reflect this behaviour without implementing the mandatory use of accurate thermodynamic temperature models in the HiLS library, where parameterization is considered as excessive effort, the HCUs shall be supplied with temperature data following the predicted temperature method.

2.5.1. Predicted temperature method

Even for conventional vehicles the emission behaviour depends on various system temperatures whereby here the engine operation pattern stays the same for cold and hot engine testing during the type approval or certification. The engine is tested in cold and warm condition and the resulting emissions are measured and weighted accordingly.

Since for hybrid vehicles also the engine operation pattern itself is influenced by hybrid control systems depending on various system temperatures, it is crucial to provide appropriate temperature signals to the ECUs during the HiL simulation to derive the representative in-use engine behaviour of system and control logics for a cold start at the emission test. Therefore, temperature signals of elements affecting the hybrid control strategy need to be provided to the connected ECU(s) for the HiLS cold start run. Regardless of their profile and origin they are used for the HiL simulation to derive the HEC test cycle for cold start conditions.

However, the freedom of using any temperature signal demands the proof of correctness. This is done by recording the actually measured temperatures, which have previously been predicted for the HiLS test run, during emission measurements on the engine test bed (e.g. coolant temperature, specific temperature of after treatment system etc.) and comparing them to the predicted ones. Using linear regression analysis it has to be demonstrated that the predicted profiles have been correct and reflect actual temperature behaviour. If proved correct, the derived engine operation pattern is assumed to be correct and representative of in-use cold start operation. Figure 2.9 shows an example for three relevant temperatures predicted correctly (top) and incorrectly (bottom). The temperature profiles in red have been used for the HiLS run to generate the HEC cycle. During the engine test run on the engine test bed the blue temperatures have been recorded. The bottom figure actually shows a different system heat-up than the predicted one and therefore the derived HEC and the used temperature profiles cannot be considered as correct.

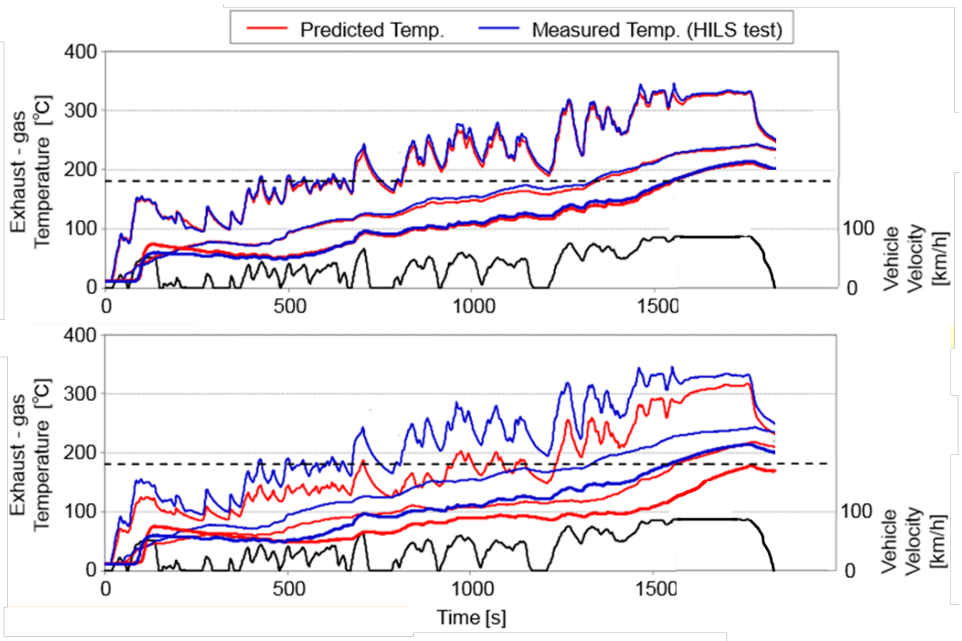


Figure 2.9 Sufficient (top) vs. insufficient (bottom) predicted temperature profile [8]

2.5.2. Summary and clarification

Choosing the method described avoids the mandatory use and the verification of thermodynamic models which clearly reduces the effort for a HiLS certification. It enables manufacturers to either use temperature signals recorded during an actual hardware test (e.g. on the chassis dyno), signals generated by thermodynamic models as present in the HiLS model library or as available at the manufacturer internally, or estimated temperature signals. Independent of their origin their correctness always has to be verified by a linear regression analysis comparing actually measured and predicted temperature profiles.

Since the method is based on the assumption that 25°C initial temperature has no influence on the detached hybrid component performance, it only allows to depict different component operation caused by specific system temperatures and the decisions taken in the hybrid logics. Overheating of specific hybrid components is not directly envisaged to be considered by this method and has to be taken into account already during the verification of the HiLS run in warm condition e.g. by thresholds for integrated current values (i^2T), time of component actuation, etc., if this occurs. If not, a successful HiLS model verification will, due to different component actuation, hardly be possible. To be able to utilize a verified HiLS model where component overheating occurs also for hybrid powertrains with different component properties (battery size, etc.), the logics for a consideration need to be physically valid and approvable by the type approval or certification authorities. This approach agreed by the HDH informal group allows a balance between accuracy and certification effort, since otherwise a HiLS model verification for each specific vehicle configuration would be needed and there would be no rational reason for a HiLS certification any longer due to the significantly increased effort.

Due to major concerns about chassis dyno testing where the entire vehicle-chassis dyno system is not fully warmed up and thus the friction of dyno and tire roller contact continuously changes, an accurate application of road loads by the dyno and therefore a successful HiLS model verification in cold condition is hardly considered possible. As currently stated in amendment 3 to gtr No.4 [3] a chassis dyno test in cold condition shall nevertheless be performed but no verification of the HiLS model using that data is required. The test can only serve to derive temperature profiles for the cold HiLS run which has to be verified using the predicted temperature method. However, since the very same provisions are valid and furthermore needed for powertrain testing they are stated in the respective section.

A verification of the predicted temperature method as described has not been performed for the three test candidates within VTP2. The time schedule only allowed to run HiLS model verifications for warm operating conditions. However, NTSEL performed a verification of the predicted temperature method [8] using a vehicle from the Japanese market where also the limit values for the linear regression analysis stated in amendment 3 to gtr No.4 have been derived from. Method and limit values have been agreed in the HDH informal group even though further testing would have been desirable. Especially hybrid systems will most likely take advantage of faster system heat up by applying different warm and cold start strategies causing different cold and hot engine operation. For systems where the HiLS model needs to be verified anyway (e.g. tested the first time, etc.) no major test burden is expected since the predicted temperature profile can quite easily be derived from actual chassis dyno tests. However, if verified HiLS models are used to certify or type approve slightly different hybrid systems which require no model re-verification, the predicted temperature profiles may be harder to obtain, which could cause multiple iteration loops (HiLS - engine test bed) until valid predicted temperature profiles are found.

3. The powertrain method

The powertrain test method specified in Annex 10 of gtr No.4 [3] delivers emission results relevant for certification or type approval of hybrid powertrains comparable to the results obtained by the HiLS procedure specified in Annex 9. Instead of using simulation models to derive the combustion engine's operation pattern, the powertrain method requires all components of the hybrid powertrain to be present in hardware. The emission measurement is directly executed at the powertrain test bed. Effectively, it reflects a chassis dyno test where chassis and most likely the final drive (and possibly the gearbox) are simulated by the test-bed controller. The components simulated are subject to the same provisions as specified for the HiLS method in Annex 9.

In the powertrain method, contrary to the HiLS method, the two steps of creating the specific engine test cycle and performing emission measurement over that specific engine test cycle are combined into one step. The same test principal and boundary conditions as for the HiLS method apply but the hybrid powertrain including its ECUs is present in actual hardware on the test bed and connected to the dynamometer. Thus no model verification is required since all relevant parts of the hybrid system and the respective hybrid operation strategy are represented by the real component instead of a simulation model.

A simulation model is only needed for those components not present as actual hardware as well as the applied road load. In most cases, the components not present as actual hardware will be the parts of the vehicle's drivetrain downstream of the transmission (i.e. final drive and tires). In a special test bed setup with two or more dynamometers even the final drive could be included as hardware. However, the only compulsory part of the simulation model is the chassis component which is responsible for representing the vehicle's tires and applying the respective road load dependent on the actual vehicle speed.

In general, the same provisions as for the creation of the specific engine cycle in the HiLS method also apply for the setting of rotational inertias and efficiencies of the powertrain (see section 2.4). But special provisions apply for all relevant parts of the hybrid system that are present in hardware, since efficiencies and rotational inertias of these hardware parts cannot be parameterized with a generic value. Thus generic efficiencies are only used for the remaining parts of the drivetrain that are represented by the simulation model. The generic combined inertia value representing the total drivetrain downstream of the gearbox output side, which is set as wheel inertia value in the chassis component, has to be correctly reduced according to the actual inertias of the respective parts present in hardware downstream of the gearbox output side.

The test bed setup, signal flow and control is even more complex than for the HiLS method since not only an interface between driver control and hybrid system control units but also a second interface between dynamometer and simulation model is required. Also the update frequency of the dyno control has to be very high in order to accurately respond to the rotational speed set-points as output from the simulation model. The principal signal flow of the powertrain method can be explained as follows and is also shown in Figure 3.1: The driver control part actuates the accelerator and brake pedal to follow the target vehicle speed cycle and thus sends a command value to the hybrid system that requests a certain amount of propulsion torque from the hybrid powertrain. The output shaft(s) of the hybrid system is connected to a dynamometer which is keeping the desired rotational speed and the provided propulsion torque from the hybrid system is measured by the dyno load cell. This measured propulsion torque value is used as an input to the simulated part of the powertrain. In the final part of the simulation model, the chassis component, a difference between propulsion torque and road load leads to a change in vehicle speed. The new vehicle speed value is used as input for the dyno control as well as for the driver control. The calculated rotational speed at the virtual connection between dyno and simulation model is used as new set-point for the dynamometer speed.

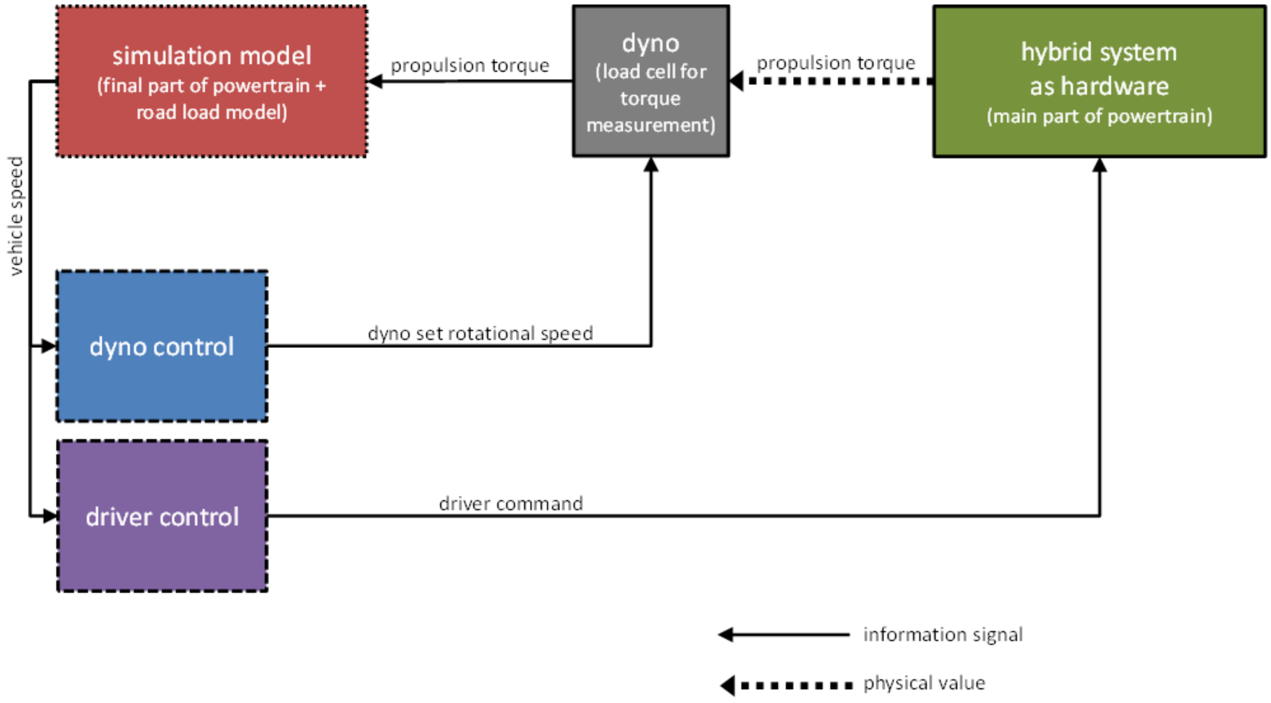


Figure 3.1 Basic principle and signal flow of the powertrain method

The powertrain method, similar to the HiLS method, also requires some kind of interface model connected to the ECUs in hardware. It is not possible to use the vehicle control units directly without disabling error handling modes and related special failure operation modes. The software interface model also has to emulate the residual CAN bus as well as ECUs that are not present in hardware (e.g. ABS, braking control unit, cooling system for hybrid components, etc.) and generate dummy signals for missing sensors in the powertrain test bed setup (e.g. wheel speed sensor, temperature sensor of cooling system, etc.). Also software changes in ECUs could be necessary in order to allow operation of hybrid powerpacks on dynamometer test bed [9].

In principal the powertrain method is intended to lead to the same operation pattern of the combustion engine as the HiLS method. Nevertheless, the correlation between both methods has not been tested yet due to restrictions in resources as well as availability of powertrain test beds which need to be capable of handling much higher torques compared to standard engine test beds. Thus the magnitude of the deviations between these two methods cannot be assessed since no comparable test runs with the exact same hybrid system following both methods were carried out. Theoretically both testing methods follow the same underlying test principle and should lead to the same emission results. But due to the sensitivity of the hybrid control strategy to different boundary conditions (e.g. deviation in SOC value over time between real hardware and simulation) a different decision could be triggered in the HCUs leading to a deviation in the engine operation pattern between powertrain and HiLS method. Such deviations between real hardware and simulation are very likely to occur since every simulation has an inherent error and is not able to depict the exact behaviour of the real component. Also deviations in system operation during gear shifting between real hardware and simulation as well as deviations due to the additional transformation step of the target engine cycle as set-points for the engine test bed to the actually measured engine cycle on the test bed will lead to a slightly different engine operation pattern. Nevertheless, it is not sure which method will result in the more realistic engine operation pattern. Both methods do not necessarily lead to the exactly same system behaviour as in real-world operation of the vehicle due to slight differences in boundary conditions. But also chassis dyno testing cannot exactly reproduce on-road driving of a hybrid vehicle.

4. Generic vehicle parameters

The engine operation pattern for engines installed in hybrid vehicles depends on the entire vehicle setup and therefore the consideration of the entire vehicle is necessary to determine the engine operation profile for an emission certification or type approval which aims to reflect the in-use behaviour at the certification process correctly.

Heavy duty vehicles can vary quite a lot even though the powertrain stays the same and thus testing and certifying each vehicle derivative specifically (different final drive ratio, tire radius, aerodynamics etc.) is not considered feasible even though different engine operation would be the result. In line with testing of engines installed in conventional vehicles it was agreed in the HDH informal group that a representative average vehicle, consisting of generic vehicle parameters, will be used to cope with the variety of vehicle derivatives within a reasonable test effort.

To ensure the comparability of hybrid and conventional heavy duty vehicles in terms of emissions, the generic vehicle parameters have been developed in order to realize the same system load for engines installed in conventional vehicles and hybrid systems with the same power rating.

4.1. Determination of the generic vehicle

When considering a full vehicle test like performed on a chassis dyno, the load for the vehicle's propulsion system is dependent on the vehicle properties like mass and driving resistances and the speed and road gradient pattern the vehicle is desired to drive.

When considering an engine test as regulated in gtr No.4 for engines installed in conventional vehicles, the engine load purely depends on the capabilities of the respective test engine. Specifically, it depends on the shape of its full load curve but in general the engine power defines the load to be applied for the engine certification or type approval test.

Since it was agreed that conventional and hybrid engine testing shall be aligned in order to get comparable emission results, it seems only reasonable to align the load demands for both test scenarios and demand the same system load from both, the engine installed in a conventional vehicle and the hybrid system installed in a hybrid vehicle. Because of the need to reflect an entire vehicle test for hybrid vehicles and the fixedly predefined WHVC vehicle speed pattern the remaining load defining parameters are the vehicle properties. As the load for conventional engines increases with the power rating of the engine, also the vehicle parameters need to increase the load for hybrid systems with increasing hybrid power, basically reflecting heavier vehicles for higher powered drivetrains. Therefore it was agreed in the 15th meeting of the HDH informal group [10] to make the generic vehicle parameters [11] a function of the hybrid system's power rating in accordance with equations (1) to (6). This offers the key possibility to align the system demands for conventional and hybrid engine testing as also further described and referred to in chapter 5 and 6.

$$m_{test} = 15.1 * P_{rated}^{1.31} \qquad (1)$$

$$\begin{array}{ll} for\ m_{vehicle} \le 35240\ kg & m_{curb} = -7.38 * 10^{-6} * m_{test}^{2} + 0.604 * m_{test} \\ for\ m_{vehicle} > 35240\ kg & m_{curb} = 12120 \end{array} \qquad (2)$$

$$for\ any\ m_{vehicle} \qquad c_d = \frac{(0.00299 * A - 0.000832) * 2 * g * 3.6^2}{\rho * A} \qquad (3)$$

$$\begin{array}{ll} for\ m_{vehicle} \leq 18050\ kg & A = -1.69 * 10^{-8} * m_{test}^2 + 6.33 * 10^{-4} * m_{test} + 1.67 \\ for\ m_{vehicle} > 18050\ kg & A = 7.59 \end{array} \quad (4)$$

$$for\ any\ m_{vehicle} \qquad \mu_r = 0.00513 + \frac{17.6}{m_{test}} \quad (5)$$

$$for\ any\ m_{vehicle} \qquad k_{\theta_{rot}} = 0.07 \quad (6)$$

Where:

P_{rated}	*is the vehicle traction force, N*
m_{test}	*is the vehicle test mass in accordance with chapter 4, kg*
m_{curb}	*is the vehicle curb mass in accordance with chapter 4, kg*
$k_{\theta_{rot}}$	*is the rotational mass multiplier in accordance with chapter 4, -7% of the curb mass are considered for drivetrain inertias*
μ_r	*is the rolling resistance coefficient in accordance with chapter 4, -*
A	*is the vehicle frontal area in accordance with chapter 4, m²*
c_d	*is the vehicle air drag coefficient in accordance with chapter 4, -*
g	*is the gravitational acceleration with a fixed value of 9.80665 m/s²*
ρ	*is the air density with a fixed value of 1.17 kg/m³*

The equation describing the relation of power to vehicle mass is derived from the Japanese standard vehicle specifications. Curb mass, frontal area, drag and rolling resistance are then calculated according to the equations stated in Kokujikan No.281 [1]. Beside these parameters defining the road load, a generic tire radius and final drive ratio as a function of tire radius, transmission gear rations and characteristic engine speeds have been established to complete the generic vehicle definitions [11].

The generic vehicle definition may not be representative of each individual vehicle but due to different vehicle categories in each region (EU / US / Japan) the harmonization of vehicle categories was considered very challenging and would probably have led to different categories for each region, which would in fact have increased the complexity and certification effort.

Furthermore also the demand of similar system loads for engines installed in conventional vehicles and hybrid powertrains during the emission certification of type approval test could not fully be achieved with the introduced generic vehicle parameters. Figure 4.1 illustrates the remaining difference in work load over the respective test cycle between conventional engine testing (WHTC) and hybrid powertrain testing (WHVC) applying the generic vehicle parameters for four different power ratings exemplarily.

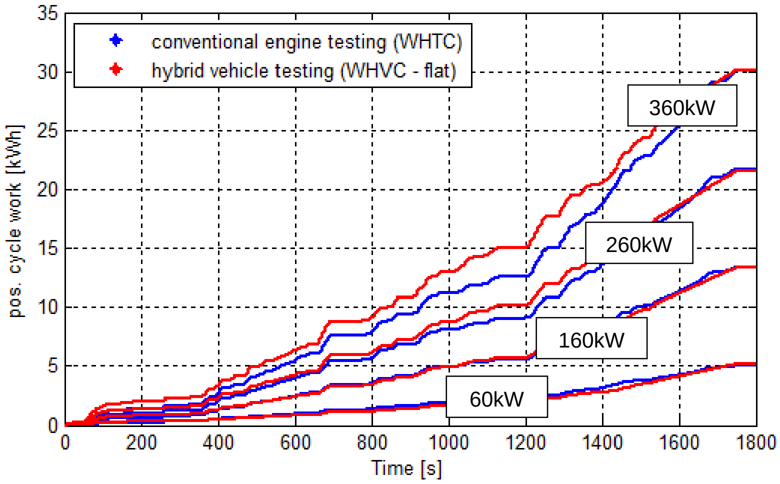


Figure 4.1 Application of generic vehicle parameters and remaining differences in cumulated work

However, since also the WHVC vehicle schedule, specifically its road gradient pattern, was developed as a function of the hybrid system rated power, the vehicle parameters do not primarily define the system load. Referring to chapter 5, the road gradient pattern is designed to further align the system load for engines installed in conventional vehicles and hybrid systems to eliminate the deviations as shown in Figure 4.1. For the proposed test procedures the interaction of generic vehicle parameters and WHVC vehicle speed profile and road gradient pattern finally defines the system load and these are designed to match up the hybrid powertrain load with the WHTC engine load for an equally powered engine of a conventional vehicle (see chapter 5). Therefore the deviation between generic and specific vehicle parameters for a test candidate has no adverse effect on the certification. Technically also one standard vehicle without power depending vehicle parameter (one fixed mass and fixed resistances) would serve the certification process since the road gradient pattern would correct the deviation between desired and actual system load due to the vehicle parameters. As explained in detail in chapter 5, the hybrid system is always loaded as it would propel the selection of representative vehicles used to define the world harmonized vehicle cycle WHVC which is at the same time the basis for the engine cycle WHTC.

4.2. Summary

Generic vehicle parameters have been introduced to cover the variety of heavy duty derivatives based on the specifications of Japanese standard vehicles.

The benefits can be summarized as follows:

a) A vehicle independent certification similar to the WHTC test schedule and engines installed in conventional vehicles can be enabled for hybrid powertrains as well. The vehicle diversity is reduced and one specific vehicle for each power rating is representatively used for the certification. This allows the manufacturer to install certified powertrains in any desired vehicle and reduces test effort.

b) The system load for hybrid vehicle testing can be aligned with conventional engine testing with reasonable effort within this amendment to gtr No.4. Deviations between actual and generic vehicle parameter have no impact on the certification procedure due to the further alignment of engine (WHTC) and vehicle (WHVC) schedule. Therefore pollutant emissions and limits of engine and vehicle test schedule are considered comparable under the premises described in chapter 6.

c) It furthermore enables a worldwide harmonization of hybrid system emission certification without the need of specific vehicle categories for each contracting party.

5. WHVC vehicle schedule

It was agreed within the Heavy Duty Hybrids (HDH) informal group that the pollutant emission type approval and certification procedure for engines installed in hybrid vehicles shall be, as far as reasonable, aligned with the test procedure specified for engines installed in conventional vehicles. This requires an alignment of the WHTC engine schedule and the WHVC vehicle schedule in terms of power and work demand since the engine schedule is not directly applicable nor reasonable for a hybrid vehicle's powertrain.

Therefore the vehicle schedule was developed with the premise that a conventional vehicle could be tested either using the engine or the vehicle schedule and both emission results would be reasonably comparable. As a matter of fact, the engine load for a given speed pattern mostly depends on the vehicle parameters (mass, rolling resistance,...) when conducting a vehicle test. Even though generic vehicle parameters were established, the power demand of WHTC and WHVC were still different and thus no comparable emission results could be expected. Directly aligning the power time curve had to be rejected, since the WHTC power pattern includes predefined sequences of gearshifts at specific times [12]. Demanding the same gearshift sequences from hybrid vehicles as used for conventional vehicles at the WHTC generation was not considered reasonable, since the gearshifts should be executed according to the real world operation and the proposed test methods for hybrids would be able to reflect those actual gearshift strategies.

Consequently this leads to an alignment of the work time curve of WHTC and WHVC where different power demand on a short time scale is possible, but the integrated power (i.e. cumulated work) matches up and ensures a similar thermal behaviour. In order to align the work demand of WHVC and WHTC, road gradients have been established in the vehicle schedule. In combination with the generic vehicle parameters (see chapter 4), the road gradients adapt the system load for a system with a specific hybrid power rating during the WHVC vehicle schedule in a way that it is equal to an engine with the same power rating running the WHTC. Additionally, it is considered that a representative amount of negative work is provided by the vehicle schedule, which is especially vital for hybrid vehicles.

5.1. Reference WHTC engine schedule

In order to align WHVC and WHTC cycle work, a normalized reference WHTC time curve needs to be available which can easily be de-normalized by using the rated power of the respective system. Common WHTC de-normalization considers the shape of the engine full load and therefore gives different results even though the rated power would be the same. Since for hybrid vehicles no full load curve is easily available nor the WHTC de-normalization would be reasonable due to speeds below engine idle speed, a reference WHTC needed to be established only depending on the rated power [12].

The most obvious assumption was to use the normalized power time curve of the original WHVC vehicle schedule which was recorded during the world-wide in-use research of heavy commercial vehicles, but additional investigations demonstrated that this was no longer representative for de-normalized WHTCs of typical engines [12]. This is mostly due to the drivetrain and gearshift model used and modifications needed during the WTHC design process. However, to cope with the situation an average WHTC was generated by de-normalizing WHTC cycles for 15 different engines and normalizing them to their rated power. The normalized power time curve so derived is representative for the power pattern of an engine at its crankshaft and was confirmed by OEMs and agreed in the Heavy Duty Hybrids (HDH) informal group of GRPE. The resulting data can be found in the respective section of the appendix.

To calculate the power pattern at the wheel hub, which is the only general valid point for comparing power demands of conventional and hybrid vehicles, the reference WHTC power pattern was lowered by considering twice a generic efficiency of 0.95 for a gearbox and a final drive of a conventional vehicle. This was agreed in the HDH informal group and provides a reference power pattern at the wheel hub which can easily be de-normalized by the rated power of any system and gives a reference cycle work and work time curve.

5.2. The basic Minicycle concept

Road gradients have been designed to adapt the power demand resulting from the WHVC speed profile and the vehicle's road load due to the generic vehicle parameters to the work time curve of the average WHTC. Their calculation is based on the re-fitting of the actual vehicle running conditions to the conditions present during the in-use measurements for the WHTC generation including their corrections during the WHTC design process. The road gradients are used to adapt the load in order to reproduce the vehicle payload and the road profile for each section of the WHTC test cycle specifically. This section shall outline the fundamentals and describe the calculation methods used.

The WHTC engine schedule was originally derived from the WHVC vehicle schedule. During in-use measurements the recorded propulsion power demand for each vehicle was normalized to its engine rated power and the data of the most representative vehicles was combined to the WHVC speed and normalized power time curve [4]. It basically consists of 12 Minicycles[1] where each Minicycle reflects a specific representative vehicle from the in-use data base. For the following figures the size of the vehicle body represents vehicle mass and the size of the driver's cab represents the respective vehicle's ICE power. The graphs in Figure 5.2 and subsequent illustrate just 5 instead of 12 Minicycles including the corresponding vehicles for a better readability.

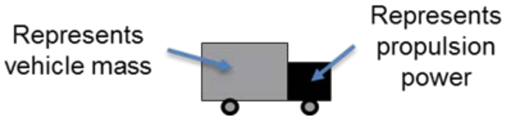


Figure 5.1 Exemplary vehicle

The upper graph in Figure 5.2 represents the conditions during the WHTC in-use measurements. Each vehicle in the upper graph has a certain mass and ICE power rating from where the specific power to mass ratio can be derived. This defines the engine load in relation to its maximum capacities when following the given speed profile. The power demands for each vehicle have been normalized to its ICE rated power to be able to combine them afterwards and establish the basic normalized WHTC power pattern. Ignoring the required WHTC de-normalization method, depending on the ICE full load curve as specified in gtr No.4 [2] for the moment, the normalized WHTC power pattern could in principle be de-normalized by the rated power of the test candidate. This is illustrated in the lower graph of Figure 5.2 for the "blue" engine as test candidate. Considering the fact, that the power to mass ratio is implied in the normalized WHTC power pattern and it will be de-normalize using the power rating of the "blue" engine only, the engine is operated as it would propel a vehicle which

---

[1] Minicycle describes a WHVC sub-section from standstill to standstill

changes payload for each Minicycle. This is also what happens during the emission certification while running the WHTC on the engine test bed and it is of course reasonable since the WHTC test cycle is supposed to cover typical engine operation representative of a large number of vehicles.

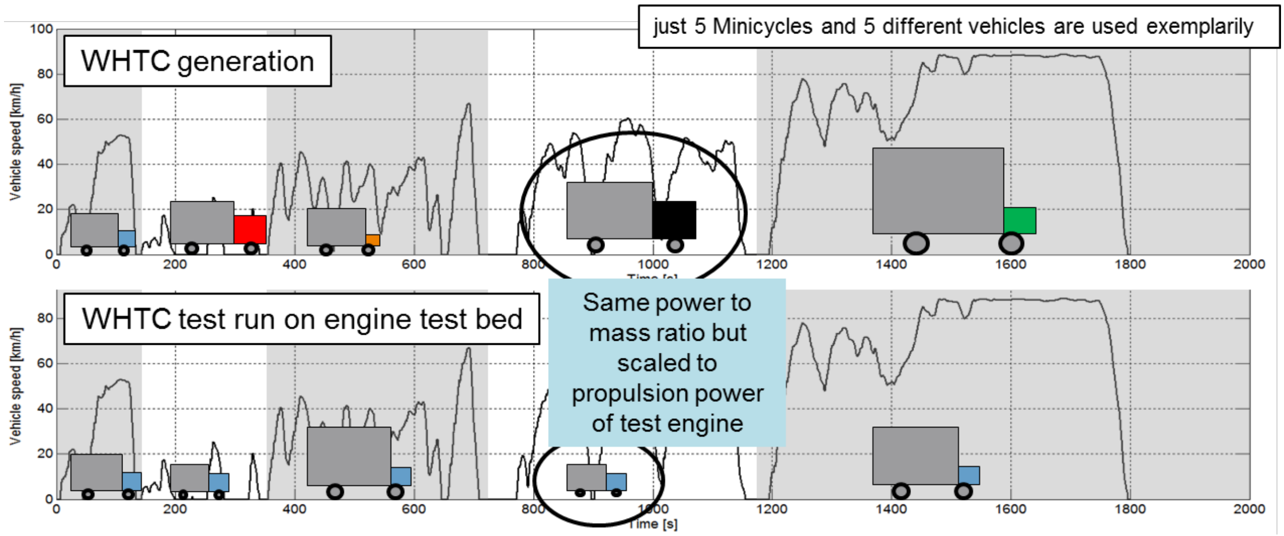


Figure 5.2 WHTC fundamentals

Since the developed test procedure for hybrid vehicles considers the entire vehicle and not only the engine, the vehicle properties are fixed for the entire test run and cannot be changed at each Minicycle. This is illustrated in the lower graph of Figure 5.3, where the vehicle with the grey body and the blue driver's cab stays constant during the entire test. In order to get the same engine load when following the WHVC speed profile, road gradients are applied to reflect the difference in payload for each Minicycle. The timestamps used to separate the WHVC into 12 Minicycles are listed in Table 5.1 below.

1	48	139	218	243	282	306	347	653	740	900	1176	1800

Table 5.1 Minicycle timestamps [s]

A more detailed example can be given for Minicycle #1 and #2:

Figure 5.3 compares engine vs. vehicle test for the one specific engine (blue). Assuming that the vehicle properties, which are defined by the generic vehicle parameters as a function of the rated power, incidentally result in the exact same vehicle configuration which was chosen to be the representative vehicle of Minicycle #1 for the WHTC generation, no adaptations are needed and one can expect, that the vehicle in the lower graph, running the WHVC, will have the same power demand as the engine in the upper graph running the WHTC. Since the vehicle parameters will stay constant during the test, the resulting difference in payload in Minicycle #2 will cause a different power demand between engine and vehicle test. For this case the engine load needs to be lowered since the vehicle would be too heavy and would demand too much propulsion power from the engine. Because removing payload and adding a negative road gradient both decreases the system load (and vice versa), the road gradients have been chosen to imitate the difference in payload as one of their tasks.

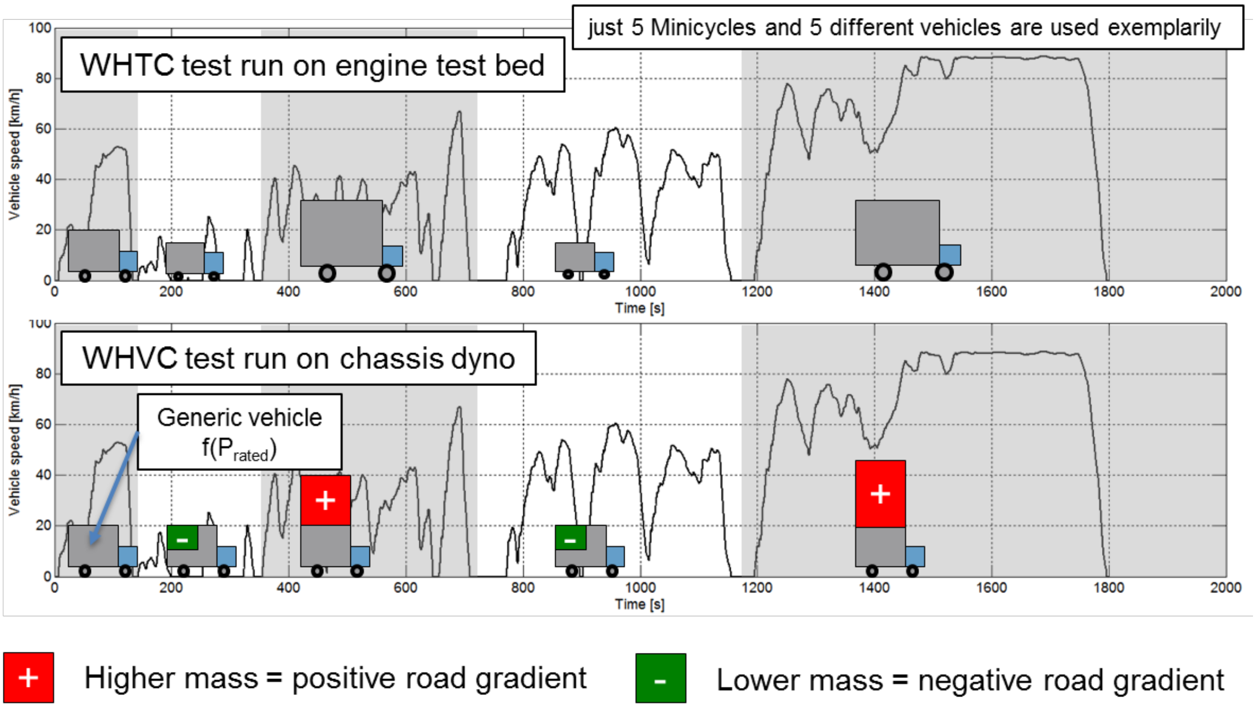


Figure 5.3 Road gradients to compensate different payloads

Following the described correlations this procedure would result in 12 different road gradients, a specific one for each Minicycle, but an adaptation has to be made during vehicle deceleration.

Beside the alignment of the positive propulsion work it is especially vital for hybrid vehicles that the developed test cycle also provides the correct amount of energy for recuperation. Considering that the road gradient represents additional (or less) payload during vehicle propulsion it needs to be adapted during deceleration. An example is given, as follows:

A positive road gradient represents a heavier vehicle which demands more propulsion power during acceleration. During braking the heavier vehicle would also be able to recuperate more energy but if the positive road gradient, which only represents the additional payload, would still be applied, the potential for energy recuperation during braking would be lowered. Contrary to vehicle propulsion, a heavier vehicle is represented by a negative road gradient during deceleration and since the value applied is representative of the payload the road gradient just needs to change its algebraic sign, as illustrated in Figure 5.4 below.

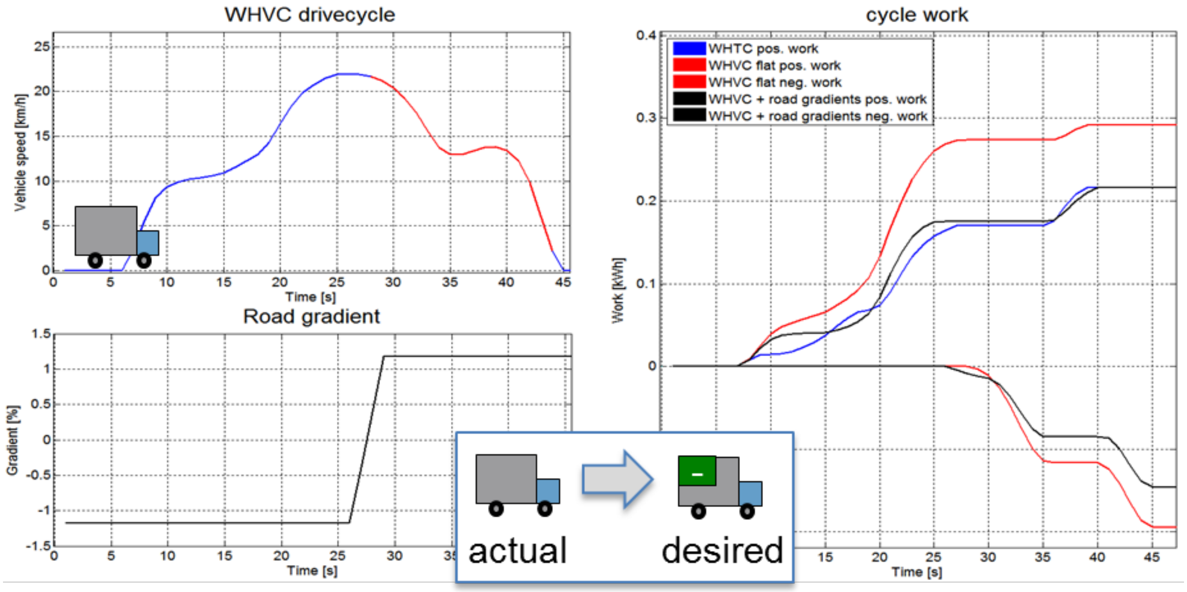


Figure 5.4 Example of inversed road gradients during deceleration

The sections where inversed road gradients need to be applied can be identified by negative or zero propulsion power demand in the reference WHTC and the WHVC. Therefore the power time curve of the reference WHTC was de-normalized using power ratings from 60 to 560kW (with increments of 20kW) and the propulsion power demand for the specific vehicles, derived from the respective power rating and the generic vehicle parameters, were calculated using the equations for vehicle longitudinal dynamics as follows:

The vehicle's average traction force for each time step on flat road is calculated as follows:

$$F_i = \left(m_{test} + m_{curb} * k_{\theta_{rot}}\right) * \left(\frac{v_{i+1} - v_i}{t_{i+1} - t_i}\right) + m_{test} * g * \mu_r + \frac{1}{2} * \rho * A * c_d * \left(\frac{v_i + v_{i+1}}{2}\right)^2 \quad (7)$$

The vehicle's average traction power for each time step on flat road is calculated as follows:

$$P_i = F_i * \left(\frac{v_i + v_{i+1}}{2}\right) \quad (8)$$

Where:

F	*is the vehicle traction force, N*
m_{test}	*is the vehicle test mass in accordance with chapter 4, kg*
m_{curb}	*is the vehicle curb mass in accordance with chapter 4, kg*
$k_{\theta_{rot}}$	*is the rotational mass multiplier in accordance with chapter 4, -*
v	*is the vehicle speed, m/s*
g	*is the gravitational acceleration with a fixed value of 9.80665 m/s²*
μ_r	*is the rolling resistance coefficient in accordance with chapter 4, -*
A	*is the vehicle frontal area in accordance with chapter 4, m²*
c_d	*is the vehicle air drag coefficient in accordance with chapter 4, -*
ρ	*is the air density with a fixed value of 1.17 kg/m³*
P	*is the vehicle propulsion power, W*

The results for each power rating/vehicle can slightly differ in specific sections but averaging them to one representative pattern does not cause an energetic impact. The averaged sections of inversed road gradients are listed in the appendix. Sections lasting shorter than or interrupted within 3 seconds are not considered or aligned in order to avoid a shaky road gradient pattern which would just harm the drivability and also has no energetic impact. While switching from a positive to a negative road gradient (and vice versa), a ramp of 3 seconds was introduced for a better applicability and driveability on the chassis dyno.

The sections of inversed road gradients during deceleration and an example of a resulting road gradient pattern is illustrated in Figure 5.5.

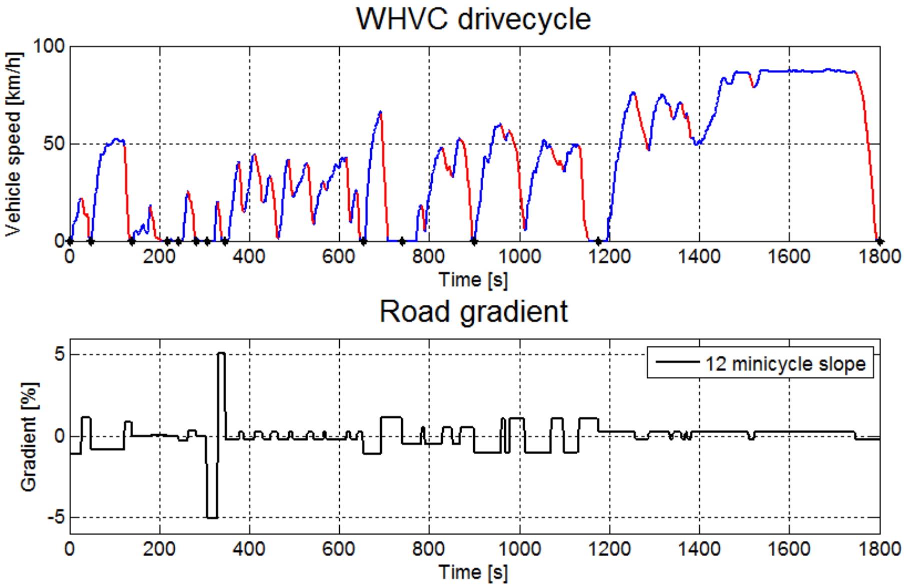


Figure 5.5 Inversed road gradients (red sections) and road gradient pattern for a 400kW, 38.7 tons vehicle

The gradients were calculated so that the positive cycle work delivered during each Minicycle in the WHVC and WHTC are equal. An exemplary result is illustrated in Figure 5.6. It indicates that already a good alignment could be achieved, the developed principle is applicable and the cycle also provides a representative amount of negative work available for energy recuperation. However, partial insufficient alignment of the work time curves remains in certain sections. This is not because the road gradient could not address the correction of payloads, which in fact works very well, but because certain sections during the WHVC speed and power profile recordings have not been driven on a flat road and in addition to the payload a real road gradient also needs to be considered when WHVC and WHTC should be aligned (see Figure 5.7).

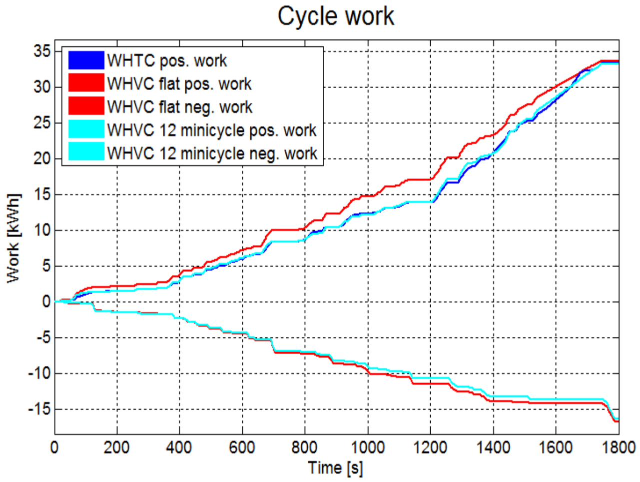


Figure 5.6 Cycle work alignment for a 400kW, 38.7 tons vehicle

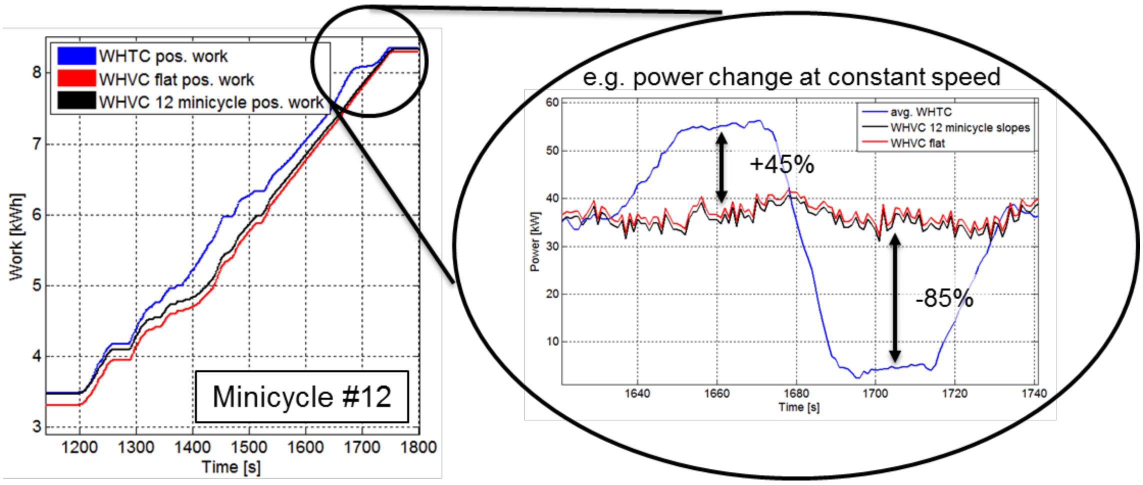


Figure 5.7 Partial insufficient work alignment using the basic Minicycle concept

To be able to consider those effects (real road gradients, head wind and variation of propulsion power in general), an alignment on a shorter time scale is needed in the respective sections where deviations occur.

5.3. The enhanced Minicycle concept

To adequately align engine and vehicle schedule, taking into account varying payloads during the vehicle cycle by the introduction of road gradients already gives satisfactory results in large sections of the cycle. However, some sections with a quite different power demand still remain unsolved. For a full alignment the introduced road gradients need to address

- the differences in payload
- and the road load fluctuations during WHTC in-use measurements, all cumulated under and considered as real road gradients.

The developed Minicycle concept therefore needs to be enhanced according to the following principal:

The basic Minicycle concept stays valid and adapts the vehicle mass by applying 12 different road gradients as described in section 5.2. In addition the real road gradients present during the WHTC in-use measurements are applied in sections where they occur. These sections can be identified by a clear difference in the work time curve of WHTC and WHVC according to the basic Minicycle concept. This is illustrated in Figure 5.8 and results in a subdivision of the respective Minicycles as listed in Table 5.2.

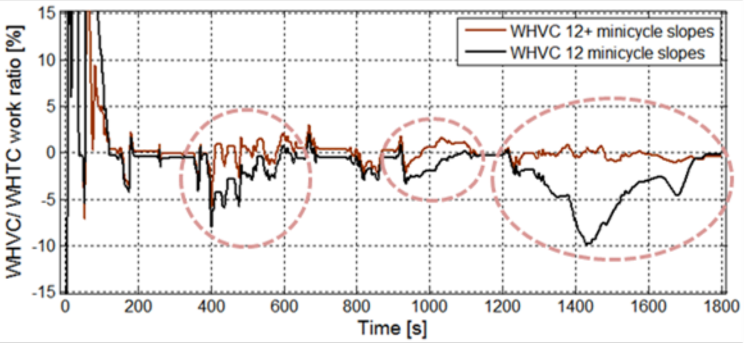


Figure 5.8 Relative positive cycle work deviation of basic and enhanced Minicycle concept vs. WHTC (high relative deviations at the beginning are caused by low absolute values)

1	48	77	139	218	243	282	306	347	388
430	464	497	544	653	740	900	1013	1176	1287
1312	1382	1430	1464	1522	1643	1681	1725	1800	

Table 5.2 Enhanced Minicycle timestamps [s]

Figure 5.9 shall illustrate the enhanced Minicycle method for Minicycle #12 exemplarily. Even though the basic Minicycle concept aligns the cycle work of WHTC and WHVC at the beginning and the end of each Minicycle almost perfectly, differences in the time curve can occur between start and end of the Minicycle. The right upper graph of Figure 5.9 illustrates the different power demands, caused by real road gradients, between WHTC and WHVC according to the basic Minicycle concept. To address those differences, the respective Minicycle is divided in sub-sections and the road gradients are adapted according to the right lower graph of Figure 5.9. This ensures a very good alignment of engine and vehicle schedule in terms of propulsion power demand but the concept of the inversed slope during deceleration needs to be revised.

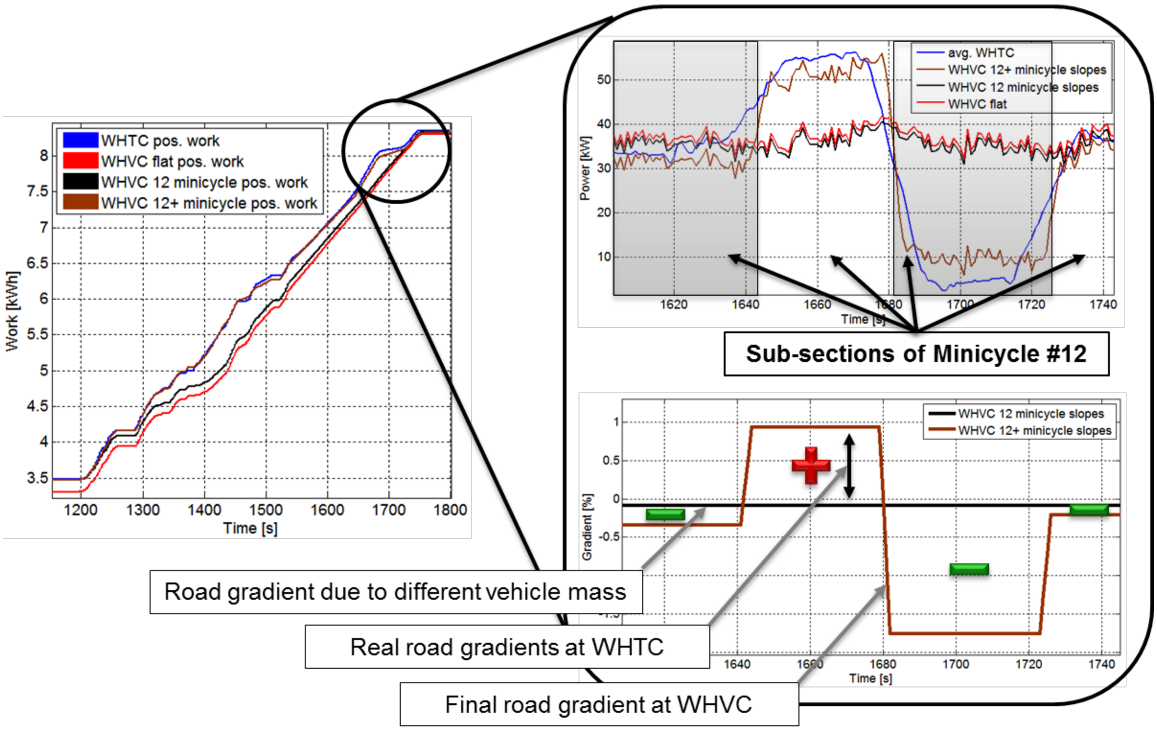
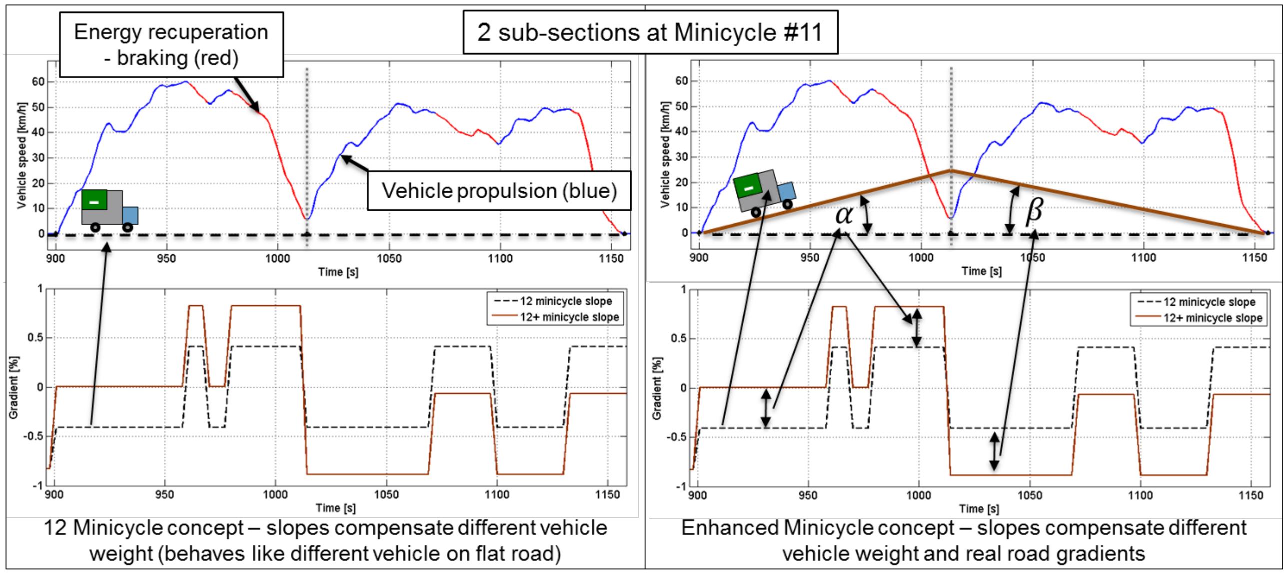


Figure 5.9 Sub-sections principle of the enhanced Minicycle concept

Since the concept of the inversed slope is only based on the imitation of vehicle payload by road gradients and the enhanced Minicycle concept now in addition implies real road gradients in the slope pattern as well, the algebraic sign cannot easily be changed during deceleration as described before and the energy available for recuperation of hybrid vehicles would be misinterpreted. The final road gradient pattern therefore needs to be calculated in a two-step approach as illustrated in Figure 5.10.

Initially the adjustments regarding the payload are made and the road gradient pattern according to the basic Minicycle concept is calculated. This is illustrated in the left graph of Figure 5.10 where no sub-sections of Minicycle #11 are considered and the dashed road gradient pattern is calculated. Since the work time curve alignment of engine and vehicle schedule is not sufficient (see Figure 5.8 at same timeslot), Minicycle #11 needs to be divided into two sub-sections. During vehicle propulsion the difference in positive power between WHTC and WHVC according to the basic Minicycle concept gives the information on the real road gradient present during the WHTC in-use measurements for each sub-section of the Minicycle (e.g. α in the 1st sub-section of Minicycle #11, right upper graph of Figure 5.10) and therefrom the new road gradient pattern can be calculated which then considers payload differences and real road gradients (brown road gradient pattern). During deceleration only the ICE’s motoring power and no braking power was recorded and therefore no information about the road condition is available. An actual calculation of the real road gradient out of the power difference is therefore not possible for these sections. Since the inversed slope concept is not applicable in sub-sections where real road gradients occurred, the assumption needs to be made and was agreed within the HDH informal group, that the road condition will not change only because the vehicle changes its driving condition from propulsion to overrun.

Consequently this results in driving conditions as illustrated in the right graph of Figure 5.10. The difference between the brown and dashed black gradient pattern during vehicle propulsion represents the real road gradient (e.g. α) for the sub-section of a Minicycle. It is superimposed to the value representing payload to imitate uphill driving but during deceleration only the slope representing payload is inversed according to the basic Minicycle concept. In addition the real road gradient is again superimposed so that the uphill driving condition also remains for the time of deceleration.



12 Minicycle concept – slopes compensate different vehicle weight (behaves like different vehicle on flat road)

Enhanced Minicycle concept – slopes compensate different vehicle weight and real road gradients

Figure 5.10 Adaptation of the inversed slope concept for the enhanced Minicycle method

The results achieved by this method demonstrated a good alignment of engine and vehicle cycle in terms of power and cycle work and also ensured that a representative amount of recuperation energy is provided by the test cycle (see Figure 5.11 exemplarily for a 430kW, 42.5 tons vehicle).

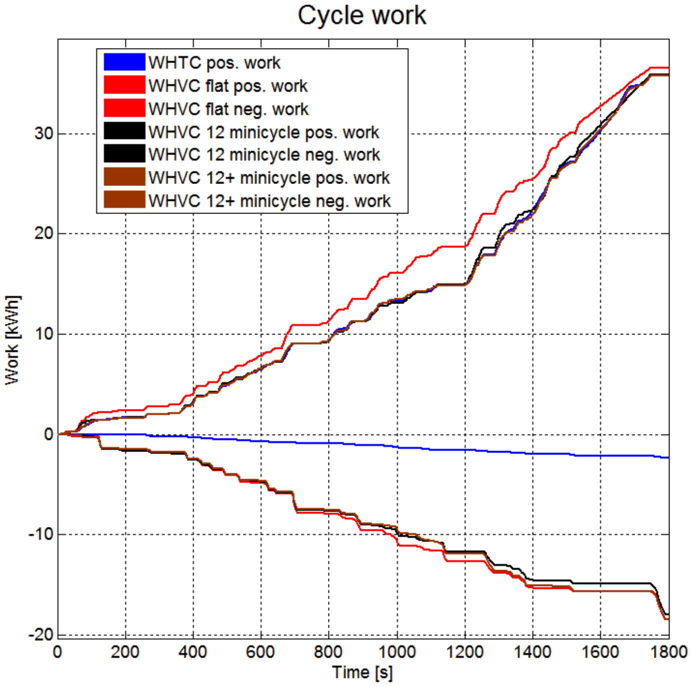


Figure 5.11 Positive cycle work alignment and representative negative work for the enhanced Minicycle method

5.4. The fixed slope approach

The calculation method described in section 5.3 demands a road gradient pattern calculation for each power rating specifically to get a good alignment of the respective WHTC and WHVC. Investigations regarding a fixed slope calculated out of an average among different power ratings needed to be rejected. In order to ease the calculation procedure, avoid the need of additional software and to ensure a practical handling for the gtr, a modified fixed slope concept was introduced. It is based on an average slope calculated from power ratings between 60 and 560kW which represents 3.5 to 60 ton vehicles according to the generic vehicle parameters. To compensate for the error in power and work alignment of different WHTCs and WHVCs when an average slope is used, a polynomial approach was developed. Since WHTC, vehicle parameters and WHVC road gradients are all dependent on the rated power the error caused by the fixed slope also does so. Introducing a 2nd order polynomial to compensate for this error enables an easy handling in the gtr without the need of additional software and without a significant loss of accuracy. The specific road gradient pattern is finally calculated as follows:

$$r_{g_i} = a_{2_i} * P_{rated}^2 + a_{1_i} * P_{rated} + a_{0_i} \qquad (9)$$

Where:

r_g	*is the actual road gradient, %*
a_0	*is the polynomial coefficient representing the averaged fixed slope pattern, %*
a_1, a_2	*are the polynomial coefficients for error compensation, %/kW², %/kW*
P_{rated}	*is the system rated power, kW*

The left graph of Figure 5.12 illustrates various specific road gradient patterns and the averaged fixed slope. The right graph shows the deviation between individual and fixed slope which is different for each power rating and compensated by the polynomial coefficients a_2 and a_1 of equation (9). The specific values can be found in Annex 1(b) of gtr No.4 [3].

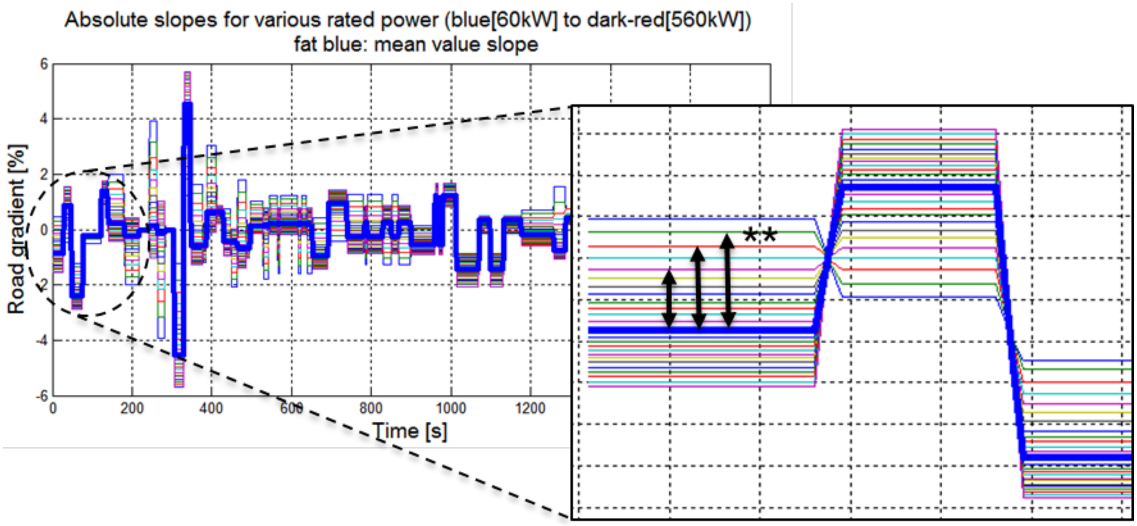


Figure 5.12 Fixed road gradient pattern and polynomial approach for error compensation

5.5. Summary and verification by actual test data

The introduction of generic vehicle parameters makes a vehicle independent certification possible, like it is done for engines installed in conventional vehicles. The required alignment of engine and vehicle schedule in terms of power and work could be achieved by the introduction of road gradients according to the enhanced Minicycle method and ensures very similar system loads for both test methods. An easy handling of the WHVC test schedule in the gtr could be achieved by the introduction of a fixed slope and a polynomial approach for an error compensation without the need of additional software.

Figure 5.13 shows actual chassis dyno measurement data recorded during the development of the WHVC vehicle schedule, with and without road gradients applied and underlines the applicability of the chosen method exemplarily for the VOLVO 7700 HYBRID tested in VTP2. Good results and a successful HiLS model verification using the final vehicle schedule as specified in Annex 1(b) of gtr No.4 [3] could also be achieved for the IVECO Eurocargo 120EL18. Even though the method was also very well applicable for the MAN Lion´s City Hybrid a mismatch of desired and delivered cycle work arises in sections where the vehicle is not able to follow the desired WHVC speed profile. The resulting consequences are described in section 5.6.

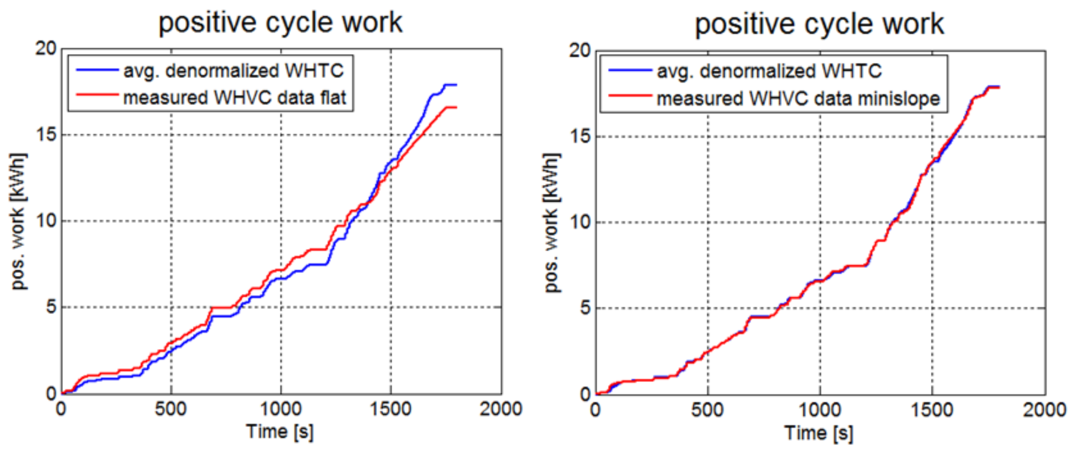


Figure 5.13 Wheel hub work of actual CD test data for flat and enhanced Minicycle WHVC

Since the work alignment of engine and vehicle schedule was proved to be satisfying, a comparison regarding final pollutant emissions for a conventional vehicle running the engine and the vehicle schedule was discussed in the HDH informal group as well. Even though the cycle work to be delivered by both test methods is very similar, the vehicle schedule allows to run the engine at any operation point (speed, torque) which can provide the actually demanded power. The engine schedule on the other hand directly specifies the specific speed and torque levels during the cycle at any time. Depending on the engine and after treatment system technology and the sensitivity of emissions on the specific engine operation, the final emissions can therefore differ between both test methods. However, since the certification of vehicles using the vehicle schedule implies the actual gear shift strategy to be used for the test, it will give emission test results more representative of in-use operation even though the specific engine operation profile cannot be predefined.

To nevertheless prove the comparability of engine and vehicle cycle also in terms of pollutant emissions, both tests would in a first instance need to be performed on the basis of a conventional vehicle. To exactly derive the WHTC engine operation from the engine when running the WHVC vehicle schedule with road gradients, which would then consequently produce the same emissions, the vehicle running the vehicle schedule would need to have the same gearbox and the same gearshift strategy as used for the WTHC generation. Since road gradients already align the power between vehicle and engine cycle the gearbox and the gearshift pattern would finally ensure the similar engine operation as well. However, it is virtually impossible to get such an actual vehicle (8-speed gearbox with predefined gear ratios and a defined final drive ratio) for a chassis dyno test and thus the check can only be performed using a conventional vehicle simulation model which uses the same gearbox model and applies the same gearshift strategy as used for the WHTC generation. Figure 5.14 shows the resulting engine operation for a 330kW test engine running the WHTC cycle denormalized for this specific engine and the engine cycle derived from the WHVC vehicle schedule for a conventional vehicle using the generic vehicle parameters, the engine's rated power and the WHVC vehicle schedule as specified in Annex 1b of gtr No.4 [3]. The gearbox model and gearshift strategy was therefore remodelled following the provisions of the 2nd interim report of the Development of a World-wide Heavy-Duty Engine Test Cycle [13] as detailed as possible. Slight implementation differences can occur since the description of the gearshift strategy in the report is not entirely clear. Nevertheless the result demonstrates the similarity of both test cycles and methods satisfactorily.

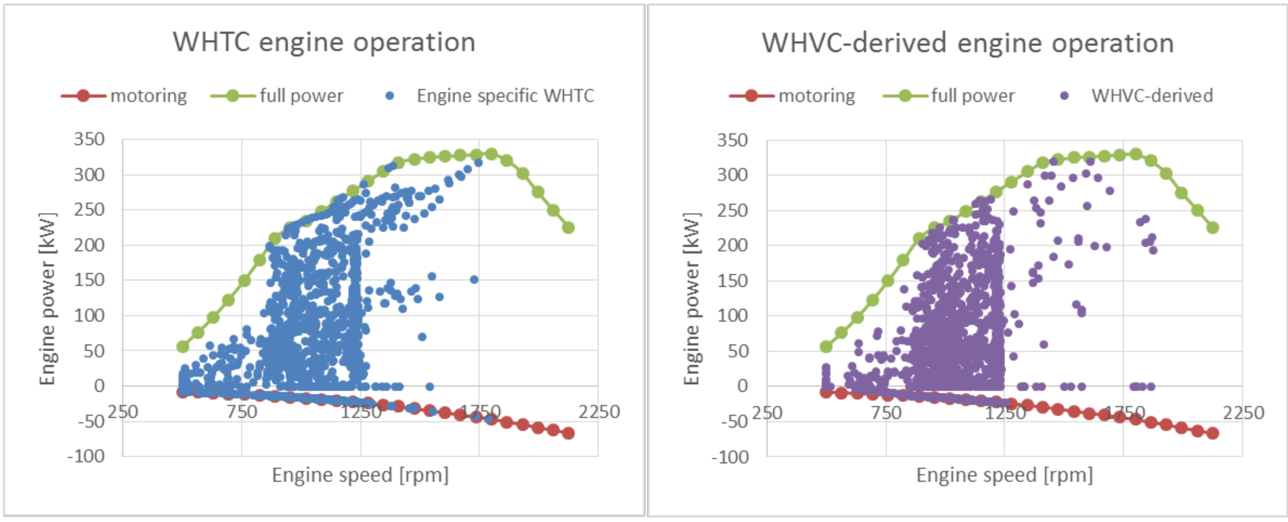


Figure 5.14 WHTC and WHVC-derived engine operation for a 330kW test engine/vehicle

Figure 5.15 in addition shows the cumulative frequency distribution of engine speed and load.

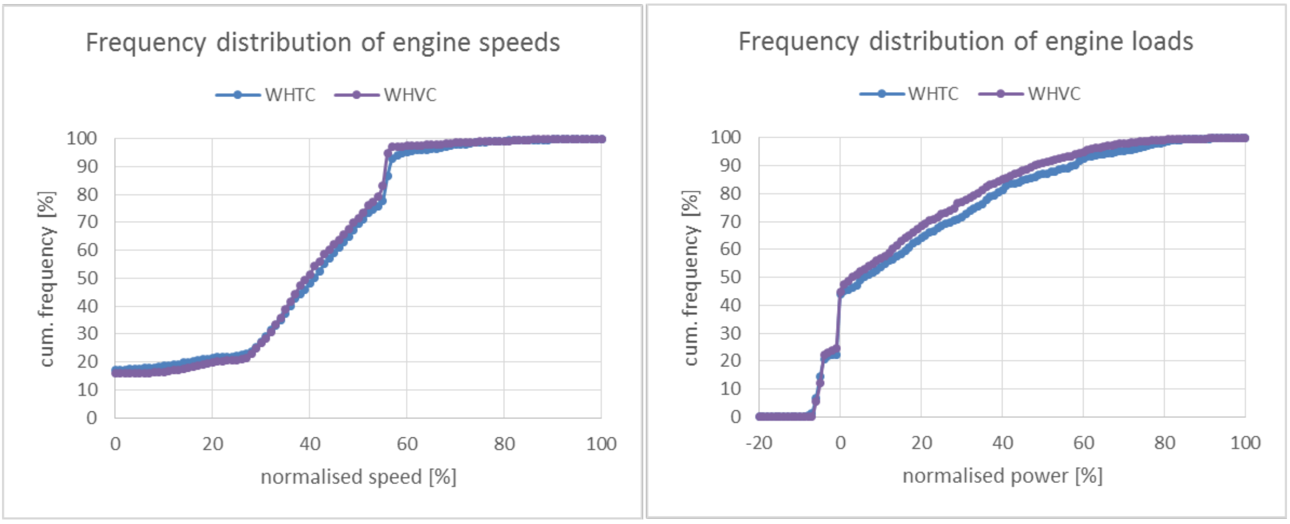


Figure 5.15 330kW test engine's frequency distribution of engine speed and load for WHTC and WHVC

Both figures illustrate that the developed vehicle schedule is, beside the alignment with the WHTC cycle work, also expected to deliver a quite similar engine operation pattern if a conventional vehicle would be tested on a chassis dyno and the WHTC-like gearshift strategy would be applied. Nevertheless, slight deviations in the engine operating points occur and are caused either by a different WHVC power demand (road gradients cannot align the power demand for each 1 Hz sample exactly) or an inaccuracy of the remodelled gearshift strategy.

To determine possible deviations caused by the re-modeled WHTC gearshift strategy the 330kW example engine's specific WHTC power time trace was used for a closed loop recalculation of the engine operating points, instead of the propulsion power derived from the WHVC speed and road gradient pattern and the vehicle parameters for a 330kW vehicle using vehicle longitudinal dynamics. Using the WHVC vehicle speed and the WHTC power time trace the provisions for selecting the gears and thus deriving the engine operation points were applied again. The result of the calculation process is expected to be the same as the input, which can be proved in Figure 5.16 and Figure 5.17 and therefore also proves the applicability of the re-modeled gear shift strategy sufficiently.

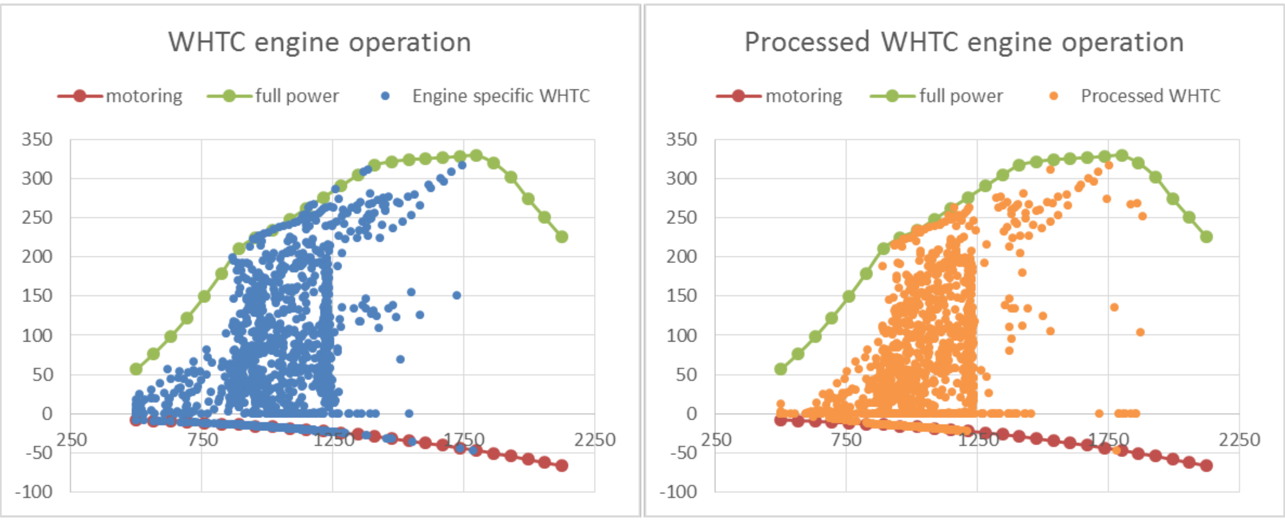


Figure 5.16 Closed loop test of the re-modeled WHTC gearshift strategy (a)

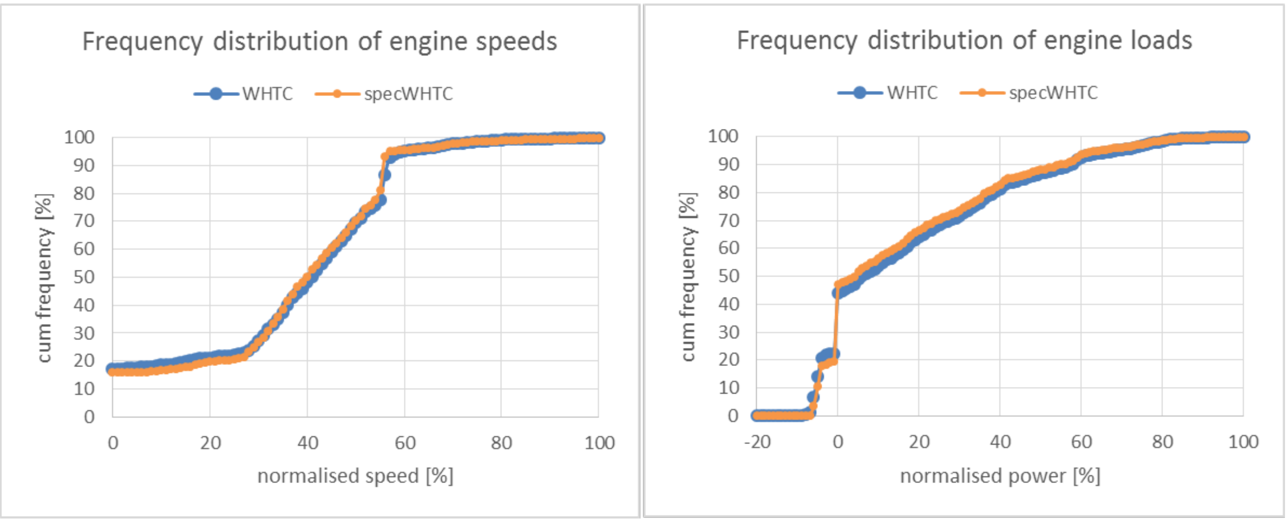


Figure 5.17 Closed loop test of the re-modeled WHTC gearshift strategy (b)

Single operation points in Figure 5.16 are still different and indicate that the re-modeled gear shift strategy can probably not fully depict the original behaviour but no further documentation is available in the WHTC reports and the results are considered as sufficient.

As a final conclusion the newly developed vehicle schedule can be expected to deliver similar emission results to the corresponding WHTC and the slight deviation in engine operation is mostly caused by slightly different propulsion power demand between WHTC and WHVC for less than a few seconds, which cannot be adjusted by the developed road gradients. However, since the HiLS test method anyway demands the vehicle’s actual gearshift strategy to be applied and thus enables a free engine operation for a predefined power demand, this is not a stringent criteria for an assessment.

5.6. Restrictions and clarification

Even though the developed WHVC vehicle schedule with road gradients was tested during VTP2 with three different vehicles on the chassis dyno, some boundaries need to be considered or should at least be mentioned here for clarification.

5.6.1. Mismatch of calculated and measured cycle work on the chassis dyno

Since the road gradient calculation is based on the power difference of engine and vehicle schedule and the power time curve of the vehicle schedule is calculated using vehicle longitudinal dynamics, it is especially vital for a good alignment of engine and vehicle cycle that the calculation of propulsion power is representative and gives similar results to the propulsion power actually measured on the chassis dyno for each vehicle. To ensure this the main focus will most likely need to be laid on the accuracy of the vehicle setup on the chassis dyno but also on the allowable deviations in vehicle speed during driving and the assumption that the rotational inertias of a powertrain are approximately 7% of the curb mass needs to be considered. All these issues can cause a mismatch of calculated and actually measured propulsion power. Since the figure for the rotational inertias was derived from average conventional vehicles it might not be representative for each vehicle specifically, either conventional or hybrids. In case there is a high deviation between assumed and actual rotational inertia, the actually driven vehicle speed differs quite a lot from the desired one or the chassis dyno is not capable of applying the desired road loads accurately enough, the work and power alignment of engine and vehicle schedule will be less accurate when using the calculated road gradient pattern as specified in in Annex 1(b) of gtr No.4 [3]. Consequently this can lead to a value for the actually measured cycle work on the rollers that is different from the desired one.

However, since the measurements on the chassis dyno are only executed to validate a HiLS model it does not directly have an impact on, nor it is harmful for the final powertrain emission certification result. The model in any case needs to be parameterized according to the actual running conditions of the vehicle on the chassis dyno to pass the HiLS model verification. Even though this can lead to a situation where the actually measured data on the chassis dyno and the HiLS model data differ from the desired cycle work, for the verification the only crucial point is, that the model represents the behaviour of the vehicle according to the criteria specified in gtr No.4 [3]. Since for the emission certification the model parameter are anyway changed to the same generic values (e.g. rotational inertia of the drivetrain is set to 7% of curb mass,…) which have been used to calculate the road gradient pattern and the HiLS model applies the road load precisely, the loop is closed and the only uncertainty which could cause a difference between delivered (generic vehicle parameter, WHVC + road gradients) and demanded (reference WHTC) cycle work remains for the vehicle speed. However, also the speed is specified to be within a +/- 2 km/h tolerance for the certification and therefrom also no major impacts on the cycle work alignment can be expected as long as the vehicle is able to follow the WHVC speed profile.

5.6.2. Vehicles not capable of running the desired WHVC speed profile

As already indicated in subsection 5.6.1, the alignment of engine and vehicle schedule works quite well as long as the specific vehicle on the dyno, but more importantly in the HiLS model, is able to follow the desired WHVC speed profile. Especially city buses, as the MAN Lion´s City Hybrid tested during the VTP2, are often equipped with vehicle speed limiters or are by design not able to exceed velocities higher than demanded for inner-city operation. In large sections of the test cycle this is not an issue at all but since the WHVC also consists of a motorway part with speeds up to ~88 km/h this can cause deviations and consequently this results in differences between conventional engine and hybrid vehicle certification in terms of cycle work.

Figure 5.18 illustrates the work time curve as it could look like for the MAN Lion´s City Hybrid with an assumed speed limit of 65 km/h. Since the vehicle is not able to follow the desired WHVC speed profile in the motorway part and the road load is lower when running 65 km/h instead of ~88 km/h, the vehicle needs to produce less power for propulsion and thus generates less work at the wheel hubs during the last part of the cycle. Driving on a lower power level usually demands less fuel and would then also most likely release less mass emissions of pollutants (motorway part related issues for serial hybrid concepts will be treated in chapter 6 separately). On the other hand nearly the same amount of energy is available for recuperation, since the considered last part of the cycle mainly consists of driving at constant speed and only of short periods of decelerations. Thus the total propulsion work over the whole cycle would be significantly lowered, whereas the recuperated energy would nearly stay the same, which would give an advantageous ratio of positive to negative work and would allow more recuperated energy to be used. Just considering these aspects it could result in an advantage for vehicles not able to follow the WHVC speed profile, but since the system work was agreed to be used for the specific emission calculation this value is also lowered and probably levels out the advantages. A detailed case study on possible emission impacts was not performed during VTP2 but especially systems which do not fully warm up during a cold start run of the test cycle might have slight disadvantages when less power is demanded to warm up their propulsion and after treatment systems. This could probably cause higher emissions for the cold cycle and the subsequent warm cycle run.

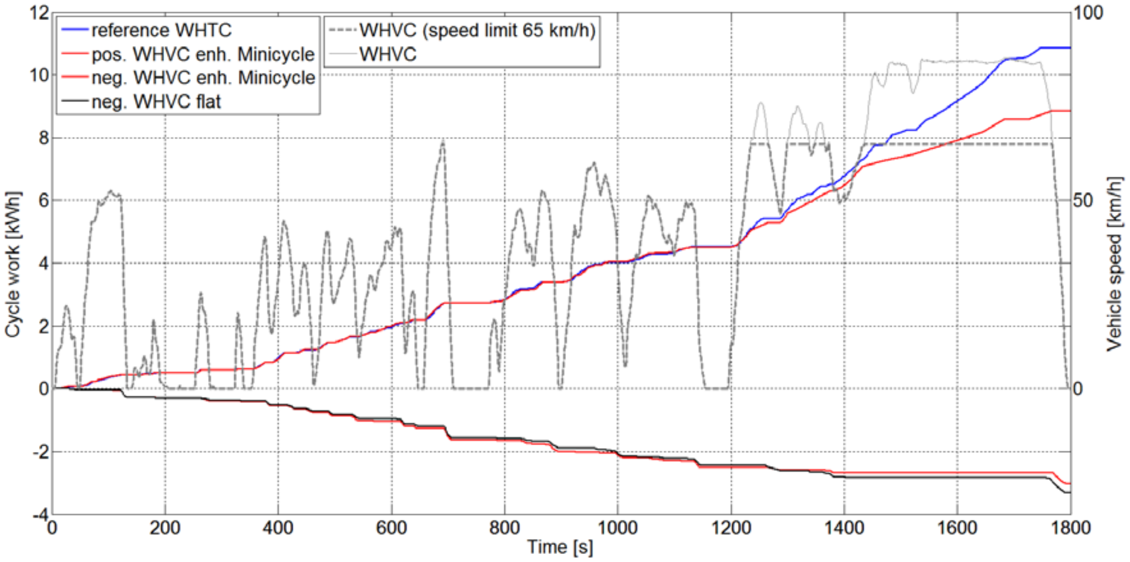


Figure 5.18 MAN Lion´s City Hybrid example data with assumed speed limit of 65 km/h

A proposed method to align WHTC and WHVC cycle work, even though a vehicle has a speed limitation lower than ~88 km/h, was discussed in the HDH informal group. Figure 5.19 illustrates an adapted road gradient pattern for the MAN Lion´s City Hybrid example given in Figure 5.18 to ensure that the reference WHTC work will be delivered over the cycle. In order to increase the system load when running 65 km/h instead of ~88 km/h the road gradient in principal needs to be increased in the motorway part. This approach was also tested and actual chassis dyno measurements have been performed during VTP2. However, since the vehicle is designed for inner-city operation and not really capable of running uphill quite steep at maximum speed over a couple of hundred seconds the system tended to overheat, vehicle system protection functions kicked in and the behaviour did not give a representative on-road vehicle operation. Apart from this disadvantage and the fact that for a special consideration of vehicles with speed limitations in the WHVC vehicle schedule then a calculation software would probably be necessary, it was agreed within the HDH informal group that no special consideration would take place. Instead, the test candidate needs to have the accelerator pedal fully pressed in sections where it is not capable of following the WHVC vehicle schedule.

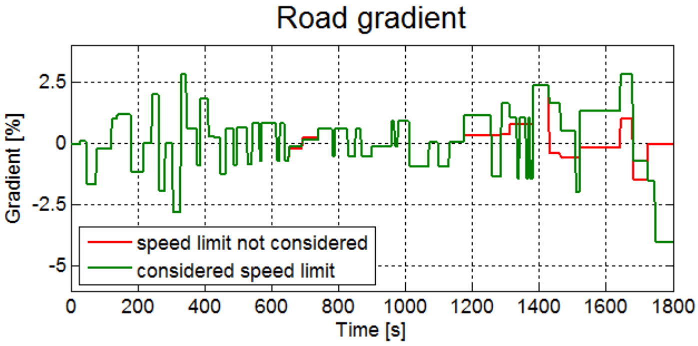


Figure 5.19 Adapted road gradients for the MAN Lion´s City Hybrid with 65 km/h speed limit

5.6.3. WHVC vehicle schedule and vehicle independent hybrid powertrain certification

The introduction of generic vehicle parameters in combination with the developed WHVC vehicle schedule allows a vehicle independent powertrain certification for hybrid powertrains as it is done for engines installed in conventional vehicles. However, the power consumption of the WHTC is based on conventional vehicle data which is representative of in-use operation of conventional vehicles. The WHVC vehicle schedule for hybrid vehicles now also imitates this power consumption to ensure an alignment of both test methods. If the specific vehicle properties, especially the power to mass ratio of a specific hybrid vehicle, are very different to a conventional vehicle, the emission certification test may not be deemed to be accurately representative of the in-use operation of the specific hybrid vehicle but this also occurs when conventional engines are operated differently to the engine test cycle during in-use operation. Following a vehicle independent certification approach a more in-use representative testing is thus hardly possible and the question of test cycle representativeness of each specific case will always remain. Since hybrids are more likely designed or at least adapted for specific operation patterns to improve performance and fuel savings, they are probably more sensitive to different test scenarios and their in-use operation and emission behaviour is probably harder to depict using just one average power demand like the WHTC or the WHVC combined with a vehicle independent certification approach. But generating engine test cycles more representative of in-use operation and emission behaviour of specific hybrid vehicles would consequently require the definition of specific vehicle test cycles and not allow a vehicle independent certification any more.

5.6.4. General chassis dyno applicability

The applicability of the developed WHVC vehicle schedule on the chassis dyno was tested during VTP2 using 3 different vehicles. Two of them were buses with a propulsion power between 130 and 190kW and one of them was a small delivery truck with a similar power rating. Even though the test results have been quite positive the test candidates represent just a small group of heavy duty vehicles and the impacts on more powerful, heavier and thus more sluggish vehicles could not be tested.

6. System work concept

Emission limits for engines installed in conventional heavy duty vehicles are defined in emissions per kilowatt hours work delivered. This is a convenient metric, since only one energy converter for propulsion of the vehicle is installed, i.e. the internal combustion engine, and the work delivered by the engine over the duty cycle can easily be calculated from speed and torque values directly measured on the engine test bed.

As explained in chapter 5, the basis for the development of the hybrid load cycle for a vehicle as a combination of vehicle speed, vehicle parameters and road gradients was that the propulsion power demand of the resulting load cycle is very close to the demand of the WHTC engine cycle with the same power rating. However, hybrid vehicles can provide the necessary propulsion power by two (or more) separate energy converters. A fraction of this propulsion energy can be recuperated by a hybrid vehicle by storing energy during decelerations of the vehicle. In order to be in line with testing of engines used in conventional heavy duty vehicles where the engine work equals the vehicle propulsion work, also for heavy duty hybrid vehicles the work for propelling the vehicle over the duty cycle and not only the engine work was agreed to be considered within the Heavy Duty Hybrids (HDH) informal group of GRPE. This propulsion work delivered by the hybrid system over the duty cycle shall be used as basis for calculating the emission values, since this approach allows a fair comparison between conventional and hybrid powertrains. It is referred to as system work.

From an environmental point of view the consideration of the system work as basis for the specific emission calculation can be argued as follows:

For a conventional vehicle when driven on a specific route a certain amount of propulsion work will need to be delivered by the vehicle’s combustion engine. It produces emissions in relation to the work the ICE delivers. For a specific route, specific mass emissions released to the environment are the result. If the same route is driven with a hybrid vehicle which has the very same vehicle parameters (mass, rolling resistance, etc.) the same propulsion work will be needed to run the same vehicle speeds. Unlike the conventional vehicle, the hybrid is able to recuperate energy and use it for propulsion again. This consequently lowers the work the ICE has to deliver and thus the mass emissions released to the environment for the same route would be reduced, which can be compared with stricter emission limit values for conventional vehicles. To allow the hybrid vehicle to emit the same mass emissions as a conventional vehicle the system work is used as a calculation reference. Finally this allows higher engine brake specific ICE emissions as for engines installed in conventional vehicles but nevertheless the system work concept does not lead to a negative environmental impact since the mass emissions for the specific route will stay the same for hybrids and conventional vehicles. It furthermore enables the equal treatment of hybrids and conventional vehicles and may open ways to further reduce fuel consumption by operating the ICE at higher engine brake specific emissions.

6.1. System work determination

Since there is no universal reference point for the determination of the propulsion power similar to the crankshaft of a conventional engine that is valid for all different layouts of hybrid systems, the wheel hub was defined as the common reference point. Figure 6.1 illustrates the effects of different reference points for work determination exemplarily for a parallel hybrid vehicle. In order to run the WHVC vehicle schedule, a certain propulsion work will need to be delivered at the wheel hub. Considering the efficiencies in the drivetrain the work upstream the wheel will differ and the work to be used for emission calculation would need to be determined for each hybrid layout separately. The lower it is the higher the specific emissions would be for the very same vehicle cycle. Since a case by case decision is not desirable for a gtr the only common reference point valid for all type of hybrids was agreed to be the wheel hub.

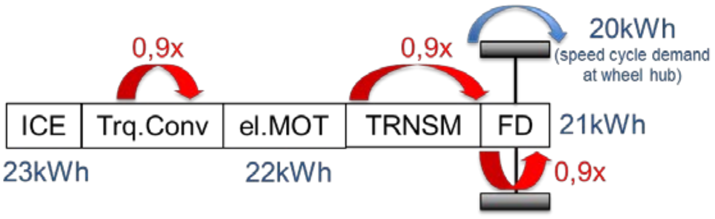


Figure 6.1 Different propulsion work demand depending on system layout and point of determination (efficiency values are just examples)

To be coherent with testing of engines installed in conventional heavy duty vehicles, where the propulsion power and work for emission calculation is directly measured at the engine's crankshaft, some adaptations have to be made. The fair evaluation of emissions among all type of vehicles (conventional and various hybrid vehicles) would consequently require the reference point for propulsion work determination to be at the wheel hub for all of them. Since conventional engine testing according to gtr No.4 [2] and the respective emission limit values are already in place in national legislation of some member countries and will not be changed, the hybrid regulation has to take that into account. Instead of referencing the emissions for conventional engines to the work at the wheel hub to have them comparable to hybrid vehicles, the emissions of hybrid vehicles are referenced to a virtual combustion engine independent of their layout as follows.

Figure 6.2 illustrates a conventional vehicle and should serve to compare engine and vehicle testing exemplarily. It also illustrates the consequences of different work determination used for the specific emission calculation. Running the WHTC engine schedule for this example on the test bed only would demand 30kWh at the ICE crankshaft. If this engine would be mounted in a conventional vehicle's drivetrain as illustrated in Figure 6.2 and the engine would run the same cycle, it would result in less work at the wheel hub due to the efficiency losses in the drivetrain. When aligning engine and vehicle cycle it needs to be considered, that less work at the wheel hub will be demanded by the vehicle schedule in order to get the same engine work for engine and vehicle testing. For the development of the WHVC vehicle schedule an efficiency of 0.95 was considered twice, for the gearbox and the final drive, to get the reference work at the wheel hub. Since the WHTC engine cycle is based on in-use measurements of conventional vehicles the consideration of a gearbox and final drive efficiency is reasonable and the value of 0.95 will not have an influence as it will be outlined later. Running the vehicle schedule for this example would demand 27kWh at the wheel hub but the engine would have to deliver 30kWh at the crankshaft and would also produce emissions according to the 30kWh work delivered. So directly using the wheel hub work for specific emission calculation would cause a higher burden when using the vehicle cycle. Therefore the wheel hub work has to be corrected using the same generic efficiencies of 0.95 for gearbox and final drive as used for the WHVC vehicle schedule calculation to get the same specific emissions for engine and vehicle testing.

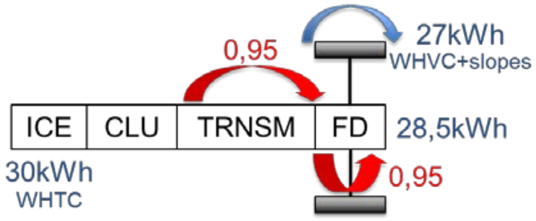


Figure 6.2 Conventional vehicle example

The system work used for calculating the specific emissions is therefore determined as follows:

$$W_{Sys} = \frac{W_{WheelHub}}{0.95^2} \qquad (10)$$

This ensures, that the same reference work is used for the specific emission calculation for engine and vehicle testing. Since the efficiencies of 0.95 are used to calculate the vehicle schedule based on the engine schedule downstream towards the wheel hub and the work at the wheel hub is corrected upstream using the very same efficiencies, their specific values do not have any influence because they cancel out each other. To avoid miss adjustments in demanded power levels the values were only chosen to be reasonably representative.

To ensure a fair comparison of conventional and hybrid vehicles, the same concept as explained for a conventional vehicle above needs to be applied for hybrids as well and independent of the actual hybrid layout the work delivered at the wheel hub during the vehicle schedule will need to be transferred to a virtual combustion engine according to equation (10) also. Considering hybrids as virtual conventional vehicles allows the alignment in specific emission calculation and in fact this is exactly as if the wheel hub work was used for specific emission calculation of engines installed in conventional vehicles tested with the engine schedule which is due to actual legislation not considered as direct possibility.

6.2. System work application for HiLS and powertrain testing

For the HiLS method as specified in Annex 9 of gtr No.4 [3], the propulsion power at the wheel hub is a standard output of the simulation model where the work at the wheel hub can be calculated from directly. The work finally has to be converted to the virtual engine crankshaft reference point by dividing it by the two generic efficiencies according to equation (10). For the specific emission calculation this value is furthermore corrected if deviations between the reference engine work over the HEC duty cycle from the HiL simulation output and the actual engine work measured on the engine test bed running the HEC cycle occur. If the engine provides less work over the duty cycle on the engine test bed, also the system work value for the specific emission calculation will be lowered to take the lower absolute emissions released by the ICE due to less delivered work into account. A linear correlation is used as follows:

$$W_{Sys} = \frac{W_{WheelHub}}{0.95^2} * \frac{W_{act}}{W_{HEC}} \qquad (11)$$

Where:

W_{Sys}	*is the system work used for specific emission calculation, kWh*
$W_{WheelHub}$	*is the HiLS model output for the wheel hub work, kWh*
W_{act}	*is the engine work measured on the engine test bed running the HEC, kWh*
W_{HEC}	*is the HiLS model output for the hybrid engine cycle work, kWh*

For the powertrain method as specified in Annex 10 of gtr No.4 [3], a chassis model at least has to be part of the test setup and the propulsion power at the wheel hub can be directly derived from there as well. The same method as for the HiLS procedure has to be applied and the value derived has to be converted to the virtual engine crankshaft point by dividing it by the two generic efficiencies in accordance with equation (10) as well. The system work derived by the powertrain method does not need any further correction (as opposed to the HiLS method), since in this case the engine is directly driven over the duty cycle with the whole hybrid system installed on the test bed and there is no additional step in between where a simulation output is used as a reference input cycle for the engine test bed.

6.3. Summary

The developed concept ensures a fair comparison of conventional and hybrid vehicles in terms of criteria pollutant emissions as it was requested by the HDH informal working group. Its concept and calculation principles are directly linked to the developed WHVC vehicle schedule described in chapter 5 and the determination of the rated power in chapter 7. The efficiency values used for correcting the work at the wheel hub shall therefore not be changed.

Since the developed vehicle test procedure is deemed to deliver similar results for conventional vehicles as the engine test procedure for the respective engine, the existing emission limit values should also be considered as valid and should allow a comparison of emissions between conventional engines and hybrid powertrains of a similar power rating used to propel the same vehicle.

However, as recognized in VTP2, drawbacks for specific vehicle configurations can result when a vehicle test, using the developed WHVC vehicle schedule in combination with the system work concept is applied. Even though this can lead to disadvantages compared to conventional engine testing for specific hybrid vehicle layouts in terms of pollutant emission certification, it nevertheless reflects the impact on the environment correctly as outlined in section 6.4.

6.4. Restrictions and clarification

As recognized in VTP2, the underlying system work concept may lead to disadvantages concerning emissions for some hybrid vehicles which are primarily designed for urban mission profiles. Due to the reference vehicle speed cycle WHVC, which represents an average worldwide mission profile of heavy duty vehicles, also the vehicles with urban mission profiles are forced to run at ~88 km/h (or at least their maximum design speed) during the last part of the test cycle. Especially for serial hybrid vehicles which are designed for stop and go operation at lower speeds and not for constant high speed driving, this causes quite high emissions during this part of the cycle.

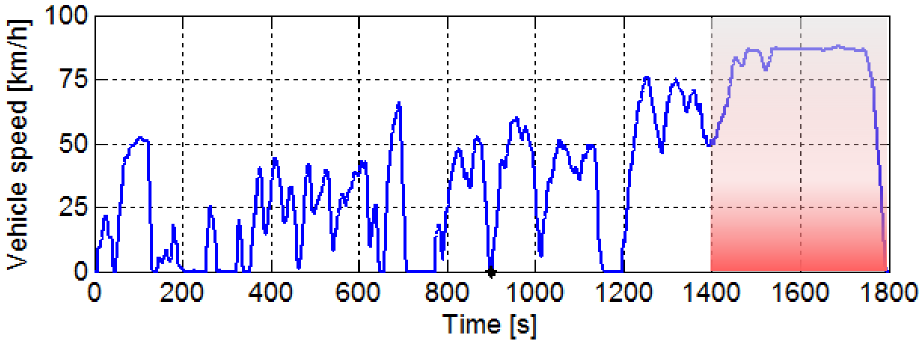


Figure 6.3 World harmonized vehicle cycle WHVC

The higher emissions are caused by multiple efficiency losses of a serial hybrid powertrain between traction machine and ICE, which has to deliver the energy for constant driving at high speeds (power) over a longer period to ensure a sustaining battery charge. For relatively little propulsion work at the wheel, the ICE needs to produce quite a lot of work and thus emits a quite high emission mass. However, the developed test procedures are able to depict and evaluate the in-use behaviour. The question remains valid whether urban mission vehicles would indeed run such speed profiles during in-use vehicle operation. But this is more likely a question of appropriate test cycles and not of the developed system work concept.

Potential solutions for this problem would require a mission specific testing of the hybrid powertrain or weighting of certain parts of the test cycle, and may limit the application of the hybrid powertrain to one specific type of vehicle instead of allowing a vehicle independent application. However, weighting of certain parts of the test cycle also poses some problems that will be explained below. Further investigations and evaluations of serial hybrids have not been performed within the HDH informal working group.

Weighting factors for the three sub-parts of the WHVC were also developed as part of the work in the HDH informal group. The application of respective weighting factors to the three sub-parts of the cycle (urban, rural, motorway) could in principle be used to represent mission specific testing with vehicle operation closer to real-world conditions without the additional effort of performing several test cycles depending on the respective missions of the vehicles the powertrain is installed in. The detailed methodology for deriving the weighting factors as well as the final values for all mission profiles can be found in [14] and [15]. Nevertheless, the usage of weighting factors cannot be recommended for emission certification for several reasons: If weighting factors were only introduced for hybrid vehicles, there would be no comparability of the emission results between hybrid and conventional vehicles. Consequently, weighting factors would need to be introduced for all engines to be certified regardless of their in-vehicle application. Furthermore, the application of weighting factors would lead to vehicle or mission profile specific certification and not allow vehicle independent certification any more. This would mean that the installation of a certified engine was limited to certain vehicle classes. Additionally, the application of weighting factors would lead to an unfair higher weighting of chronologically early test phases (first and second phase of WHTC/WHVC) for some vehicles, where the conversion efficiencies of the exhaust aftertreatment system are low due to insufficient warm-up. In the case of a city bus only the first (i.e. urban) part of the test cycle would be considered due to a weighting of 100 percent. For this extreme example, the emissions would be determined only during the first 900 seconds, where the specific emissions in g/kWh would be high due to insufficient warm-up of the exhaust aftertreatment system. In the case of a long-haul truck, where mainly the last (i.e. motorway part) of the test cycle would be considered, it would be the other way round and lead to a significant advantage due to lower specific emissions in g/kWh resulting from the already sufficiently warmed up exhaust aftertreatment system. In order to get representative, average emission values for a specific vehicle, mission specific test cycles with the same total duration but a different load profile, which is representative for a specific mission would be necessary, instead of the weighting of different parts of the cycle.

7. Rated power determination

The test procedures for engines installed in conventional vehicles (WHTC engine schedule) and for hybrid systems (WHVC vehicle schedule) have been aligned in terms of power and work demand. To be able to do so, vehicle parameter and road gradients as a function of rated power described in chapter 4 and 5 have been established. This ensures that the same load is applied to hybrid systems and conventional engines with the same power rating during the respective test procedure. Since all load defining parameters for a hybrid vehicle emission certification are dependent on the rated power of the system this also implies the importance of a suitable power rating determination procedure.

While the rated power of a combustion engine is a well-known and determinable parameter, nothing comparable is available for hybrid systems where the maximum power output can differ with test time depending on parameters like RESS size, peak power capability, SOC level, thermal restrictions of components and so on. Just summarizing power ratings of individual components to derive the rated hybrid system power is not considered reasonable for multiple reasons, and therefore the rated power test procedure must determine a representative power rating for the respective hybrid system which reflects its performance during in-use vehicle operation. In addition, the procedure needs to be applicable for both hybrid system test methods as regulated in Annex 9 and Annex 10 of gtr No.4 [3] and performing the test with a conventional vehicle should with good approximation result in the power rating of the combustion engine installed to ensure the comparability of conventional and hybrid vehicles. Since the HiLS method requires a model verification where no major modifications to the model are allowed afterwards, the developed test method needs to be applicable without changes to a verified model as well.

7.1. Rated power determination

The power capability of a hybrid system very much depends on the actual system conditions like SOC level, thermal restrictions of components etc. as outlined above. The most obvious way to derive a hybrid power rating would be to just summarize the power ratings of all different energy converters in the drivetrain, but apart from the fact that the definition of an electric machine's rated power is not straightforward, this would not give a useful power rating for the hybrid system and it would also not be able to reflect power limitations due to the system compound and the actual operation pattern. In addition the maximum power of different energy converters would most likely be at different rotational speeds and would probably not simultaneously occur during in-use operation of the hybrid system.

Figure 7.1 illustrates the result of summarizing the component power ratings for two different hybrid system layouts. Even though the powertrain consists of the same components, the power available at the wheel hub to propel the vehicle is different. To establish a hybrid rated power definition which is robust, considers the hybrid system limitations due to the specific application and is comparable to conventional vehicles, a different approach was chosen: comparing maximum driving performance instead of specific component power ratings.

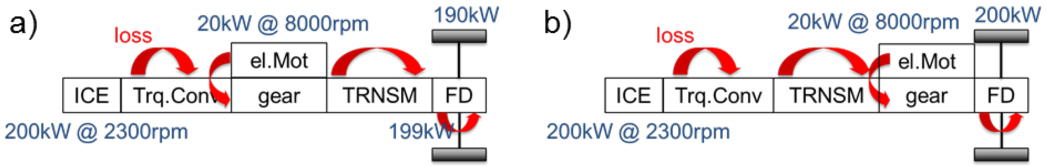


Figure 7.1 Effects of system layout on available propulsion power

The developed method is based on the System Power Concept [16] presented in the EVE informal working group under GRPE for a different purpose. It originally consisted of a full powertrain test for passenger cars where a vehicle is mounted on a test bench at the wheel hubs directly to avoid tire-roller influences. A full load acceleration is performed and the power at the hubs is recorded as exemplarily illustrated in Figure 7.2.

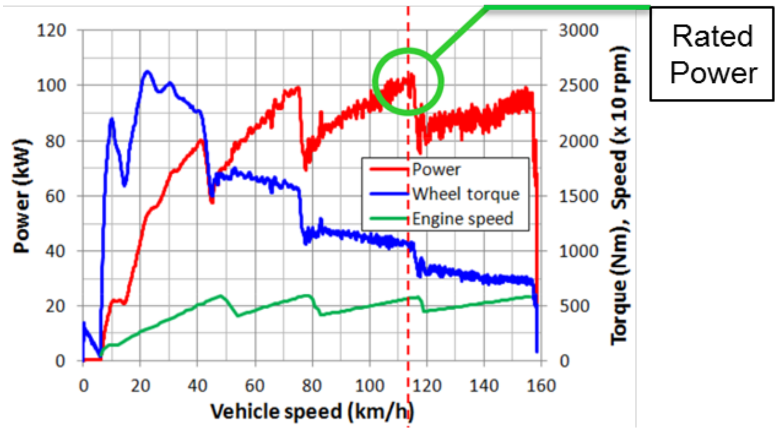


Figure 7.2 Full load acceleration of a parallel hybrid vehicle [16]

The hybrid rated power determination procedure developed in the HDH informal group consists of multiple standard drive manoeuvres to determine the maximum vehicle performance independent of conventional or hybrid vehicle drivetrains and their specific system layouts. Specifically several full load accelerations starting from different speeds and applying different loads are performed in accordance with Table 7.1 either using the HiLS or the powertrain test method as regulated in Annex 9 and 10 of gtr No.4 [3]. This is considered representative of in-use vehicle operation scenarios as well as of scenarios carried out according to the WHVC vehicle schedule.

Even though the result may differ from what could be expected when single component power ratings are summarized, it is nevertheless representative of the maximum power which can be released by the system during in-use operation. Using the resulting power rating for hybrid systems to adjust the power and work demand of the test cycle ensures a representative in-use system load and thus a representative emission behaviour which reflects the environmental impact of the vehicle at the certification.

Road gradient [%]	**Initial vehicle speed [km/h]**		
	0	**30**	**60**
0	*Test #1*	*Test #4*	*Test #7*
2	*Test #2*	*Test #5*	*Test #8*
6	*Test #3*	*Test #6*	*Test #9*

Table 7.1 Hybrid system rated power test conditions

In line with the system work concept in chapter 6 and the WHVC vehicle schedule in chapter 5, the common reference point to determine the rated power for all types of vehicles again is the wheel hub. Considering a conventional vehicle, the power recorded at the wheel hub when running the vehicle test procedure would, due to efficiency losses in the drivetrain, be lower than the combustion engine's power and therefore the same standard efficiencies as used before have to be used to correct this circumstance. In accordance with equation (12) the recorded power at the wheel hub is thus divided by 0.95^2 to calculate the characteristic hybrid rated power for any vehicle and hybrid system configuration. Even though 0.95 may not be representative of each vehicle, this does not matter, since all alignments regarding test schedule and system work are based on the reference point at the wheel. The generic efficiencies have only been introduced to be able to transfer the WHTC power demands to the wheel for a conventional vehicle as a reference basis.

$$P_{Sys_{raw}} = \frac{P_{WheelHub}}{0.95^2} \qquad (12)$$

Where:

$P_{Sys_{raw}}$ *is the raw hybrid system power, kW*
$P_{WheelHub}$ *is the power at the wheel hub, kW*

In order to determine the maximum performance of the hybrid system, it was agreed that the system should be in warm condition and sufficient energy should be available (SOC level > 90% of used range) before the start of each test scenario. Under the assumption that a hybrid vehicle is designed to have stored recuperated energy for an acceleration available during most of the in-use operation time (the desired SOC level during in-use operation is between minimum and maximum), the initial SOC level for the rated power determination test procedure was suggested to be set to $\frac{SOC_{min}+SOC_{max}}{2}$ where $SOC_{min} + SOC_{max}$ are defined by the OEM (e.g. 35% to 65%). 0% and 100% SOC level have not been considered as a representative system status. However, on behalf of group members of the HDH informal group it was agreed to specify the rated power under full storage conditions (SOC level > 90% of used range) to determine the maximum performance the system is able to deliver even though this can cause incidents as outlined in section 7.3.

To avoid the declaration of power spikes as rated power (illustrated in Figure 7.3 at sec. 15), which may occur especially during gear shifts, the raw data of $P_{Sys_{raw}}$ has to be processed to derive the hybrid system rated power P_{rated}.

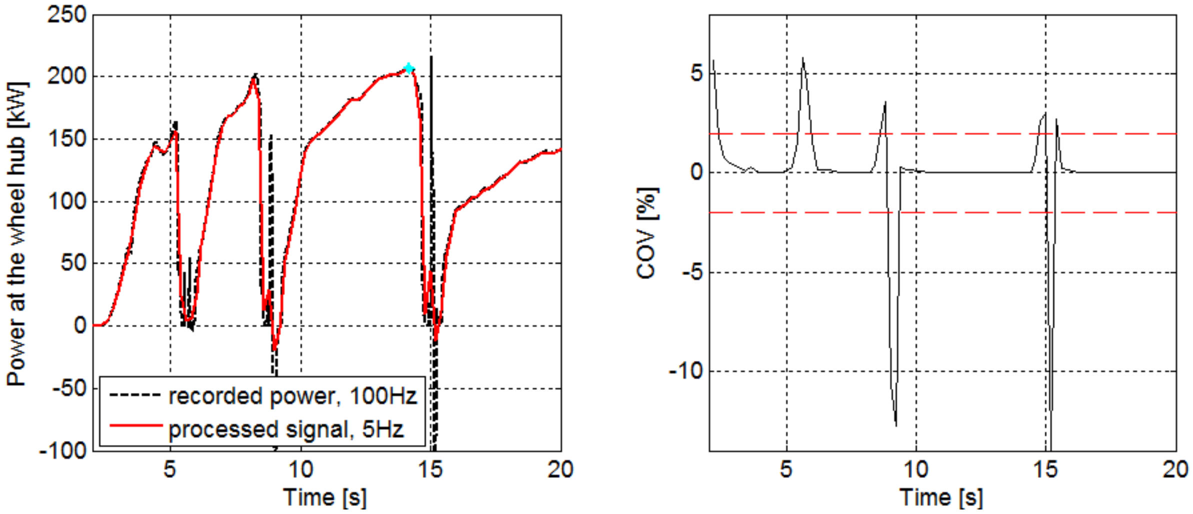


Figure 7.3 Example of recorded and processed wheel hub power signals

The power signal $P_{Sys_{raw}}(t_1)$ at the wheel hub is initially required to be recorded with 100 Hz during the HiLS or powertrain test. Parallel to this, a processed signal $P_{\mu}(t_2)$ has to be generated with a resolution of 5 Hz where one sample of the processed signal represents the mean value of 20 recorded samples of $P_{Sys_{raw}}(t_1)$ for the respective time window (see Figure 7.4).

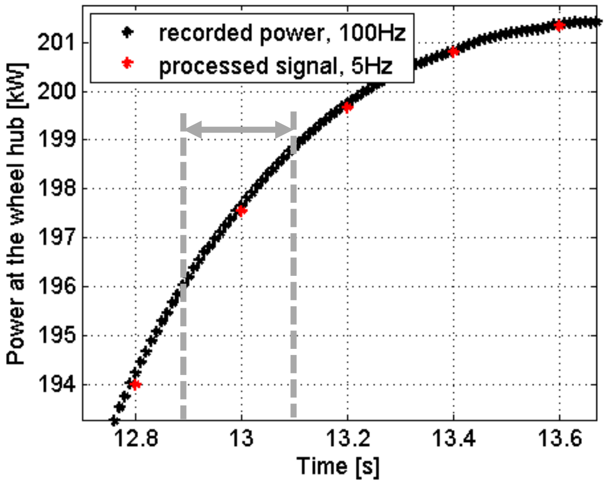


Figure 7.4 Down sampling of the recorded power signal

The standard deviation $\sigma(t_2)$ shall then be calculated using $P_{Sys_{raw}}(t_1)$ and $P_\mu(t_2)$ in accordance with:

$$\sigma(t_2) = \sqrt{\frac{1}{N} * \sum_{n=1}^{N} (x_n - P_\mu(t_2))} \qquad (13)$$

Where:

x_n	*are the N=20 samples of $P_{Sys_{raw}}(t_1)$ previously used to calculate the respective $P_\mu(t_2)$ values at the time step t_2, kW*

The coefficient of variation COV shall then be calculated in accordance with:

$$COV(t_2) = \frac{\sigma(t_2)}{P_\mu(t_2)} \qquad (14)$$

The hybrid system rated power P_{rated} shall finally be the highest determined power $P_\mu(t_2)$ where the coefficient of variation COV is below ± 2 per cent to avoid the declaration of power spikes (see Figure 7.3 at sec. 14.2 exemplarily).

7.2. Summary

Due to the limited availability of hybrid energy and design properties of the hybrid systems, the determination of a representative power rating is more complex than for conventional engines. Nevertheless a test method was developed where the hybrid system can be rated in a way that the test cycle demands its full load capacities in any case.

Furthermore the agreed method allows the alignment of conventional engine and hybrid system testing in terms of

- system load demand of the respective test cycle
- system work for emission calculation
- rated power determination

and is valid and applicable to the powertrain and the HiLS method without any changes to be made on a verified HiLS model. The chosen approach of comparing driving performance instead of component power ratings additionally avoids the discussion on the definition of electric (hybrid) peak vs. continuous power which would always vary depending on the hybrid system setup and actual state of operation and would always make a case by case justification of the type approval or certification authority necessary, which is certainly not suitable for a gtr.

The developed procedure was tested during VTP2 by 3 different OEMs using a

- SiL system representing a serial hybrid vehicle
- SiL system representing a parallel hybrid vehicle
- HiL system representing a parallel hybrid vehicle

Overall, reasonable results and a positive feedback could be reported to the HDH informal group but also a drawback could be observed for a specific hybrid vehicle configuration as outlined in the following section. Further testing/comparison with actual vehicles was therefore recommended but could not be performed due to the tight project schedule.

Even though the test procedure is theoretically applicable on a powertrain test bed, no tests were performed during VTP2 and thus no experience could be gathered regarding the practical applicability of the developed procedure on an actual hybrid powertrain test bed and possible arising problems.

7.3. Restrictions and clarification

As indicated in the previous section, performing a test where the maximum performance of a hybrid system (no system limitations active, SOC level > 90%) is considered as the characteristic rated power can result in a non-representative power rating. The WHVC vehicle schedule derived from that power rating can demand more power than the vehicle can deliver at a certain time in the cycle. Figure 7.5 illustrates the HiLS simulation output for a vehicle where the power rating was chosen higher than the hybrid system capabilities on purpose and a HiLS test was performed. Most of the time the vehicle is able to follow the desired WHVC vehicle schedule but the hybrid system is permanently operated at its upper limits during the test and with ongoing test time, the systems tends to overheat. As a result the electric motor needs to decrease its power or fully shut off as illustrated in the violet marked section in Figure 7.5 even though the accelerator pedal is fully pressed at the same time.

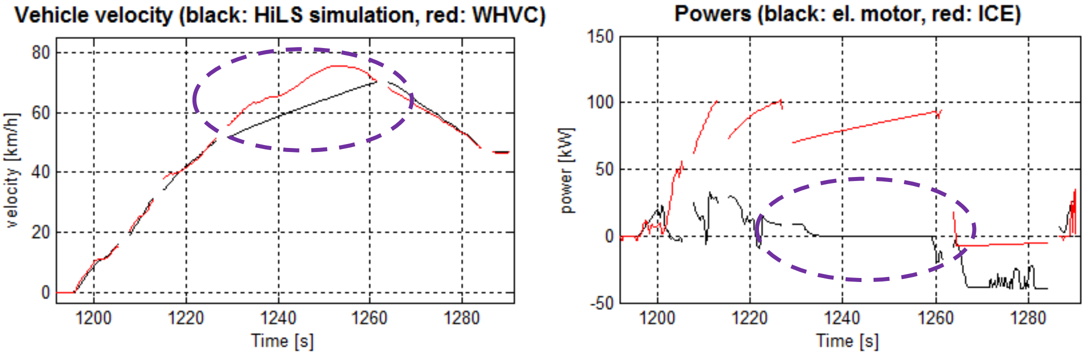


Figure 7.5 HiLS test with overheating hybrid system

A power limitation cannot only occur due to thermal issues, it can also occur due to limitations of the hybrid system which take place depending on insufficient SOC level or other system decisions during the cycle. This can systemically not be covered by a rated power test procedure which lasts shorter than the WHVC vehicle schedule.

However, a violation of the WHVC vehicle schedule speed tolerances would per se not be an instance which causes an invalidity of the certification test. Since the vehicle is operated at maximum operator demand, at least the combustion engine will release as much power as possible in order to follow the desired speed profile during sections where the alternative propulsion system is deactivated or operated at a lower power level. This consequently leads to a shift of propulsion work towards the combustion engine and the ratio of ICE propulsion work to electric/alternative machine propulsion work increases. Finally this has, due to the consideration of the system work for the specific emission calculation, an effect on the final emission result as outlined below.

Figure 7.6 illustrates different HiLS test results for one specific hybrid powertrain which was tested with various power ratings independent of the rated power determination test procedure result. Each power rating would of course give a different absolute system work but to be able to compare the different test results, positive ICE and electric machine work have been normalized to the respective system work. Thus, the share of ICE and electric machine work on the overall propulsion work can be illustrated. Since the SOC level needs to be balanced over the test cycle, the electric machine work is quite exactly the work which could be recuperated during the test cycle and this of course lowers the work the ICE needs to deliver during the test. Therefore also the output of mass emissions by the ICE is reduced and since the system work is used to calculate the specific emissions, this generates a benefit for hybrid vehicles.

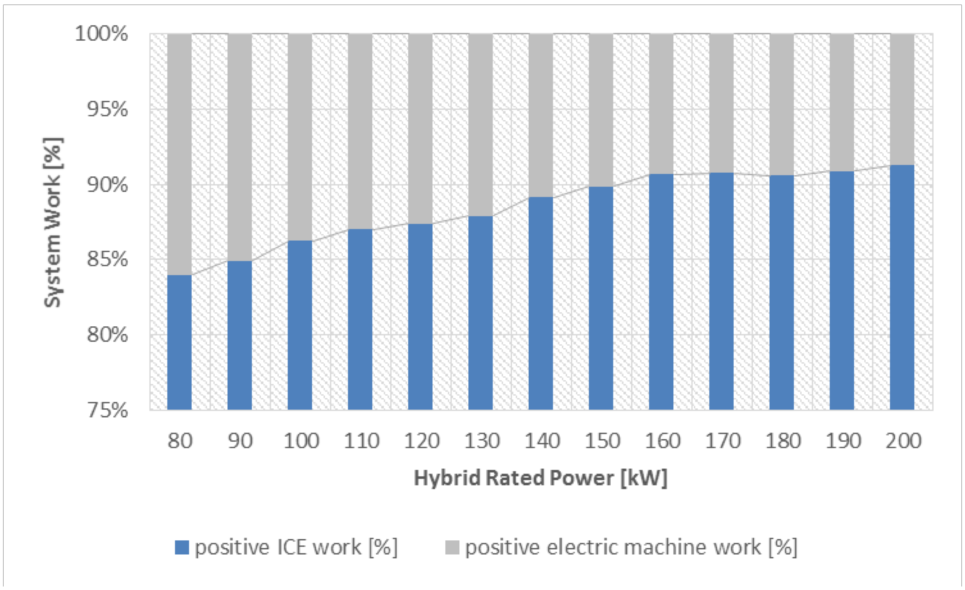


Figure 7.6 HiLS results of different power ratings for one specific hybrid powertrain

With an increasing power rating used to de-normalize the WHVC vehicle schedule and to determine the generic vehicle parameters, the ratio of ICE to electric machine work also increases and thus consequently lowers the benefit which hybrid vehicles would gather by the consideration of the system work for the specific emission calculation. Especially systems which have a high peak power capability but a permanent load capability of very short duration (e.g. small electric machine with high specific power which causes fast thermal overheating) might be affected by this issue because they are able to deliver a high power during the rated power test procedure, which increases the WHVC power demands, but not during the entire WHVC vehicle schedule.

Consequently, only an iteration process where the vehicle schedule and the vehicle parameters are calculated with different power ratings would serve to identify the power rating where the vehicle is able to follow the test schedule, its full load capacities are tested and the frequency distribution of power in relation to its full load capacities is similar to the WHTC test schedule. However, depending on the design of a hybrid system, limitations may occur even when a different test scenario is used and the fulfilment of all three aforementioned demands may not be possible. Therefore it was agreed by the HDH informal group that the rated power test scenario as described is considered reasonable for this amendment of gtr No.4.

8. The Hybrid powertrain family concept

For the certification and type approval of engines installed in conventional heavy duty vehicles, special provisions in the regulations of gtr No.4 have been established to lower the test burden for engine manufacturers. An engine family concept was introduced where similar engines can be bundled into one engine family. Assuming that all engines in a family have the same emission characteristics, just the parent engine, which has to be the engine with the highest power rating, has to be certified or type approved.

To lower the test burden for engines installed in hybrid powertrains as well, a similar approach was chosen. Therefore hybrid powertrains with similar emission characteristics can also be bundled into a hybrid powertrain family and only one representative powertrain, or specifically its engine, needs to be certified or type approved. Whereas conventional engines within a family are certified vehicle independent (i.e. the engine test cycle is independent of the ICE power rating, the vehicle type and properties), the situation is slightly different for hybrid systems and needs to be distinguished as follows.

The HiLS and the powertrain method as specified in Annex 9 and 10 of gtr No.4 [3] are in principal valid to reflect each vehicle configuration specifically for a certification or type approval but it would cause a very high test burden if each hybrid powertrain needed to be certified separately according to its operation in the specific vehicle. Also using an average driving profile like the WHVC would then be less reasonable and most likely the certification would need to get completely vehicle specific, including vehicle specific mission profiles, to reflect the environmental impact for each vehicle correctly. To reduce the quite likely not manageable test effort, generic vehicle parameters as a function of the hybrid rated power have been established which represent one generic vehicle for each power rating of the powertrain and thus already realize a family approach on a vehicle level (as illustrated in Figure 8.1). The powertrain certification is independent of real vehicle variants which is similar to conventional engines where the engine can also be installed in any vehicle configuration.

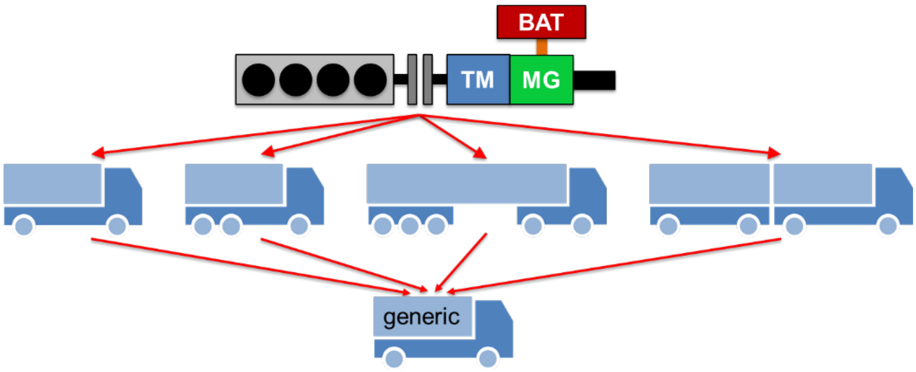


Figure 8.1 Family concept on vehicle level

Further following the family approach for engines installed in conventional vehicles, where just the most powerful engine of an engine family needs to be certified, it would also be desirable for hybrid powertrains to just certify the most powerful one. For conventional vehicles where the operation points of the engine test cycle in relation to the engine operation map stay constant independent of the ICE power rating (assuming the same shape of the engine's fullload curve), similar emission characteristics can be considered reasonable within one family. In contrast to that, the engine test cycle for hybrid powertrains will most likely change if one component in the hybrid powertrain compound (e.g. a less powerful engine) is varied. Figure 8.2 illustrates this issue for two similar powertrains with the same power rating but a different battery size.

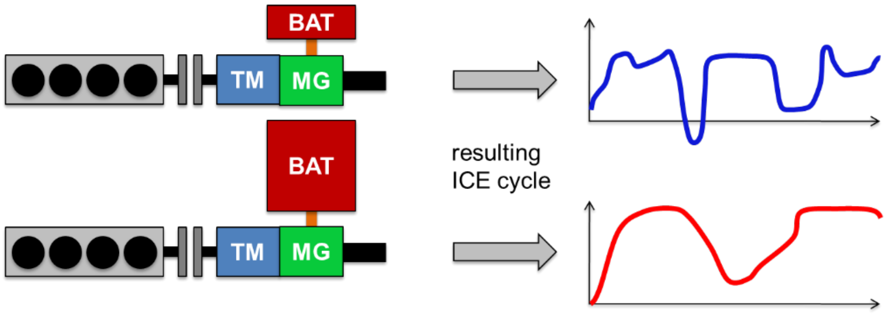


Figure 8.2 Different ICE operation for same power rating due to different component size and hybrid strategy

The principle of similar emission characteristics for all powertrains with the same hardware and layout but with a different power rating can therefore not be considered valid without any restrictions.

To ensure similar emission behaviour among different hybrid powertrains, a hybrid powertrain family concept was agreed on within the HDH informal group. For this concept, the similarity of resulting engine cycles has to be proved for all different hybrid powertrains which are supposed to be grouped into the same family. In accordance with the rationales of the family concept for engines installed in conventional vehicles, only a similar engine operation is supposed to lead to similar emission characteristics. The hybrid powertrain family concept was therefore agreed on as illustrated in Figure 8.3.

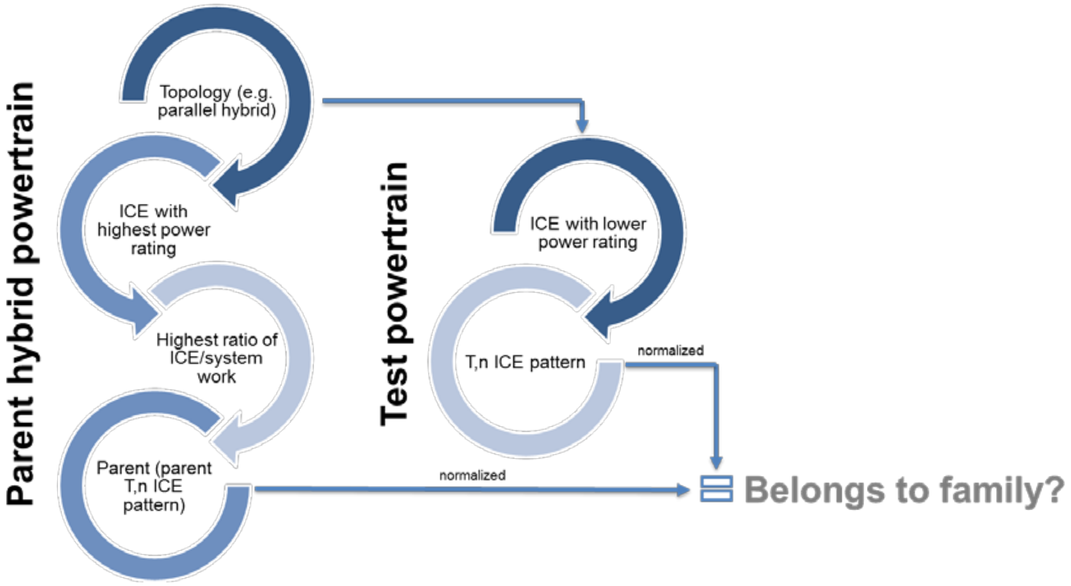


Figure 8.3 Parent hybrid powertrain determination and proof of family membership

In accordance with Figure 8.3 the powertrain with the most powerful combustion engine defines the parent. In case the most powerful engine is used in multiple configurations, the smallest possible energy storage is used as additional criterion to define the parent. To prove the family membership, the normalized torque values of the respective duty cycles of parent and actual test powertrain are evaluated against each other by means of a linear regression analysis. In case the linear regression analysis meets the tolerances as specified in gtr No.4 [3], only the parent needs to be certified or type approved. But due to the presumable uniqueness of the ICE operation pattern of different hybrid powertrains, it is quite likely that each hybrid powertrain configuration defines its own family and the inclusion of children into an existing family is hardly possible. Nevertheless, and even though it increases the test effort, similar emission characteristics can simply not be assumed.

9. Validation test program 2 (VTP2)

As part of the development process of amendment 3 to gtr No.4 [3], three different European heavy duty hybrid vehicles served to validate the proposed HiLS test procedure. Since hybrid systems are still a niche application in the heavy duty sector and not widely spread over all vehicle categories, two of them were buses and one vehicle was a delivery truck (see Figure 9.1). Two parallel hybrid system layouts with different electric to combustion engine power ratios and one serial hybrid system installed in a city bus with a relatively small energy storage system, inducing a transient combustion engine operation, were tested within this research program.


VOLVO 7700 Hybrid **MAN Lion's City Hybrid** **IVECO Eurocargo 120EL18**

parallel hybrid bus serial hybrid bus parallel hybrid truck

Figure 9.1 Test candidates in validation test program 2

Guided by the Japanese regulation Kokujikan No.281 [1] a HiLS model verification procedure for the participating vehicles was started in May 2013 covering

- vehicle measurements on the chassis dynamometer
- application of generic vehicle parameters and resulting developed vehicle schedule including road gradients (WHVC)
- HiLS/SiLS/MiLS model verification

Not all OEMs were able to rely on existing HiL test systems and therefore also SiLS/MiLS was used, so that a fully valid HiLS test could only be performed by IVECO. Regardless of the system used, all model verification tests were performed under warm hybrid system conditions only and cold start could not be evaluated within the given project time schedule.

Since the vehicle schedule was developed in parallel to the test program it was applied according to its actual status of development at the time of chassis dyno testing. The same is valid for the generic vehicle parameters. However, vehicle parameters and vehicle schedule used for the chassis dyno measurements and the HiLS model verification were the same in any case so that it effectively did not harm the evaluation of the model verification process.

The powertrain method as specified in Annex 10 of gtr No.4 [3] could not specifically be tested within the validation test program. However, a verification was conducted by US EPA and Environment Canada which demonstrated the general feasibility of the method [9].

9.1. Chassis dyno testing

The chassis dyno tests within VTP2 were performed at the JRC test centre in Ispra (ITA) [17] in close cooperation of JRC, OEMs and the institutes of the universities. Participating vehicles were tested twice, starting the first measurement series in the end of May 2013 for all vehicles and repeating the tests in fall 2013 and winter 2014 for VOLVO and IVECO. MAN as well repeated the measurements on their in-house roller bench in the beginning of February 2014. All test data gained served as basis for the development of the WHVC vehicle schedule as well but was used primarily as reference data for the HiLS model verification procedure performed in accordance with the regulations of Kokujikan No.281 [1].

Even though the tests were conducted in the same way as for conventional vehicles without the need for any special provisions with respect to the chassis dyno setup, performing the tests nevertheless helped to get confident with measurements on the dyno especially targeting a HiLS model verification later on. This section shall summarize the chassis dyno measurements performed and outline the issues observed.

Most commonly used heavy duty chassis dynos are equipped with one driven axle where the propelled vehicle axle is placed on. Since the remaining axles are standing still, some modifications to the vehicles needed to be made to ensure a proper system operation on the chassis dyno. With the intention to get a representative in-use operation, no major modifications should be made to the vehicle and its control systems, if possible. Examples can be given as follows:

- For the specific tests, and quite likely for most modern vehicles, the ABS sensor signals for the non-driven axles needed to be modified to allow an adequate vehicle operation on the dyno.
- Considering the vehicle schedule, a forwarding of the road gradient signal to the vehicle's control logics would seem logical, but the road gradient was and shall not be recognized by the vehicle's ECUs. As outlined in chapter 5, the road gradient is just imitating payload and only the accelerator pedal position needs to take care of additional or less vehicle load.

Further system modifications may be necessary depending on the actual test system.

During the test runs various vehicle cycles were tested and further developed regarding their drivability and their load alignment with the corresponding engine test cycle (WHTC). An overview is listed as follows:

- WHVC flat
- WHVC including road gradients (various modifications)
  - Minicycle approach [18]
    - Basic Minicycle approach
    - Minicycles considering a balanced altitude
    - Road gradient modifications for vehicles not capable of 87km/h maximum speed
    - Enhanced Minicycle approach as regulated in Annex 1(b) to gtr No.4 [3], finally tested at JRC using the IVECO vehicle [19]
  - 30 seconds moving average approach [18]

The WHVC vehicle schedule as regulated in Annex 1(b) to gtr No.4 [3] could only be tested with one vehicle due to the availability of chassis dyno test time, vehicles and final version of the vehicle schedule. Nevertheless, the positive feedback on the drivability of the WHVC vehicle schedule for the IVECO vehicle is considered to be valid for other vehicles as well. As the test cycles used for the second measurement series of the VOLVO and especially the MAN vehicle were quite highly developed at the time of testing and they also reported a positive feedback on the driving behaviour, this assumption seems valid.

However, since all tests primarily served to get reference data for the HiLS model verification, certain vehicle signals needed to be either directly measured or recorded on the vehicle's CAN bus. Preferably the entire CAN bus is logged to be able to provide additional signals to the simulation model later on if needed. In any case the following signals needed to be recorded for the vehicles tested:

- engine and electric motor speed
- engine torque and command value (e.g. fuel injection amount)
- electric motor torque and torque command value (e.g. torque request)
- vehicle speed
- SOC level
- brake and accelerator pedal position
- actual and desired gear
- battery voltage and current

For the measurements in Ispra also an emission measurement system was installed where the tail pipe emission for the different vehicle schedules were recorded.

As the chassis dyno measurements provide the reference data for the model verification later on, the accuracy of the dyno measurements turned out to be a key enabler for a successful model verification.

The developed vehicle schedule was driveable quite well on the rollers with the tested vehicles (two busses and one light delivery truck in a low to medium power range), nevertheless heavier and more sluggish vehicles could not be tested and the conclusions drawn may not be valid and representative of all types of vehicles.

9.2. OEM specific HiLS verification results

After the chassis dyno measurements had been performed, the vehicle models were configured using the same parameters as applied during the actual vehicle tests. Vehicle mass, driving resistances and inertias were set the same as for the chassis dyno test, considering the non-driven front axle on the chassis dyno for the model verification as well. Auxiliary loads, either mechanical or from the high/low voltage electrical system, were estimated and provided to the model where no data recording was possible.

To ensure that the CAN values which were used to determine the combustion and the electric machine’s torque are correct, the CAN command values for the energy converters were recorded and transferred to actual values using component maps recorded during the component tests. Actual speed, CAN command value and respective component map result in an actual torque value for the energy converters. Since the same ECUs and command values were used for component testing where the torque was directly measured on a test bed, this method proves the correctness of the torque values recorded via CAN.

After setting up the models the verification was performed in accordance with the Japanese regulation Kokujikan No.281 [1] and its given provisions and limits. The method is based on a data comparison of actually measured and simulated data using a linear regression analysis. Since linear regression compares the similarity of signals based on their time characteristics and a similar behaviour of recorded and simulated signals can barely be expected during gearshifts, the data during gearshift is not considered for the verification. The actually measured gear shift event triggers the data omission.

In accordance with Kokujikan No.281 [1] the verification was performed following a two-step approach. In a first step, characteristic values as listed in Table 9.1 are compared only for the first 140 seconds of the test. For this first step it is compulsory to use accelerator and brake pedal signals recoded during the chassis dyno test as model input. The second step compares signals listed in the respective column of Table 9.1 for the entire test run. Accelerator and brake pedal signal can be parameterized freely here if desired.

WHVC (140 sec.)	Vehicle	Electric Motor		ICE		Battery
	Speed	Torque	Power	Torque	Power	Power
Kokujikan desired R^2	0.97	0.88	0.88	0.88	0.88	0.88

WHVC (1800 sec.)	Vehicle	ICE	
	Speed	Torque	Positive engine work
Kokujikan desired R^2	0.97	0.88	>0.97

Table 9.1 HiLS model verification limit values

Table 9.2 gives a quick overview of the achieved final verification results. The details for each vehicle can be found in the respective section below.

OEM	Concept	Details	Setup	Validation passed
IVECO	Parallel Hybrid Truck	6 speed AMT	HiLS	Yes
VOLVO	Parallel Hybrid Bus	12 speed AMT	SiLS	No
MAN	Serial Hybrid Bus	Fixed gear, transient ICE operation	SiL(MiL)S	No

Table 9.2 HiLS verification results, overview

9.2.1. VOLVO 7700 Hybrid

The vehicle model verification for the VOLVO 7700 Hybrid bus could not be performed using a HiLS setup, therefore a SiL system was used instead. Because the vehicle schedule and road load parameter definitions as stated in gtr No.4 were not fully developed at the time the chassis dyno tests were performed, the parameters in accordance with Kokujikan No.281 [1] were used. Since normally a model can be verified using any reference data representative of real-world system dynamics, it is assumed that this has no influence on the final verification result.

The test parameters were:

Vehicle test mass:	15073.0	kg	Rolling resistance coefficient:	0.0063	-
Vehicle curb mass:	12460.5	kg	Air drag coefficient:	0.4265	-
Frontal area:	8.1	m^2	Hybrid rated power:	193	kW

Performing the model verification including different data post processing methods led to results as shown in Table 9.3. For all results shown the model was operated in open loop (recorded accelerator and brake pedal signals were used as model input). Even though the results are close to valid, a fully valid model verification in accordance with gtr No.4 [3] could not be achieved (see WHVC + road gradients*, 1sec. before and after + data during gearshift removed).

The table already indicates the importance of accurate gear shift simulation. For the flat WHVC it is already sufficient to remove the data for the regression analysis as specified in the regulation. This also covers slight inaccuracies in gearshift timing and omits the data so that gearshift offsets smaller than approximately one second are accepted. For the WHVC including road gradients removing the data for one second is not sufficient and a more generous removal would be needed to achieve the demanded limit values. Accurate gearshift simulation has thus been identified to have a significant influence on a successful model verification and the more gears a vehicle offers the harder it is for the simulation model to exactly imitate the vehicle's behaviour on the rollers.

WHVC (140 sec.)	**Vehicle**	**Electric Motor**		**ICE**		**Battery**
	Speed	Torque	Power	Torque	Power	Power
desired R²	0.97	0.88	0.88	0.88	0.88	0.88
WHVC flat no data removed	0.99	0.77	0.72	0.67	0.68	0.72
WHVC flat 1 sec. before and after + data during gearshift removed	0.99	0.96	0.91	0.93	0.90	0.91
WHVC + road gradients* no data removed	0.99	0.69	0.70	0.68	0.63	0.68
WHVC + road gradients* 1sec. before and after + data during gearshift removed	0.99	0.92	0.86	0.84	0.82	0.83
WHVC + road gradients* 2sec. before and after + data during gearshift removed	0.99	0.97	0.92	0.94	0.89	0.90

WHVC (1800 sec.)	**Vehicle**	**ICE**	
	Speed	Torque	Positive engine work
desired R²	0.97	0.88	>0.97**
WHVC flat no data removed	0.99	0.78	1.07
WHVC flat 1 sec. before and after + data during gearshift removed	0.99	0.90	1.07
WHVC + road gradients* no data removed	0.99	0.78	1.08
WHVC + road gradients* 1sec. before and after + data during gearshift removed	0.99	0.90	1.08
WHVC + road gradients* 2sec. before and after + data during gearshift removed	0.99	0.93	1.08

*slightly different than the road gradients specified in Annex 1(b) of gtr No.4 have been used because the vehicle schedule was not fully developed at the time of chassis dyno testing

**no upper limit value was defined at time of test

Table 9.3 VOLVO model verification results

Figure 9.2 shows the difference in gears for a 140 seconds test run exemplarily and illustrates the corresponding ICE torque pattern in the graph on the right side. As long as the gears match up, the torque also matches perfectly well. However, once a different gear is engaged (see e.g. at second 70) the torque pattern may behave absolutely different (rising vs. falling) which has a significant impact on the linear regression analysis and significantly worsens the results.

A different gear of course also influences the rotational speeds and thus the respective torques of all traction machines mechanically coupled. Since a different operation point most likely causes different efficiencies, also the energy flows become different which leads to a different SOC behaviour and probably an altogether different operation strategy. Therefore an accurate simulation of the gear shift behaviour seems to be a key enabler for successful model verification.

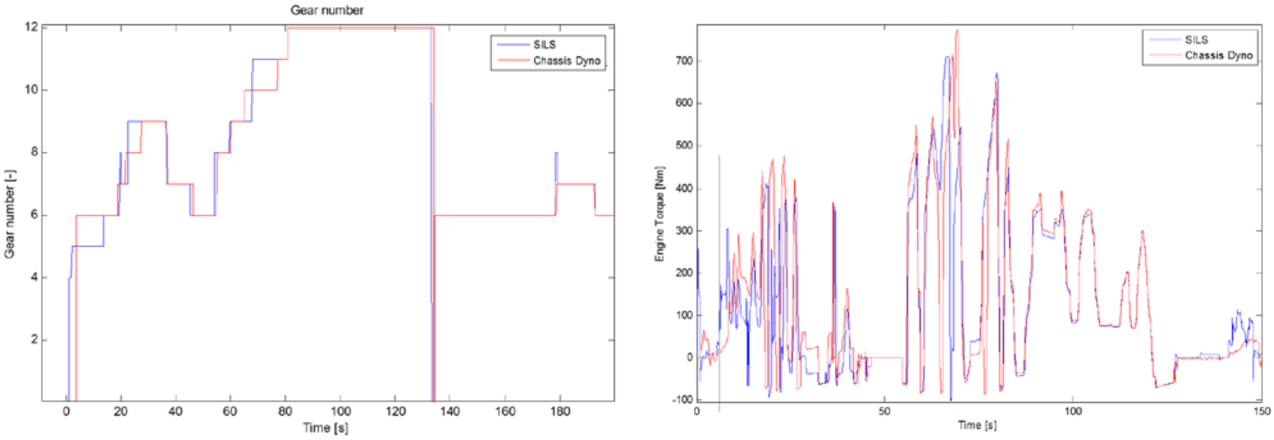


Figure 9.2 Exemplary gear mismatch during model verification

Another instance rather hard to depict is the timing of an engine shut down as shown in Figure 9.3. Compared to the gear mismatch, this does not directly cause bad R² values in engine torque and speed since the linear regression of both signals gives 1, but it influences the vehicle’s energy flows with an impact on the SOC level and thus on possible further ECU decisions. More detailed time history patterns of validated signals are illustrated in [18].

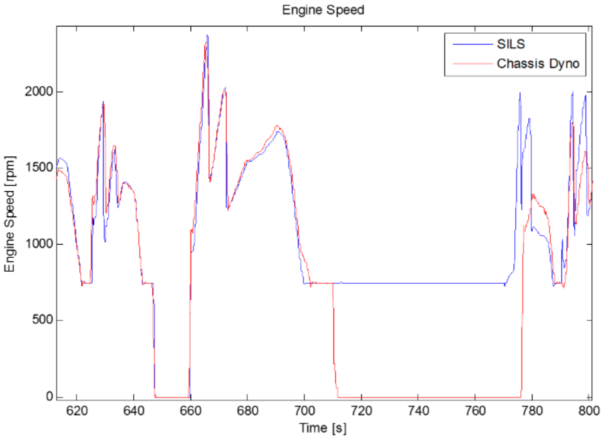


Figure 9.3 Engine idle vs. engine off during model verification

9.2.2. IVECO Eurocargo 120EL18

The vehicle model verification for the IVECO Eurocargo 120EL18 could be performed using a complete HiLS setup including the HCU in the loop. Since the IVECO was the last vehicle tested on the rollers also the generic vehicle parameter and the vehicle schedule were available as finally stated in the annexes of gtr No.4 [3] at the time of testing. In addition a torque measurement shaft was installed on the gearbox output side to allow a proper calibration of efficiencies and losses in the drivetrain. However, the rated power test procedure was not completed and thus the combustion engine’s rated power had to be used instead. This seemed reasonable since the hybrid logics were assumed to limit the maximum propelling power to the combustion engine’s maximum power anyway.

The test parameters were:

Vehicle test mass:	8876.5	kg	Rolling resistance coefficient:	0.0071	-
Vehicle curb mass:	4779.9	kg	Air drag coefficient:	0.6019	-
Frontal area:	5.96	m²	Hybrid rated power:	130	kW

The model verification was performed twice for two different test cycles using different data post processing methods. The results are shown in Table 9.4. The simulation model was therefore parameterized just once using the data recorded in run 1. For the model verification of run 2 no parameters were changed and thus the model proves to be valid also for this test cycle. A fully valid model verification in accordance with gtr No.4 [3] could thus only be achieved by IVECO.

Different than the VOLVO bus this vehicle is equipped with a 6 instead of a 12 speed transmission, which makes it easier to align the gear shifts of measurement and simulation.

WHVC (140 sec.)	**Vehicle**	**Electric Motor**		**ICE**		**Battery**
	Speed	Torque	Power	Torque	Power	Power
desired R^2	0.97	0.88	0.88	0.88	0.88	0.88
WHVC + road gradients (run 1) no data removed (OLD)	1.00	0.84	0.82	0.93	0.94	0.75
WHVC + road gradients (run 1) 1sec. before and after + data during gearshift removed (OLD)	1.00	0.96	0.95	0.95	0.96	0.96
WHVC + road gradients (run 2) no data removed (OLD)	1.00	0.86	0.83	0.93	0.94	0.83
WHVC + road gradients (run 2) 1sec. before and after + data during gearshift removed (OLD)	1.00	0.94	0.90	0.92	0.93	0.91

WHVC (1800 sec.)	**Vehicle**	**ICE**	
	Speed	Torque	Positive engine work
desired R^2	0.97	0.88	>0.97*
WHVC + road gradients (run 1) no data removed (CLD)	1.00	0.83	1.03
WHVC + road gradients (run 1) 1sec. before and after + data during gearshift removed (CLD)	1.00	0.89	1.03
WHVC + road gradients (run 2) no data removed (CLD)	1.00	0.87	1.00
WHVC + road gradients (run 2) 1sec. before and after + data during gearshift removed (CLD)	1.00	0.93	1.00

(OLD) …. Open loop driving, recorded accelerator and brake pedal signals were used as model input
(CLD) …. Closed loop driving, a driver model was used to operate accelerator and brake pedal
*no upper limit value was defined at time of test

Table 9.4 IVECO model verification results

The IVECO vehicle is quite similar to Japanese vehicles which were certified using HiLS in accordance with Kokujikan No.281 [1] and thus a successful model verification was achieved as anticipated due to the similarity in system design. Detailed time history patterns of validated signals are illustrated in [19].

Beside the model verification, also the reproducibility of the reference data recorded on the chassis dyno was investigated. Even though the vehicle was run in the same reference speed cycle twice, it was operated by a human driver and therefore slight differences in the pedal actuation consequently occurred. Since a hybrid system is quite sensitive to specific events or limit values, even small differences can lead to completely different system behaviour. Therefore it was not assumed that a test run could be repeated on the chassis dyno fulfilling the same criteria as specified for the model verification. Table 9.5 shows the results for a WHVC test cycle in accordance with Annex 1(b) of gtr No.4 [3] driven twice by a human driver.

(140 sec.)	**Vehicle**	**Electric Motor**		**ICE**		**Battery**
	Speed	Torque	Power	Torque	Power	Power
desired R^2	0.97	0.88	0.88	0.88	0.88	0.88
WHVC + road gradients 1sec. before and after + data during gearshift removed	1.00	0.51	0.47	0.73	0.76	0.51

(1800 sec.)	**Vehicle**	**ICE**	
	Speed	Torque	Positive engine work
desired R^2	0.97	0.88	>0.97
WHVC + road gradients 1sec. before and after + data during gearshift removed	1.00	0.82	0.98

Table 9.5 Repeatability of chassis dyno test runs

However, if a verified vehicle model is able to depict the vehicle behaviour of multiple test cycles when the accelerator and brake pedal signal is used as model input, the reproducibility of the chassis dyno test run need not be a problem in general since the model proves a holistic validity anyway. In addition the MAN results in subsection 9.2.3 prove to be repeatable when a driving robot is used, even for a system drastically more complex to verify than the 6 speed parallel hybrid IVECO.

9.2.3. MAN Lion's City Hybrid

The vehicle model verification for the MAN Lion's City Hybrid bus could not be performed using a HiLS setup, instead a SiL (and partly MiL) system was used. For clarification of the chassis dyno test data recorded in Ispra and to double check the verification results, the chassis dyno tests were repeated at the MAN site in Munich in February 2014.

Vehicle and road load parameter definitions as stated in gtr No.4 [3] had already been fully developed at the time the chassis dyno tests were performed and could therefore be used. As for the IVECO vehicle, the rated power determination procedure was not finally developed and thus the system's highest occurring propulsion power was agreed to be the hybrid rated power. Also the test cycle was not finalized but quite close to, already following the enhanced Minicycle concept as stated in section 5.3. Since the vehicle is not capable of exceeding speeds above 64 km/h and running the highway speed of the WHVC vehicle schedule at 87 km/h demands a higher propulsion power, the road gradients were increased to compensate this power mismatch for the tests cycles which consider road gradients. Even though the HDH informal group agreed to discard this method later on, no negative effects are assumed for the model verification.

The test parameters were:

Vehicle test mass:	10242.0	kg	Rolling resistance coefficient:	0.0068	-
Vehicle curb mass:	5411.8	kg	Air drag coefficient:	0.6039	-
Frontal area:	6.38	m²	Hybrid rated power:	145	kW

Performing the model verification led to the results as shown in Table 9.6. For the first 140 seconds the model was operated in open loop (recorded accelerator and brake pedal signals were used as model input), for the entire cycle a driver model was used. A fully valid model verification in accordance with gtr No.4 [3] could also not be achieved.

WHVC (140 sec.)	**Vehicle**	**Electric Motor**		**ICE**		**Battery**
	Speed	Torque	Power	Torque	Power	Power
desired R²	0.97	0.88	0.88	0.88	0.88	0.88
WHVC + road gradients* no data removed	0.99	0.81	0.85	0.88	0.88	0.83

WHVC (1800 sec.)	**Vehicle**	**ICE**	
	Speed	Torque	Positive engine work
desired R²	0.97	0.88	>0.97
WHVC + road gradients* no data removed	1.00	0.75	0.95

*road gradient compensates lower power demand due to vehicles speed limit < 87 km/h

Table 9.6 MAN model verification results

Different to parallel hybrid concepts and vehicles equipped with a shift transmission, no data can reasonably be removed for this vehicle concept when performing the linear regression analysis. This does not need to be a disadvantage at all, but for serial hybrid concepts the more challenging issue turned out to be that the combustion engine is in addition not mechanically coupled to any rotating part of the drivetrain. This adds an extra degree of freedom compared to parallel hybrid concepts where at least the engine's rotational speed is correct if the vehicle model is following the desired vehicle speed and the correct gear is engaged. Furthermore, if the driving resistances and drivetrain efficiencies and thus the power demand are adjusted correctly, the engine's torque will also match up.

For serial hybrid concepts the ICE speed and torque depends on various boundary conditions and to meet all of them accurately turned out to be harder than for parallel hybrid vehicle concepts, especially when the energy storage capacity is rather small and the ICE needs to be operated transiently, as is the case for the MAN hybrid bus. Once a different system behaviour occurs in the simulation, this can trigger different controller decisions later on, which may results in a very different system operation and avoid a successful model verification. Detailed time history patterns of validated signals can also be found in [19].

As already indicated in subsection 9.2.2 also the repeatability of chassis dyno measurements was investigated for the MAN test runs. Therefore the vehicle schedule was run and repeated on the chassis dyno using a driving robot. Figure 9.4 compares the two test runs and illustrates both vehicle speed and ICE torque patterns.

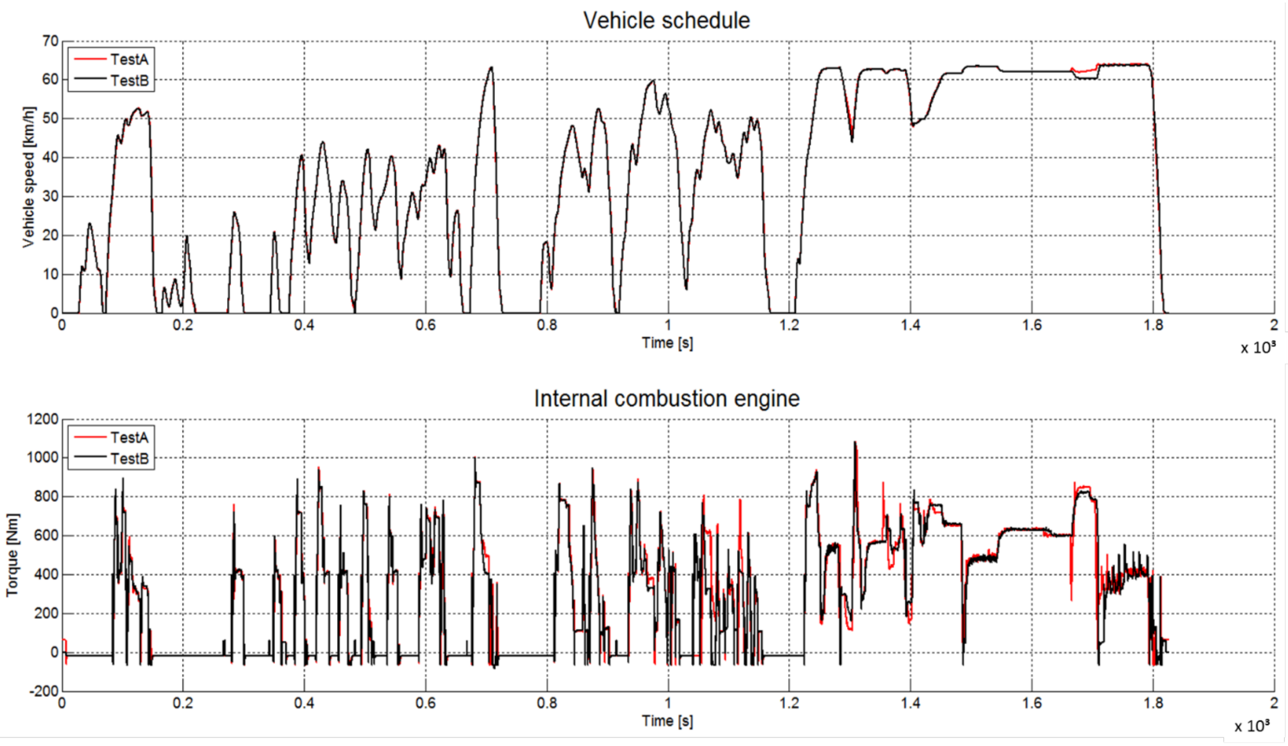


Figure 9.4 Repeatability of chassis dyno test using a driving robot

The linear regression analysis proves for the remaining verification parameters what Figure 9.4 already indicates for the ICE torque. Using a driving robot it seems possible to reproduce the vehicle behaviour on a chassis dyno, even though the most complex vehicle in terms of repeatability and simulation model verification was used here.

WHVC (1800 sec.)	Vehicle	Electric Motor		ICE		Battery
	Speed	Torque	Power	Torque	Power	Power
desired R^2	0.97	0.88	0.88	0.88	0.88	0.88
WHVC + road gradients* no data removed (10Hz raw)	1.00	0.93	0.94	0.92	0.93	0.91

*road gradient compensates lower power demand due to vehicles speed limit < 87 km/h
** filtering the quite noisy data increases the achievable results by up to 0.03 points

Table 9.7 Verification of chassis dyno repeatability (TestA vs. TestB)

9.3. On-road model verification

During the setup of the VTP2 work program road tests were considered as an attractive alternative to a chassis dyno vehicle measurement based model verification. Especially for hybrid vehicles equipped with multiple driven axles or brake energy recuperation on different axles, it is vital to reproduce these circumstances correctly on a chassis dyno. This might be difficult on a single roller driven chassis dyno or at least requires chassis dynos with appropriate capabilities for heavy duty hybrid vehicles, which are probably not easily available.

On-road testing on the other hand would naturally consider such circumstances but at the same time would face different challenges like changing environmental conditions, uncontrolled temperatures or unknown driving resistances. Also running the WHVC and its slope pattern on road would not be possible and the model verification would need to be performed based on any arbitrary road cycle. However, developing a procedure seems technically feasible and the IVECO tests have at least shown, that their verified HiLS model (using the WHVC including road gradients) was able to depict the hybrid system behaviour for a different test cycle as well without changing any parameters (see subsection 9.2.2).

To be as flexible as possible and prove the basic feasibility of a road verification procedure it was checked in a first step, if an on-road measurement based HiLS model verification would be valid and as accurate as its chassis dyno based counterpart. Therefore the HiLS model verification for the VOLVO 7700 Hybrid was also run based on an on-road data set following the same method and criteria as specified in gtr No.4 [3]. Since it is vital to know the driving resistances for a model verification, but no torque measurement rims were available, an initial test was performed just driving the vehicle on-road with the same vehicle weight as used for the chassis dyno tests in Ispra and no other measurement equipment than a CAN bus data logger. The driving profile is illustrated in Figure 9.5 where the road gradient was logged by the vehicle's internal acceleration sensor only. The engine operation pattern shows that the entire engine map was covered by the test run similar to the WHVC in accordance with Annex 1(b) of gtr No.4 [3].

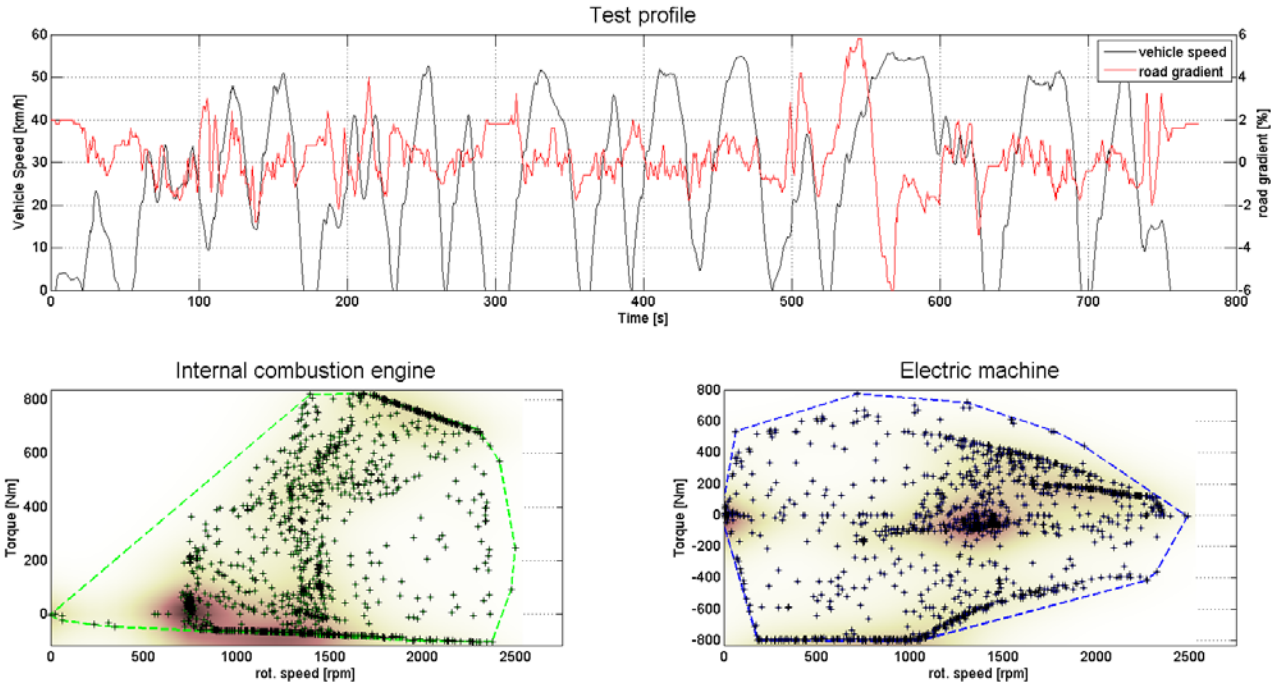


Figure 9.5 VOLVO on-road test profile

Using the HiLS model not fully verified at that time and parameterized with data from the chassis dyno tests in Ispra, the verification was performed also with the on-road data set which unfortunately needed to be recorded with a different bus available on site in Gothenburg. Average values for rolling and drag resistance coefficients were used since no actual values were available. Figure 9.6 illustrates the initial result for the vehicle speed only and shows quite high deviations which are far from passing the verification criteria. Even though the logged pedal positions were used as model input, the differences and variations in driving resistances on-road were too big compared to the chassis dyno run, which was used for parameterizing the model, and caused a clear mismatch between simulated and recorded data.

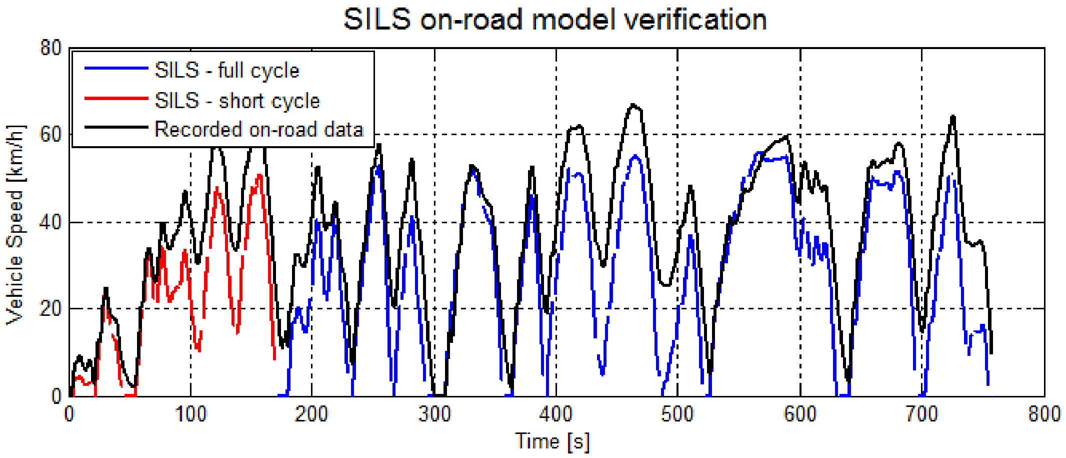


Figure 9.6 VOLVO on-road model verification (hot system temperature)

Since general doubts were expressed by members of the HDH informal group whether a model is able to depict the vehicle behaviour correctly when running the WHVC vehicle schedule for a HiLS certification but a different cycle was used for model verification and with respect to the remaining workload in the project, no more investigations were done and the HDH informal group agreed on the on-road verification procedure being out of scope of VTP2 [20]. Therefore also no further investigations depicting the rolling resistance on-road have been made, even though encouraging possibilities have at least been discussed.

9.4. Summary and Conclusions

The chassis dyno tests performed to gather reference data for a subsequent simulation model verification turned out to be already the first significant link in a sensitive chain to a successful model verification. Especially the desired road loads need to be adjustable as accurately as possible for the test runs. Therefore the roller and roller-tire system should be preconditioned and preferably operated in a constant temperature range where the resulting losses are known. To prove the system’s accuracy it is further suggested to also perform constant speed tests prior to the verification test runs and compare measured and calculated traction powers to ensure a certain accuracy at least for constant speeds. Since the vehicle’s energy flows are also affected by auxiliaries, an accurate acquisition of their power consumption is also desirable.

The HiLS model library was developed in parallel to the model verification process and thus no OEM was able to use the final model version for the verification tests, nevertheless the version IVECO used was close to final. All OEMs considered the models as sufficiently flexible to represent all vehicle and component properties, the interfacing with hardware controllers was also sufficient. IVECO was also the only one who used a full HiLS setup and could finally succeed in validating their vehicle model. This is certainly not only because of these two instances but furthermore roots in vehicle properties and a hybrid system layout quite similar to vehicles in the Japanese market which have already been certified using HiLS. However, independent of the use of HiLS, SiLS or MiLS it was demonstrated that an increased hybrid system complexity increases the model verification effort significantly and the replication of the vehicle behaviour gets especially challenging when the simulation horizon is large. Consequently, the model verification for the MAN serial hybrid system, which is the most complex of all systems tested in terms of model verification, was not successful when applying the Japanese verification criteria. Due to increased degrees of freedom for the VOLVO vehicle (12 vs. 6 speed gearbox) the verification criteria could also be met only partly. Both buses simply offer more degrees of freedom in their operation and thus make a model verification more difficult. Considering the fact that both performed a verification with specific focus on a second by second signal and vehicle behaviour alignment over a 30 minutes total simulation period for the first time, the results are still quite satisfactory. In addition the Japanese delegation, which's members already have practical experience in HiLS vehicle certification, felt confident that the verification criteria could also be met for these two vehicles if additional effort was put into the model parameterization. Also the use of the latest HiLS model library version may offer potential for further optimization.

The fact that future hybrid system models, with increased system complexity and even more degrees of freedom in their operation, may not be able to be verified also raised demands for less stringent verification criteria and methods in the group. Therefore alternative criteria were pre-investigated. Comparing integrated values (e.g. component work) and frequency distributions was considered but to ultimately ensure the same emission behaviour for an actual test vehicle and the HEC cycle resulting from its simulation model, only the second by second alignment of engine speed and torque and thus the linear regression analysis and its limit values seem appropriate. All other methods with less focus on the chronological behaviour of the combustion engine which have been considered cannot ensure that the HEC cycle and thus its resulting emissions reflect the vehicle emissions during real world operation (running the WHVC). Further investigations could not be performed within the timeframe of the HDH mandate but alternatives like a stepwise verification could be aimed at, where the model is operated in open loop using different extents of measured data as model input to demonstrate its validity (e.g. gears could once be pre-set according to the measured data and once be shifted by the respective ECU). Partitioning the verification in sub-section (e.g. Minicycles) could also serve to eliminate cumulative errors which may trigger different system behaviours. However, it was agreed at the 17th meeting of the HDH informal group to adopt the verification criteria as laid down in Kokujikan No. 281 [1] and consider a modification of the criteria or the verification method in a potential amendment later on.

The final method developed to consider thermal behaviour of the hybrid system in the simulation could not be tested within the VTP2 directly, since the verification tests had been performed before the method was fully developed. The model verification was therefore performed just for warm system conditions. However, NTSEL conducted a HiLS test including the predicted temperature method and demonstrated its feasibility.

Final emission results, comparing actual vehicle emissions on the chassis dyno, emissions measured on an engine test bed when running the recorded chassis dyno engine cycle and emissions measured when running the HEC cycle derived from a verified simulation model on the engine test bed, could not be evaluated within the given project time schedule. Resulting emissions and the effects considering the respective system work for a specific emission calculation, are of further interest.

It was shown that the reproducibility of vehicle measurements on the chassis dyno is rather challenging, but good results could be achieved using a driving robot. However, assuming a verified vehicle model is generally valid and able to depict the vehicle behaviour for any test cycle, there is hardly a need for a repeatable chassis dyno test. However, additional test data would have been desirable. The investigation and development of an on-road model verification procedure, which is intended to make the model verification easier but may also face different problems, was agreed to be aborted before meaningful test data could be obtained due to concerns regarding the general feasibility and model validity for various test cycles raised by contracting parties of the group. Conducting various test cycles on the rollers and performing a model verification could already help to get familiar and confident with a possible procedure and at least the IVECO tests demonstrated their model validity for two different test runs and thus indicated further possibilities there.

10. CO_2 determination methods

In certain national legislations different CO_2 determination procedures and methods for conventional heavy duty vehicles are already available or in a quite advanced development stage. The European Union for example is currently developing a CO_2 calculation tool for conventional HD vehicles (VECTO) based on vehicle simulation, in the United States provisions for simple hybrid systems based on actual powertrain testing are already available. However, no methods are currently known which can easily and accurately assess CO_2 emissions for hybrid vehicles during in-use operation and would thus allow a reasonable CO_2 vehicle labelling. The shortcoming of all existing CO_2 determination procedures is that the specific hybrid control strategy, which is one of the decisive influence factors on fuel consumption, cannot be integrated into the simulation. Since the developed HiLS procedure is able to consider actual hybrid system operations and so would allow to derive representative in-use fuel consumption behaviour, the HDH informal group started to investigate possible interfacings of current CO_2 determination methods and the developed HiLS exhaust emission procedure for heavy duty hybrid vehicles. The pre-studies are mainly based on CO_2 determination by HiLS or linking the VECTO tool to HiLS.

10.1. Possibilities of calculating CO_2 emissions from HDH

Test procedures for vehicle related CO_2 emissions from HD vehicles exist in Japan, the US as well as in China and are in a preparation stage in the EU. These test procedures use a simulation tool for calculating the CO_2 emissions over a vehicle speed cycle which is representative of the respective vehicle class. In the simulation tools the power demand from the engine to overcome the driving resistances, the losses in the drivetrain and the power demand from auxiliaries is calculated and transferred into an engine load cycle (i.e. speed and torque) by a transmission model. The fuel consumption is then interpolated from an engine map. How the necessary input data (i.e. vehicle mass, air resistance, rolling resistance, engine map etc.) is measured and in which detail these test results are implemented into the simulation tool is different for each regulation and also different for the single components (from vehicle class dependent default values up to vehicle specific test data).

Since vehicle related CO_2 emissions should be directly comparable for HDH and for conventional HDV, a harmonisation of the approaches for CO_2 testing for both vehicle categories is important. Since the existing approaches for conventional HDV around the world are not harmonised and certainly will give different results when applied for the same vehicle, the HiLS method can hardly be made comparable to all existing methods.

Several options to provide a standardized interface between the different CO_2 simulation tools and the HiLS simulation tool were drafted in order to make the HiLS approach applicable to the determination of vehicle specific CO_2 emissions [14]. The initial investigations regarding the exchange of power or speed and torque demand over time between the two simulation tools did not deliver the expected results [21]. The high gradients in torque that occur when tracking the given target speed and torque traces by controlling the actual torque generated by the hybrid system led to errors during the simulation runs with real ECUs in the HiLS model.

The following investigations were concentrated on linking the European CO_2 simulation tool VECTO with HiLS, since VECTO was the most advanced and complex CO_2 simulation tool at this time but the basic methodology could be applied to other CO_2 simulation tools as well. The VECTO tool is able to calculate fuel consumption for a complete vehicle over a speed cycle or in engine-only mode dependent on the speed and torque points. Since it is not possible to cover all different layouts of hybrid systems and especially their respective operation strategy in VECTO, the engine-only mode enables a viable link for hybrid vehicles. The approach chosen for the investigations was to set up the same vehicle (i.e. driving resistances and mass) with conventional powertrain in VECTO and with hybrid powertrain in HiLS. This is necessary because the reference mission profiles in the EU method are defined as target speed over distance and a conversion into actual vehicle speed over time as the input for the GTR HiLS tool is needed, since the HiLS model is not capable of simulating target speed cycles with all the advanced driver functionalities included in VECTO (e.g. look-ahead cruising before mechanical braking, overspeed functions, acceleration demand limits). In order to make the vehicles' performance comparable and to produce realistic speed cycles, a virtual combustion engine that represents the hybrid power pack has to be defined in VECTO. Then VECTO is used to produce the test cycle (i.e. vehicle speed and gradients over time) as input for HiLS. After this transformation step, the HiLS simulation is run with the converted actual vehicle speed cycle from VECTO. In a final step the resulting combustion engine load cycle from the HiLS tool is used to calculate the fuel consumption using the engine-only mode in VECTO. This is necessary to ensure comparability of results between HDV and HDH by using the exact same interpolation routine for calculating the fuel consumption from the engine map that is not available in the HiLS tool. In a post processing step, the total fuel consumption over the test cycle is calculated from the specific fuel consumption of the hybrid powerpack in the HiLS model in g/kWh and the cycle work from the VECTO tool in kWh/km to harmonize the results for HDV and HDH. This additional step is necessary due to differences in total cycle work of the two simulation models resulting mainly from the driver model but also from slightly different system dynamics in HiLS.

In principle the evaluated approach is based on a simple data exchange in two steps, one step from VECTO to HiLS and a second step back from HiLS to VECTO, and should work with all existing CO_2 simulation tools requiring only minor adaptions of the existing tools. The principle and the data flow of this approach are shown in Figure 10.1 and a more detailed explanation can be found in [22].

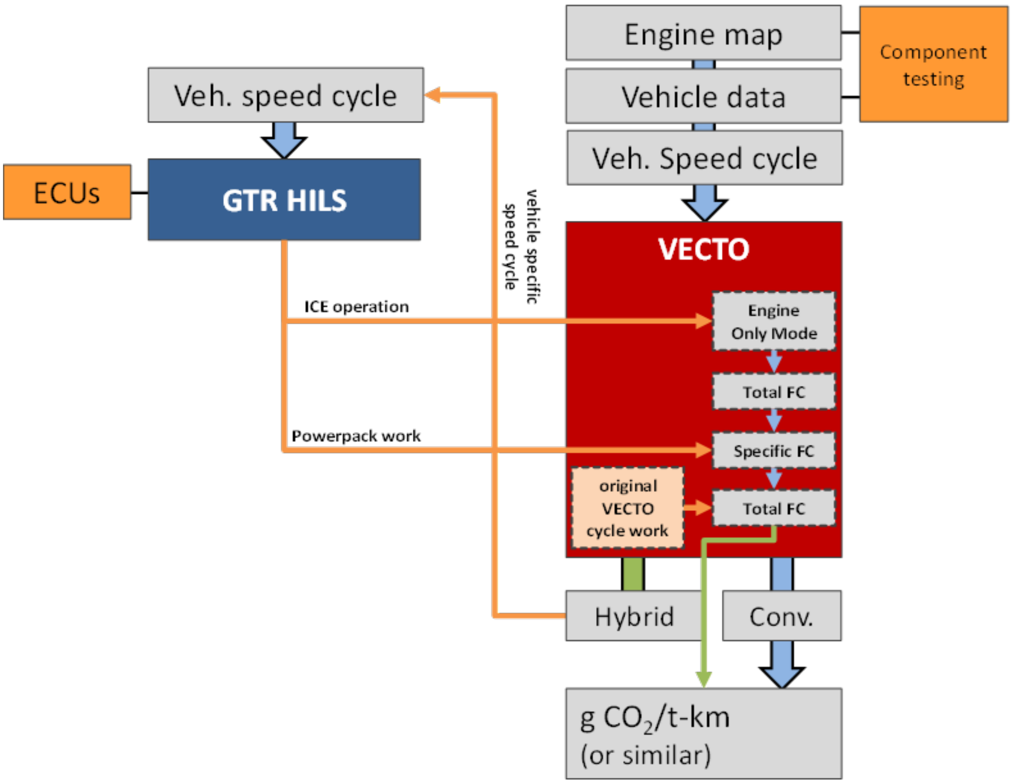


Figure 10.1 Interaction between VECTO and HiLS

10.2. Restrictions and clarification

The performed investigations showed that the interaction between the CO_2 calculation tools and the HiLS simulation could work in principle and deliver reasonable results. Nevertheless, there were some weaknesses identified that are described below and need to be investigated in detail in order to establish a stable method for CO_2 declaration of HDH in the future.

The existing simple driver model in the HiLS tool is not able to follow the given reference vehicle speed trace from the VECTO tool exactly (see Figure 10.2). Due to the dynamic system behaviour of the forward calculating GTR HiLS model with the driver model engaged in a feedback loop, there is a time delay and the system cannot react immediately to the requested reference speed. Additionally, overshoots of the vehicle speed occur at points in the cycle where phases of acceleration or deceleration change directly into cruising phases. As shown in Figure 10.2, the simple driver model also leads to a very transient operation of the hybrid power pack with high load changes compared to the much smoother operation of the VECTO tool which just calculates an average power demand over one second. This very aggressive pedal actuation is not representative of a normal driver but simply due to the dynamic system behaviour of a forward calculating model as well as the simple controller used for the driver model. A more advanced driver model could improve these shortcomings and lead to smoother operation, especially of the combustion engine. Thus the possibility and feasibility of an advanced driver model with some kind of look-ahead functionality should be investigated in order to establish a better comparability and correlation between the CO_2 simulation tools and HiLS.

If a more advanced driver model that is able to follow a given speed profile from VECTO more smoothly was implemented, a standard procedure for the definition of the virtual combustion engine (or powertrain including equivalent efficiencies, respectively) in VECTO that is equivalent to the hybrid powerpack is another open issue to be solved. Only a virtual combustion engine that is representative of the hybrid powerpack in the respective HDH in HiLS would deliver a realistic speed cycle as output from VECTO that can be tracked by the vehicle model in HiLS.

Since the given reference speed cycle from VECTO can never be tracked exactly, even with a perfectly optimized driver model, the avoidance of the transformation of the distance-based target speed cycle to the actual time-based speed cycle in VECTO would be an even better long-term solution. In order to minimize the inherent error due to the detour via VECTO for the transformation of the target speed cycle, a complex driver model with similar, advanced driver functionalities as in VECTO as well as smoother operation characteristics of the vehicle has to be implemented into the HiLS tool. This would need investigations concerning the feasibility of the suggested concept as well as the implementation and comparison of different approaches for the complex driver model.

An additional issue would be to define a standardized driver model that is still compatible with any vehicle. Especially functions like look-ahead coasting with pre-calculation of the resulting decelerations to determine the proper timing for releasing the accelerator pedal pose a challenging task for a standardized driver model. The future decelerations in look-ahead coasting mode (i.e. accelerator pedal completely released) for a conventional HDV can easily be pre-estimated since they are only dependent on the engine's motoring torque curve. Whereas in hybrid vehicles different hybrid systems will react differently (e.g. eco-roll with engine off and no recuperation vs. active recuperation) to the driver releasing the accelerator pedal, making a projection of the future vehicle deceleration difficult. Even one specific hybrid system could react differently to the driver releasing the accelerator pedal depending on the current operation mode (e.g. different degree of recuperation). These characteristics could be very vehicle specific for hybrid systems thus making it difficult to define a standardized driver compatible with all vehicles or probably requiring an even more complex driver model, from which certain parts can be adapted to a specific vehicle.

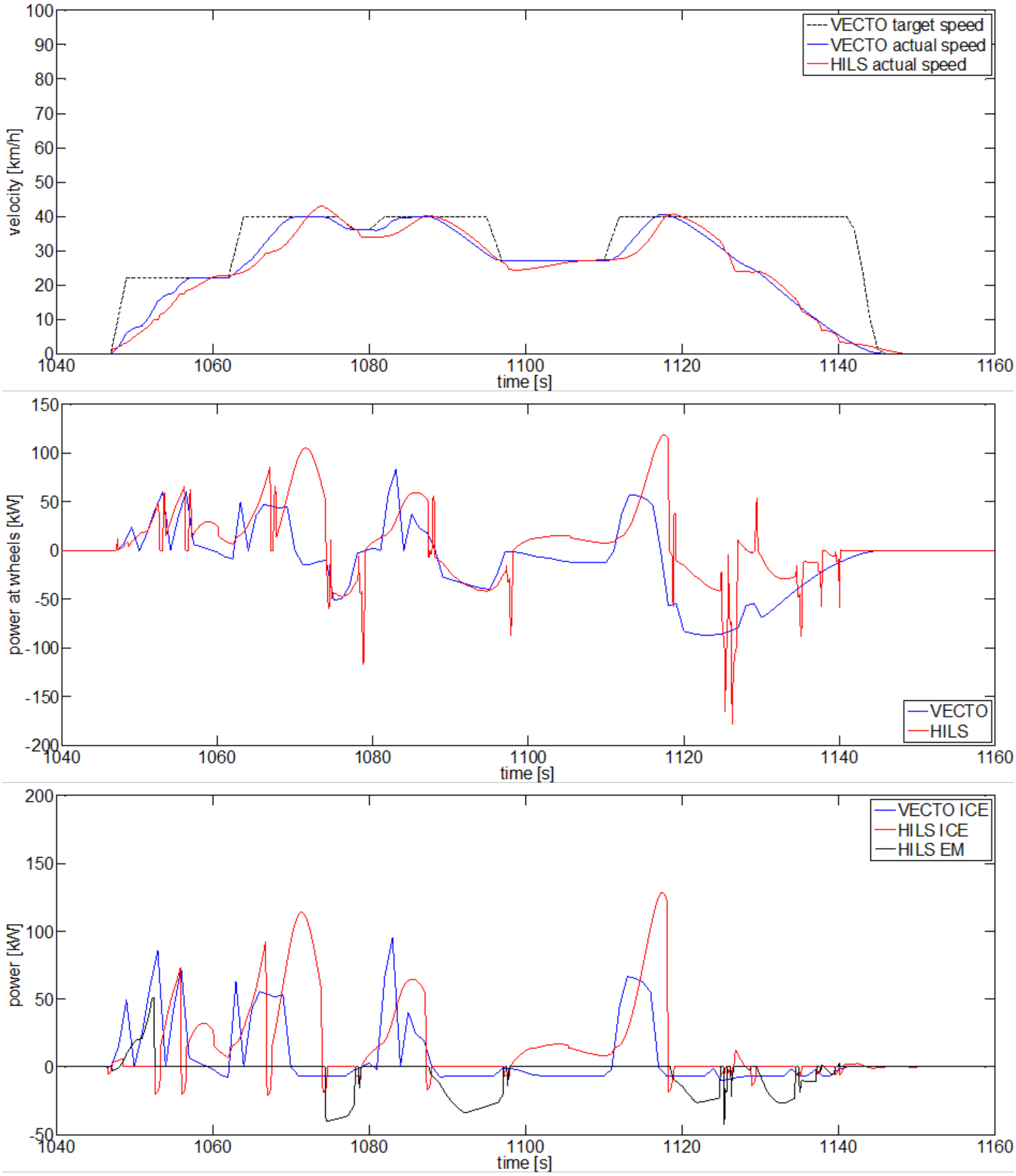


Figure 10.2 Exemplary part of the test cycle

Another open issue is the handling of auxiliaries or power take-off units for HDH. Auxiliaries are not considered in exhaust emission testing for HDH in order to be consistent with testing of engines installed in conventional vehicles. But auxiliaries will definitely be considered for the calculation of CO_2 emissions and simulation of their additional power demand will be part of the CO_2 simulation tools. The final solution for the handling of auxiliaries is still under development in the European CO_2 consumption method and detailed investigations cannot be started before the boundary conditions are defined for conventional HDV. The simple approach of a generic power demand over time for each auxiliary component is already be covered by the simple auxiliary models (i.e. electrical and mechanical power over time) in the current HiLS tool. The more complex approach of detailed models for each auxiliary component would require high programming effort to implement the respective additional component models into the HiLS tool. A simple handing-over of power demand over time from VECTO to HiLS is no viable option since the actuation and control of individual auxiliaries may depend on the specific hybrid control strategy.

10.3. Summary and Outlook

Even though pre-investigations were made, it was agreed by the HDH informal group to leave CO_2 out of the scope of the current work program and to leave the handling of the CO_2 declaration to the respective national authorities due to the different, non-harmonized approaches for the simulation of CO_2 emissions.

Since the effort for setting up a HiLS system is very high, especially the construction of the interface and the model verification, it is not ensured that all HDH will be certified for pollutant emissions using a HiLS system in the near future. Therefore, basic interim options for handling HDH in CO_2 certification are needed until the HiLS approach is evaluated in its practical application and is fully established for exhaust emission type approval. These interim options could either be generic table values for the fuel saving potential of HDH compared to a conventional vehicle with the same vehicle parameters or generic hybrid system models with generic hybrid operating strategies included in VECTO. The generic table values could be normalized to reasonable parameters influencing the potential of energy recuperation like storage capacity, electric machine power and vehicle mass. The generic hybrid system models could be adapted for a specific vehicle with just a few parameters that could easily be derived from datasheets without requiring a verification of the model. Certainly, the resulting fuel consumption derived with these simple approaches would not be accurately representative of the real vehicle. Nevertheless the simulation would show a realistic fuel saving compared to a conventional vehicle.

All more complex options would consider the specific hybrid control strategy by integrating the ECUs (as hardware or software) into the simulation tool and thus deliver more realistic fuel consumption values representative of the real vehicle. Nevertheless, all of these complex approaches require a forward simulating approach with the downside that the runtime for the simulation increases significantly and integration of the specific control units always requires a complex verification procedure. Forward simulation is characterized by a driver model that actuates the vehicle control elements (accelerator and brake pedal, clutch, gearbox, etc.) to follow a driving cycle as well as possible and the actual vehicle speed is the result of solving the differential equations of motion with the propulsion power generated according to the driver command value. Whereas in backward simulation the required propulsion power is calculated based on the desired vehicle speed as an average value over a certain time period. The forward approach allows for more detailed modelling of each component and considers the dynamic system behaviour, but demands significantly more modelling effort and is generally less stable than backward modelling. The runtime in forward simulation will increase to real-time in most cases which means that the simulation of a test cycle takes exactly the time of cycle duration, especially for more complex driver models in combination with HiLS. Verification of the simulation model always needs high effort due to measurement runs of the real vehicle (most likely on a chassis dyno) to generate reference data in order to prove the validity of the integrated control algorithms.

Nevertheless, the methodology proposed and investigated during the research of the HDH informal working group is considered as a good basis for further investigations concerning the harmonization of simulation of CO_2 emissions between HDV and HDH as well as for the development and improvement of the driver model according to the issues identified.

11. Conclusions and outlook

After presenting all relevant aspects of the new developed test procedures as well as describing their background and interrelations in detail in the previous chapters, this chapter shall conclude the work performed on a less detailed level and give an outlook on areas of possible future activity. Additionally, more detailed sub-summaries are available at the end of each chapter.

Considering the ambitious project schedule and the novelty of the developed test procedures for engine emission type approval or certification on a global basis, a quite notable proposal for amendment 3 to gtr No.4 could be achieved and finalized by the HDH working group within the scheduled period of time. A fundamental basis, especially for the developed HiLS method, was given by the Japanese regulation Kokujikan No.281 [1], which, although it has the same basic principle, needed to be adapted extensively to make an alignment of conventional engine testing in accordance with gtr No.4 and testing of engines installed in hybrid vehicles possible. Since the developed HiLS method is largely based on vehicle simulation and certain manufacturers and type approval or certification authorities currently have the need for alternative test methods as well, a test method closer to conventional engine testing, based on an actual hybrid powertrain hardware test on a powertrain test bed, was developed in parallel as well. Both methods root in the same test cycle and test principles and are therefore supposed to deliver identical test results. Whereas the HiLS method derives the ICE operation for emission measurements on the engine test bed by simulation, the powertrain method directly measures ICE emissions on the powertrain test bed. However, due to the complexity and the strong dependence of hybrid systems on actual system and boundary conditions, the similarity of both test methods could not be entirely proven. Although it would have been desirable, testing and comparing both methods could not be conducted within the validation test programs performed.

Especially when starting from scratch, the developed procedures for a hybrid engine certification seem to increase the test effort and complexity compared to conventional engine testing (WHTC) quite notably. Nevertheless, they enable a manufacturer to consider the hybridization of the powertrain and thus the difference in ICE operation also for the emission certification of the engine, including all its advantages and disadvantages. With regard to the developed system work concept this, however, seems to offer a potential for a simplification of the engine or the exhaust system or may even allow to improve fuel consumption still meeting the existing pollutant emission limit values. Since the engine test cycle derived by the new test methods is more vehicle specific than the WHTC, it is expected to also reflect the ICE operation and thus the emission behaviour during in-use operation of a specific vehicle more appropriate and thus to give a more representative sample of the expectable environmental impact.

A common basis for all test methods specified in the draft proposal of gtr No.4 [3] is the similar load demand for each propulsion system, either hybrid or conventional. For a conventional engine test procedure the respective WHTC represents the power required for vehicle propulsion, for the HiLS and the powertrain test procedure the WHVC including road gradients and the respective vehicle parameters define the propulsion power demand for the hybrid system in the test cycle. To nevertheless allow a comparability and consider the current WHTC emission limit values as valid also for the newly developed test procedures, both test cycles were aligned in terms of power and work demand. This could be achieved by adding road gradients to the vehicle schedule in accordance with the enhanced Minicycle method and the introduction of generic vehicle parameters.

For conventional engine testing the absolute load level of the respective engine WHTC is defined by the engine’s power, more specifically the shape of its full load torque curve. This ensures a test up to the engine's maximum capacities. A similar definition to define the load level during the test was needed for hybrid systems as well. Different to the WHTC engine test, the system load for a test in accordance with Annex 9 or 10 is defined by the WHVC vehicle schedule and its road gradients and the respective vehicle parameters. Using the individual parameters for each test vehicle specifically would vary the load even though it would be always the same hybrid system (one hybrid system in different vehicles) and demanding its full load capacities would not be granted. To test the hybrid system up to its maximum capacities and define the load level for the test, both load defining parameters (WHVC vehicle schedule and vehicle parameters) have also been made a function of the hybrid system's rated power. This makes a partially vehicle independent hybrid system certification possible, since each power rating is then associated with a specific representative vehicle and a specific test cycle. Furthermore a family approach similar to the engine family was adopted also for hybrids. As a result, road gradients and vehicle parameters were designed as a function of power to demand the same load from a hybrid system as the WHTC would demand from an equally powered combustion engine. A consideration of the hybrid system's full load torque had to be rejected and a test procedure for the rated power of a hybrid system was developed instead.

Due to the limited availability of hybrid energy and design properties of the hybrid systems, the determination of a representative power rating turned out to be more complex than for conventional engines. Nevertheless, a test method was developed where the hybrid system can be rated in a way that the test cycle demands the system's full load capacities in any case. An approach of comparing driving performances instead of component power ratings was chosen in order to avoid the discussion on the definition of electric (hybrid) peak vs. continuous power. Even though reasonable results were obtained and a positive feedback could be reported for the tested vehicles in VTP2, a drawback could also be identified which may need some further consideration (section 7.3).

E*nsuring* similar boundary conditions by measures as described in this report for all test procedures, the hybrid system can finally be tested either using the HiLS or the powertrain method. Both aim to reflect a chassis dyno test and are thus supposed to deliver the same test result. The HiLS method focuses on the simulation of powertrain components to reduce test effort. Compared to Kokujikan No.281 [1] an entirely new and more flexible modelling environment was established. Once a powertrain model has proved its accuracy, it can be used for multiple powertrain derivatives following certain provisions, consequently minimizing test effort. To also align the new method with the procedures for conventional engine testing in gtr No.4, comprehensive accompanying measures were made in addition to the modifications to Kokujikan No.281 [1]. All developed measures like the vehicle schedule, the generic vehicle parameters, the hybrid rated power test procedure, the system work concept and the predicted temperature method are interrelated and can only be adapted jointly, if needed. Since the powertrain method reflects the same test principle on an actual test bed as performed by the HiLS model in simulation and the powertrain components are present in actual hardware, most of the provisions in Annex 9 can also be applied to Annex 10. Some special provisions were needed for the powertrain method, mostly targeting the hardware setup of the powertrain on the test bed.

F*or* calculating the final emission results in g/kWh it was agreed to consider the entire propulsion work delivered by the hybrid system and not only the combustion engine's work over the test cycle. This allows a fair comparison of conventional and hybrid vehicles in terms of criteria pollutant emissions and allows to consider the benefits of hybridization at the certification as well. In addition the environmental impact is reflected correctly by this method for both vehicle types, conventional and hybrid vehicles. However, as was recognized in VTP2, drawbacks for specific vehicle configurations can result when a hybrid vehicle test, using the developed WHVC vehicle schedule in combination with the system work concept, is applied. Even though this can lead to disadvantages compared to conventional engine testing for specific hybrid vehicle layouts in terms of pollutant emission certification, it nevertheless reflects the impact on the environment correctly and the disadvantages do not originate from the system work concept. In fact the WHVC vehicle schedule is simply inappropriate for certain vehicles (section 6.4).

***A**ll* complementary measures achieved and agreed in the HDH work group can briefly be summarized in the development of:

- The WHVC vehicle schedule which was aligned with the WTHC engine schedule in terms of power and cycle work demand by introducing road gradients
- A method to account for the propulsion work delivered by the entire hybrid system which defines the basis for the calculation of specific emissions of hybrid propulsion systems
- A procedure to determine a representative power rating for a hybrid system with variable power capabilities during operation
- Generic vehicle parameters which make it possible to align conventional and hybrid vehicle testing and also reduce the effort for the certification test procedure
- A hybrid family concept similar to the engine family concept in gtr No. 4 [2]

***V**alidation* test program 2 served to develop and validate the previously described procedures. Chronologically starting with the chassis dyno test for each vehicle, it could be identified that especially the application of driving resistances and the correct determination of the power flows in the system form the basis for a successful model verification. The developed HiLS model library was confirmed as sufficiently flexible by all participating OEMs. Although VOLVO and MAN were quite close, a successful model verification could only be achieved for the IVECO vehicle using a complete HiLS setup. During the VTP2 it could be clearly identified that more complex vehicles which offer more degrees of freedom in their system operation make a model verification increasingly difficult and thus alternative verification methods were also investigated and discussed. However, the Japanese delegation, which has clearly more experience in HiLS model verification, felt confident that further effort would give positive verification results and thus the verification criteria as stated in the original Japanese regulation have been agreed on within the HDH informal group.

***T**he* open issues identified in the final report of validation test program 1 [12] could be solved to a satisfactory extent by the HDH informal working group. Remaining issues can probably be identified for C7 [12], which targets the distinction of conventional and hybrid engine testing and H1, which is about the future maintenance of the HiLS model library. Even though specific provisions were installed in the draft proposal of gtr No.4 [3] for C7, they may not be conducive to a global harmonization and adaptions of the criteria for distinction may be needed later on. At least they allow a stepwise introduction of the newly developed test procedures at this point in time. In the same context, H1 was only partially discussed in the group.

Further concerns to C7 were addressed by the US EPA in [23]. Without discussing the details, a key issue for both developed test procedures in terms of result verifiability by governments or their representatives, seems to be the lacking practical experience without an OEM involvement at this time. This naturally raises concerns about the independent verifiability. To gain experience and get confident with the methods proposed, further testing would of course be desirable. However, since hybrid powertrains are supposed to get even more complex in the future, there will always be the ever increasing need to involve OEMs or their suppliers in the certification and type approval process as well. Fully independent testing without OEM input is even now hardly possible and even for the powertrain method in [9] a manufacturer involvement was required and the ECU firmware needed to be modified by the supplier. Nevertheless, a broader test experience, as demanded by US EPA, would be desirable.

However, due to the novelty of the developed test procedures, limited testing time and capacities, future discussions or improvements of the procedures will probably be needed, especially regarding the bullet points listed below. Details are presented in the respective sections of the report.

Powertrain method:

- Application of the powertrain method and actual measurements in accordance with Annex 10, which could not be performed within VTP2
- Evaluation of final emission test results for both test methods comparing one specific hybrid powertrain

HiLS method:

- Application and review of the HiLS model verification criteria considering more and more complex test vehicles, also with regard to the applicability of the test method for higher powered vehicles on the chassis dyno as well as for different, more complex hybrid topologies
- Application and review of the defined cold and hot start procedures using the predicted temperature method, which could not be extensively tested during VTP2

Rated power test procedure:

- Validating the developed test method by additional powertrain/HiLS tests. Possible overestimations of the rated power could occur depending on the hybrid component properties, which could result in too high power demands in the test cycle
- Evaluation of the applicability on a powertrain test bed, since no tests were performed during VTP2 and thus no experience could be gathered

Hybrid family concept:

- Application and review of the hybrid family concept. Due to the uniqueness of the ICE operation pattern of different hybrid powertrains, it is quite likely that each hybrid powertrain defines its own family and the inclusion of children into an existing family is hardly possible

WHVC vehicle schedule:

- Identification of emission improvement potential due to individual ICE torque/speed patterns also for conventional vehicles and identification of variances of emissions derived by WHTC engine testing compared to HiLS/powertrain testing of a conventional vehicle (application of Annex 9/10 on conventional powertrain)
- Evaluation and review of vehicle schedule for heavy and more sluggish vehicles on a chassis dyno

General:

- Evaluation of the distinction criteria for hybrid and conventional vehicles (definition of micro-hybrids)
- Applicability of developed procedures on hybrid vehicles revealing different topologies than commonly used parallel or serial ones
- Identification of interferences and demands to current national legislations with respect to CO_2 or in-service conformity requirements

12. Bibliographie

[1] „Kokujikan No.281,“ 16 03 2007. [Online]. Available: https://www2.unece.org/wiki/download/attachments/4064802/TS%2012-2-34%20-%20281.pdf?api=v2. [Date of access 07 10 2014].

[2] UNECE - Transport, „UN gtr No.4,“ 25 01 2007. [Online]. Available: http://www.unece.org/trans/main/wp29/wp29wgs/wp29gen/wp29glob_registry.html. [Date of access 2014 09 16].

[3] UNECE - GRPE, „GRPE-69-10, Proposal for draft Amendment 3 to gtr No.4,“ 05-06 06 2014. [Online]. Available: https://www2.unece.org/wiki/download/attachments/23102088/GRPE-69-10.pdf?api=v2. [Date of access 16 09 2014].

[4] Steven, H., „Development of a Worldwide Harmonised Heavy-duty Engine Emissions Test Cycle, Final Report,“ 01 06 2001. [Online]. Available: http://www.unece.org/fileadmin/DAM/trans/doc/2001/wp29grpe/TRANS-WP29-GRPE-42-inf02.pdf. [Date of access 04 09 2014].

[5] Hausberger S., Rexeis M., Luz R., „HDH-13-04e, Transmission and Gear Shift calculation in VECTO,“ 21 03 2013. [Online]. Available: https://www2.unece.org/wiki/download/attachments/5800673/HDH-13-04e.pdf?api=v2. [Date of access 23 09 2014].

[6] AUTOSAR, „Explanation of Application Interfaces of the Powertrain Domain,“ AUTOSAR, 31 10 2013. [Online]. Available: http://www.autosar.org/fileadmin/files/releases/4-1/application-interfaces/powertrain/auxiliary/AUTOSAR_EXP_AIPowertrain.pdf. [Date of access 16 09 2014].

[7] UNECE GRPE HDH, „HiLS Model library,“ Graz, Vienna and Chalmers University of Technology, 30 05 2014. [Online]. Available: https://www2.unece.org/wiki/download/attachments/4064802/HILS_GTR_v1.02%20%281%29.zip?api=v2. [Date of access 31 07 2014].

[8] Kawai, T. , „HDH-17-05e, Response of HILS to Cold-Start Test,“ NTSEL Japan, 09 04 2014. [Online]. Available: https://www2.unece.org/wiki/download/attachments/18546752/HDH-17-05e.pdf?api=v2. [Date of access 04 08 2014].

[9] EC, EPA, „HDH-11-08e, Heavy Duty Hybrid Powertrain Testing,“ EC, EPA, 10 10 2012. [Online]. Available: https://www2.unece.org/wiki/download/attachments/2523354/HDH-11-08e.pdf?api=v2. [Date of access 07 08 2014].

[10] Stein, H.J., „HDH-15-11e, Minutes of the meeting,“ Technical secretary of the HDH informal group to GRPE, 24 10 2013. [Online]. Available: https://www2.unece.org/wiki/download/attachments/12943378/HDH-15-11e.pdf?api=v2. [Date of access 04 09 2014].

[11] Danczyk, C., „HDH-15-06e, Consideration on Vehicle Parameters for HILS Simulation,“ OICA, 24 10 2013. [Online]. Available: https://www2.unece.org/wiki/download/attachments/12943378/HDH-15-06e.pdf?api=v2. [Date of access 01 08 2014].

[12] Six C., Silberholz G., Fredriksson J., et al., “Final report of the Research Program (VTP1) on an Emissions and CO2 Test Procedure for Heavy Duty Hybrids (HDH),” TNO innovation for life, Delft, The Netherlands, 2013.

[13] TNO Automotive, TÜV Automotive, „Development of a World-wide Heavy-Duty Engine Test Cycle, 2nd Interim Report,“ Delft, The Netherlands, 2000.

[14] Hausberger S., Silberholz G., Kies A., et al., „Report of the Research Program on an Emissions and CO2 Test Procedure for Heavy Duty Hybrids (HDH),“ TNO innovation for life, Delft, The Netherlands, 2012.

[15] Silberholz G., „HDH-15-07e, Development of WHVC weighting factors,“ 24 10 2013. [Online]. Available: https://www2.unece.org/wiki/download/attachments/12943378/HDH-15-07e.pdf?api=v2. [Date of access 18 09 2014].

[16] Choi, D., „Introduction to System Power Concept and its Application,“ KATRI (Korea Automobile Testing and Research Institute), 17 10 2013. [Online]. Available: https://www2.unece.org/wiki/download/attachments/12058681/EVE-07-06e.pdf?api=v2. [Date of access 28 07 2014].

[17] Perujo, A. , „HDH-15-09e, HDH Validation Program 2 (HILS),“ EC-DG JRC, Inst. for Energy and Transport, Sustainable Transport Unit, 24 10 2013. [Online]. Available: https://www2.unece.org/wiki/download/attachments/12943378/HDH-15-09e.pdf?api=v2. [Date of access 08 08 2014].

[18] Silberholz, G., Six., C., „HDH-15-04e, Report of the Institutes,“ Graz, Vienna and Chalmers University of Technology, 24 10 2013. [Online]. Available: https://www2.unece.org/wiki/download/attachments/12943378/HDH-15-04e.pdf?api=v2. [Date of access 08 08 2014].

[19] Silberholz, G., Six., C., „HDH-17-07e, Report of the Institutes,“ Graz, Vienna and Chalmers University of Technology, 08 04 2014. [Online]. Available: https://www2.unece.org/wiki/download/attachments/18546752/HDH-17-07e.pdf?api=v2. [Date of access 08 08 2014].

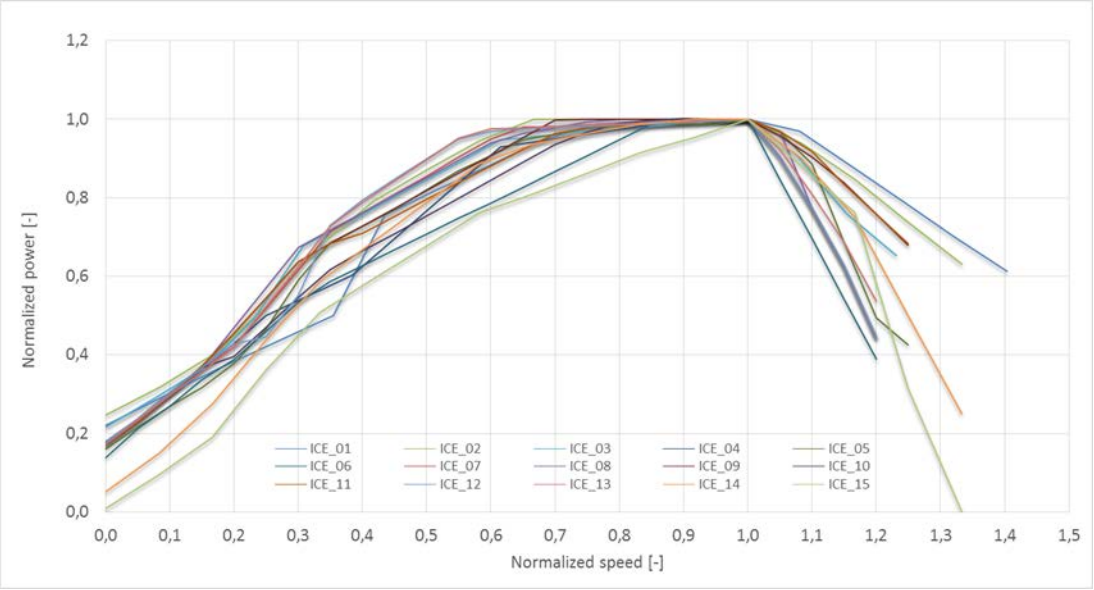
[20] Stein, H.J., „HDH-16-08e, Minutes of the meeting,“ Technical secretary of the HDH informal group to GRPE, 07 01 2014. [Online]. Available: https://www2.unece.org/wiki/download/attachments/15764041/HDH-16-08e.pdf?api=v2. [Date of access 25 08 2014].

[21] JASIC, „HDH-11-05e, Results of Examination and Issues to Address Regarding WHDHC,“ JASIC, 10 10 2012. [Online]. Available: https://www2.unece.org/wiki/download/attachments/2523354/HDH-11-05e.pdf?api=v2. [Date of access 29 09 2014].

[22] Kies A., Rexeis M., Silberholz G., et al.,, „Options to consider future advanced fuel-saving technologies in the CO2 test procedure for HDV,“ FVT GmbH, Graz, Austria, 2013.

[23] US EPA, „HDH-18-04e, Memorandum,“ US EPA, 03 06 2014. [Online]. Available: https://www2.unece.org/wiki/download/attachments/23102088/HDH-18-04e.pdf?api=v2. [Date of access 08 10 2014].

A Reference WHTC



Time [s]	normalized Power [kW/kW]
1	0
2	0
3	0
4	0
5	0
6	0
7	0,015877471
8	0,108598396
9	0,006959579
10	0,00431147
11	0,007974647
12	0,050048471
13	0,0426029
14	0,071152768
15	0,087853358
16	0,092551893
17	0,096975136
18	0,048073728
19	0
20	0,102598794
21	0,203291986
22	0,216022294
23	0,15395782
24	0,114060512
25	0,077070606
26	0,054180005
27	0,0440679
28	-0,078426763
29	-0,075137384
30	-0,069881314
31	-0,062658803
32	-0,053528162
33	-0,043539901
34	-0,035418068
35	-0,031488009
36	0,155692777
37	0,150457981
38	0,138106259
39	0
40	0
41	0
42	0
43	0
44	0
45	0
46	0
47	0
48	0
49	0
50	0,024323607
51	0,095530234
52	0,130640155
53	0,212445539
54	0,105088846
55	0
56	0,086401673
57	0,172531464
58	0,08687866
59	0
60	0,117265135
61	0,231256574
62	0,115050628
63	0
64	0,263147409
65	0,532650932
66	0,490580901
67	0,451191018
68	0,415503199
69	0,532230592
70	0,240371456
71	0,158587785
72	0,141064727
73	0,095573827
74	0,099027032
75	0,1507832
76	0,156602713
77	0,124366524
78	0,062384278
79	0
80	0,137986694
81	0,280055311
82	0,241010324
83	0,245669066
84	0,107271614
85	0,06919898
86	0,061030364
87	0,116605213
88	0,135711093
89	0,139000518
90	0,147501372
91	0,164479339
92	0,189563178
93	0,204803305
94	0,208030764
95	0,192093295
96	0,172158293
97	0,1608867
98	0,164340472
99	0,16845214
100	0,167297594
101	0,162673158
102	0,159604463
103	0,158926992
104	0,155095891

Time [s]	normalized Power [kW/kW]	Time [s]	normalized Power [kW/kW]	Time [s]	normalized Power [kW/kW]	Time [s]	normalized Power [kW/kW]
105	0,143822958	149	0	193	0	237	0
106	0,131684527	150	0	194	0	238	0
107	0,124663149	151	0	195	0	239	0
108	0,117286251	152	0	196	0	240	0
109	0,098922393	153	0	197	0	241	0
110	0,066008863	154	0,011794704	198	0	242	0
111	0,028792754	155	0,05554609	199	0	243	0
112	0,043713337	156	0,056912972	200	0	244	0
113	0,065859406	157	0,06833213	201	0	245	0
114	0,16456218	158	0,075101491	202	0	246	0
115	0,190944096	159	0,078936867	203	0	247	0
116	0,135056758	160	0,084931068	204	0	248	0
117	0,11008248	161	0,199879348	205	0	249	0
118	0,108670609	162	0,165653617	206	0	250	0
119	0,135757584	163	0,09041009	207	0	251	0
120	0,149444659	164	0,039005951	208	0	252	0
121	0,155586162	165	0,026674387	209	0	253	0,05866883
122	0,078025486	166	0,013796575	210	0	254	0,036862168
123	0	167	0,006931599	211	0	255	0,075091537
124	-0,0759451	168	0,007960254	212	0	256	0,336687694
125	-0,062360095	169	0,008860925	213	0	257	0,16656146
126	0	170	0,010727408	214	0	258	0
127	-0,072579551	171	0,010043584	215	0	259	0,307893534
128	-0,055473217	172	0,031746955	216	0	260	0,601273339
129	-0,04154674	173	0,075424456	217	0	261	0,64391755
130	-0,028226544	174	0,055025087	218	0	262	0,679859677
131	0	175	0,055112696	219	0	263	-0,121378938
132	0	176	0,041870518	220	0	264	-0,116272724
133	0	177	0,02349725	221	0	265	-0,100639424
134	0	178	0,020557959	222	0	266	-0,084090229
135	0	179	0,041492255	223	0	267	-0,075477286
136	0	180	0,059221405	224	0	268	-0,072579551
137	0	181	0,041916327	225	0	269	-0,071044763
138	0	182	0,027697835	226	0	270	-0,068131131
139	0	183	0,041091883	227	0	271	-0,063090221
140	0	184	0,057949175	228	0	272	-0,056982339
141	0	185	0,061570265	229	0	273	-0,050654199
142	0,009105112	186	0,048631288	230	0	274	-0,043803303
143	0,013582088	187	0,038544465	231	0	275	-0,03537519
144	0,06063696	188	0,023736636	232	0	276	-0,025482785
145	0,077148224	189	0,010944002	233	0	277	-0,016520374
146	0,03208426	190	0	234	0	278	0
147	0	191	0	235	0	279	0
148	0	192	0	236	0	280	0

Time [s]	normalized Power [kW/kW]
281	0
282	0
283	0
284	0
285	0
286	0
287	0
288	0
289	0
290	0
291	0
292	0
293	0
294	0
295	0
296	0
297	0
298	0
299	0
300	0
301	0
302	0
303	0
304	0
305	0
306	0
307	0
308	0
309	0
310	0
311	0
312	0
313	0
314	0
315	0
316	0
317	0
318	0
319	0
320	0
321	0
322	0
323	0
324	0,087027982
325	0,143995077
326	0,213772314
327	0,252468704
328	0,26604481
329	0,00067574
330	-0,064355975
331	-0,055191507
332	-0,046814762
333	-0,038977644
334	-0,031396445
335	-0,024028651
336	-0,016520374
337	0
338	0
339	0
340	0
341	0
342	0
343	0
344	0
345	0
346	0
347	0
348	0
349	0
350	0
351	0
352	0
353	0
354	0,000922271
355	0,009105112
356	0,164736744
357	0,180597231
358	0,340592394
359	0,16652025
360	0
361	0,214349871
362	0,436188675
363	0,700492158
364	0,351478647
365	0
366	0,326904142
367	0,642649809
368	0,269702345
369	0,135395324
370	0
371	0,228665293
372	0,458765584
373	0,60949613
374	0,633036281
375	0,652006727
376	-0,062759402
377	-0,062278123
378	-0,059587674
379	-0,054315444
380	-0,063316864
381	-0,073464917
382	-0,085925364
383	-0,069745284
384	-0,058475619
385	-0,048652363
386	-0,043078692
387	-0,040087557
388	0,053089752
389	0,072495107
390	0,15735489
391	0,433735602
392	0,568478934
393	0,283097197
394	0
395	0,265244849
396	0,538441875
397	0,591292921
398	0,634932571
399	0,685705311
400	0,755125012
401	0,834864028
402	0,417299049
403	0
404	0,263404149
405	0,521023614
406	0,696059461
407	0,771551661
408	0,281482157
409	0,176392643
410	0,045341461
411	-0,074591609
412	-0,073133624
413	-0,071195792
414	-0,069560516
415	-0,067497822
416	-0,06503062
417	-0,062041171
418	-0,058604558
419	-0,055065219
420	-0,052187425
421	-0,049897732
422	-0,047587617
423	0
424	-0,078316628
425	-0,067870658
426	-0,056825308
427	0
428	-0,072943539
429	-0,064734706
430	0,246057241
431	0,308748675
432	0,334933863
433	0,122984654
434	0,006684509
435	-0,06689404
436	0,153521585
437	0,342796074
438	0,426484589
439	0,210997434
440	0
441	0,262612213
442	0,526967764
443	0,2639485
444	0
445	0,024690465
446	0,050077808
447	0,025379477
448	0
449	-0,080208153
450	-0,074165535
451	-0,067870658
452	-0,061268897
453	-0,054315444
454	0
455	-0,080208153
456	-0,068016556

Time [s]	normalized Power [kW/kW]
457	-0,057797269
458	0
459	-0,061774969
460	-0,047239037
461	-0,03537519
462	-0,025379561
463	0
464	0,002780325
465	0,070715081
466	0,11197456
467	0,151923351
468	0,186240682
469	0,223722659
470	0,285861437
471	0,38163428
472	0,186825402
473	0
474	0,337323501
475	0,673193893
476	0,954053822
477	0,472433229
478	0
479	0,348924623
480	0,693745359
481	-0,118175082
482	-0,084630542
483	-0,071698212
484	0,449656028
485	0,637629384
486	0,793096515
487	-0,066755502
488	-0,065498894
489	-0,061524601
490	-0,055385342
491	0
492	-0,080538893
493	-0,065710953
494	-0,054991072
495	-0,048240741
496	-0,044734739
497	0,067501354
498	0,22882172
499	0,171626344
500	0,094900603
501	0,101678411
502	0,0991495
503	0,102446875
504	0,106682463
505	0,366883191
506	0,296523792
507	0,158918615
508	0,162543032
509	0,177639389
510	0,180485167
511	0,351673237
512	0,268030334
513	0,184060308
514	0,100354683
515	0,050237004
516	0
517	0,044366675
518	0,089134746
519	0,147011912
520	0,377025605
521	0,484108976
522	0,618698185
523	0,473549015
524	0,191018409
525	0,119858039
526	0,022224246
527	-0,061041339
528	-0,060623537
529	-0,059587674
530	-0,057797269
531	-0,055191507
532	-0,051868773
533	0
534	-0,07715224
535	-0,061041339
536	-0,047388935
537	0
538	-0,084846673
539	-0,076702214
540	-0,063164988
541	-0,0522365
542	-0,04500157
543	0,171284269
544	0,357476188
545	0,454578128
546	0
547	0,191507821
548	0,387881181
549	0,251332002
550	0,113803022
551	0,463627363
552	0,230333437
553	0
554	0,046130979
555	0,093275205
556	0,412977911
557	0,395803378
558	0,37646453
559	0,356173752
560	0,33489183
561	0,226221561
562	0,1757149
563	0,112178045
564	0,003283068
565	0
566	-0,068982374
567	-0,065498894
568	-0,061647543
569	-0,057797269
570	-0,055385342
571	0,041494133
572	0,287643135
573	0,279987753
574	0,311615085
575	0,183785534
576	0,113759403
577	0,115888141
578	0,058609597
579	0
580	0,058620699
581	0,117619405
582	0,134958604
583	0,0867142
584	0,050514448
585	0,121907401
586	0,140050552
587	0,39892695
588	0,527181343
589	0,197560435
590	0,187919745
591	0,240601122
592	0,045194111
593	-0,059059802
594	-0,058219517
595	-0,056982339
596	-0,055385342
597	-0,054315444
598	0,091210783
599	0,130251234
600	0,280137151
601	0,43894745
602	0,410810121
603	0,499694942
604	0,589420924
605	0,679497635
606	0
607	-0,069745284
608	-0,068313106
609	-0,066364979
610	-0,064355975
611	-0,062896915
612	0,278554705
613	0,598649568
614	0,787104753
615	-0,06936199
616	-0,068131131
617	-0,063773279
618	-0,05705954
619	-0,051202818
620	-0,045677773
621	0,184894252
622	0,246554623
623	-0,057377761
624	-0,048881329
625	0,23343015
626	0,260656564
627	0,128190788
628	0
629	0,063248879
630	0,130563299
631	0,063804435
632	0

Time [s]	normalized Power [kW/kW]
633	0,176333221
634	0,360701458
635	0,424710788
636	0,408835427
637	0,346699089
638	-0,055191507
639	-0,054768963
640	-0,050768772
641	-0,044481196
642	-0,036218042
643	-0,028742565
644	0
645	0
646	0
647	0
648	0
649	0
650	0
651	0
652	0
653	0
654	0
655	0
656	0,006344508
657	0,039032766
658	0,126724121
659	0,0432946
660	0
661	0,340527249
662	0,654411807
663	0,330040972
664	0
665	0,380082569
666	0,754679564
667	0,374560033
668	0
669	0,386705284
670	0,775135185
671	0,759684528
672	0,817710137
673	0,807557847
674	0,856280456
675	0,730602667
676	0,718232581
677	0,742402667
678	0,771336362
679	0,386164619
680	0
681	0,217784669
682	0,434909835
683	0,408145405
684	0,676868309
685	0,828607811
686	0,900011517
687	0,861461821
688	0,426523147
689	0
690	0,213945503
691	0,428553452
692	0,417458064
693	-0,045983374
694	-0,042777669
695	0
696	-0,078625605
697	-0,080374335
698	-0,066364979
699	-0,056699551
700	0
701	-0,07445913
702	-0,05705954
703	-0,046287423
704	-0,039227017
705	-0,029813918
706	-0,023171171
707	0
708	0
709	0
710	0
711	0
712	0
713	0
714	0
715	0
716	0
717	0
718	0
719	0
720	0
721	0
722	0
723	0
724	0
725	0
726	0
727	0
728	0
729	0
730	0
731	0
732	0
733	0
734	0
735	0
736	0
737	0
738	0
739	0
740	0
741	0
742	0
743	0
744	0
745	0
746	0
747	0
748	0
749	0
750	0
751	0
752	0
753	0
754	0
755	0
756	0
757	0
758	0
759	0
760	0
761	0
762	0
763	0
764	0
765	0
766	0
767	0
768	0
769	0
770	0
771	0,040875088
772	0,054764027
773	0,148855743
774	0,275010462
775	0,226120605
776	0,109935922
777	0
778	0,086675358
779	0,176806753
780	0,097610231
781	-0,057510789
782	-0,057377761
783	-0,055968607
784	0,261074272
785	0,275186559
786	0,268649071
787	-0,056982339
788	-0,042352764
789	-0,031765594
790	0,123647291
791	0,096544938
792	0,094828545
793	0,048605282
794	0
795	0,147166521
796	0,299626608
797	0,148902074
798	0
799	0,163754854
800	0,328887114
801	0,395482304
802	0,471318119
803	0,550034747
804	0,64118211
805	0,32038619
806	0
807	0,190066002
808	0,382148046

Time [s]	normalized Power [kW/kW]	Time [s]	normalized Power [kW/kW]	Time [s]	normalized Power [kW/kW]	Time [s]	normalized Power [kW/kW]
809	0,520808207	853	0,452369396	897	0	941	0,446280876
810	0,664828232	854	0,497009777	898	0	942	0,460324437
811	0,576561943	855	0,528780303	899	0	943	0,457278452
812	0,587910422	856	0,555006135	900	0	944	0,458239072
813	0,578513233	857	0,580445313	901	0,010753096	945	0,494888338
814	0,543226665	858	0,626935958	902	0,052822519	946	0,486357706
815	0,507038394	859	0,647365715	903	0,089348846	947	0,239121565
816	0,471782143	860	0,325383802	904	0,120504242	948	0,086982847
817	0,510163958	861	0	905	0,176588729	949	0,124824653
818	0,527472439	862	0,226938932	906	0,071341902	950	0,168282762
819	0,323227519	863	0,457050365	907	0,03549095	951	0,187703319
820	0,161531874	864	0,309663562	908	0	952	0,193037406
821	0	865	0,228788318	909	0,045137836	953	0,193536827
822	0,155921732	866	0,137596774	910	0,091847093	954	0,221161375
823	0,313674564	867	-0,05197585	911	0,075450639	955	0,246021065
824	0,291582156	868	-0,051768588	912	0,352046709	956	0,23457231
825	0,201954729	869	-0,051392402	913	0,030138341	957	0,249119224
826	0,191090079	870	-0,050768772	914	0	958	0,268574185
827	0,101863461	871	-0,050179818	915	0,185556204	959	-0,065610521
828	-0,044089482	872	-0,049458532	916	0,370625258	960	-0,064130734
829	-0,043469675	873	-0,048881329	917	0,182470949	961	-0,062508096
830	0	874	-0,048313822	918	0	962	-0,061188255
831	-0,077371397	875	-0,048064435	919	0,304058692	963	-0,059059802
832	-0,078183429	876	-0,047862053	920	0,603143333	964	-0,056626664
833	-0,075477286	877	-0,047471305	921	0,635306335	965	-0,055274669
834	-0,072164016	878	-0,046115997	922	0,639863218	966	-0,054391213
835	-0,068717207	879	0	923	0,702531463	967	-0,052801487
836	-0,064734706	880	-0,079499803	924	0,659658528	968	-0,051082169
837	-0,060222227	881	-0,072027876	925	0,58221279	969	0,038537982
838	-0,056045679	882	-0,064047637	926	0,505719774	970	0,20105884
839	-0,052922771	883	-0,055547003	927	0,43085568	971	0,378720043
840	0,293868442	884	-0,048881329	928	0,418788085	972	0,341301166
841	0,489728605	885	0	929	0,486206308	973	0,299413505
842	0,344284008	886	-0,076250768	930	0,452533637	974	0,275450694
843	0,000571565	887	-0,068439977	931	0,480958431	975	0,253957338
844	-0,057684472	888	-0,060222227	932	0,491671092	976	0,238582609
845	-0,057280178	889	-0,051202818	933	0,46188223	977	0,197722919
846	-0,055968607	890	-0,041234719	934	0,48887335	978	-0,059059802
847	-0,053528162	891	-0,03473799	935	0,490615255	979	-0,058353554
848	-0,050286944	892	-0,028099946	936	0,246289017	980	-0,056699551
849	-0,046890066	893	-0,022918402	937	0	981	-0,056045679
850	-0,044278549	894	0	938	0,175663324	982	-0,055473217
851	0,222454143	895	0	939	0,353006127	983	-0,054471626
852	0,29867187	896	0	940	0,399277485	984	-0,053171517

Time [s]	normalized Power [kW/kW]
985	-0,051663471
986	-0,050179818
987	-0,049241766
988	-0,048652363
989	-0,047388935
990	-0,045677773
991	-0,044621162
992	-0,043803303
993	0
994	-0,080664398
995	-0,076805147
996	-0,071698212
997	-0,064355975
998	-0,057171442
999	-0,050654199
1000	0
1001	-0,070580398
1002	-0,058974743
1003	0
1004	-0,078316628
1005	-0,069231603
1006	-0,060623537
1007	0
1008	-0,070334617
1009	-0,061348607
1010	-0,05197585
1011	-0,040897579
1012	-0,032480951
1013	0,006791394
1014	0,02837191
1015	0,088706097
1016	0,046497754
1017	0
1018	0,037242567
1019	0,072730945
1020	0,123273172
1021	0,11010913
1022	0,055134684
1023	0
1024	0,127531704
1025	0,255730033
1026	0,376760047
1027	0,18904451
1028	0
1029	0,146065584
1030	0,298437127
1031	0,257747229
1032	0,162926585
1033	-0,051468833
1034	-0,050286944
1035	-0,048528483
1036	0,126724389
1037	0,233280769
1038	0,236416442
1039	0,247943937
1040	0,29859812
1041	0,338171235
1042	0,286926708
1043	0,241845587
1044	0,32287158
1045	0,500156928
1046	0,447367595
1047	0,223740739
1048	0
1049	0,085657993
1050	0,17224539
1051	0,314672535
1052	0,385742552
1053	0,405362962
1054	0,12090866
1055	0,098922393
1056	0,077085053
1057	0,084280545
1058	0,100245457
1059	-0,048240741
1060	-0,046531226
1061	-0,044806889
1062	0,058912892
1063	0,153528931
1064	0,112121248
1065	0,160288416
1066	-0,046355784
1067	-0,046208684
1068	-0,045374604
1069	-0,044734739
1070	-0,044734739
1071	-0,043984213
1072	0
1073	-0,080795238
1074	-0,079170105
1075	-0,077371397
1076	-0,074591609
1077	-0,071698212
1078	-0,06912596
1079	-0,066755502
1080	-0,064467568
1081	-0,062658803
1082	-0,061524601
1083	-0,061188255
1084	-0,060002964
1085	-0,059207863
1086	-0,058604558
1087	0,190028151
1088	0,192668326
1089	0,187073855
1090	0,163542557
1091	0,029897878
1092	0,033967812
1093	0,031228345
1094	-0,059777486
1095	-0,058353554
1096	-0,056045679
1097	-0,054198845
1098	-0,051768588
1099	0,013260365
1100	0,289348503
1101	0,335400873
1102	0,29510136
1103	0,339540428
1104	0,327179871
1105	0,323538099
1106	0,336444109
1107	0,344316622
1108	0,225729343
1109	0,224568258
1110	0,224127491
1111	0,222843305
1112	0,221644167
1113	0,219222528
1114	0,220601271
1115	0,110432897
1116	0
1117	0,146100382
1118	0,296603371
1119	0,250392769
1120	0,077064495
1121	0,075504498
1122	0,039400539
1123	0,073879687
1124	0,107485551
1125	0,208601103
1126	0,180585988
1127	0,186422099
1128	0,162669371
1129	0,206136357
1130	0,183393248
1131	-0,046890066
1132	-0,046115997
1133	-0,04500157
1134	-0,044553642
1135	0
1136	-0,080374335
1137	-0,069881314
1138	-0,059777486
1139	0
1140	-0,080795238
1141	-0,06369778
1142	0
1143	-0,037734283
1144	-0,027969922
1145	-0,021745988
1146	0
1147	0
1148	0
1149	0
1150	0
1151	0
1152	0
1153	0
1154	0
1155	0
1156	0
1157	0
1158	0
1159	0
1160	0

Time [s]	normalized Power [kW/kW]
1161	0
1162	0
1163	0
1164	0
1165	0
1166	0
1167	0
1168	0
1169	0
1170	0
1171	0
1172	0
1173	0
1174	0
1175	0
1176	0
1177	0
1178	0
1179	0
1180	0
1181	0
1182	0
1183	0
1184	0
1185	0
1186	0
1187	0
1188	0
1189	0
1190	0
1191	0
1192	0
1193	0
1194	0
1195	0
1196	0,037911306
1197	0,127971268
1198	0,108229141
1199	0,054869413
1200	-0,062278123
1201	-0,060321874
1202	0,109344054
1203	0,054493547
1204	0
1205	0,084920591
1206	0,17068243
1207	0,085464817
1208	0
1209	0,312282066
1210	0,615344361
1211	0,678419503
1212	0,759960595
1213	0,376449054
1214	0
1215	0,325352905
1216	0,649140691
1217	0,581132504
1218	0,603310065
1219	0,622118198
1220	0,652486189
1221	0,679554577
1222	0,714244167
1223	0,726066481
1224	0,754322874
1225	0,777635602
1226	0,786987622
1227	0,818133991
1228	0,842906364
1229	0,807765558
1230	0,876950306
1231	0,914114054
1232	0,933148517
1233	0,95353172
1234	-0,203878311
1235	-0,186884581
1236	-0,13935055
1237	-0,099486588
1238	0,755014138
1239	0,763911234
1240	0,772565721
1241	0,790801311
1242	0,801896617
1243	0,816903692
1244	0,822158151
1245	0,830211988
1246	0,413747067
1247	0
1248	0,275419166
1249	0,549832762
1250	0,489404339
1251	0,400887737
1252	0,412689433
1253	0,311416998
1254	0,262612985
1255	0,228083722
1256	0,164224782
1257	0,148430206
1258	-0,057684472
1259	-0,056626664
1260	-0,055191507
1261	-0,053626635
1262	-0,051868773
1263	-0,050361819
1264	-0,048945963
1265	-0,047657517
1266	-0,046531226
1267	-0,045482454
1268	-0,044278549
1269	0
1270	-0,068717207
1271	-0,066665661
1272	-0,064622642
1273	-0,062658803
1274	-0,0608611
1275	-0,059207863
1276	-0,057684472
1277	-0,056126601
1278	-0,054575426
1279	-0,053171517
1280	-0,051868773
1281	-0,050654199
1282	-0,049318643
1283	-0,047784228
1284	-0,045823008
1285	-0,043803303
1286	0
1287	0,290425453
1288	0,592094995
1289	0,699489506
1290	0,693327224
1291	0,759873435
1292	0,788996152
1293	0,815641779
1294	0,849300588
1295	0,888639469
1296	0,902695225
1297	0,454218091
1298	0
1299	0,360962445
1300	0,71762393
1301	0,766745074
1302	0,816404506
1303	0,816657642
1304	0,827777231
1305	0,834457252
1306	0,840978935
1307	0,418847955
1308	0
1309	0,173866585
1310	0,347665902
1311	0,441322128
1312	0,73850676
1313	0,796946396
1314	0,825519907
1315	0,834363036
1316	0,841378127
1317	0,273145652
1318	0
1319	0,203570808
1320	0,394951375
1321	0,327352442
1322	0,300734109
1323	0,152731388
1324	0
1325	0,007036097
1326	0,106551356
1327	0,400679417
1328	0,504656894
1329	0,412166458
1330	0,36054201
1331	0,116670586
1332	0,235605473
1333	0,354185436
1334	0,171126239
1335	-0,050361819
1336	-0,049318643

Time [s]	normalized Power [kW/kW]
1337	-0,047908218
1338	-0,046287423
1339	-0,044806889
1340	-0,043416539
1341	0,160089026
1342	0,553643436
1343	0,542484063
1344	0,409165224
1345	0,325425215
1346	0,535761798
1347	0,539790778
1348	0,498571336
1349	0,495396209
1350	0,553657983
1351	0,654324654
1352	0,526124914
1353	0,342682276
1354	0,390934757
1355	0,47626973
1356	0,342980669
1357	0,308682689
1358	0,301812042
1359	0,241881215
1360	0,166393746
1361	-0,05197585
1362	-0,051082169
1363	-0,049897732
1364	-0,048397006
1365	-0,047162247
1366	-0,045823008
1367	-0,044621162
1368	-0,04333294
1369	0,328670158
1370	0,507886427
1371	0,514703953
1372	0,264961126
1373	-0,046355784
1374	-0,044621162
1375	0
1376	-0,067653255
1377	-0,064467568
1378	-0,0608611
1379	-0,058475619
1380	-0,055547003
1381	0
1382	0,400426707
1383	0,805786696
1384	0,811871469
1385	0,405742993
1386	0
1387	0,319298729
1388	0,667906922
1389	0,411659343
1390	0,22041354
1391	0
1392	0,362154513
1393	0,724087374
1394	0,949250077
1395	0,729812395
1396	0,449232885
1397	0,777343655
1398	0,388797745
1399	0
1400	0,142456117
1401	0,271030958
1402	0,405340973
1403	0,527882597
1404	0,644584484
1405	0,683506542
1406	0,678682632
1407	0,539910208
1408	0,337696254
1409	0,267800959
1410	0,432863975
1411	0,512630313
1412	0,515866288
1413	0,51813545
1414	0,521580828
1415	0,576711852
1416	0,582680202
1417	0,332067875
1418	0,414677041
1419	0,497214733
1420	0,579712261
1421	0,596619939
1422	0,601720031
1423	0,607860536
1424	0,614169455
1425	0,615190092
1426	0,616578306
1427	0,616765218
1428	0,625818401
1429	0,31331123
1430	0
1431	0,214306317
1432	0,430245044
1433	0,476780588
1434	0,523174899
1435	0,546988076
1436	0,552978653
1437	0,622446481
1438	0,661102911
1439	0,669442804
1440	0,694229564
1441	0,709561018
1442	0,726627128
1443	0,737325207
1444	0,745155424
1445	0,749624506
1446	0,759410988
1447	0,763982007
1448	0,774334145
1449	0,780470183
1450	0,791718851
1451	0,787853443
1452	0,796041431
1453	0,55341004
1454	0
1455	-0,071340409
1456	-0,070580398
1457	-0,069881314
1458	-0,069560516
1459	-0,068871326
1460	-0,068016556
1461	-0,068016556
1462	-0,06689404
1463	-0,066364979
1464	-0,066259944
1465	-0,065987212
1466	-0,065987212
1467	0,066975556
1468	0,135119551
1469	0,171198
1470	0,178315862
1471	0,213004506
1472	0,319027986
1473	0,683788826
1474	0,751561753
1475	0,786351392
1476	0,79707655
1477	0,806075028
1478	0,813937922
1479	0,82354482
1480	0,829638994
1481	0,755345665
1482	0,560791204
1483	0,402646778
1484	0,292268752
1485	0,207142742
1486	0,162997229
1487	0,141103242
1488	0,138907089
1489	0,19018163
1490	0,182216084
1491	0,159775404
1492	0,218458681
1493	0,241831273
1494	0,195169579
1495	0,174930332
1496	0,151432909
1497	0,182447033
1498	0,20003872
1499	0,184187339
1500	0,166109377
1501	0,210576558
1502	0,222269731
1503	0,214965821
1504	0,209350879
1505	0,203945259
1506	0,269029022
1507	0,368913814
1508	0,223501088
1509	0,011195167
1510	-0,074020187
1511	-0,073133624
1512	-0,072943539

Time [s]	normalized Power [kW/kW]
1513	-0,071698212
1514	-0,070334617
1515	-0,069560516
1516	-0,068016556
1517	-0,066976557
1518	-0,065987212
1519	-0,064237113
1520	-0,063773279
1521	-0,063164988
1522	-0,063164988
1523	-0,06369778
1524	-0,064355975
1525	0
1526	0,184937084
1527	0,548050004
1528	0,597012896
1529	0,610383058
1530	0,621386511
1531	0,61305142
1532	0,605358849
1533	0,603852578
1534	0,612639537
1535	0,596284078
1536	0,589420745
1537	0,571081126
1538	0,547686237
1539	0,524893415
1540	0,501419201
1541	0,614070472
1542	0,51496726
1543	0,415574946
1544	0,339642762
1545	0,289405918
1546	0,265753649
1547	0,238220536
1548	0,230866261
1549	0,230662767
1550	0,234742188
1551	0,244461646
1552	0,261339827
1553	0,282743946
1554	0,306437734
1555	0,30677162
1556	0,313576838
1557	0,32167262
1558	0,329030498
1559	0,335776303
1560	0,331699581
1561	0,329334666
1562	0,321867055
1563	0,305511507
1564	0,314231502
1565	0,317826991
1566	0,322165501
1567	0,332372814
1568	0,332372814
1569	0,32167262
1570	0,317859012
1571	0,322900411
1572	0,316289501
1573	0,307879178
1574	0,316030746
1575	0,320184829
1576	0,333523538
1577	0,35037657
1578	0,369121999
1579	0,412488054
1580	0,420953819
1581	0,429272714
1582	0,428987572
1583	0,422751187
1584	0,423923461
1585	0,420505016
1586	0,41106763
1587	0,405991061
1588	0,389672941
1589	0,377528405
1590	0,375584251
1591	0,380038427
1592	0,375584251
1593	0,371872956
1594	0,378272076
1595	0,376510478
1596	0,375696901
1597	0,364580427
1598	0,368427107
1599	0,368172203
1600	0,374807827
1601	0,374807827
1602	0,365085483
1603	0,371324554
1604	0,370506792
1605	0,368809164
1606	0,368638045
1607	0,370314694
1608	0,36749783
1609	0,37737563
1610	0,36772614
1611	0,36865919
1612	0,369763063
1613	0,365085483
1614	0,368172203
1615	0,366335555
1616	0,365481753
1617	0,370162454
1618	0,358036407
1619	0,345668922
1620	0,363308907
1621	0,393787467
1622	0,397880369
1623	0,383178429
1624	0,37147701
1625	0,371271403
1626	0,389672941
1627	0,397565218
1628	0,394649643
1629	0,407402316
1630	0,400216558
1631	0,396167025
1632	0,395030874
1633	0,397152914
1634	0,405068287
1635	0,40912179
1636	0,424335764
1637	0,426330961
1638	0,441947394
1639	0,454797929
1640	0,47491852
1641	0,481051742
1642	0,482395881
1643	0,492983728
1644	0,512828846
1645	0,517173449
1646	0,547011897
1647	0,550733788
1648	0,564955905
1649	0,575340959
1650	0,59238449
1651	0,60117246
1652	0,602265526
1653	0,605618012
1654	0,609393654
1655	0,606480599
1656	0,610670201
1657	0,606886585
1658	0,601937424
1659	0,607339864
1660	0,608014955
1661	0,612625969
1662	0,611319585
1663	0,614487179
1664	0,618294438
1665	0,616454049
1666	0,611755683
1667	0,606480599
1668	0,622325888
1669	0,620756107
1670	0,622930145
1671	0,622673694
1672	0,603592466
1673	0,60396006
1674	0,597539429
1675	0,573128628
1676	0,536674665
1677	0,506924272
1678	0,47952425
1679	0,428679818
1680	0,390649733
1681	0,356012109
1682	0,32745251
1683	0,303186974
1684	0,275552177
1685	0,229456122
1686	0,183481636
1687	0,145526949
1688	0,110000535

Time [s]	normalized Power [kW/kW]
1689	0,078947629
1690	0,07083324
1691	0,051332256
1692	0,051217848
1693	0,048694079
1694	0,03970382
1695	0,028406265
1696	0,027304282
1697	0,043364879
1698	0,037227355
1699	0,048321194
1700	0,044995703
1701	0,04589689
1702	0,048321194
1703	0,047423147
1704	0,053789529
1705	0,050154679
1706	0,050970787
1707	0,053730458
1708	0,052020621
1709	0,058325013
1710	0,056361617
1711	0,05889969
1712	0,060868006
1713	0,049411669
1714	0,044748298
1715	0,057265461
1716	0,087667242
1717	0,108835562
1718	0,127309703
1719	0,143243354
1720	0,158502504
1721	0,181899942
1722	0,197559349
1723	0,225998403
1724	0,242869416
1725	0,259409281
1726	0,285053805
1727	0,304562318
1728	0,317412311
1729	0,342415817
1730	0,361127035
1731	0,384066095
1732	0,404772239
1733	0,420998507
1734	0,426917666
1735	0,429653853
1736	0,416132402
1737	0,413490031
1738	0,408759858
1739	0,409096566
1740	0,400422236
1741	0,402449163
1742	0,402216264
1743	0,402216264
1744	0,390413792
1745	0,402449163
1746	0,405335164
1747	-0,075223382
1748	-0,074812196
1749	-0,074020187
1750	-0,072710194
1751	-0,072579551
1752	-0,071449839
1753	-0,070580398
1754	-0,069560516
1755	-0,068016556
1756	-0,066976557
1757	-0,065987212
1758	-0,064237113
1759	-0,063090221
1760	-0,061774969
1761	-0,060623537
1762	-0,059587674
1763	-0,058353554
1764	-0,056699551
1765	-0,054471626
1766	-0,051468833
1767	-0,048528483
1768	-0,045753078
1769	0
1770	-0,065987212
1771	-0,062360095
1772	-0,058604558
1773	-0,054910931
1774	-0,051392402
1775	-0,048313822
1776	-0,045178468
1777	0
1778	-0,074344177
1779	-0,066976557
1780	-0,059684373
1781	-0,05237299
1782	0
1783	-0,076805147
1784	-0,064047637
1785	-0,058353554
1786	-0,046287423
1787	-0,040330266
1788	-0,034603708
1789	-0,028685195
1790	-0,024028651
1791	-0,019999879
1792	0
1793	0
1794	0
1795	0
1796	0
1797	0
1798	0
1799	0
1800	0

B Sections of inversed road gradients

0… application of regular road gradient
1… application of inversed/modified road gradient

Time [s]	Value [0-1]	Time [s]	Value [0-1]	Time [s]	Value [0-1]	Time [s]	Value [0-1]	Time [s]	Value [0-1]	Time [s]	Value [0-1]
1	0	39	1	78	0	117	0	156	0	195	1
2	0	40	1	79	0	118	0	157	0	196	1
3	0	41	1	80	0	119	0	158	0	197	1
4	0	42	1	81	0	120	0	159	0	198	1
5	0	43	1	82	0	121	0	160	0	199	1
6	0	44	1	83	0	122	0	161	0	200	1
7	0	45	1	84	0	123	1	162	0	201	1
8	0	46	0	85	0	124	1	163	0	202	1
9	0	47	0	86	0	125	1	164	0	203	1
10	0	48	0	87	0	126	1	165	0	204	1
11	0	49	0	88	0	127	1	166	0	205	1
12	0	50	0	89	0	128	1	167	0	206	1
13	0	51	0	90	0	129	1	168	0	207	0
14	0	52	0	91	0	130	1	169	0	208	0
15	0	53	0	92	0	131	1	170	0	209	0
16	0	54	0	93	0	132	1	171	0	210	0
17	0	55	0	94	0	133	1	172	0	211	0
18	0	56	0	95	0	134	1	173	0	212	0
19	0	57	0	96	0	135	0	174	0	213	0
20	0	58	0	97	0	136	0	175	0	214	0
21	0	59	0	98	0	137	0	176	0	215	0
22	0	60	0	99	0	138	0	177	0	216	0
23	0	61	0	100	0	139	0	178	0	217	0
24	0	62	0	101	0	140	0	179	0	218	0
25	0	63	0	102	0	141	0	180	0	219	0
26	0	64	0	103	0	142	0	181	1	220	0
27	0	65	0	104	0	143	0	182	1	221	0
28	1	66	0	105	0	144	0	183	1	222	0
29	1	67	0	106	0	145	0	184	1	223	0
30	1	68	0	107	0	146	0	185	1	224	0
31	1	69	0	108	0	147	0	186	1	225	0
32	1	70	0	109	0	148	0	187	1	226	0
33	1	71	0	110	0	149	0	188	1	227	0
34	1	72	0	111	0	150	0	189	1	228	0
35	1	73	0	112	0	151	0	190	1	229	0
36	1	74	0	113	0	152	0	191	1	230	0
37	1	75	0	114	0	153	0	192	1	231	0
38	1	76	0	115	0	154	0	193	1	232	0
		77	0	116	0	155	0	194	1	233	0

Time [s]	Value [0-1]
234	0
235	0
236	0
237	0
238	0
239	0
240	0
241	0
242	0
243	0
244	0
245	0
246	0
247	0
248	0
249	0
250	0
251	0
252	0
253	0
254	0
255	0
256	0
257	0
258	0
259	0
260	0
261	0
262	0
263	0
264	1
265	1
266	1
267	1
268	1
269	1
270	1
271	1
272	1
273	1
274	1
275	1
276	1
277	1
278	1
279	1
280	1
281	0
282	0
283	0
284	0
285	0
286	0
287	0
288	0
289	0
290	0
291	0
292	0
293	0
294	0
295	0
296	0
297	0
298	0
299	0
300	0
301	0
302	0
303	0
304	0
305	0
306	0
307	0
308	0
309	0
310	0
311	0
312	0
313	0
314	0
315	0
316	0
317	0
318	0
319	0
320	0
321	0
322	0
323	0
324	0
325	0
326	0
327	0
328	0
329	0
330	1
331	1
332	1
333	1
334	1
335	1
336	1
337	1
338	1
339	1
340	0
341	0
342	0
343	0
344	0
345	0
346	0
347	0
348	0
349	0
350	0
351	0
352	0
353	0
354	0
355	0
356	0
357	0
358	0
359	0
360	0
361	0
362	0
363	0
364	0
365	0
366	0
367	0
368	0
369	0
370	0
371	0
372	0
373	0
374	0
375	0
376	0
377	0
378	1
379	1
380	1
381	1
382	1
383	1
384	1
385	1
386	1
387	1
388	0
389	0
390	0
391	0
392	0
393	0
394	0
395	0
396	0
397	0
398	0
399	0
400	0
401	0
402	0
403	0
404	0
405	0
406	0
407	0
408	0
409	0
410	0
411	0
412	1
413	1
414	1
415	1
416	1
417	1
418	1
419	1
420	1
421	1
422	1
423	1
424	1
425	1
426	1
427	1
428	1
429	1
430	0
431	0
432	0
433	0
434	0
435	0
436	0
437	0
438	0
439	0
440	0
441	0
442	0
443	0
444	0
445	0
446	0
447	0
448	1
449	1
450	1
451	1
452	1
453	1
454	1
455	1
456	1
457	1
458	1
459	1
460	1
461	1
462	1
463	1
464	0
465	0
466	0
467	0
468	0
469	0
470	0
471	0
472	0
473	0
474	0
475	0
476	0
477	0
478	0
479	0
480	0
481	0
482	0
483	0
484	0
485	0
486	0
487	0
488	1
489	1
490	1
491	1
492	1
493	1
494	1
495	1
496	1
497	0

Time [s]	Value [0-1]	Time [s]	Value [0-1]	Time [s]	Value [0-1]	Time [s]	Value [0-1]	Time [s]	Value [0-1]	Time [s]	Value [0-1]
498	0	542	1	586	0	630	0	674	0	718	0
499	0	543	0	587	0	631	0	675	0	719	0
500	0	544	0	588	0	632	0	676	0	720	0
501	0	545	0	589	0	633	0	677	0	721	0
502	0	546	0	590	0	634	0	678	0	722	0
503	0	547	0	591	0	635	0	679	0	723	0
504	0	548	0	592	0	636	0	680	0	724	0
505	0	549	0	593	0	637	0	681	0	725	0
506	0	550	0	594	0	638	0	682	0	726	0
507	0	551	0	595	0	639	0	683	0	727	0
508	0	552	0	596	0	640	1	684	0	728	0
509	0	553	0	597	0	641	1	685	0	729	0
510	0	554	0	598	0	642	1	686	0	730	0
511	0	555	0	599	0	643	1	687	0	731	0
512	0	556	0	600	0	644	1	688	0	732	0
513	0	557	0	601	0	645	1	689	0	733	0
514	0	558	0	602	0	646	1	690	0	734	0
515	0	559	0	603	0	647	1	691	0	735	0
516	0	560	0	604	0	648	0	692	0	736	0
517	0	561	0	605	0	649	0	693	1	737	0
518	0	562	0	606	0	650	0	694	1	738	0
519	0	563	0	607	0	651	0	695	1	739	0
520	0	564	0	608	0	652	0	696	1	740	0
521	0	565	1	609	0	653	0	697	1	741	0
522	0	566	1	610	0	654	0	698	1	742	0
523	0	567	1	611	0	655	0	699	1	743	0
524	0	568	1	612	0	656	0	700	1	744	0
525	0	569	1	613	0	657	0	701	1	745	0
526	0	570	1	614	0	658	0	702	1	746	0
527	0	571	0	615	0	659	0	703	1	747	0
528	0	572	0	616	1	660	0	704	1	748	0
529	1	573	0	617	1	661	0	705	1	749	0
530	1	574	0	618	1	662	0	706	1	750	0
531	1	575	0	619	1	663	0	707	1	751	0
532	1	576	0	620	1	664	0	708	1	752	0
533	1	577	0	621	1	665	0	709	1	753	0
534	1	578	0	622	1	666	0	710	0	754	0
535	1	579	0	623	1	667	0	711	0	755	0
536	1	580	0	624	1	668	0	712	0	756	0
537	1	581	0	625	0	669	0	713	0	757	0
538	1	582	0	626	0	670	0	714	0	758	0
539	1	583	0	627	0	671	0	715	0	759	0
540	1	584	0	628	0	672	0	716	0	760	0
541	1	585	0	629	0	673	0	717	0	761	0

Time [s]	Value [0-1]	Time [s]	Value [0-1]	Time [s]	Value [0-1]	Time [s]	Value [0-1]	Time [s]	Value [0-1]	Time [s]	Value [0-1]
762	0	806	0	850	1	894	1	938	0	982	1
763	0	807	0	851	0	895	1	939	0	983	1
764	0	808	0	852	0	896	1	940	0	984	1
765	0	809	0	853	0	897	1	941	0	985	1
766	0	810	0	854	0	898	0	942	0	986	1
767	0	811	0	855	0	899	0	943	0	987	1
768	0	812	0	856	0	900	0	944	0	988	1
769	0	813	0	857	0	901	0	945	0	989	1
770	0	814	0	858	0	902	0	946	0	990	1
771	0	815	0	859	0	903	0	947	0	991	1
772	0	816	0	860	0	904	0	948	0	992	1
773	0	817	0	861	0	905	0	949	0	993	1
774	0	818	0	862	0	906	0	950	0	994	1
775	0	819	0	863	0	907	0	951	0	995	1
776	0	820	0	864	0	908	0	952	0	996	1
777	0	821	0	865	0	909	0	953	0	997	1
778	0	822	0	866	0	910	0	954	0	998	1
779	0	823	0	867	0	911	0	955	0	999	1
780	0	824	0	868	0	912	0	956	0	1000	1
781	0	825	0	869	1	913	0	957	0	1001	1
782	0	826	0	870	1	914	0	958	0	1002	1
783	1	827	0	871	1	915	0	959	0	1003	1
784	1	828	0	872	1	916	0	960	1	1004	1
785	1	829	1	873	1	917	0	961	1	1005	1
786	1	830	1	874	1	918	0	962	1	1006	1
787	1	831	1	875	1	919	0	963	1	1007	1
788	1	832	1	876	1	920	0	964	1	1008	1
789	1	833	1	877	1	921	0	965	1	1009	1
790	0	834	1	878	1	922	0	966	1	1010	1
791	0	835	1	879	1	923	0	967	1	1011	1
792	0	836	1	880	1	924	0	968	1	1012	1
793	0	837	1	881	1	925	0	969	0	1013	0
794	0	838	1	882	1	926	0	970	0	1014	0
795	0	839	1	883	1	927	0	971	0	1015	0
796	0	840	1	884	1	928	0	972	0	1016	0
797	0	841	1	885	1	929	0	973	0	1017	0
798	0	842	1	886	1	930	0	974	0	1018	0
799	0	843	1	887	1	931	0	975	0	1019	0
800	0	844	1	888	1	932	0	976	0	1020	0
801	0	845	1	889	1	933	0	977	0	1021	0
802	0	846	1	890	1	934	0	978	0	1022	0
803	0	847	1	891	1	935	0	979	1	1023	0
804	0	848	1	892	1	936	0	980	1	1024	0
805	0	849	1	893	1	937	0	981	1	1025	0

Time [s]	Value [0-1]	Time [s]	Value [0-1]	Time [s]	Value [0-1]	Time [s]	Value [0-1]	Time [s]	Value [0-1]	Time [s]	Value [0-1]
1026	0	1070	0	1114	0	1158	0	1202	0	1246	0
1027	0	1071	1	1115	0	1159	0	1203	0	1247	0
1028	0	1072	1	1116	0	1160	0	1204	0	1248	0
1029	0	1073	1	1117	0	1161	0	1205	0	1249	0
1030	0	1074	1	1118	0	1162	0	1206	0	1250	0
1031	0	1075	1	1119	0	1163	0	1207	0	1251	0
1032	0	1076	1	1120	0	1164	0	1208	0	1252	0
1033	0	1077	1	1121	0	1165	0	1209	0	1253	0
1034	0	1078	1	1122	0	1166	0	1210	0	1254	0
1035	0	1079	1	1123	0	1167	0	1211	0	1255	0
1036	0	1080	1	1124	0	1168	0	1212	0	1256	0
1037	0	1081	1	1125	0	1169	0	1213	0	1257	0
1038	0	1082	1	1126	0	1170	0	1214	0	1258	1
1039	0	1083	1	1127	0	1171	0	1215	0	1259	1
1040	0	1084	1	1128	0	1172	0	1216	0	1260	1
1041	0	1085	1	1129	0	1173	0	1217	0	1261	1
1042	0	1086	1	1130	0	1174	0	1218	0	1262	1
1043	0	1087	1	1131	0	1175	0	1219	0	1263	1
1044	0	1088	1	1132	1	1176	0	1220	0	1264	1
1045	0	1089	1	1133	1	1177	0	1221	0	1265	1
1046	0	1090	1	1134	1	1178	0	1222	0	1266	1
1047	0	1091	1	1135	1	1179	0	1223	0	1267	1
1048	0	1092	1	1136	1	1180	0	1224	0	1268	1
1049	0	1093	1	1137	1	1181	0	1225	0	1269	1
1050	0	1094	1	1138	1	1182	0	1226	0	1270	1
1051	0	1095	1	1139	1	1183	0	1227	0	1271	1
1052	0	1096	1	1140	1	1184	0	1228	0	1272	1
1053	0	1097	1	1141	1	1185	0	1229	0	1273	1
1054	0	1098	1	1142	1	1186	0	1230	0	1274	1
1055	0	1099	0	1143	1	1187	0	1231	0	1275	1
1056	0	1100	0	1144	1	1188	0	1232	0	1276	1
1057	0	1101	0	1145	1	1189	0	1233	0	1277	1
1058	0	1102	0	1146	1	1190	0	1234	0	1278	1
1059	0	1103	0	1147	1	1191	0	1235	0	1279	1
1060	0	1104	0	1148	1	1192	0	1236	0	1280	1
1061	0	1105	0	1149	1	1193	0	1237	0	1281	1
1062	0	1106	0	1150	1	1194	0	1238	0	1282	1
1063	0	1107	0	1151	1	1195	0	1239	0	1283	1
1064	0	1108	0	1152	1	1196	0	1240	0	1284	1
1065	0	1109	0	1153	1	1197	0	1241	0	1285	1
1066	0	1110	0	1154	1	1198	0	1242	0	1286	1
1067	0	1111	0	1155	1	1199	0	1243	0	1287	0
1068	0	1112	0	1156	0	1200	0	1244	0	1288	0
1069	0	1113	0	1157	0	1201	0	1245	0	1289	0

Time [s]	Value [0-1]	Time [s]	Value [0-1]	Time [s]	Value [0-1]	Time [s]	Value [0-1]	Time [s]	Value [0-1]	Time [s]	Value [0-1]
1290	0	1334	0	1378	1	1422	0	1466	0	1510	1
1291	0	1335	1	1379	1	1423	0	1467	0	1511	1
1292	0	1336	1	1380	1	1424	0	1468	0	1512	1
1293	0	1337	1	1381	1	1425	0	1469	0	1513	1
1294	0	1338	1	1382	0	1426	0	1470	0	1514	1
1295	0	1339	1	1383	0	1427	0	1471	0	1515	1
1296	0	1340	1	1384	0	1428	0	1472	0	1516	1
1297	0	1341	0	1385	0	1429	0	1473	0	1517	1
1298	0	1342	0	1386	0	1430	0	1474	0	1518	1
1299	0	1343	0	1387	0	1431	0	1475	0	1519	1
1300	0	1344	0	1388	0	1432	0	1476	0	1520	1
1301	0	1345	0	1389	0	1433	0	1477	0	1521	1
1302	0	1346	0	1390	0	1434	0	1478	0	1522	0
1303	0	1347	0	1391	0	1435	0	1479	0	1523	0
1304	0	1348	0	1392	0	1436	0	1480	0	1524	0
1305	0	1349	0	1393	0	1437	0	1481	0	1525	0
1306	0	1350	0	1394	0	1438	0	1482	0	1526	0
1307	0	1351	0	1395	0	1439	0	1483	0	1527	0
1308	0	1352	0	1396	0	1440	0	1484	0	1528	0
1309	0	1353	0	1397	0	1441	0	1485	0	1529	0
1310	0	1354	0	1398	0	1442	0	1486	0	1530	0
1311	0	1355	0	1399	0	1443	0	1487	0	1531	0
1312	0	1356	0	1400	0	1444	0	1488	0	1532	0
1313	0	1357	0	1401	0	1445	0	1489	0	1533	0
1314	0	1358	0	1402	0	1446	0	1490	0	1534	0
1315	0	1359	0	1403	0	1447	0	1491	0	1535	0
1316	0	1360	0	1404	0	1448	0	1492	0	1536	0
1317	0	1361	1	1405	0	1449	0	1493	0	1537	0
1318	0	1362	1	1406	0	1450	0	1494	0	1538	0
1319	0	1363	1	1407	0	1451	0	1495	0	1539	0
1320	0	1364	1	1408	0	1452	0	1496	0	1540	0
1321	0	1365	1	1409	0	1453	0	1497	0	1541	0
1322	0	1366	1	1410	0	1454	0	1498	0	1542	0
1323	0	1367	1	1411	0	1455	0	1499	0	1543	0
1324	0	1368	1	1412	0	1456	0	1500	0	1544	0
1325	0	1369	0	1413	0	1457	0	1501	0	1545	0
1326	0	1370	0	1414	0	1458	0	1502	0	1546	0
1327	0	1371	0	1415	0	1459	0	1503	0	1547	0
1328	0	1372	0	1416	0	1460	0	1504	0	1548	0
1329	0	1373	0	1417	0	1461	0	1505	0	1549	0
1330	0	1374	1	1418	0	1462	0	1506	0	1550	0
1331	0	1375	1	1419	0	1463	0	1507	0	1551	0
1332	0	1376	1	1420	0	1464	0	1508	0	1552	0
1333	0	1377	1	1421	0	1465	0	1509	0	1553	0

Time [s]	Value [0-1]
1554	0
1555	0
1556	0
1557	0
1558	0
1559	0
1560	0
1561	0
1562	0
1563	0
1564	0
1565	0
1566	0
1567	0
1568	0
1569	0
1570	0
1571	0
1572	0
1573	0
1574	0
1575	0
1576	0
1577	0
1578	0
1579	0
1580	0
1581	0
1582	0
1583	0
1584	0
1585	0
1586	0
1587	0
1588	0
1589	0
1590	0
1591	0
1592	0
1593	0
1594	0
1595	0
1596	0
1597	0
1598	0
1599	0
1600	0
1601	0
1602	0
1603	0
1604	0
1605	0
1606	0
1607	0
1608	0
1609	0
1610	0
1611	0
1612	0
1613	0
1614	0
1615	0
1616	0
1617	0
1618	0
1619	0
1620	0
1621	0
1622	0
1623	0
1624	0
1625	0
1626	0
1627	0
1628	0
1629	0
1630	0
1631	0
1632	0
1633	0
1634	0
1635	0
1636	0
1637	0
1638	0
1639	0
1640	0
1641	0
1642	0
1643	0
1644	0
1645	0
1646	0
1647	0
1648	0
1649	0
1650	0
1651	0
1652	0
1653	0
1654	0
1655	0
1656	0
1657	0
1658	0
1659	0
1660	0
1661	0
1662	0
1663	0
1664	0
1665	0
1666	0
1667	0
1668	0
1669	0
1670	0
1671	0
1672	0
1673	0
1674	0
1675	0
1676	0
1677	0
1678	0
1679	0
1680	0
1681	0
1682	0
1683	0
1684	0
1685	0
1686	0
1687	0
1688	0
1689	0
1690	0
1691	0
1692	0
1693	0
1694	0
1695	0
1696	0
1697	0
1698	0
1699	0
1700	0
1701	0
1702	0
1703	0
1704	0
1705	0
1706	0
1707	0
1708	0
1709	0
1710	0
1711	0
1712	0
1713	0
1714	0
1715	0
1716	0
1717	0
1718	0
1719	0
1720	0
1721	0
1722	0
1723	0
1724	0
1725	0
1726	0
1727	0
1728	0
1729	0
1730	0
1731	0
1732	0
1733	0
1734	0
1735	0
1736	0
1737	0
1738	0
1739	0
1740	0
1741	0
1742	0
1743	0
1744	0
1745	0
1746	0
1747	1
1748	1
1749	1
1750	1
1751	1
1752	1
1753	1
1754	1
1755	1
1756	1
1757	1
1758	1
1759	1
1760	1
1761	1
1762	1
1763	1
1764	1
1765	1
1766	1
1767	1
1768	1
1769	1
1770	1
1771	1
1772	1
1773	1
1774	1
1775	1
1776	1
1777	1
1778	1
1779	1
1780	1
1781	1
1782	1
1783	1
1784	1
1785	1
1786	1
1787	1
1788	1
1789	1
1790	1
1791	1
1792	1
1793	1
1794	1
1795	1
1796	1
1797	0
1798	0
1799	0
1800	0