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Report of study of the HILS method

Summary

In this report possible test methods and regulatory issues for emission certification of heavy-duty hybrid electric vehicles and especially the potential use of Hardware-In-the-Loop Simulations (HILS) for type-approval tests is investigated.

Exhaust emissions certification for conventional heavy-duty vehicles are today performed on engine-level in an engine test cell. In the near future, in-use compliance will also be required. Hybrid technology puts new demands on type-approval tests as the utilisation of additional torque providers, such as electric machines, decouples the engine operation from the vehicle power requirements. Existing predefined standardised engine torque-speed cycles used for certification are therefore not applicable as the engine operates differently in a hybrid vehicle compared to a conventional vehicle.

In Japan a method for emission certification of heavy-duty hybrid electric vehicles using HILS has been developed. The method uses measured data from certain components like the traction battery, electric motor and engine. This data is then inserted as parameters in standardised component models making up a complete vehicle simulation model, with the exception of some physical control units. These control unit(s) are linked to the simulation via HIL and execute the, often proprietary, hybrid control strategies during a vehicle cycle simulation from which the corresponding engine torque-speed cycle can be extracted. This unique engine cycle will then be input to an exhaust emission test using a real engine.

This report studies the HILS-based method used for emission certification in Japan. The objective is to understand the requirements that need to be placed on a HILS type-approval method. In addition, several other possible test methods are presented and both regulatory and technical concerns are highlighted. The report also considers practical aspects and adaptation requirements for existing test facilities.

In conclusion, HILS-based methods are very suitable for emission certification of heavy-duty hybrid vehicles and the Japanese method is a good example of this. It is currently the only HILS method in operation for emission certification. Its use of a virtual vehicle model also allows specific quantities of emissions to be expressed in basically any unit e.g. per km, per ton-km or per kWh.

Terminology

Abbreviation	Description
ACEA	European Automobile Manufacturers' Association
AMT	Automated Manual Transmission
EATS	Exhaust Aftertreatment System
ECU	Electronic Control Unit
EECU	Engine ECU
EEV	Enhanced Environmentally friendly Vehicle
EM	Electric Motor
EMC	Electromagnetic Compatibility
ESC	European Stationary Cycle
ESS	Energy Storage System
ETC	European Transient Cycle
GRPE	Working Party (Reporting Group) on Pollution and Energy
HD	Heavy-Duty
HDH	Heavy Duty Hybrid
HEV	Hybrid Electric Vehicle
HIL	Hardware In the Loop
HILS	Hardware In the Loop Simulation/Simulator
ICE	Internal Combustion Engine
MCU	Motor Control Unit
MIL	Model In the Loop
NMHC	Non-Methane Hydrocarbons
PM	Particulate Matter
RCP	Rapid Control Prototyping
SIL	Software In the Loop
TECU	Transmission ECU
THC	Total Hydrocarbons
UNECE	United Nations Economic Commission for Europe
WHDC	Worldwide harmonised Heavy-Duty Certification procedure
WHSC	World Harmonised Steady-state Cycle
WHTC	World Harmonised Transient Cycle
WHVC	World Harmonised Vehicle Cycle

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1. Introduction

1.1. Project information

Hybrid Commercial Vehicle (HCV) is a FP7 EU-funded initiative for reducing the emission of climate changing gases and other unwanted emissions in urban areas. Commercial vehicles contribute to a significant part of pollution in today's city environments and hybridisation of said applications can to a large degree decrease the emitted substances. Electric hybrids have so far shown a large potential, however the commercial success is heavily dependent on both the cost and benefit.

The HCV project aims to further reduce the fuel consumption and to decrease the cost of a hybrid system.

Test methods, certification procedures and subsystems will be further developed and the market opportunities and barriers for hybrid commercial vehicles will be evaluated in conjunction with commercial vehicle operators in a user forum [1].

1.2. Scope

This report investigates possible test methods and regulatory issues for emission certification of heavy-duty hybrid electric vehicles and especially the potential use of Hardware-In-the-Loop Simulations (HILS) for type-approval tests[1].

By definition, hybrid vehicles differ from conventional heavy-duty vehicles with the introduction of several sources of propelling power. Currently the focus is the combination of a traditional combustion engine and a supporting electric motor. There are several advantages arising from hybridisation; fuel consumption is usually stated as the primary driving factor. Other factors are noise reduction, electrification of auxiliary loads, full electric take-off, and automated engine shutdown during stops.

This report will focus on the parallel electric hybrid configuration, but the reasoning may also be applicable to other types of hybrid configurations.

These new hybrid configurations will affect the way emission certification is conducted. Motivating examples for this change of emission certification procedure are:

- *Dual power source configuration*
  A dual power source configuration changes the pattern of operation points of the combustion engine. Sophisticated control of the power split will most often let the electric motor handle the transient loads and the combustion engine the base load. Less variation in load and engine speed will give less emissions per produced kWh.

- *Practical issues*
  Most engine test facilities do not handle the addition of an electric motor. Issues include safety aspects related to hazardous voltages and handling of traction batteries. In addition, temperature control of the engine exhaust aftertreatment system (EATS) has large impact on emissions [18].

1The term "type-approval" means the procedure whereby a Member State certifies that a type of vehicle, system, component or separate technical unit satisfies the relevant administrative provisions and technical requirements [2]. These technical requirements often relate to environmental impact and safety aspects of a product to be fulfilled before being allowed into market. In this report the type-approval scope is the regulated exhaust emissions from heavy-duty hybrid vehicles (HD-HEV).

- *Load cycle*
  The load cycle is today calculated directly from a vehicle cycle into an engine cycle. Introducing several sources of power invalidates this approach.

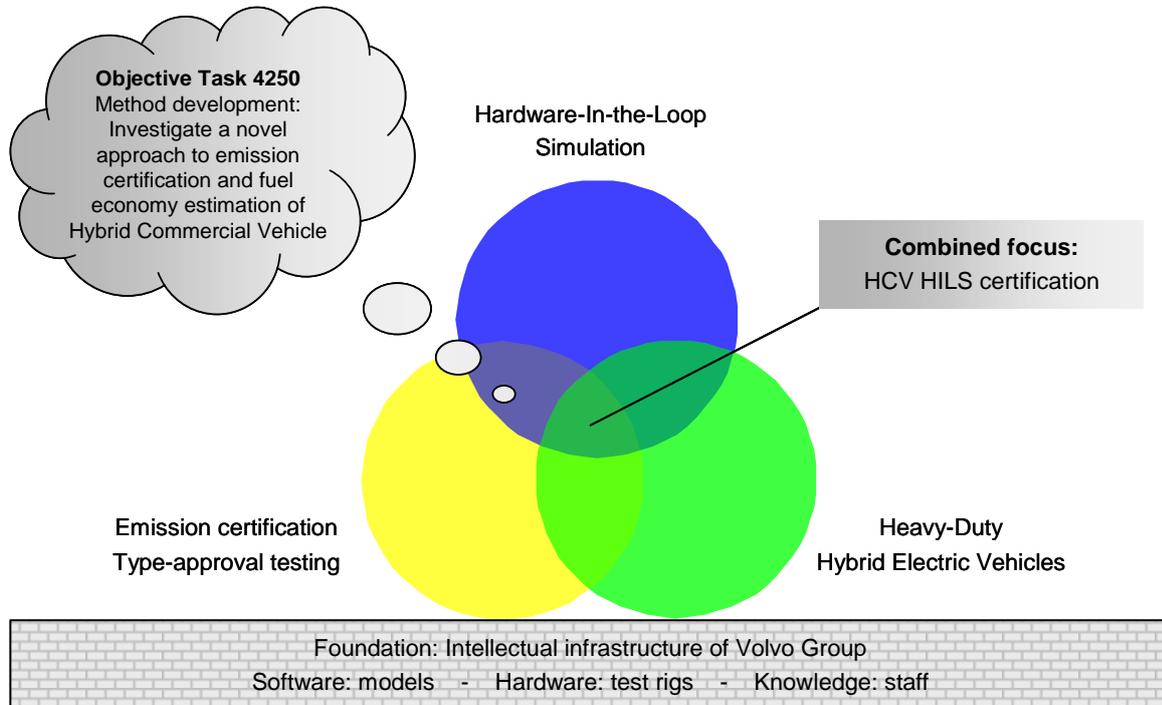The report scope is summarized in Figure 1-1.

Figure 1-1   **Overview of the three perspectives of this investigation: the simulation technique, the vehicle/powertrain technology and the emission regulations.**

1.3. Task 4250, aim of the report

A method using a Hardware-In-the-Loop Simulator (HILS) for HD-HEV emission certification has been developed and is being used in Japan [3]. This method has been investigated in this task of the HCV project. In short, the method consists of two parts:

- A HIL simulation of a vehicle model over a vehicle speed cycle, in order to obtain the corresponding transient engine cycle

- Emission measurement in an engine test cell operating over the specific transient engine cycle

Initially there are three main questions which this report will attempt to answer:

- A. What are the benefits and challenges of the Japanese method?

- B. What requirements must be put on the necessary numerical models and the hardware needed to close the loop, in terms of accuracy, complexity, availability and degree of validation for proper HIL simulations?

C. What needs to be updated or modified in terms of hardware and software to adapt existing engine test cells to allow running the specific transient cycle and performing the emission measurements?

# 2. Background

2.1. Overview

Currently, type-approval tests regarding emission standards for conventional heavy-duty (HD) diesel trucks and busses are not required to be performed on complete vehicles, instead only the engine is tested. The reason for this is the multitude of different applications for heavy-duty engines making separate certification tests for each application economically impossible.

2.2. Emission certification

Due to environmental protection and public health concerns all vehicles emitting harmful pollutants are required to meet legislated emission standards.

Standardized test cycles for HD vehicles are defined in terms of engine torque/speed sequences and testing is performed in an engine dynamometer laboratory. These engine cycles are often created from a basic vehicle-powertrain model with real-world vehicle driving data as input.

The standard emission tests have been designed to result in emissions representing real-world driving and usually consist of one stationary and one transient cycle according to Figure 2-1 and Figure 2-2 and Figure 2-3.
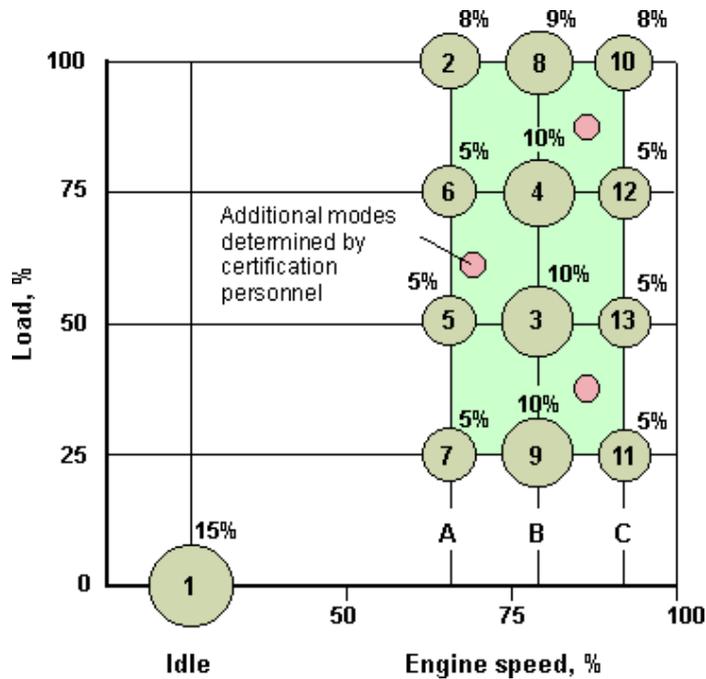
Source: DieselNet, 2011

Figure 2-1   **The European Stationary Cycle (ESC) consists of 13 stationary load points with individual weight factors (shown as percentage value).**
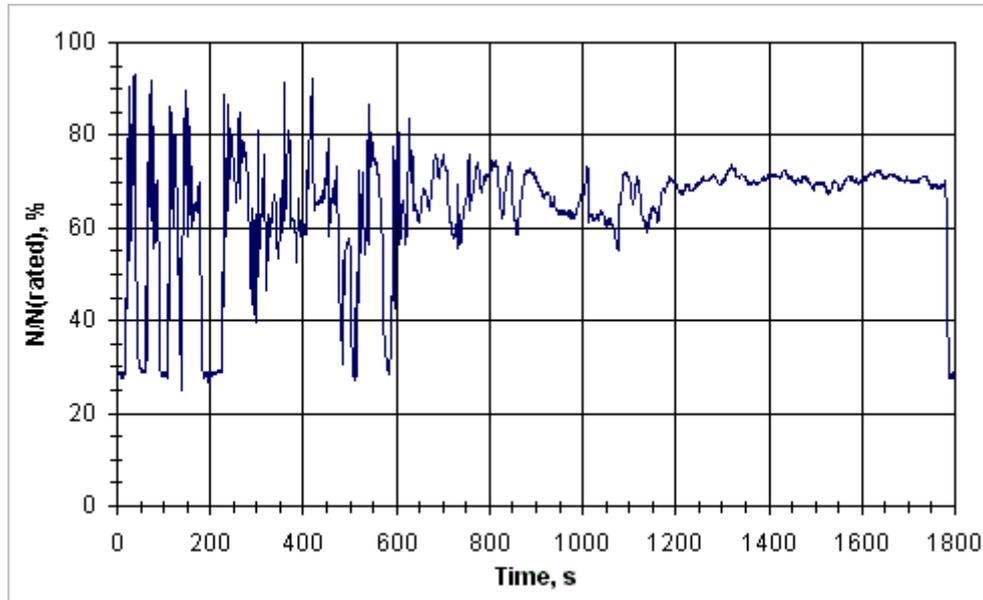
Source: DieselNet, 2011

Figure 2-2 **European Transient Cycle (ETC). The engine speed is expressed in relation to the rated speed of the specific engine to be tested.**

Source: DieselNet, 2011

Figure 2-3   **European Transient Cycle (ETC). The engine torque is expressed in relation to the maximum torque of the specific engine to be tested.**
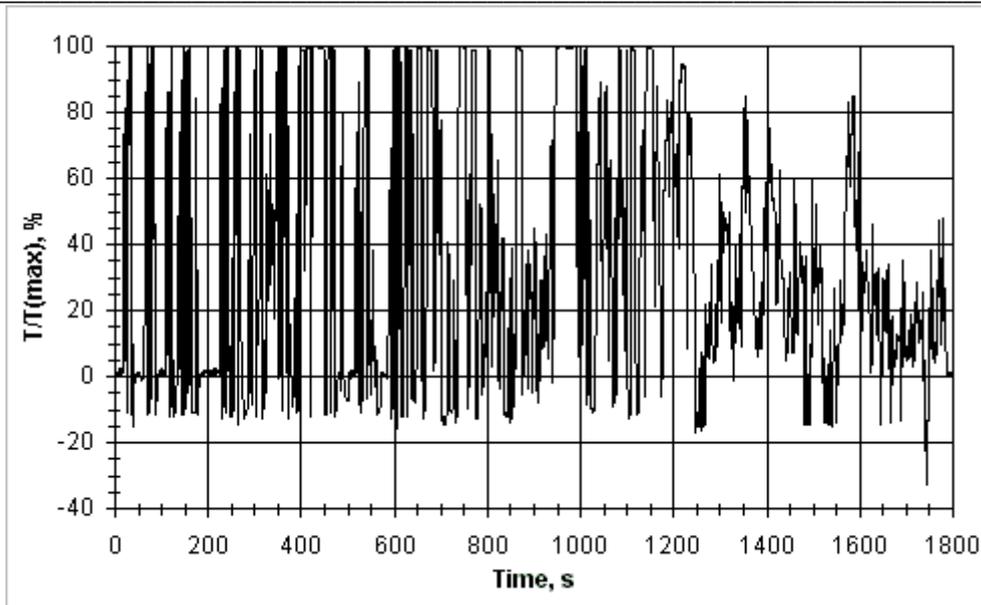
As a consequence of solely the engine being tested[2], the regulated emission limits are stated as the ratio of cumulated pollutant mass to positive engine shaft energy over the cycle expressed in the unit [g/kWh]. This is also referred to as *brake specific emissions.* Table 2-1, Table 2-2 and Table 2-3 show the EU emission standards [22] for heavy-duty diesel engines.

Table 2-1   **EU Emission Standards for HD Diesel Engines, g/kWh (smoke in m-1)**
                          (Smoke opacity is measured during the European Load Response (ELR) test)

Tier	Date	Test	CO	HC	NOx	PM	Smoke
Euro III	*1999.10, EEVs only*	*ESC & ELR*	*1.5*	*0.25*	*2.0*	*0.02*	*0.15*
	2000.10	ESC & ELR	2.1	0.66	5.0	0.10 0.13[a]	0.8
Euro IV	2005.10		1.5	0.46	3.5	0.02	0.5
Euro V	2008.10		1.5	0.46	2.0	0.02	0.5
a - for engines of less than 0.75 dm^3 swept volume per cylinder and a rated power speed of more than 3000 min^{-1}							

Source: DieselNet, 2011

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[2] In contrast, cars and light-duty vehicles are required to be tested as complete vehicles on a chassis dynamometer where a vehicle speed cycle is to be followed and the emission limits are expressed in the unit [g/km].

Table 2-2   Emission Standards for Diesel and Gas Engines, g/kWh

Tier	Date	Test	CO	NMHC	CH$_4$[a]	NOx	PM[b]
Euro III	*1999.10, EEVs only*	*ETC*	*3.0*	*0.40*	*0.65*	*2.0*	*0.02*
	2000.10	ETC	5.45	0.78	1.6	5.0	0.16 0.21[c]
Euro IV	2005.10		4.0	0.55	1.1	3.5	0.03
Euro V	2008.10		4.0	0.55	1.1	2.0	0.03
a - for gas engines only (Euro III-V: NG only; Euro VI: NG + LPG) b - not applicable for gas fueled engines at the Euro III-IV stages c - for engines with swept volume per cylinder < 0.75 dm^3 and rated power speed > 3000 min^{-1}							

Source: DieselNet, 2011

Table 2-3   Euro VI Emission Limits (compression ignition engines)

Tier	Date	Test	CO (mg/kWh)	THC (mg/kWh)	NO$_x$[(1)] (mg/kWh)	NH$_3$ (ppm)	PM mass (mg/kWh)	PM[(2)] number (#/kWh)
Euro VI	2013.01	WHSC	1500	130	400	10	10	8.0×10^{11}
Euro VI	2013.01	WHTC	4000	160	460	10	10	6.0×10^{11}
[(1)] The admissible level of NO$_2$ component in the NO$_x$ limit value may be defined at a later stage. [(2)] A new measurement procedure shall be introduced before 31 December 2012.								

Source: EU Regulation No 595/2009 amended by Regulation No 582/2011, May 2011

A non-mandatory and stricter emission standard, Enhanced Environmentally friendly Vehicle (EEV), was introduced together with the Euro III Standard; as seen in Table 2-1 and Table 2-2, to allow for tax incentives to encourage both the use, and to advance development, of clean and energy-efficient vehicles. EEV is a technology- and fuel-neutral emission standard and the limit values may be adopted for hybrid vehicles, still the corresponding test procedures do not correlate with real-world engine operation in most hybrid vehicles.

2.2.1. Declaration of commercial vehicles, emissions and carbon dioxide

For clarity, it should be noted that the term *emissions* in the context of concurrent regulation refers to particulate matter (PM) and nitrogen oxides (NO$_x$). For a complete overview of regulated emissions, see Table 2-1, Table 2-2 and Table 2-3.

The fact that carbon dioxide (CO$_2$) is not a regulated emission surprises many. Future regulations, and for example the Euro VI and US10 standards, consider the reduction of CO$_2$. Its reduction is however driven by cost in the form of increasing fuel prices. The present status of CO$_2$ declaration for commercial vehicles is voluntary and handled by the industry itself. The European Automobile Manufacturers' Association (ACEA) are preparing a declaration procedure for CO$_2$ [9].

In order for the user of a commercial vehicle to make an informed choice when buying a vehicle, the expected fuel consumption and the related emission of CO$_2$ declaration of the commercial vehicle will be considered [9]. This is already the case for cars which is a much

easier task due to the similarities within product families. Most commercial vehicles are customised which make every vehicle unique. Furthermore, commercial vehicle carry loads and therefore the unit of measurement of transport efficiency will differ from cars. The unit used are gram CO_2 per distance for cars versus gram CO_2 per weight for commercial vehicles.

There is a connection between different emissions and CO_2 output. Regarding PM and NO_x this is well-known, see Figure 2-4. The CO_2 to NO_x relation is less investigated and there is a high likelihood of that compliance to emission regulations can be achieved at the expense of a higher CO_2 declaration [7].
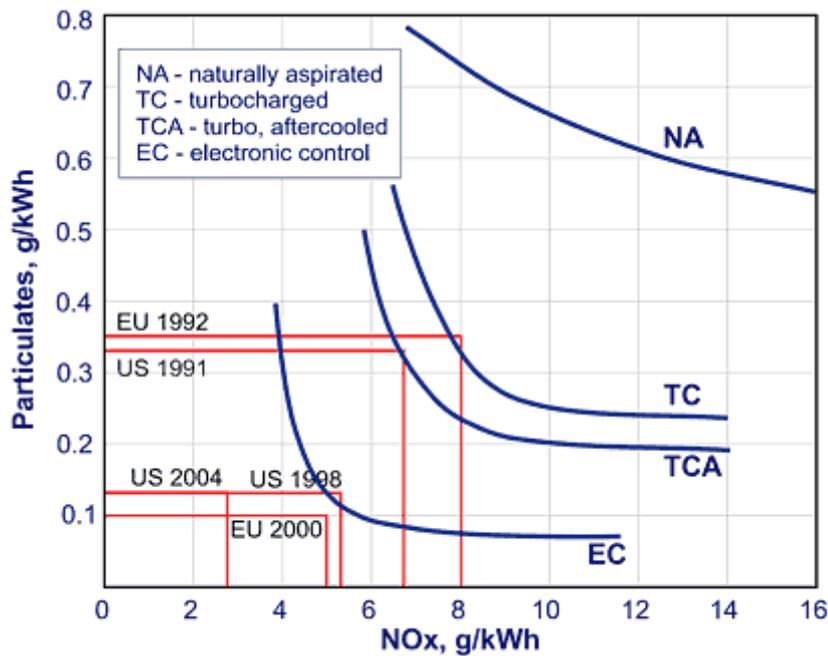

Figure 2-4   Trade-off between PM and NOx

2.3. Simulation techniques, MIL, SIL and HIL

This chapter aims to give an overview of the structure of a generic closed-loop system in order to clarify one possible and generally accepted way to distinguish between Model-In-the-Loop (MIL), Software-In-the-Loop (SIL) and Hardware-In-the-Loop (HIL).
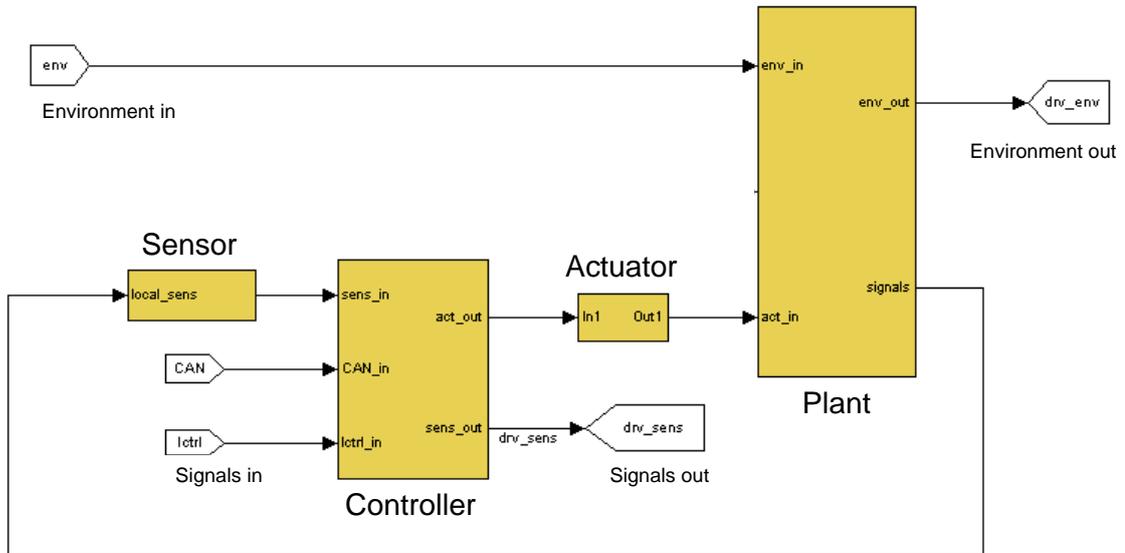
Figure 2-5 **In a closed-loop system each block reacts to the signals from the previous block. The feed-back loop through the sensor block allows the controller to react via the actuator block to changes in the plant**

The division between the controller and the plant is crucial, see Figure 2-5. In the plant the physical properties are modelled and the controller handles the functional logic. The sensors and actuators deal with the known limitations of the communication between the two. Limitations are for example signal saturation, delays and noise.

Furthermore, the division makes it possible to generate production code to download to the hardware controller in the vehicle. The division also allow a structured way to describe the difference between MIL, SIL and HIL, see Table 2-4.

The effort and cost are also reflected in the table, but the advantage of this model-based method during product development motivates this, see Figure 2-8.

Table 2-4 An overview of the different configurations based on the generic closed-loop system model with separated controller and plant.

	Technique	Controller	Plant	Comment	Level of effort in setup
MIL	Model in the loop	Modelled ECU	Model	All models in native simulation tool, e.g. computer	Low
SIL	Software in the loop	Code-generated ECU	Model	Part of model exist in native simulation tool and part as executable code, e.g. virtual ECU	Medium
HIL	Hardware in the loop	Physical ECU	Model	Part of model runs in real-time simulator, and part exist as physical hardware	High
	This definition is based on the perspective of the plant (column Technique)				

The term 'HILS' found in literature and in this document have a dual meaning. The 'S' may stand for either 'Simulation' or 'Simulator', where the former refers to the *use* of the latter. The context in which the abbreviation is used will distinguish its ambiguous interpretation.

2.3.1. Model-In-the-Loop

Designers use software simulation tools [10] to develop complex electronic control systems. The designer initially builds a model of the new components in pure software. The controller model is then used to run simulations in conjunction with models of the rest of the vehicle to study the behaviour of the overall system. At this stage it is possible to verify the algorithms and routines of a new component before building a prototype. It is unnecessary for the fully software simulation to operate in real-time. It will usually simulate faster than real-time enabling many tests with variations in parameters.

Employing full software simulation can provide a designer insight into the behaviour of a system under varying internal and external conditions. However, for complex systems, it is often impractical or impossible to accurately model every characteristic of a system.

2.3.2. Software-In-the-Loop

Sophisticated development tools [11] allow the possibility automatically generate code from the controller model that is specifically tailored to the target hardware controller, see section 2.3.1. This software code still executes in the native software simulation environment together with the models for the plant, sensors and actuators. Target specific software issues such as performance, numerical errors and debugging interface can be developed.

2.3.3. Hardware-In-the-Loop

Hardware-In-the-Loop simulation extends the pure software simulation by allowing the developer to replace portions of it with physical components. The HIL simulation incorporates and reveals the characteristics of real-time interaction, such as sampling and time lags, as if the complete real system was operating.

The physical components or subsystems respond to simulated signals as though they are operating in a real system because the simulated signals generated by software models accurately and in real time mimic the signals that would occur in the environment and with other real subsystems [4].

Continuing the example from the steps in previous sections 2.3.1 and 2.3.2, HIL simulation often follows when looking from a development process perspective. In such a viewpoint, the new physical ECU hardware is now required, however the new engine may still not be available, but nor is it needed as the engine plant model is available. The target specific software code from the previous step can now be downloaded and executed on the new physical ECU. However, by introducing a physical ECU, the connection to the numerical engine plant model running in the simulation environment is broken. Additional hardware, in the form of a real-time physical/numerical interface, is required to close the loop again. Several products providing this interface function exist on the market, most are quite generic but some are specialised for a certain application, like engine control or electric motor drive control.

In some cases, the most efficient way to develop an embedded control system, e.g. an ECU, is to connect it to the real plant, if such a plant yet exists. In other cases, HIL simulation is more efficient. The metric of development and test efficiency is typically a formula that includes the following factors [6]:

- Cost
- Time-to-market
- Safety
- Feasibility
- Reproducibility
- Engineering effort

The major drawback of converting physical subsystems into numerical models is the reduced accuracy of the results, see Figure 2-6. The acceptable amount of increased uncertainty must be evaluated in each separate case.
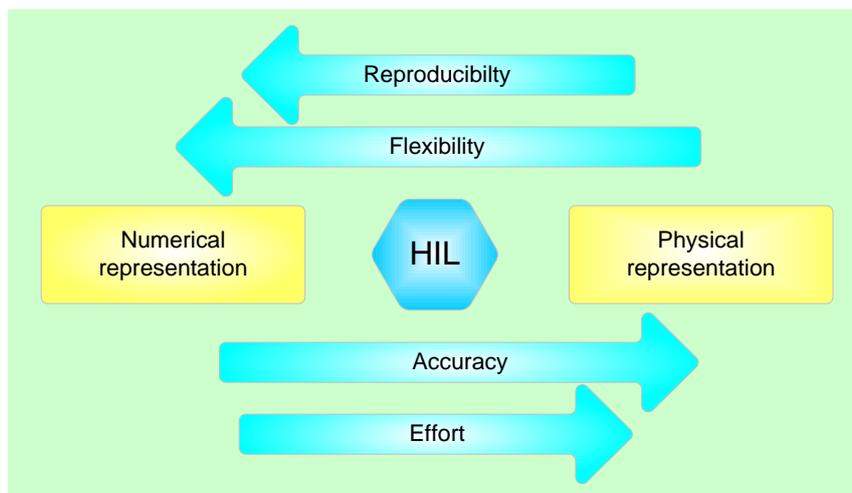

Figure 2-6   **Hardware-In-the-Loop trade-off**

In this context, a special HIL variant referred to as Rapid Control Prototyping (RCP) should be mentioned. RCP, opposite to regular HIL, implies that the actual plant makes up the physical part while the controller is implemented/modelled in numerical form and executed on a real-time control prototyping platform, see Figure 2-7. The RCP focus is on the development of functionality and algorithms of the controller. Using a flexible prototyping platform, instead of the actual control unit, and its accompanying development tools can often reduce the turnaround time experienced for each update or modification, which are usually quite many in the early development phase.
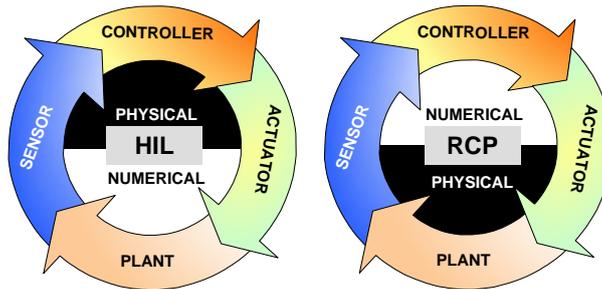
Figure 2-7   **Rapid Control Prototyping (RCP) is a HIL variant offering potential time savings in early development.**

At this point it is clear that there are many possible ways to combine numerical models and physical components into a system. They all share the property that they provide a complete system, vehicle or component, which can be used in a real-life-like manner to predict behaviour of dynamic systems. These might be for development purposes as well as for certification or use case estimations in sales.
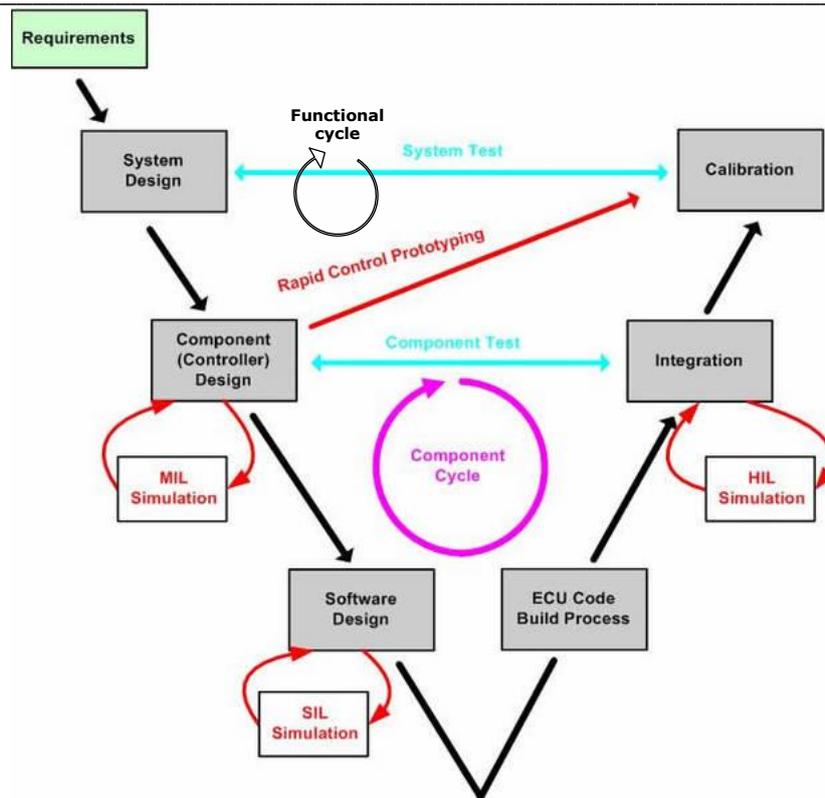
Source: Magna Powertrain (http://www.ecs.steyr.com/Advanced-Combustion-Engines, 2011)

Figure 2-8   V-cycle for model based control software development

Rapid Control Prototyping tools, [11], facilitate early functional development. RCP may seem to be a development shortcut, bypassing the lower part of the V-cycle as seen in Figure 2-8, but this is just temporary; eventually, if aiming for series production, target specific code must be developed and tested, both in SIL and in HIL with dedicated ECU hardware.

Figure 2-8 puts MIL, SIL and HIL in a complete system development context. In software development the HIL step is normally considered the final testing before the software is released to be downloaded and calibrated on the real system. However, HIL simulation is not only used for testing; one example is the studied emission test method in Section 2.5 where HILS is used to perform advanced system calculations.

2.3.4. Dynamic and static (averaging) techniques

Apart from the above described techniques there are other types that will briefly be mentioned for completeness.

Simulation techniques can be divided in to two categories as either dynamic [23] or static (averaging). Currently dynamic techniques are so common that the static category, usually much simpler and basic techniques is forgotten.

MIL, SIL and HIL are regarded as dynamic. They operate as a time series where the current state is the input to the next state in time. This opens the possibility to model complex systems with non-linearity properties (saturation, slew, noise) and time-dependent factors

(delays). Models and calculations solve this with ordinary differential equations (ODE). This complexity is hidden from the user by the development tool [10].

A static technique is to use overall energy and power equations in combination with experience and measurements. By its nature it can not describe a state at a given time. However, in the estimation of an overall fuel consumption or total emissions this level of detail is often not needed.

For certification purposes the desired level of detail excludes this static method, though it can be used to give a preliminary estimate for early justification of more elaborate tests. Another use of static simulation is for advanced and hard to model features such as road prediction and waste heat recovery. For practical reasons these can be lumped together and deducted as an "emission reduction bonus". In that case, a single average figure will do.

2.4. Hybrid powertrain concepts

Commercial electric hybrid vehicles can have different configurations; usually the placement of the motor is the key distinction.

2.4.1. Classifiers

Hybrid vehicles are classified according to their Powertrain configuration [12] [13], see Table 2-5 for an overview of the main classes.

Table 2-5   Overview of classes based on hybrid powertrain configuration

Configuration	Example typical configuration
Parallel hybrid (P-HEV)	
Series hybrid (S-HEV)	
Power-split or series-parallel hybrid	
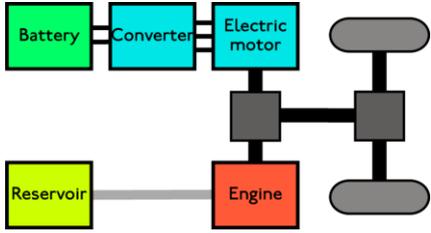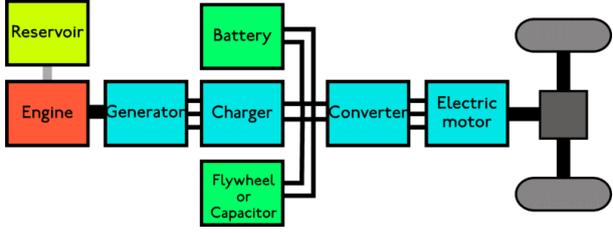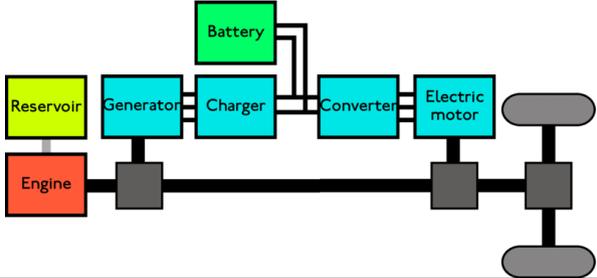
Another differentiating property is the usage of the hybrid system. Depending on the system's ability, mainly due to the sizing of components, the degree of hybridization an additional classification can be done, see Table 2-6. This is not as well defined as the classification based on the configuration.

Table 2-6   Additional classification criteria for hybrid electric vehicles based on the ability and usage

Degree of hybridization	Examples of typical features
Full hybrid	Pure electric take-off, full regenerative braking, full torque assist
Mild hybrid	Electric auxiliaries can run when ICE is off, limited torque assist
Plug-in hybrid	Vehicle are charged during standstill using external power source

2.5. Japanese exhaust emission test procedure

The Japanese method [3] is described in this chapter. An outline of the method is shown in Figure 2-9. The figure[3] exemplifies a parallel hybrid setup although the method can be used for series hybrids also.
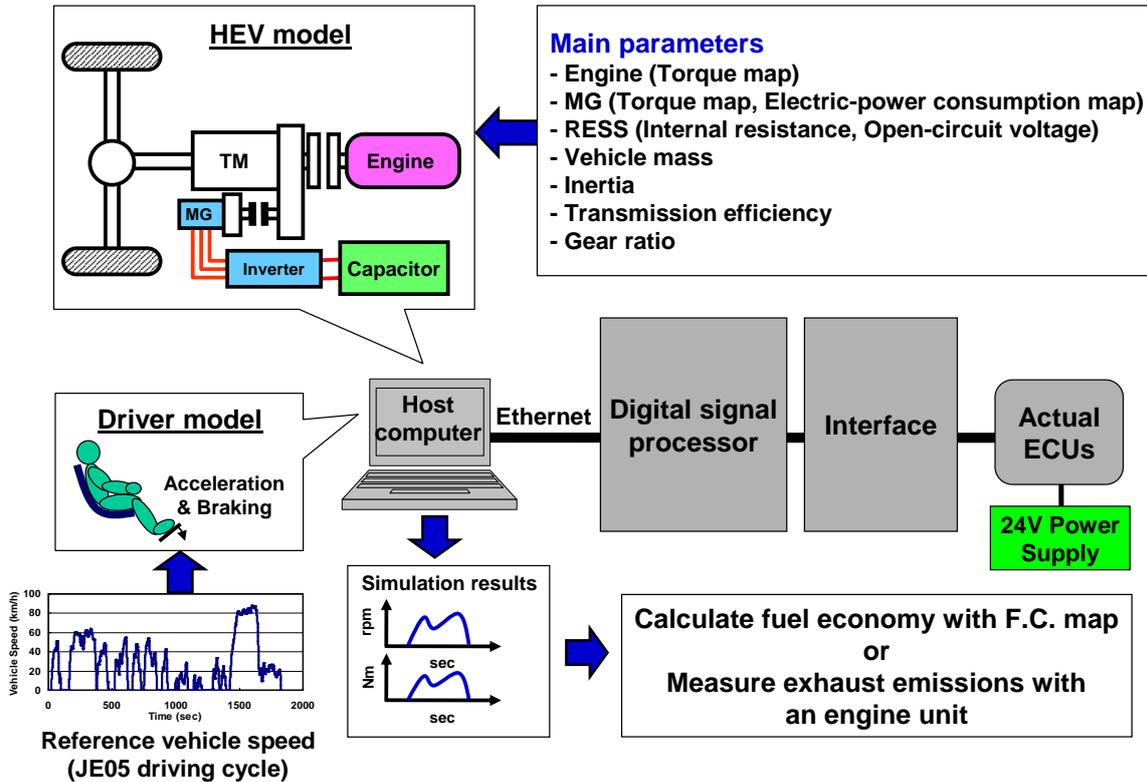
Source: [14]

Figure 2-9   **Block diagram presenting the concept of the Japanese HILS based test procedure.**

As mentioned earlier, this method is already approved and in use in Japan for emission certification of heavy-duty HEVs. Therefore, information and requirements already exist on how to apply the method for type-approval testing.

Input provided by type-approval authorities

- Vehicle speed cycle, in Japan certification requires the JE05-mode cycle.

- Standardised models for driver, driveline and powertrain components, covering both series and parallel HEV configurations.

- Test procedures for obtaining the component model parameters.

- Reference parameters of all component models for each hybrid configuration.

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[3] Terminology used in the figure: MG – Motor/Generator i.e. an electric machine. RESS – Rechargeable Energy Storage System, e.g. a battery pack or a capacitor bank

- Reference ECU model with basic control strategies for each hybrid configuration.

- Verification criterion and allowed tolerances.

- Standard vehicle specifications.

Equipment needed and provided by vehicle manufacturer

- A HIL system, i.e. a real-time computer.

- Actual ECU(s) with software containing the hybrid operation functionality.

- Test facilities and measurement equipment for component testing, vehicle testing and the final engine emission test.

Intermediate output

- Exhaust gas measurement cycle, i.e. the simulated engine cycle in terms of torque and speed as time-data, to be reproduced on a real engine during an emission test in an engine dynamometer test cell.

- Integrated system shaft output, i.e. the total simulated positive mechanical propulsion energy of the hybrid system. For a parallel hybrid this means the combined work of both the engine and the electric motor.

Final output

- Measured masses of exhaust-gas emission components corresponding to hybrid vehicle operation. The emission factors [g/kWh] needed for comparison against the legislated certification limits for type-approval decision must be calculated using the integrated system shaft energy.

The procedure begins, as shown in the flow diagram in Figure 2-10, with component testing to obtain all model parameters.

- The summed effort to perform tests on all components is not to be underestimated; however tests only need to be performed for new or changed components

- The models are fairly basic, which helps to keep down the number of parameters and in turn the time required for component testing

- Road load parameters, i.e. rolling resistance and aerodynamic drag coefficients are calculated by provided formulas using vehicle data from the standard vehicle specifications

- Vehicle model parameters, e.g. dynamic wheel radius, final gear and frontal area are provided from the standard vehicle specifications depending on vehicle category and its gross weight
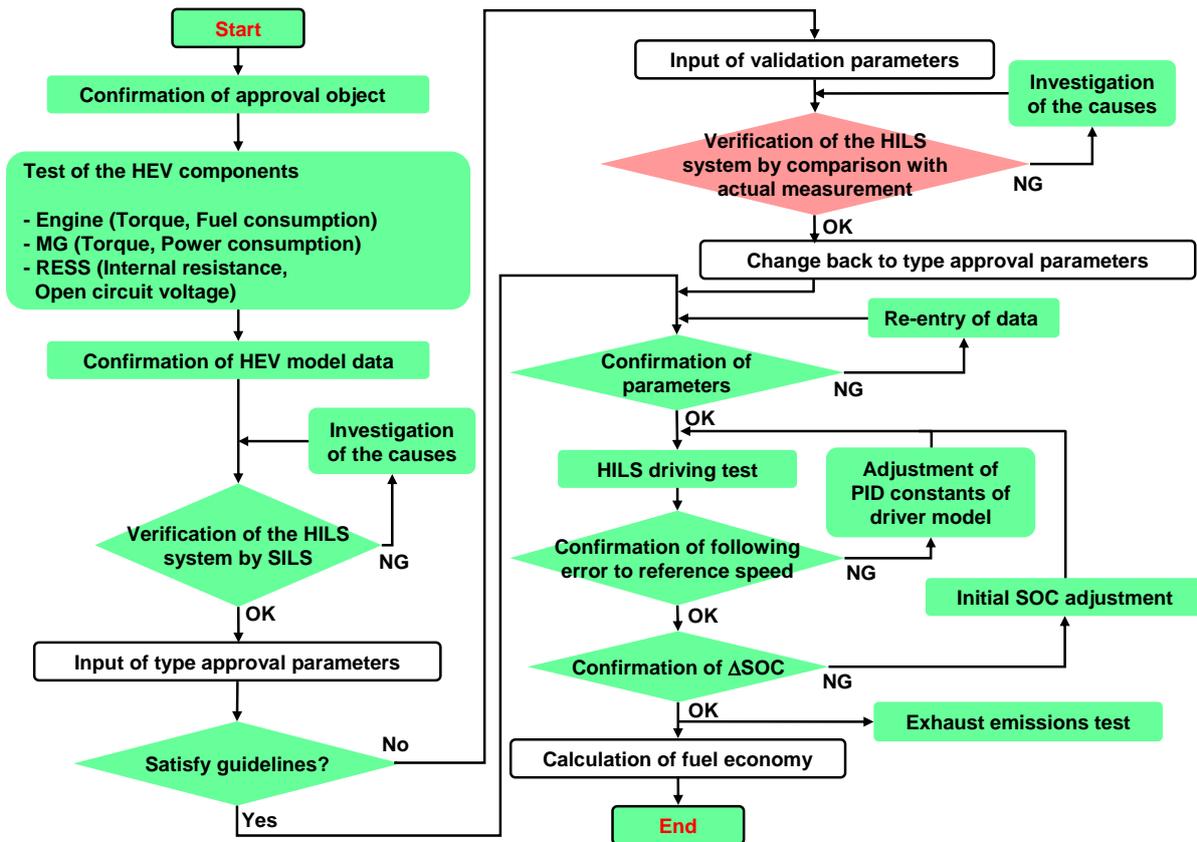
Source: [14]

Figure 2-10   Flow chart of HILS method

Next, the HEV model is verified by performing a SIL simulation with the provided reference ECU model, i.e. the SIL, executing in the model environment and controlling the HEV model. Using the provided reference parameters for the component models, a simulation is run and the time series data of the main variable quantities, like current, voltage, torque and speed, are recorded and compared to reference data.

Next step is to input the previously measured model parameters and according to certain guidelines confirm that the HILS system is representative of the actual vehicle undergoing the type-approval test. If equivalence is confirmed, the HIL simulation can be performed; otherwise additional verification tests using the actual vehicle need to be run [3]. Cases requiring this additional verification, besides the first time the HILS system is used, are e.g. when the layout of the powertrain is changed like switching from series to parallel or changing the location of the electric motor or the clutch. Keeping the same type of components but changing their characteristics, as those measured during the component tests, will not require this verification.

During the HIL simulation some iterative loops for tuning may have to be run to confirm that:

- the driver model follows the vehicle speed cycle within given tolerances

- the net electrical energy in relation to the total engine propulsion work over the cycle is below given limits

With a successful simulation, the engine torque-speed cycle is recorded and this data can now be used to measure exhaust emissions by replaying the cycle data on a real engine testbed.

3. Investigation of requirements on models

The emission certification test procedure has to be designed in such a way that the subsequent road-use also is in line with the intention of the regulations. This puts requirements and constraints on the model in a HILS system.

3.1. Model complexity, accuracy and proprietary issues

3.1.1. Requirements on models for use in certification

When designing a setup for certification testing some additional factors to development testing must be handled. Two major factors regard trust and acceptance. The trust factor is based on the fact the industry parties must be allowed to maintain their technological integrity and that the tests are possible to perform with a reasonable effort. The factor regarding acceptance the test procedures from the industry is related to feasibility and cost. Public acceptance is based on that the certification process is hard to tamper with and produces products that are in line with the legislators' intentions.

The solution to the trade-off between model complexity, accuracy, proprietary issues and cost and feasibility is not obvious. In the wide range of possible solutions quite a few can be disregarded if underlying principles and practical issues are considered. Hopefully, this approach will give a manageable number of candidates to investigate in-depth.

Factors can be grouped:

- Trust
    - Protection of intellectual properties
    - Third-party verification
    - Complexity
    - Feasibility
- Acceptance
    - Tamper proof
    - In-service conformity testing possible
    - Accuracy in model
    - Cost, development and maintenance

3.1.2. Public or proprietary systems

A bridge to combining proprietary and public systems is public interface definitions. Terms such as 'black-box' and 'server-based' solutions are implementations of this. The client can, through the public interface, use the service of the server to get correct response and function without detailed information of the content and algorithm. If the server can be trusted, its inner details can for all practical purposes stay hidden. Potential trust issues are removed by a mutually trusted third party.

For certification purposes, three separate ways to protect proprietary system while ensuring trust between parties:

- Complied code in native simulation platform
- Externally executed code
- Embedded software

3.1.3. In-service conformity

The European Union has adopted regulation for emission testing regarding In-Service Conformity [24][25]. This is similar to the North American In-Use Compliance. Article 21 states:

"In order to better control actual in-use emissions including off-cycle emissions and to facilitate the in-service conformity process, a testing methodology and performance requirements based on the use of portable emission measurement systems should be adopted within an appropriate timeframe."

3.1.4. Consequences of different model complexity

As a mathematical model of the system becomes increasingly detailed, the accuracy of the computations is expected to increase. This is for simple systems mostly the case, but for larger and especially integrated systems it can not be guaranteed. The factors involved are accumulated error in variance of estimated parameters, saturated states and phase-shifts such as delays. Also, a detailed system has more parts and the number of interaction itself will increase exponentially, even though the potential sources of error only increases in a linear fashion.

For the application of constructing a simulation model for use in certification, acceptance of the validity from all parties is a key issue. The system's ability to be analysed and approved by all parties puts constrains on the design.

Obviously, in a world of commerce the cost of development and maintenance also sets a boundary of how elaborate a model can get.

For these reasons very complex and detailed models might defeat the overall purpose.

3.2. Vehicle drive cycles

Drive cycles are a description of the scenario the vehicle will face. It strongly depends on the application; a city-bus will drive completely different from a coach. The level of variations in the load also varies as well as the magnitude. To complicate matters even more there are two approaches to this scenario description. The drive cycle can be either time based or position based. The time based usually specifies the speed at every point in time, the distance based describes the conditions such as stops and speed limits and then let the vehicle decide how to accomplish this mission.

3.2.1. Stop and go

Full stops are frequent for delivery trucks, refuse trucks and obviously for city buses. These give an opportunity to shut down the ICE and reducing the output of CO_2 to zero. Shutting down the engine will eventually lower the temperature of the after-treatment system and will have a negative impact on the amount of NO_x emissions, but for short stops the interrupted

exhaust flow will help keep up the temperature longer, as opposed to the cooling effect of exhaust flowing during idling [18].

Also, shutting down the ICE will require the use of stored energy for e.g. air-conditioning and door openers. This reduces the energy available for propulsion.

The vehicle can use full electric take-off and avoid using the ICE at operation points of low efficiency and disturbing noise emission [15].

3.2.2. Power split and implications on load cycles

The introduction of hybrid vehicles will change the way load cycles for emission testing is produced. The main reason is the occurrence of several power sources in the vehicle. The intelligent split between the power sources and optimised regenerative braking are the main contributors to fuel saving. Usually, in an electric hybrid vehicle the propelling torque is either from the electric motor, the internal combustion engine or a combination of these two, Figure 3-1.

1. Electric motor
2. Diesel engine
3. Hybrid mode
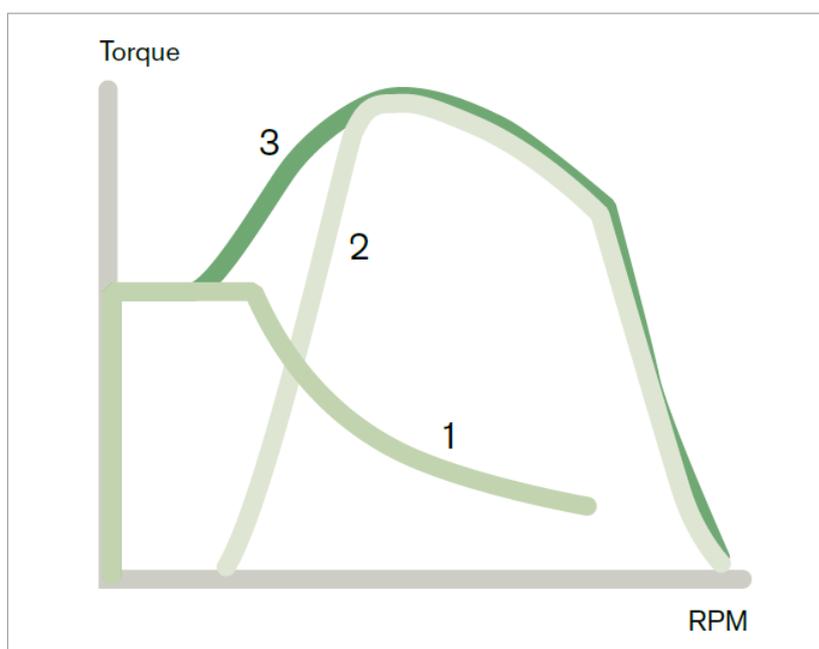
Figure 3-1   **Example from Volvo FE Hybrid [15] showing the possible combinations of the engine and the electric motor. This demonstrates the possibility to adjust the operation point of the engine over the full engine and vehicle speed range.**

Figure 3-3 shows the WHVC, a vehicle cycle of speed following kind, with its three regions. The normalised power curve is a consequence of a computer model of the drive train. It is not applicable for a hybrid vehicle. The Figure 3-1 illustrates how the power-split renders the power curve in WHVC invalid for hybrids. The hybrid controller shifts the operation point of the engine.

A vehicle simulation model will generate a configuration specific load cycle. The basis for this simulation is a standardised transport mission in the form of a scenario describing the road condition and constraints regarding total time and drivability.

With the basis of a transport mission a vehicle cycle can be measured or constructed. This format can feed a chassis dynamometer or a complete vehicle simulation model. Complete hybrid drivelines can also, with minor adjustments, use this format. For engine testing a load cycle or a steady state map has to be calculated. This calculation will result in some loss of
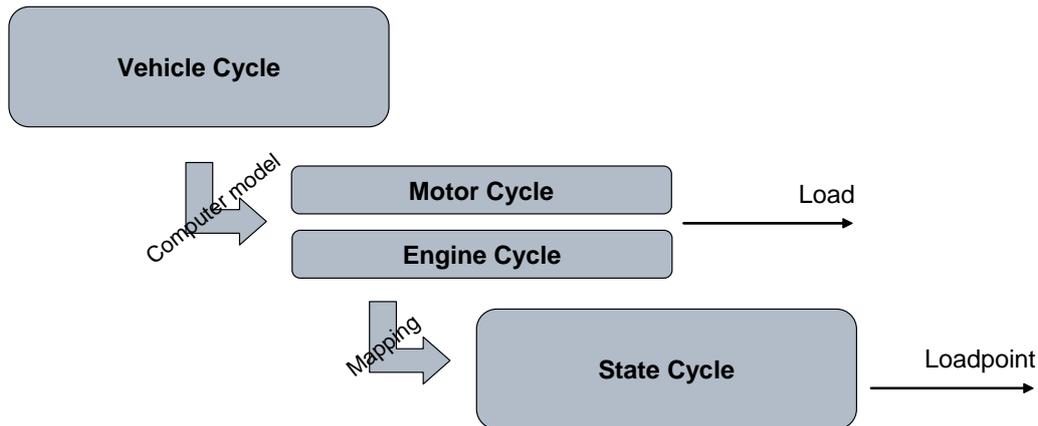
information, see Figure 3-2.

Figure 3-2   Reduction of the vehicle road cycle to engine cycle and a steady state cycle

It is not possible to reverse the process without detailed knowledge of the model and data maps in Figure 3-2. In an electric parallel hybrid the sum of the engine and electric motor torque will be the propelling torque.

Table 3-1   Overview of several types of transport mission scenarios

Vehicle cycle		Time-based	Distance-based	Example
Speed following	Speed vs time	x		WHVC
Road conditions	Desired cruise speed	x		Database
Road conditions	Road speed limits		x	Database
Road conditions	Desired cruise speed and events		x	Database
Engine cycle		Time-based	Distance-based	Example
Load cycle	Torque and engine speed	x		WHTC

Examples of events are duration of stop with engine idling, use of auxiliaries such as door openers etc. This type of event based duty cycle is describes the conditions under which the vehicle drive.

The scenario representing the transport mission must allow the hybrid vehicle to show its full potential, speed-following vehicle cycles does not allow this. Forcing the vehicle into specific acceleration patterns and omitting the topology is a severe limitation.
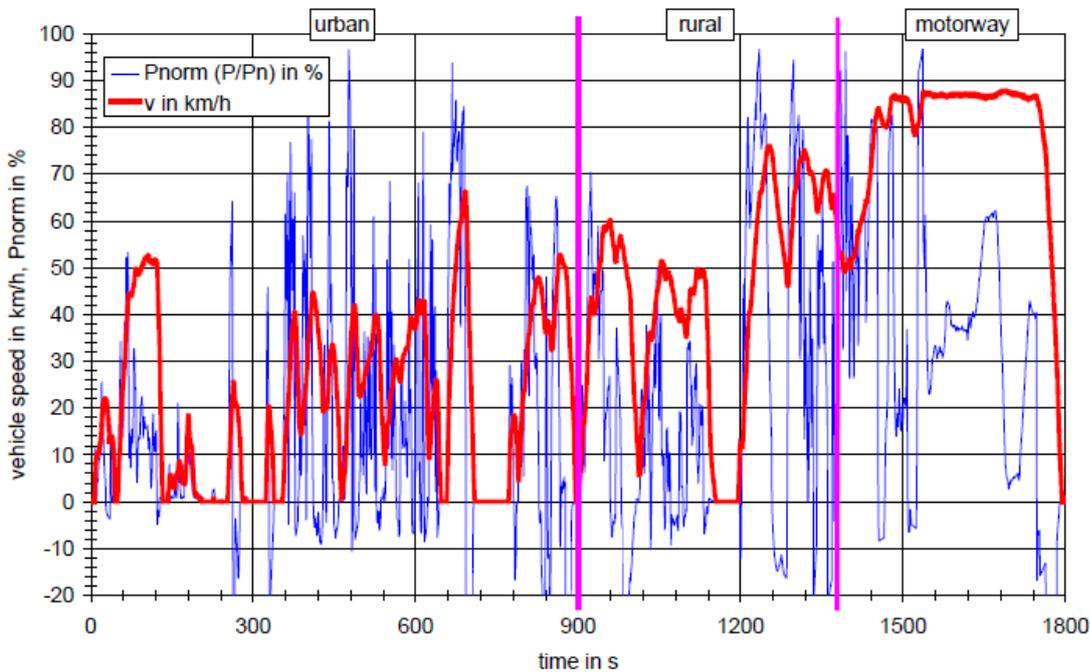

Figure 3-3   **WHVC with speed and normalized power [16] displaying three distinctly different road types with weights of 50, 25 and 25 percent based on road use database and power to weight ratio, see Figure 3-4**

Vehicle category	Power-to-mass ratio (kW/ton)	Region	Road type	Valid number of combinations (cells)
Light and Rigid trucks, incl. Special purpose trucks and coaches	3 classes	USA Japan Europe	Urban Rural Motorway	27
Trucks with trailers and semi-trailers	3 classes	3 classes	3 classes	27
Public transport buses	1 class	3 classes	2 classes	6
			sum	60

Figure 3-4 **Power to weight ratio, selection of vehicles for generation of WHTC [17]**

3.2.3. Vehicle applications impact on duty cycle

The duty cycle must be meaningful for the particular application. Commercial vehicles are working platforms tailored to specific use cases. For example, a city bus will most likely not spend much time on the motorway. Thus, the vehicle cycle must reflect the application, also called vocation.

vehicle cat.	power to mass ratio class	Europe			Japan			USA			Sum
		urban	rural	motor way	urban	rural	motor way	urban	rural	motor way	
rigid trucks	1	5.2%	1.8%	2.0%	3.4%	1.2%	0.9%	3.3%	1.8%	0.6%	20.2%
rigid trucks	2	3.1%	1.7%	2.3%	6.0%	2.1%	1.6%	4.4%	2.4%	0.8%	24.3%
rigid trucks	3	3.2%	2.0%	2.5%	4.0%	1.4%	1.1%	2.6%	1.4%	0.5%	18.7%
trailer trucks	1	0.8%	1.0%	2.2%	0.3%	0.1%	0.1%	1.1%	0.8%	0.8%	7.1%
trailer trucks	2	0.8%	1.0%	2.3%	0.4%	0.2%	0.1%	2.1%	1.6%	1.5%	10.0%
trailer trucks	3	1.0%	1.3%	2.8%	0.2%	0.1%	0.1%	2.9%	2.2%	2.1%	12.6%
buses	1	2.8%	1.2%	0.0%	1.4%	0.4%	0.0%	0.7%	0.5%	0.1%	7.1%
	Sum	16.9%	9.9%	14.1%	15.7%	5.4%	3.9%	17.0%	10.7%	6.3%	100.0%

Figure 3-5 **UNECE-GRPE WHDC Working Group bases the weights on the three road segments on a power to mass ratio. Buses spend zero per cent time on motorways [17]**

The World Harmonized Vehicle Cycle (WHVC) has a global average based on the power to weight ratio Figure 3-5 shows how the WHVC is derived using averages from several vehicle types. [17]. Even though city buses spend no time on the motorway according to the data base, it will still get a 25 % part of it in the WHVC.

ACEA propose a classification that also incorporates the application [9].

3.2.4. Topography and altitude information

For hybrid vehicles the regeneration of energy is important. Retardation sequences are a good source of free energy that would go to waste as friction and heat in the brakes. Retardations are rather short in time and put demands on the power the hybrid system can

absorb. The topography has another time frame but are still good source of storable energy requiring lower power ability. For a hybrid system to perform at its best, topography information will always be of benefit.

Most speed-following certification drive cycles claim to have this topography built in. A recommendation would be that the drive cycle would end at the same altitude. Since hybrid vehicles can take advantage of down slopes to do regenerative braking using the electric motor as a generator any difference in start and end altitude will affect the charge of the battery. To remove any doubts regarding this impact on fuel efficiency and emissions any duty cycle should have the same start and end altitude. An obvious solution to this is to use a cycle that returns to the same location.
A simplified reverse calculation using the WHVC and the WHTC, indicate that it does not support this requirement.

Another complication with the inclusion of topography information in a speed-following drive cycle is that small deviations in the speed compliance would accumulate and give different positions, and thus altitude, in the later part of the cycle.

3.3. Driver model setting

The driver settings are an expression of the driving style. In a speed following duty cycle the freedom to select different drive styles is limited. In a transport mission cycle the ways to execute it is multitude. In some sense the functionality is shared with the energy management strategy. This is a complicated matter which is avoided by the use of speed following cycles.

4. Investigation of requirements on test facilities

This study indicates that development of accurate and cost-effective test methods for emission certification of HD-HEVs must consider the operation of the complete vehicle, in order to quantify the true exhaust emissions resulting from the engine operation. This does not mean that a test method, in order to qualify, must require a real and complete vehicle as test object.

In Chapter 4.1 below several test methods for emission certification of HD-HEVs are presented including the approved Japanese method as reference.

In this chapter, the test facility requirements to perform tests according to some of these methods will be highlighted.

4.1. Possible test methods for HD-HEV emission certification

The following list is a menu of possible and meaningful test procedures. The list starts with the most obvious and hardware-oriented test and ends with a fully simulated approach:

Vehicle on road test

Run the vehicle on the intended or a representative route with on-board emission measurement system. This requires the vehicle to be in production.

Vehicle on chassis dynamometer test

Run the vehicle in a chassis dynamometer on any route with on- or off-board emission measurement system.

Vehicle run with engine load-recording and subsequent engine test

Run the vehicle on the road or in a chassis dynamometer - record the engine cycle - replay the engine cycle in an engine test cell with emission measurement system.

Simulated vehicle test with complete powertrain

Run the powertrain including the transmission hardware in the test facility with emission measurement system.

Simulated vehicle test with reduced powertrain

Run the powertrain without the transmission hardware in the test facility with emission measurement system.

Simulated vehicle test with real engine

Simulate the vehicle linked via HIL to a real engine in the test cell with emission measurement system. This test is also referred to as Engine-In-the-Loop.

Engine emission test

This is the current method used for conventional vehicles using pre-defined engine cycles.

Simulated vehicle test with real ECU(s) and subsequent engine emission test

Simulate the vehicle except some ECUs which are instead linked to the simulation via HIL and record the engine cycle - replay engine cycle in engine test cell with emission measurement system. This is the Japanese method, described in Chapter 2.5.

Simulated vehicle test with both real and virtual ECU(s) and subsequent engine test

Simulate the vehicle except some ECUs which are instead linked to the simulation via SIL and HIL and record the engine cycle - replay engine cycle in engine test cell with emission measurement system.

Engine emission test on micro cycles and subsequent simulation

Run the engine on predetermined standard transient micro cycles - measure the emissions from each micro cycle - simulate the vehicle and record the engine cycle to obtain distribution of micro cycles, and then calculate the weighted contributions from each micro cycle measurement. The separation between emission test and simulation can be regarded as a reversed Japanese method. The benefit of this method is the availability of pre-defined engine cycles.

Simulated vehicle test with only virtual ECU(s) and subsequent engine test

Simulate the vehicle except some ECUs which are instead linked to the simulation via SIL and record the engine cycle - replay engine cycle in engine test cell with emission measurement system.

Simulated fully virtual vehicle test

Simulate the virtual vehicle (MIL) and calculate the emissions. This method requires verified emission models approved for certification which currently does not exist. However, for fuel economy tests there are models of acceptable performance.

4.2. Test facilities

The test methods presented in Chapter 4.1 can be grouped with respect to the test object and in turn the facilities and equipment required to perform the tests. Below is an attempt of such a grouping:

4.2.1. Vehicle testing

Common to the following three test methods is the requirement of a complete vehicle:

- *Vehicle on road test*

- *Vehicle on chassis dynamometer test*

- *Vehicle run with engine load-recording and subsequent engine test*

In a chassis dynamometer the driving wheels will be subjected to follow a wheel load-speed pattern. Driving on the actual road, the whole vehicle will be subjected to a vehicle load-speed pattern including the real effects of road load including the road grade and curvature.

Road test reproducibility is low due to variations in driver performance and road, traffic and weather conditions. Driving on a test track will improve reproducibility and even more so would testing in a chassis dynamometer using a robot driver, but at the same time the real-world driving conditions are gradually being reduced.

The emission measurement equipments for these three methods are quite different:

- Testing on the road would require an on-board or Portable Emission Measurement System (PEMS) approved for emission certification. PEMS normally measures the concentrations of the emission components in the exhaust line in a continuous manner. By direct measurement or by calculation from transmitted data from an engine ECU, the exhaust mass flow can be determined. The mass of each exhaust gas component can then be calculated. To calculate the engine work, which is needed to express the results as regulated brake specific emissions in [g/kWh], PEMS sometimes rely on the torque signal from the engine ECU The accuracy of the results will therefore also depend on how well the engine ECU estimates the torque. An alternative to PEMS is to use sampling bags to collect emissions during driving for subsequent analysis in a laboratory.

- The chassis dynamometer has the advantage of being able to use well-proven and accurate laboratory emission measurement systems. Also estimation of engine work can be made more accurately using the measured wheel power, especially if a direct connection to the wheels without the tyre interface can be made.

- The last of the three methods above, where only the engine torque-speed pattern is recorded during driving, relies on the subsequent use of an engine test cell to measure the emissions. Similar to the other vehicle test methods, true engine torque is difficult to obtain without the often complicated installation of an actual torque sensor. Testing according to this method can be performed on the road, but a chassis dynamometer may be preferred due to the higher reproducibility.

For HEV certification it is necessary to balance the electrical energy charged and discharged over the drive cycle. Several runs of the drive cycle is usually needed to minimize the difference in stored electrical energy at the beginning to the end of the cycle in relation to the energy of the fuel consumed during the cycle. This gets more pronounced the larger the usable electrical energy storage the HEV has and for short cycles. In comparison with other

test methods, vehicle testing normally has a high cost per run and additionally having to run several cycles is a clear disadvantage.

4.2.2. Powertrain testing

HILS allows for several parts and components of a vehicle to be replaced with models, thereby reducing the physical test object but still keeping with the need for a complete vehicle approach for HEV certification.

If the powertrain test facility is focusing on testing fuel economy and exhaust emissions for HD-HEVs it could have the schematic look shown in Figure 4-1. Here it is assumed that the dynamometer, by itself sized to handle a HD engine, is augmented by a fixed gear to handle the high-torque-low-speed situations normally experienced downstream the transmission of a vehicle.
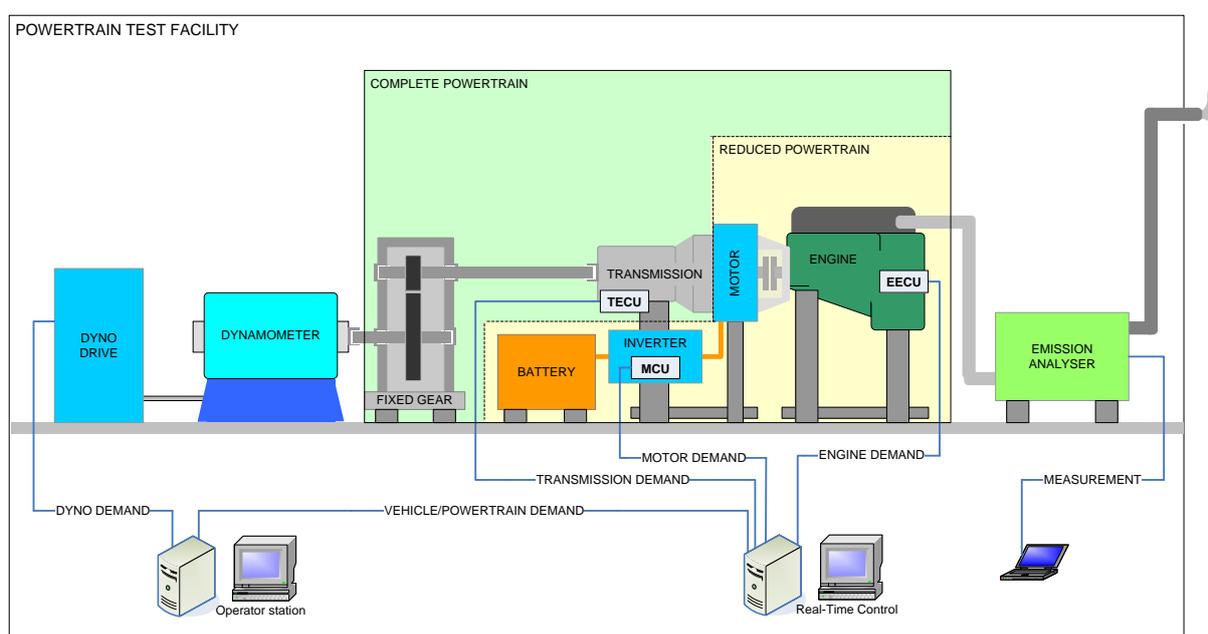

Figure 4-1 **Powertrain test facility showing examples of both a complete and a reduced parallel hybrid powertrain configuration including a Real-Time controller enabling simulation of a complete vehicle**

Common to the following two test methods is the requirement of including both the engine and the electric motor drive system, i.e. motor and inverter:

- *Simulated vehicle test with complete powertrain*

- *Simulated vehicle test with reduced powertrain*

The difference between these two methods is that only the complete powertrain contains a transmission. When testing a reduced powertrain, the fixed gear can be removed. Basically, this converts the powertrain test facility into an engine test facility.

Including the transmission and its control unit has the advantage of providing real gear selections and gear shifts, which is often difficult to simulate without quite complex models. On the downside is the need for a high-torque-low-speed dynamometer or an additional gearbox as suggested in Figure 4-1. Obviously, more space is required and the effort and complexity of setting up the test object increases for each additional component. To actuate

the gear shifts, compressed air may be needed, which however is normally available in a test facility, but it adds to the complexity and increases the risk of malfunctions.

Conducting the tests in a powertrain test facility generally has the advantage of the availability of accurate emission measurement equipment.

The increase in models to make up a complete vehicle may require a dedicated real-time computer to unload the test facility control computer and to ensure stable real-time behaviour.

Introducing energy storage systems like a traction battery into the test facility requires measures to be taken to ensure safe usage, handling and storage including safety functions like detectors for explosive gas and monitoring of electrical insulation.

For additional safety it is usually preferred to have the traction battery located in a dedicated battery test cell and then run the required power and signal cables into the adjacent test facility for connection to the electric motor drive system.

A battery pack or an ultra-capacitor bank is not needed if a battery simulator[4] is available. Using a simulator has the great advantage of allowing the test operator to rapidly set and reset the state-of-charge to arbitrary values, without having to wait for time-consuming charge and discharge sequences, normally predefined by the ESS manufacturer, to adjust the actual state-of-charge. Test repeatability is also immensely improved.

Regardless what type of electrical power source-load is used, including the electric motor drive system will always require attention to hazardous voltages and high currents.

The real-time system must have enough computational power to handle all this, i.e. simulate the models of the driver and the vehicle chassis-body-wheels in addition to communicating with and sending demand values to the ECUs of the remaining hardware components.

The demand to the dynamometer is usually a reference speed signal calculated from the measured torque, the road load and the combined rotational and vehicle mass inertias.

4.2.3. Engine testing

Further virtualisation of the vehicle using HILS makes it possible to also replace the electric motor and the battery with numerical models. Whether the electric motor can be replaced with a model or not sometimes depends on if a battery model is available, because there is usually no reason to keep the battery if the motor is removed. By this, the physical setup becomes even smaller but the computational effort of the real-time system increases. Now, only the engine remains as a physical component as shown in Figure 4-2 with the rest of the vehicle including the driver is simulated on a real-time-system. Replacing the engine is difficult and mostly avoided because it is a complex device directly responsible for the emissions, which in turn are difficult to model with the accuracy required to be approved for emission certification.

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[4] Usually a power electronic device acting as a current dependent voltage source capable of both sourcing and sinking current as demanded by an external device like an electric machine. The voltage output is often calculated by an internal battery model with the actual current as one of its inputs.
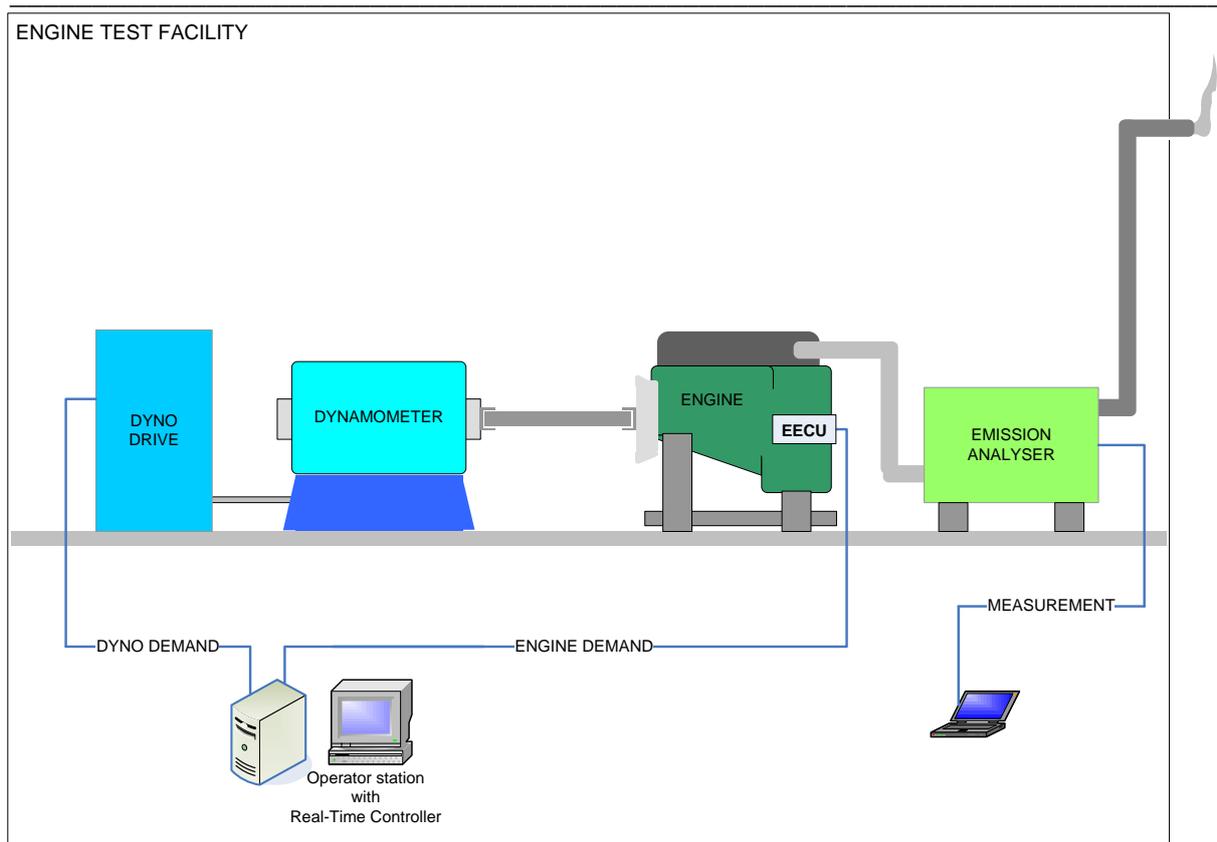
Figure 4-2   Engine dynamometer test setup with emission measurement

From the list of potential test methods mainly one favours this level of HIL, where only the engine remains as a physical component:

▪ *Simulated vehicle test with real engine*
This test method is often referred to as Engine-In-the-Loop and for obvious reasons it has the highest demands on the real-time system, in comparison to the other test methods. Using a real engine instead of a model has the benefit of direct incorporation of its true transient behaviour and its effect on the exhaust emissions.

In addition, if the intended vehicle is equipped with an Automated-Manual-Transmission (AMT), this method could benefit greatly from including the actual transmission ECU as HIL to obtain more correct gear shifts. In could also be beneficial to include the physical sensor-actuator layer, to avoid spending too much effort on interfacing and wiring.

Most of the remaining test methods presented in Chapter 4.1 still require a test facility setup according to Figure 4-2, but without the need of simultaneous HIL simulation and in some cases SIL rather than HIL is required:

▪ *Engine emission test*
This is the standard engine emission test currently used for conventional vehicles. As mentioned earlier, this method is not suitable for HEV certification

▪ *Simulated vehicle test with real ECU(s) and subsequent engine emission test*

This refers to the Japanese method described in Chapter 2.5. Valid engine cycles representative of hybrid vehicle operation have already been obtained in a simulation, using HILS with only one or a few physical ECUs constituting the hardware. In this case the test facility is used only for standard engine emission measurements.

The following two methods are variants of the Japanese method but they all have the two-step procedure in common, i.e. a simulation followed by laboratory measurement. The difference is that the physical ECUs are partly or completely replaced by virtual ECUs simulated as SIL:

▪ *Simulated vehicle test with real ECU(s) and virtual ECU(s) and subsequent engine test*

▪ *Simulated vehicle test with virtual ECU(s) and subsequent engine test*

The difference between these two methods is that the first method requires a real-time system for the simulation due to the inclusion of real ECU(s), the second method does not.

4.3. Interfacing computer models with real hardware

In the previous Chapter 4.1, some test facilities requires equipment for real-time HIL simulations. Hardware-in-the-loop has the most complex setup of the three techniques; MIL, SIL and HIL. One particular obstacle is the interfacing of electric signals with the numerical data in the simulation computer. Apart from obvious physical connections with possible EMC problems or just regular cable breaks, bad connections or short-circuits, the interfacing system itself might introduce delays and limitations that might affect the performance and stability of the complete simulated system.

To close the loop between the hardware and the remaining numerical models in a HIL setup, as mentioned in Chapter 2.3.3, a physical-to-numerical interface is needed, translating electrical output signals from an ECU, e.g. control signals to the actuators, like the fuel injectors, into numerical values that can be used by an engine plant model running on a computer workstation, see Figure 4-3. Likewise, a numerical-to-physical interface is needed, translating calculated numerical signals from a plant model, e.g. measurement signals from the sensors, like the engine speed, into an electrical input signal to an ECU. Whether sensors and actuators should be modelled or included as additional hardware in the loop is again a trade-off according to the previous illustration in Figure 2-6.
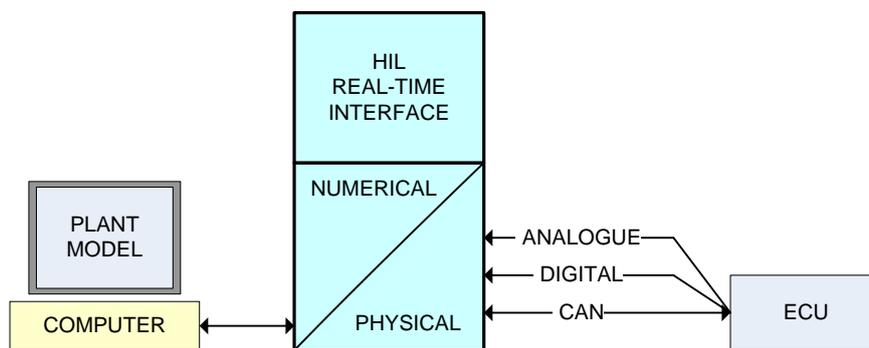

Figure 4-3   **General Hardware-In-the-Loop setup with real-time interface**

Usually, besides the obvious need of supplying power to the ECU, inter-ECU-communication needs to be established. Wired signals between an ECU and its physical plant often only

account for a fraction of the total number of signals processed by the ECU. The additional signals are sent and received on one or several serial communication links, often according to the Controller Area Network (CAN) protocol [5], for interaction with other ECUs on the vehicle network.

An ECU often has a certain physical signal interface tailored to its corresponding component. Even for the same type of component, but from a different manufacturer, the signal interface will most likely be different as no standards exist. The HIL interface equipment generally has a generic interface to handle all types of signals; still changes to the I/O-interface are far from effortless. Sending and receiving signals on a serial communication link, like the standardised CAN-bus, helps this situation; adding or removing signals is then handled by software configurations. New sensors with built-in digital interfaces, e.g. the SENT protocol [21], allow traditional analogue signals to be moved onto serial communication links. Besides easier HIL interfacing, this is beneficial for many reasons, like reduced wiring and higher noise immunity.

4.3.1. Distributed functionality

During the study of the Japanese method, it became evident that the allocation of functions among the vehicle ECUs is somewhat different between Japanese and European manufactures. This is also noted in [20]. It seems all hybrid configurations evaluated in [14] have a hybrid control ECU. This is not always the case among European manufacturers and even if a hybrid ECU exists it alone does not necessarily hold all of the hybrid control strategies.

A high degree of distributed functionality will force the HILS to require rather many physical ECUs and in turn this will drastically increase the effort needed of setting up the HILS. If regulatory requirements like *trust* and *acceptance* can be fulfilled, as mentioned in Chapter 3.1.1, the use of SIL instead of HIL can be an alternative solution and it will reduce the effort needed to set up the simulation environment.

The Japanese method also seems to assume that the engine ECU is dedicated to engine control only. This is of course preferred in the last step of the Japanese method when the simulated engine cycle is to be replayed in an engine emission test cell. But suppose that the control strategy for the torque split between engine and motor is implemented in the engine ECU. Either, means to disable the split function within the software would be required or perhaps using non-hybrid engine ECU software during the emission test can be permitted as long as identical exhaust aftertreatment strategies can be guaranteed.

4.4. Engine test cell adaptation

The final part of the Japanese method described in Chapter 2.5 involves setting up the engine in an engine dynamometer test cell and connect the emission measurement equipment.

The emission test part is considered basic knowledge compared to the issues involved obtaining the engine cycle data. The physical setup is as straightforward as for any engine test, normally as illustrated in Figure 4-2. The adoption of this conventional setup is one of the benefits with the Japanese method.

Running the test according to the engine torque-speed cycle obtained during the preceding HIL simulation will however present a few practical issues.

Depending on the hybrid powertrain control strategy of the vehicle being certified, one practical issue that must be handled by the engine test cell concerns the *engine-off* condition. Most parallel hybrids offer this as an idle elimination feature, mainly during stop and go driving. Series hybrids also perform engine shutdown when the energy storage buffer is full and/or when the power consumption is low.

Any test cell can issue an *Ignition Off* command to shut down the engine like in a vehicle; however this may not have the intended effect as it will also turn off the engine ECU. The need to both wake up the engine ECU and crank the engine could have a slight negative impact on the engine re-start time and it could also produce more start-up emissions if the crank fuel amount is higher than for re-start.

Attempting a bypass approach like interrupting the actuator signals to the fuel injectors will definitely generate unwanted fault responses from the diagnostic system. An engine ECU adapted for hybrid operation, i.e. with an externally available signal allowing fuel cut-off without upsetting the diagnostic system, is therefore needed to perform the test properly.

Existing certification cycles for conventional vehicles, like the WHTC, are often expressed in tabular form as exemplified in Table 4-1.

Table 4-1   **Example extract of a time-speed-torque data list for a transient engine cycle**

Time (s)	Normalised Speed (%)	Normalised Torque (%)	Comment
1	0	0	Idle speed control by engine ECU
2	0	0	Dyno zero torque control to simulate open clutch
3	2.6	4.7	
4	20.5	18.3	Dyno/Engine: Speed/Torque Control
5	49.4	78.4	
6	34.6	0	Engine torque interrupt to simulate gear shifting
7	42.6	39.5	
8	56.3	m	Engine motored (m) i.e. propelled by the Dyno resulting in a
9	48.7	m	negative torque to simulate released accelerator pedal
10	18.8	0	
11	…	…	

Normalised speed 0 % means idle speed i.e. during certification of engines for conventional vehicles the engine is always running. For certification of hybrid vehicles, this specification will clearly need to be updated to account for engine shutdown and engine re-start.

5. Recommendations and Discussion

The study of HILS-based methods for type-approval of commercial heavy-duty hybrid vehicles has been found to be a wide subject. In this chapter a few topics are highlighted and briefly discussed and some recommendations are provided.

The existing and proposed methods presented in Chapter 4.1 can be ranked by their ratio of amount of hardware to software. A fully hardware based method is a complete vehicle and a fully software based method is a computer based model. Table 5-1 is a summary of the different test methods studied in this report and some properties most associated with them. The possible ways are numerous and the list is not complete but it contains feasible ways of performing certification. When deciding on a particular method, this ranking can be used to balance the factors involved, found in the columns to the right.

The drive cycle has great impact on the emissions. These cycles can be formulated in different ways which are described in Chapter 3.2. The world-harmonised vehicle cycle (WHVC) is a potential candidate for HILS-based certification tests. However, in this study some weaknesses have been identified when simulating hybrid vehicles on the WHVC. The main concern is that the topography information is not present, some hybrid vehicle concepts rely on topography information to a great extent and the omission will be a severe fuel and emission penalty. At the least, it is recommended that the altitude should be the same at the starting point of the cycle as at the end point. Additionally, there is the issue of using a single long drive cycle for all types of vehicles. For example, the underlying statistics show that a European city bus will spend no time at all on the highway, still the WHVC enforce that 25 per cent of the time is spent there. A recommendation, if this drive cycle is to be used, is to split it into its three major components, urban, rural and highway, and weight the emissions according to a more realistic usage. The net energy usage of any electrical energy storage buffer should be minimised for each sub-cycle. The weights might be extracted from simulation or statistical databases.

The Japanese method currently provides open models for some components, like vehicle, energy storage system, engine and motor drive system. It also provides test methods for obtaining the data to parameterize these models. It is recommended to encourage development and standardization of open models and methods to gain wide acceptance and trust. It is also recommended that these models are kept as simple as possible to minimize the test and measurement efforts required to retrieve the parameters, while still being accurate enough for type-approval usage. If the obtained component data cannot be publicly exposed it is further recommended that either a third-party accredited body can be involved or that component specific validation procedures are devised to ensure data credibility.

Models running on a computer platform are designed according to their intended purpose. If models are to be executed in real-time for use in type-approval tests they must be designed accordingly. These design considerations might affect the development process of the models so they already from the start can be used in real-time simulations. It also puts a limit to how detailed and elaborate the models are allowed to become.

Issues related to distributed functionality are presented in Chapter 4.3.1. For emission testing the minimum amount of hardware needed is the engine and its control unit. For engines operating in hybrid powertrains, it is likely that the engine ECU requires interaction with other hybrid control related ECUs, including both control and diagnostics functionality. During the emission measurement, which is considered the final step of the Japanese method, this could present a problem as the engine ECU is expected to operate standalone. A requirement is therefore implicit on the engine ECU software that it can handle this situation.

As mentioned in Chapter 4.2.3, the Japanese method could be considered a two-step procedure:

1. Simulation using a real-time HIL controller to link physical ECUs with numerical plant models in order to convert a vehicle drive cycle into an engine load cycle reflecting its operation in a hybrid powertrain configuration.
2. Emission measurement in an engine test cell using a real engine operating according to the load cycle produced in the first step.

The first step of this method specifies the use of a real-time controller to perform the HIL simulation. Due to the multitude of various configurations of hybrid powertrains, each with a unique control system architecture and interfaces, it is recommended that a validation procedure is conceived to allow any real-time controller to be used as long as it can be shown to fulfil certain validation requirements, e.g. regarding timing determinism and accuracy aspects. This validation procedure could be similar to the SIL verification required by the Japanese method, where a known result within certain tolerances is expected by performing a simulation on the HIL-simulator using a predefined reference model and parameters.

An alternative to the two-step Japanese method is the one-step Engine-in-the-Loop method. In this method the real-time HIL controller is instead installed in the engine test cell and is additionally connected to both the real engine via its ECU and to the test cell control system, besides being connected to the necessary physical ECUs containing the hybrid control functions. Real-time control capability and handling of external models is already a quite common feature of today's test cell control systems, if not it is most likely available as an add-on. As this one-step approach includes the real engine in the loop, the true transient engine performance will automatically be accounted for in the measurement results. Component tests to obtain engine model parameters are not required with this approach. Another advantage is that the HIL-simulator provides the surrounding control environment eliminating any standalone requirements on the engine ECU software. The drawback of this approach is that the additional cycles needed for tuning the driver model and finding the initial SOC value are run on a real engine instead of simulated using an engine model.

Transient engine testing is for conventional vehicles considered an effective way to obtain more real-world representative results. Surprisingly, for hybrid vehicles this does not need to be true. The most common control strategy of a series hybrid driveline is that the engine operates at its optimum load point at all times. As shown in Figure 3-1 the engine in a parallel hybrid driveline can also be controlled, to a certain degree, to work according to the principle of running the engine at its optimal load point. This implies that the need for a transient test cycle becomes less urgent. Drawing this conclusion to its extreme, a stationary test cycle will be sufficient if the load points can be weighted correctly. Simulation can be a tool to calculate these weight factors. Following this principle, a complete separation of engine test and simulation can be achieved which will reduce the requirements on the test facility. A significant simplification of the certification procedure is the result.

Table 5-1   **Summary of possible test methods for HD-HEV emission certification with ranking of regulatory and technical concerns**

HIL ratio	General position	Test method	Test object	Regulatory concerns				Technical concerns			
				Proprietary parts of system with part number	Third-part cerification required	Resonable tamper proof	In-service conformity testing possible	Development effort	Possibility of error, test to reality	Vehicle equipment demand	Test equipment demand
100% / Hardware	India China	Road test	Vehicle	YES	YES	YES	YES	LOW	LOW	HIGH	LOW
		Chassis dyno	Vehicle	YES	YES	YES	YES	LOW	LOW	HIGH	HIGH
		Vehicle test with recording of engine cycle for subsequent engine test	Vehicle + Engine	YES	YES	YES	NO	AVG	LOW	HIGH	AVG
	US	Complete powertrain in test cell	Powertrain	YES	YES	YES	YES	AVG	LOW	HIGH	HIGH
		Reduced powertrain in test cell	Powertrain	YES	YES	YES	YES	AVG	LOW	HIGH	AVG
		Simulated vehicle with real engine in test cell	Engine	YES	YES	YES	YES	AVG	AVG	AVG	AVG
		Engine test	Engine	YES	YES	YES	YES	AVG	HIGH	AVG	AVG
	JPN	Simulated vehicle with ECUs as HIL and subsequent engine test	HIL-SIM + Engine	YES	YES	NO	NO	HIGH	AVG	AVG	AVG
	EU	Simulate complete vehicle with ECUs as SIL and HIL, run engine in test cell	HIL-SIL-SIM + Engine	YES	NO	NO	NO	HIGH	AVG	AVG	AVG
		Run real engine on reduced duty cycles and measure their emission contribution, simulate and calculate total emissions for full cycle	Engine + SIM	YES	NO	NO	NO	HIGH	HIGH	AVG	AVG
Software		Simulate vehicle with ECUs as SIL, run engine in test cell	MIL-SIM + Engine	YES	NO	NO	NO	HIGH	HIGH	AVG	LOW
100%		Full MIL, no engine test	MIL-SIM	NO	NO	NO	NO	HIGH	HIGH	LOW	LOW

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