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Industrial Electrical Engineering and Automation

Master Thesis
Development of validation methods for HEV (Hybrid Electrical Vehicle)

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Abstract

Developing a hybrid electric power train is a complex task where achieving the best in market performance poses a true challenge for the research and development engineers. When developing such complex systems it is utterly important to verify and validate these systems, since they are developed to be used in production vehicles. An extra iteration due to errors, faults or shortages found during the validation and verification in the development process is very costly and should be avoided, however sending an unfinished product to the market is not an option since it can not be afforded in the competitive car industry. For that reason, the possible extra iterations in the development process are a cost effective way to improve quality.

This thesis presents two methodologies:

- The first is used to generate high level test plans for validation and verification of the components and systems that are specific for a Hybrid Electric Vehicle (HEV) application. It is divided in two, parts one identification phase and one specification phase, which describes how to identify, analyze, evaluate and finally how to validate the identified requirement.

- The second part describes how to generate a detailed test plan, to be used for in vehicle testing, from the previously generated high level test plan.

Both of these methodologies are applied in the thesis as a proof of concept.

In addition to this a component efficiency based approach on, how to value consumed electrical energy in the battery seen as conventional fuel, is presented. If applied making it possible to value used energy from the battery during a drive cycle as conventional fuel used in liters.

The details in the tests are limited due to corporate secrecy.
Several describing pictures, details and full chapters have been removed due to corporate secrecy.

Acknowledgements

The author wishes to express his gratitude to his supervisors Leif Hermansson at GM Powertrain Sweden AB in Trollhättan and professor Mats Alaküla at the department of Industrial Electronics and Automation. Both are to be thanked for inspiring dialogues and giving recommendations on paths to explore. The author also wishes to thank all at the department of Hybrid Control in Trollhättan for all the invaluable knowledge and life experience. Finally my family is to be thanked especially my baby sister Liselotte Nordholm for valuable discussions and advices.

Table of Contents

1 Introduction

The hybrid electric drive system might be seen as the next logical step in power train development towards lower emissions and fossil fuel consumption, in combination with higher performance in our vehicles. Or as Jason Mark, director of the clean vehicles program for the Union of Concerned Scientists, said: "Hybrid vehicles are the bridge between conventional vehicles and fuel cells." [1]

The hybrid system technology which is used for serial production is fairly new in its current context, although it has been used on an experimental basis for many years. Regarding the future of hybrids Jim Press, president of Toyota Motor Sales USA, said in an interview with Associated Press "I think everything will be a hybrid, eventually. It will either be a gas hybrid, a diesel hybrid, or a fuel-cell hybrid." [1].

There is a significant increase in the degrees of freedom when developing hybrid vehicles instead of conventional vehicles. The addition of degrees of freedom is due to the fact that the control of operating point for the ICE now is to be combined with those of the electric machine(s). The mechanical brakes are to be combined with regenerative braking with the electrical machines used as actuators. This certainly increases the complexity of the system further. In some hybrid systems there is no direct relationship between ICE speed and torque and wheel speed and torque, as is the case in a conventional driveline. This lack of direct relationship also increases the complexity of the system. Although the increase in degrees of freedom poses a challenge for the development engineers it is also in this property that the advantages are to be found.

The hybrid power train differs substantially from a conventional power train both in control and hardware, making it necessary to complement conventional validation and verification methods with hybrid specific validation and verification methods.

1.1 Purpose

The purpose of this thesis is to develop methodologies for identifying and validating potential problem areas that are hybrid specific, as well as describing the performance measurement methods to be used in order to obtain data suitable for benchmarking with conventional vehicles. The methodologies developed should be used as tools to increase the performance and quality of the vehicle and thereby increase customer value. The methodologies are used to develop several high level test plans, but also low level tests regarding Zero Emission Driving and capability of a Battery Management systems capability. This is made as a proof of concept.

Those validation requirements that are same as for conventional power trains refer to the validation plans and specifications used for conventional vehicles.

1.2 Problem Description

The introduction of hybrid drive systems in cars increases vehicle complexity and as a result validation complexity as well. This thesis addresses the problems involved when creating hybrid specific validation methods.

1.3 Goal

The goal of this master thesis includes multiple instances:

a) Give a brief explanation of the difference between a conventional vehicle and a hybrid vehicle and describe the different degrees of hybridization. Describe various hybrid configurations.

b) Develop methodologies for validation and verification of the hybrid power train. The methodologies describe a work flow to be used when developing test plans.

c) The test plans are developed for testing functionality of the complete power train, as well as on a subsystem level. The test plans is to be developed with regard to quality, time and cost. Also identifying and evaluating, the most suitable validation type simulation, Hardware In the Loop, HIL, test driving or a combination of these.

d) The test plans being developed should be valid for generic hybrid power trains. Generic in this context means that there are no restraints made on the dimensions of the components of the power train or the way they are configured. Except for the fact that some test plans are not applicable to certain configurations and dimensions of components.

e) Perform simulations on an identified hybrid specific requirement.

The basis for the problem description is found in the master thesis proposal presented in appendix 1.

1.4 Limitations

This report's target group is primarily GM Power train Europe's department of hybrid control since it gives special attention to the MHD2 vehicle which is one of their test benches and the low level test methodology is based on GM specific test plan model.

The details in the tests are limited due to corporate secrecy.
Several describing pictures, details and full chapters have been removed due to corporate secrecy.

2 Validation items

2.1 The difference between an ordinary vehicle and a hybrid electric vehicle

The word hybrid is defined as “A functional unit in which two or more different technologies are combined to satisfy a given requirement.”[19].
Hybrid Electric Vehicles can be defined in many ways, however a few selected definitions are presented below:

- “A hybrid vehicle uses two different sources of tractive energy e.g. a fossil fuel and electricity that together, or one at a time can be used for vehicle propulsion.”[20]
- “A hybrid is something that has two different types of components performing essentially the same function. (Your Dictionary, 2001) In this case it is an electrical machine and a combustion engine that together, or one at a time, provide the tractive power to the vehicle.”[22]
- “A hybrid vehicle or gas-electric hybrid powered vehicle uses a mixture of technologies such as internal combustion engines, electric motors, gasoline, and batteries. Today’s hybrid cars are driven by electric motors powered by both batteries and an ICE.” [22]

The difference between a hybrid electric vehicle and a conventional vehicle is the hybrid vehicles capability to combine two or more energy sources compared to the conventional vehicle which only uses one. Normally hybrids use a secondary energy buffer to store energy, directly or indirectly produced by a Primary Power Unit, PPU. Normally the PPU is an Internal Combustion Engine, ICE, or a fuel cell. The electric energy stored in buffers is utilized when needed by electrical machine(s) used as actuators. The HEV might be configured in numerous ways with different configurations and types of PPUs, energy storages, energy buffers and gearboxes. The intention is to improve fuel economy, emissions or performance, to be exact an optimization of these is desired. This optimization will require advanced control of the power train. The HEV power train is not limited to a special fuel and can therefore be used with any fuel, both fossil and renewable, as its primary energy source.

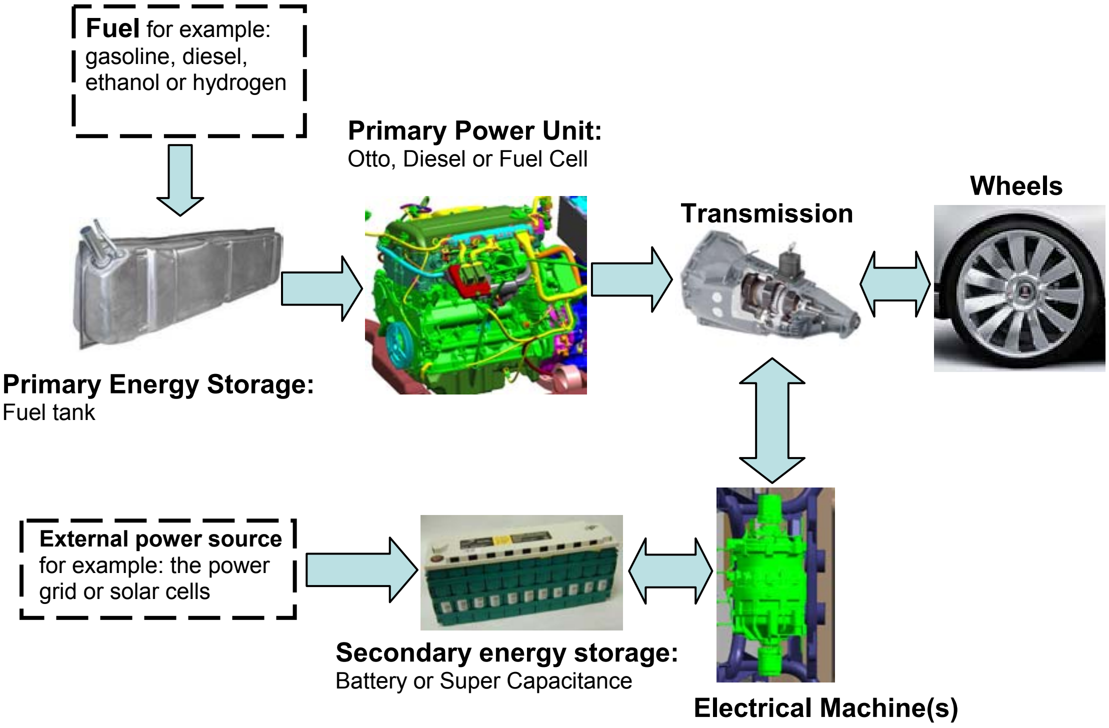

Figure 1. Hybrid Electric Vehicle System overview

The difference can be shown by comparing the energy storage capabilities of a conventional and a hybrid vehicle. A conventional vehicle only has the primary energy storage, for example the gas tank. That is if the standard 12 V battery is disregarded. 12 V batteries are commonly used in conventional vehicles and could be considered as a second energy storage, however since it is not used for any form of propulsion, except starting the engine [23]; it is neglected as secondary energy storage. In comparison a hybrid vehicle, of course depending on configuration, might have, in addition to the gas tank and the 12 V batteries, a battery with a storage capability in the range of kilo Watt hours and electrical motor(s) to help propel the vehicle.

However it is important to keep in mind that the two most important properties of the HEV are:

- Regenerative braking
- Adaptation of ICE work point

2.2 The different degrees of hybridization

Depending on the electric power level, the electric power train structure is classified into different categories.

The different categories are:

1. Micro hybrids, which could be based on a 12 Volt Belted Alternator Starter system, micro hybrids that typically has an installed electrical machine power of approximately 1 to 5 kW.

2. Mild hybrids which are the next step in hybridization enabling additional features such as regenerative braking and launch assist. This calls for greater interferences in the construction but also has a greater fuel saving potential than the micro hybrid. The typical installed electric power for a mild hybrid is in the range from 5 to 20 kW.

3. Full hybrid, which uses the same features as the two earlier mentioned hybrid types but it, has a greater installed electric power than the other two ranging from 20 kW to more than 100kW and system voltages up to 500 Volts or even more. Some full hybrids also have the capability to roll in purely electrical mode.

   There is a possibility to adopt the full hybrids to become plug in hybrids. That is they can be charged from the electrical grid directly and then be driven in pure electrical mode until the batteries run out.

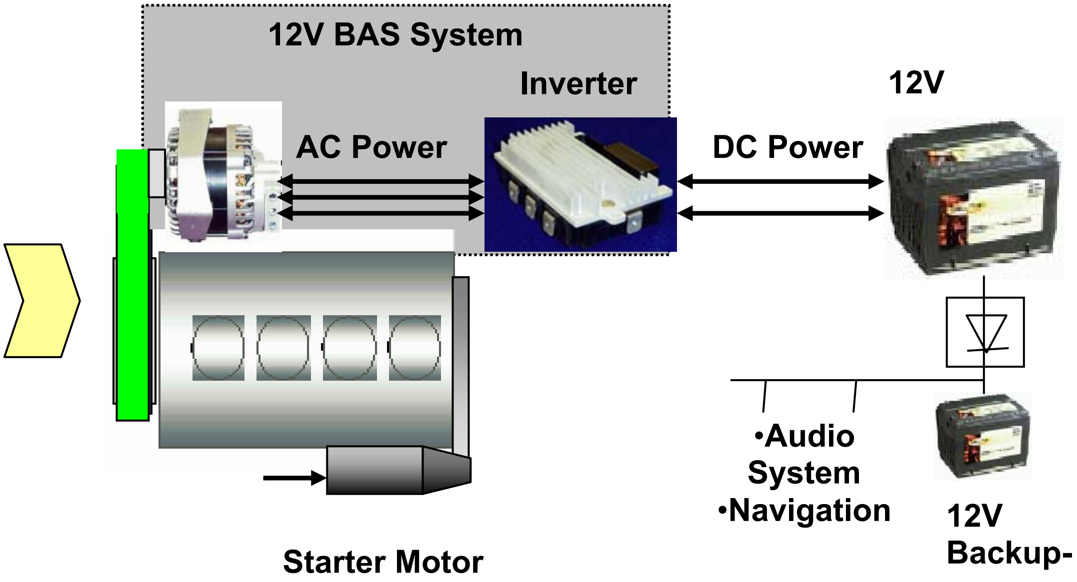

Figure 2. System overview BAS-Belted Alternator Starter [24]

2.3 Generic power train configurations and hybrid specific components

This chapter is based on a description made by Mats Alaküla, professor at the department of Industrial Electronics and Automation, LTH.

The development of hybrid drive systems among car manufacturers around the world follows certain trends where it concerns the configuration of the power train. A parallel or a complex hybrid configuration is normally used in the front of the vehicle and if the vehicle is equipped with four wheel drive capability it is, almost without exception, an electrical All Wheel Drive, eAWD. This gives the vehicle the advantage of not only four wheel drive capability, but also a higher installed electrical power. One of the great advantages with an eAWD system, when compared with a purely mechanical four wheel drive system, is that the eAWD has the capability to create negative torque and thereby contribute to regenerative braking, feeding braking energy back with high dynamics, and high power. The disadvantage, however, is that the rear axle power is limited to a couple of 10 kilowatts, which is small compared with the rear axle power capability that can be transferred from the ICE by a mechanical four wheel drive system

2.3.1 Hybrid Electric Vehicle configurations

Power trains that are based on Internal Combustion Engines, ICE, can be complemented by electrical drive systems in numerous ways, each with its pros and cons with regards to performance, weight, cost, flexibility to mention a couple of design parameters. The picture below shows a couple of examples of different configurations, with the point in common being that an Electric Rear Wheel Drive, ERD, is included. However the ERD is to be seen as optional and can easily be excluded from the configuration. The different configurations are presented separately.

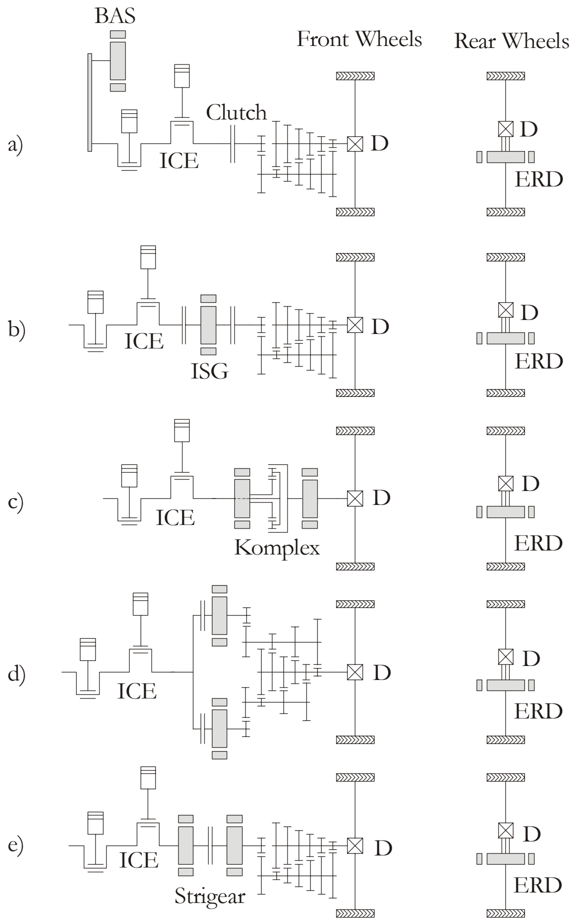

Figure 3. Different HEV configurations

a) A Belt driven Alternator Starter, BAS, is taking the place that is normally used by the generator in conventional vehicles. The BAS unit is in its simplest form a generator with increased power, which is also used as a motor. The BAS unit is usually within a power range of 3 and 8 kW making it the mildest form of hybrid (Micro hybrid). The BAS is normally connected to batteries in a voltage range between 14 and 42 V. The BAS unit provides the vehicle with start/stop capability and a significant torque addition to the ICE at low rpm (+30 to +60 Nm. This increases the elasticity of the ICE. Applications in small cars are most suitable for the BAS system, in view of the fact that it is not likely that an ERD is mounted here.

b) An Integrated Starter Generator, ISG, is placed after the ICE and before, or in the gearbox. The ISG is surrounded by clutches to enable the vehicle to propel with the ICE off and to enable shifting gears. The ISG is normally within a power range of 5 to 25 kW and can be connected to 42 Voltage, V, in the lower power range. The higher power range demands a higher voltage typically within the range of 100 to 300 V to not generate enormous currents when developing high power. The usage of an ISG is suitable in all sizes of cars; especially where a demand on four wheel drive may well be expected at which an ERD can be mounted. The solution is flexible and the same electrical machine can be used in combination with different sizes of combustion engines.

c) A complex transmission hybrid is the type that Toyota Prius and several other hybrid vehicles use. Two electrical machines are needed, with the generator connected to the solar wheel and the traction motor connected to the ring wheel. Finally, the ICE is connected to the carrier and it is thereby possible to switch off and the vehicle can by doing so be driven in a pure electric mode. Due to the connection of the sun wheel and the planet wheels the speed of the engine can simply be adjusted by varying the speed of the generator. The ICE is driven by the planet carrier. The electrical machine that drives the solar wheel is used to set the ICE operating point relative to the ring gear. The rpm of the ring wheel is directly proportional to the speed of the vehicle. The EM connected to the solar wheel is the base point for the ICE and it always output a torque that is counter directed to the ICE. The solar wheel connected EM speed can work in both directions making it possible to have both positive and negative power flows through that machine. This means that some of the ICE generated axle power takes a detour via the solar wheel EM on its way through the mechanical transmission and is then returned through the ring wheel machine. The energy taking this detour is subject to more energy conversions, which negative for the efficiency. Another drawback is that the transmission can not withstand a stronger ICE if the solar wheel EM is not upgraded to match this increase. The increase in dimensions normally requires a full redesign of the entire transmission.

d) This transmission is similar to an ISG based hybrid, but uses two electrical machines that drive separate axles on a Dual Clutch Transmission, DCT. This solution is more expensive than an ISG solution, but saves space since the transmission can be driven backwards by one of the electrical machines, thus saving the space of a rear gear. In this mode the other EM acts as an ICE driven generator, with a neutral mode on the ingoing axle to the gearbox.

e) Strigear is a patented invention giving the vehicle the capability to either drive the two electrical machines in serial hybrid drive (clutch open) or in parallel mode (clutch closed). The advantage of this configuration is that it enables the possibility of always using the best option. The disadvantage lies in an increased cost in the electrical drive system.

In all the cases presented above the hybridization can be described on a scale from micro hybrids (1 to 5 kW) to full hybrids with an installed electrical power ranging from 20 kW to more than 100 kW. When higher power or four wheel drive is desired it is natural to complement the system with an ERD.

2.3.2 Modularity

The different hybrid concepts are diverse in their ease to be modules. The most modular solution is probably a palette with a BAS or an ISG or an ISG +ERD. Designing a conversion with a BAS system from the base of a conventional power train is possible without interference in the transmission of it. If a more powerful hybridization is desired an ISG is installed between the ICE and the transmission. This hybridization which is more powerful is possible to use with the same transmission as the conventional vehicle. The ISG may be used with different sizes of ICE in the same vehicle model. If more electrical power or four wheels drive capability is desired the system may be complemented with an ERD.

For further information regarding the generic components used in a hybrid electric vehicle and in what configurations these are used please refer to Hybrid Drive Systems for Vehicles, Part I, System Design and Traction Concepts by Mats Alaküla [25], HybridCars.com [26] or Michael Duoba and Robert Larsens paper, SAE 981080 Investigation of Practical HEV Test Procedures with Prototypes from the 1997 Future Car Challenge [37].

3 Validation methods

3.1 How do the car manufacturers manage their analysis development and validation?

The development of cars is a very complex process consisting of numerous steps at different levels, reaching from determining the markets wishes to designing nuts and bolts. Due to this diversity there is a great need to manage and in some manner connect these steps in a logical way. The system used by GM today to make the connection between these levels might best be described by a top down approach, starting at the top with a focus on the customers and societies' demands on the vehicle and the vehicle manufacturer. It is important to remember that the car manufacturer is strictly controlled by several factors when developing a new car model. There are vast amounts of legislations regarding exhaust emissions, noise levels, and crash safety etcetera, limiting the initial solution space.

In addition to the requirements imposed by society a variety of additional demands ranging from non-child aggressive fronts of the cars to lowered fuel consumption must be addressed. Furthermore, the vehicles must be made appealing to the customers, in order to successfully sell the vehicle. Finally, there is the factor of maintaining and strengthening the brand of the car, in accordance with the brand specific properties used by the marketing department to sell the cars to the customers with a financial margin.

The customers' demands and wishes are gathered during different types of events ranging from interviews to showroom displays, clinics and test drives of prototype vehicles. These information gatherings are made with different intents at different stages of the development process. At the earliest stages of the development they are made with the intention to get a sense for what the potential customers wants. At later stages the customers' demands are decomposed from abstract and vivid descriptions to a more technical and real level. Thereby making it possible for the research and development engineers to make a first draft based on these descriptions. Quite often there are one or several vehicles available during these events that the engineers want feedback on.

The information gathering process described above might be considered to be a part of the first step in the Analysis Development and Validation, ADV, which is a requirement driven process. This combined with internal discussions regarding possibilities at the car manufacturers marketing and research and development department is the basis for the development of a vehicle.

3.2 The different steps in a vehicle development project

GM internal use only

3.3 Development validation items

The vehicles that are to be operated in the validation and verification tests described in this thesis range from development vehicles used solely for demonstrational activities with no intent on ever reaching series production, to test objects that are almost ready for series production. The tests describes methods designed to uncover more or less severe weaknesses or faults.

3.4 Hybrid Specific validation methods

A careful and subjective selection process is used to evaluate and determine what tests that may reveal the most severe weaknesses and give the most interesting information about the hybrid system being tested. The methodology used to develop these validation methods is presented in the next sub-chapter. This methodology has been developed by making several hybrid specific validation methods and thereby gathering information regarding how this process is best to be performed. The process is constantly iterated to improve the methodology further to make the validation process as smooth as possible

3.5 High Level Validation and verification development methodology for hybrids

The methodology used for developing tests for validation and verification is based on a logical system analysis approach. This methodology is divided into two main parts:

1. First an identification phase where a process of thought is described where a list of hybrid specific demands and requirements is generated as output.

2. The second part is a specification process where the list generated from the first part is used as input.

3.5.1 The generation of the high level validation methodology

Several validation tests are presented in this thesis, each under a separate sub-heading in appendix 3. The work flow used in the generation of these validation tests have been used to iteratively improve the high level methodology presented in this thesis. The validation tests in appendix 3 are presented in a uniform format and can be used detached from the complete thesis on a generic basis; however they are specific in some details regarding the MHD2 vehicle these details are marked.

3.5.2 Identification phase

1. General hybrid knowledge gathering phase

The first step is to identify hybrid specific components and possible configurations. The identification of components, architecture, configurations and topology in the thesis is done on three examples:

- Generic identification.
- Identification of a corporate specific vehicle
- Competitor vehicle identification e.g. benchmarking

The generic identification is based on analysis of a wide diversity of information resources in particular:

1. "Hybrid Drive Systems for Vehicles, Part I, System Design and Traction Concepts" by Mats Alaküla [25].

2. Society of Automotive Engineers, SAE articles regarding hybrids.

3. Science direct articles regarding validation.(www.sciencdirect.com)

4. Hybridcars.com [26].(www.hybridcars.com)

5. University papers regarding hybrids:

   PhD theses
   Licentiate theses
   Master Theses
   Technical reports
   Papers
   Books
   Activity reports

The identification of the corporate specific vehicle is made by analyzing the available technical specifications, data sheets and requirement documents thereby identifying potentially critical areas or areas that should be extra carefully tested.

Finally the identification regarding configuration and components of a commercially available product is made. The identification of the commercially available product is made based on publicly available information. This final identification is made primarily as a benchmarking phase to provide information on what performance and limitations the “best in class” vehicles have thus identifying critical areas.

2. Knowledge base

Once these three steps of identification have been made they are to be gathered in a knowledge base on HEV’s giving a good and easily accessible base for understanding of the hybrid power train.

3. Vehicle specification

The next step is to tie this information to a specific vehicle of interest for the validation. By determining the topology and technical specifications of this specific HEV the solution space is limited, since different configurations and components have diverse potential problem areas. Then a qualitative identification of what hybrid specific capabilities this vehicle should handle is to be made such as:

- Start/stop capability
- Regenerative braking
- Zero emission driving
- Four wheel drive
- Torque dynamics
- Mobile power generator for external loads
- Electrical boost
- Plug in capability
- High Voltage Air Conditioning

4. Identification of vehicle specific problem areas

A concentrated process to identify vehicle specific potential hybrid power train specific critical requirements and specifications is now initiated. The basis for this process is the information gathered during the identification phase. An information search to find configuration specific known critical areas and problems related to the hybrid power train should be conducted. Thereafter research on corporate specific VTS, SSTS and CTS documents acting as collections of links to documents regarding validation and verification of vehicles are used to find further critical areas. Another important input to this process is thorough test drives of commercially available HEV’s with similar configurations, if available, giving valuable input regarding potential faults and shortages in their power trains. That is the input to the process should consist of the following four elements:

1. Information search regarding configuration specific known hybrid critical areas
2. Corporate specific information
3. Commercially available information on similar vehicles.
4. Test drive of a commercially available Hybrid Electric Vehicle, Benchmarking

5. Analysis phase

The information gathered is to be analyzed and will as a result enable the identification of potential vehicle specific weaknesses, potential future problem areas and safety critical issues. The analysis phase should be initiated with a brainstorming session, where all possible ideas are accepted and gathered. Then the phase contains a systematic approach where the potentially interesting hybrid configurations are to be analyzed in mentioned order on a vehicle, subsystem and component level for weaknesses and weak spots for the hybrid configuration of interest. A systematic approach in this context means that all found potential problem areas of interest are examined.

6. Evaluation Phase

The results from the previous steps should be gathered and an evaluation of the found requirements should be made. The relevance of the gathered demands is to be evaluated bearing in mind the specific hybrid electric vehicle of interest. The demands shall differ from the validation and verification methods already available for a conventional vehicle. Special attention is to be given to safety critical areas that might be affected by the hybridization. The result from the evaluation is gathered in a list presenting the hybrid specific problem areas.

The work flow for the methodology is presented in figure 4:

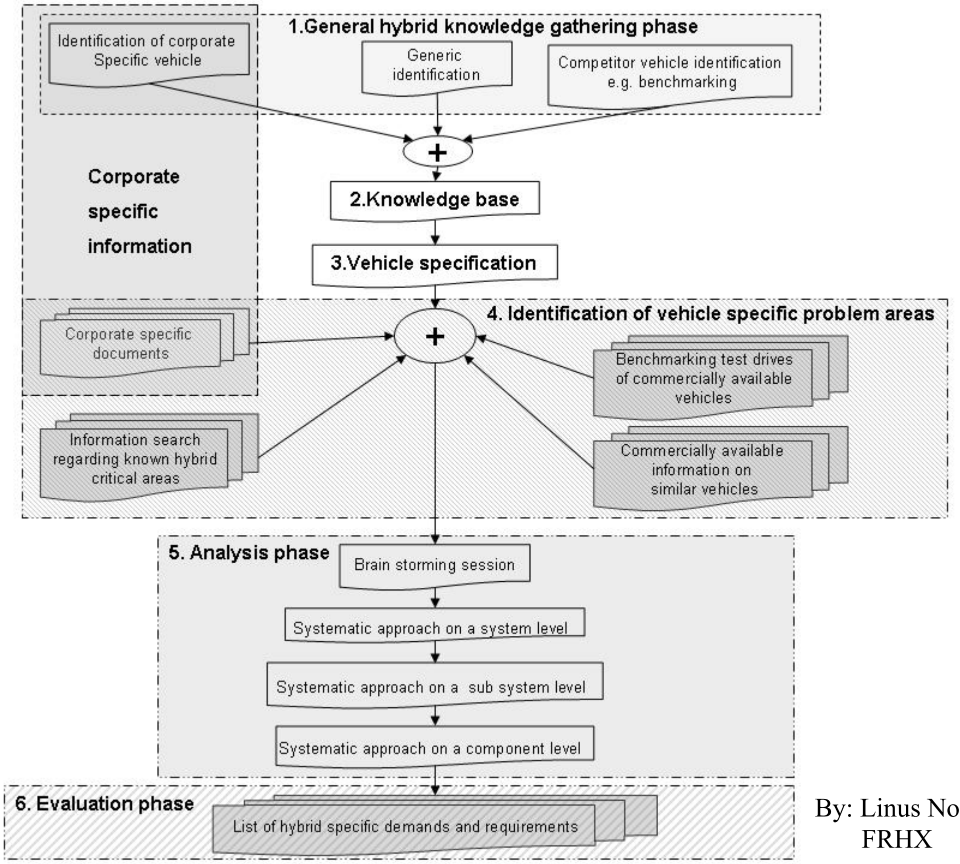

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Figure 4. High level validation methodology – Identification phase

3.5.3 Specification process

1. Once the evaluation has been conducted the demands and requirements from the list is transformed into requirements, on a VTS or SSTS level, these are quantified in technical and measurable terms.

2. The applicability of the requirement on a conventional drive line is evaluated and a brief description of the effects the requirement has on the conventional drive line is given. If the demand is applicable on a conventional vehicle the corresponding technical specification and test plan shall be evaluated and used as a basis for the further hybrid specific validation process.

3. Having analyzed the requirements applicability for a conventional drive line next the same is to be made for a hybrid drive line thus evaluating the effect of the hybridization and presenting the problem in more detail with regards to a HEV.

4. Subsequently the requirement is to be classified in a describing manner. Giving information of what type of requirement that is under review two examples of such classifications are technical specification requirement and safety critical evaluation.

5. Finally a validation part describing the requirement in more detail is to be developed, providing a discussion regarding how the demand should be evaluated as a pre-study to the VTS or SSTS document generation. A background might be given to motivate the recommended tests. This paragraph also contains suggestions of testing schemes and methods, motivation for thorough testing and more depending on the requirement and desired level of detail. The validation paragraphs prime goal is to suggest how testing can be performed and to give an understanding of the demand. The details of the validation are utterly specific for each demand or requirement. Therefore the information gathered in the identification phase is utilized to simplify the validation. The different steps of the validation method documents template are presented below:

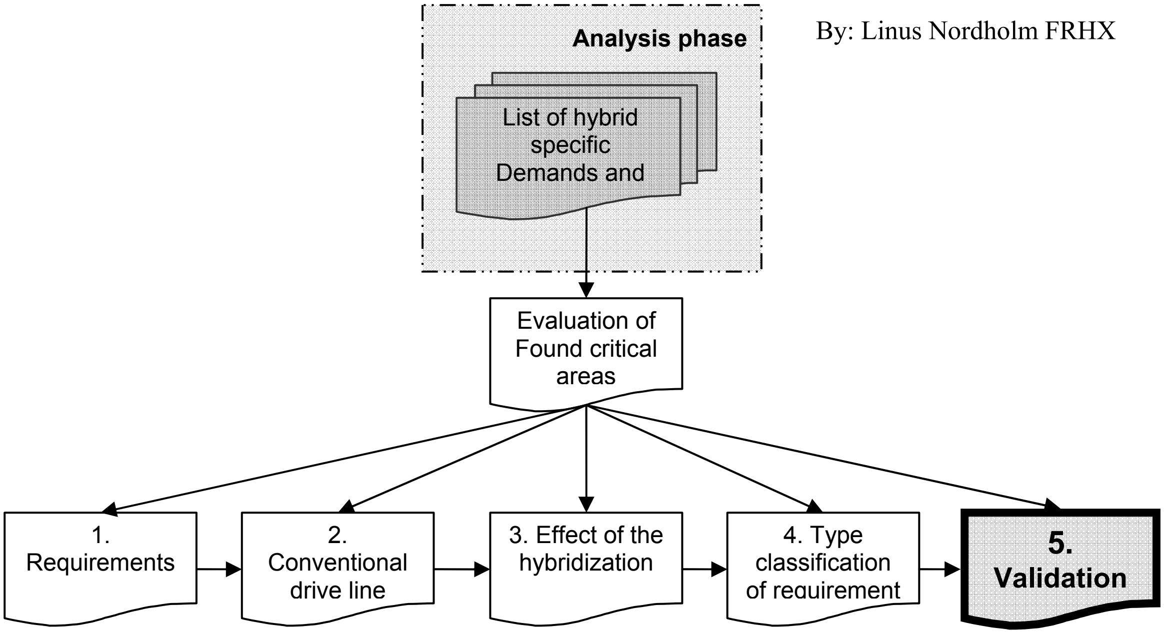

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Figure 5. High level validation methodology – specification process

3.5.4 Low level test plan generation methodology

Once the high level tests have been developed they form a basis for a decisive process where simulations and HIL tests can be made. Either the test is found to be of further interest for in-vehicle testing or not. In case there is a further interest the high-level test should be developed into a low-level test plan.

The test plan should contain details concerning the requirements that are to be tested in-vehicle and in detail describe the tests that are necessary to validate these requirements. An example of suitable contents for the test plan is presented in appendix 4. The methodology for developing low-level test plans is as follows

- Gather information and ideas from other test plans in similar field of requirements.
- Contemplate on what additional specific tests or requirements that are suitable for the specific test plan that is currently being developed or if the current constraints are to be loosened or hardened.
- Start writing a skeleton of headings based on the information gathered in appendix 4 and steps 1 and 2.
- Write the testing procedure.
- Iterate these steps making sure that everything is in order.

Then apply the test plan on the specific vehicle.

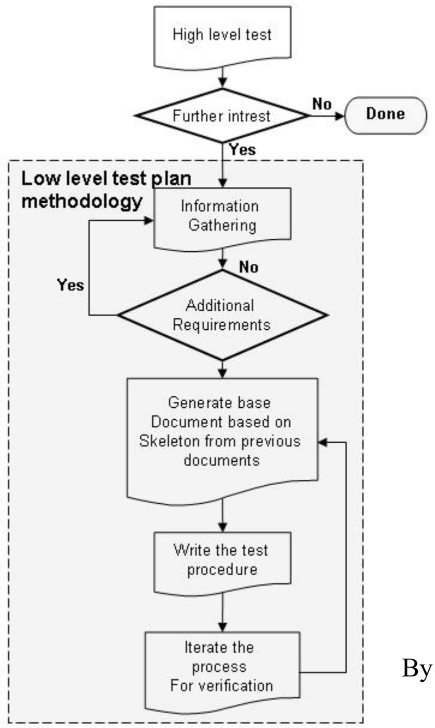

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Figure 6. Low level test plan methodology

4 Test examples

These in-depth tests are made in order to demonstrate how validation of demands and requirements originating from VTS and SSTS documents can be made. The first test to be performed is a Zero Emission Vehicle capability test and the second is a test of the Robin Hood Battery Management system charge equalization capability. Both of these tests are presented, at first with a high level description on the same format as the test procedures in the previous chapter. However, in addition to this they are then presented with test procedures, which are documents describing the test procedure in detail.

The work flow for the in-depth test is as follow:

1. Low-level methodology
2. Presentation of validation material:
   - High-Level: Zero Emission Vehicle Capability test
   - Low-level: Zero Emission Vehicle (ZEV) capability test procedure
   - High-level: Robin Hood Battery Management system charge equalization capability test
   - Low-level: Robin Hood Battery Management system charge equalization capability test procedure

3. Performing the tests according to their separate test procedure documents:

   - Presenting the simulation model and simulation results.
   - Performing the in vehicle tests

4. Conclusions

4.1 *Zero Emission Vehicle capability test*

Requirement(s)

1. Determine and adjust the quality of the battery model by hardware verification.
2. To subject a test vehicle to operation similar to that experienced by customer vehicles in zero emission mode in urban type driving and thereby get a measure of its ZEV capability.

Conventional drive line demands

Not applicable

Effect of the hybridization

The aim of the test is to obtain information about the range of the electric drive system in absence of the ICE. The information obtained from this test is used to check the vehicles pure electric mode that is ZEV, capability. In addition to the information obtained regarding the vehicles ZEV capability, information concerning the potential to use the electrical drive system as a limp home function if the ICE is broken is also obtained.

Type

Technical Performance Requirement and validation of battery model.

Validation

The test is divided in two parts, one to verify and adjust the battery model to measured data and the other is a ZEV capability test made as a complement to the top speed test in pure electrical drive mode.

MHD2 Specific

The ZEV configuration used in the MHD2 vehicle is presented below

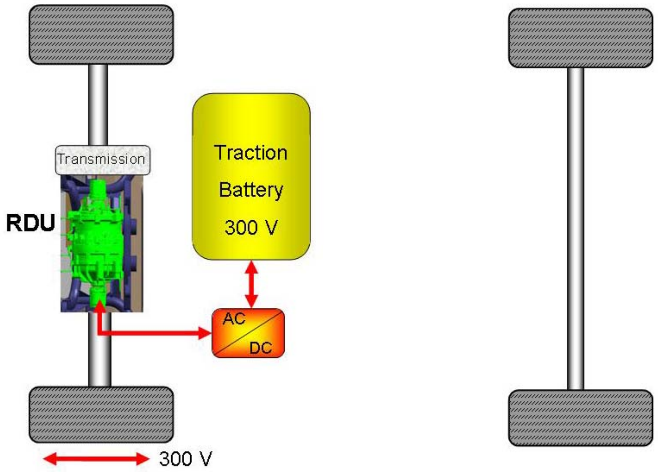

Figure 7. The Power train configuration used in ZEV mode for the MHD2 vehicle

The test is made to determine the best possible performance that may be available from the electrical drive system when used on stand alone basis and should be validated using simulations and hardware tests. An overview of current battery technology is presented in the table below:

Battery type	**Specific energy [Wh/kg]**	**Specific power [W/kg]**	**Suitable SOC swing with regards to SOH (+/- % of SOC)**	**Approximate cost[$/kW]**
Lead-Acid	35	400-500	2.5	150
NiMh	48	1300	10	600
LiIon	160	2500-3000	15-20	250 in future high volume series production
EffPower: **lead-acid chemistry in a bipolar arrangement with lead-infiltrated-ceramic (LIC™)**	25	800	2.5	To Be Determined

Table 1. Approximate battery type properties

When considering ZEV performance it is importance to especially consider:

1) The thermal properties of the battery since when utilizing high power from the battery the high temperatures generated, with insufficient battery cooling, rapidly decrease the lifetime of the battery. In general battery temperatures above 35°C are directly hazardous for battery lifetime.
2) Large SOC swings degrades the battery lifetime quickly for example a SOC swing of 80% (100-20%) can be made to a NiMh battery without noticeable performance degradation but 500 cycles degrades the battery to such extent that it is significantly degraded. The different battery technologies handle large SOC swings differently as can be seen in the table above.

Depending on the accuracy of the battery model there may be fairly large deviations between simulated results and reality. Therefore, it is necessary to first perform hardware in the loop tests to be able to verify the accuracy of the battery model and adjust it in an iterative loop if necessary until a satisfying accuracy of the battery model is obtained.

The discharging cycle for the battery may be done in several ways a suggestion is presented here. It is divided into two measurements:

- The first of the measurement setups is made to verify the batteries capability to handle thermal heating during high-power cycling. It is performed by simply connecting the battery to a constant load that keeps the battery discharging at a, compared to the battery capacity, high discharging rate to make sure that the battery has no heating problems when delivering the power that might be requested during a though drive cycle. The test is to be interrupted once one of the following predetermined conditions is reached:

-The battery is unable to deliver the requested power to the load.
-The battery reaches a predetermined terminal voltage or SOC.
-A predetermined thermal boundary is reached.

For the battery test the voltage, current, power, temperature and SOC from the battery are to be measured or estimated.

The data from the measurements are to be used to verify the accuracy of the battery model before the second part of the test is initiated.

- The second test is optional and should consist of measurements made on variable loads that describe a real driving situation as accurately as possible. For example, the load during the ECE15 cycle might be approximated with power load data from another similar car. Thus this data from another similar vehicle might be used to simulate and verify the battery in hardware. It is important to add all auxiliary loads used in the vehicle to the power demand from the drive cycle, if it is not already included in the data. In addition, it is important to determine the status regarding potential large power consumers such as the High Voltage Air Conditioning, HVAC before the test is to be run, since these factors influence the results greatly. This test is made to validate the models behavior during dynamic and transient loading of the battery. The opportunity to examine voltage dips during heavy loading is of special interest.

Once the battery model has been verified the next part of the test can be initiated. This second part is to be performed both on the real vehicle and as a power train simulation. First the simulations are performed to make an approximate estimation of what kind of performance that may be expected in the real vehicle test, if this data is not available from previous steps in the development process. The tests are to be performed either as a driving cycle that is followed until the batteries are depleted or another boundary condition is reached. If this gets too complicated from a measurements point of view the test can be made as a constant speed test where the vehicle is driven at a constant speed until the vehicle comes to a standstill, or as a free driving dynamic test. The choice of driving mode is not the most crucial part, as long as the simulation and in vehicle tests are performed on the same drive cycle giving directly comparable result. Thus by comparison of simulated and measured data the accuracy of the complete vehicle model is determined. If found necessary this test might be performed iteratively until desired accuracy is obtained from the model.

The interruption conditions of both the measurements and simulations are to be determined before they are initiated:

- SOC – It is suitable to set an interruption condition if the SOC gets to low during discharging since it will increase the wear on the battery if certain levels are reached. Also a to high SOC might be hazardous to the batteries lifetime.
- Temperature- If the temperature gets to high it might be hazardous for the components.
- Voltage level- When the terminal voltage gets lower than a predetermined value it might be a good idea to interrupt the simulations or driving tests since then the battery quite soon will have problems to deliver the desired power.
- Speed profile-When the vehicle is not able to follow the drive cycle anymore the test is to be terminated

Although the verification of the model might be interesting the main focus of the test is to get information about the vehicles ZEV capability thus making measurements of the distance that was traveled before the batteries where depleted as an interesting quantity.

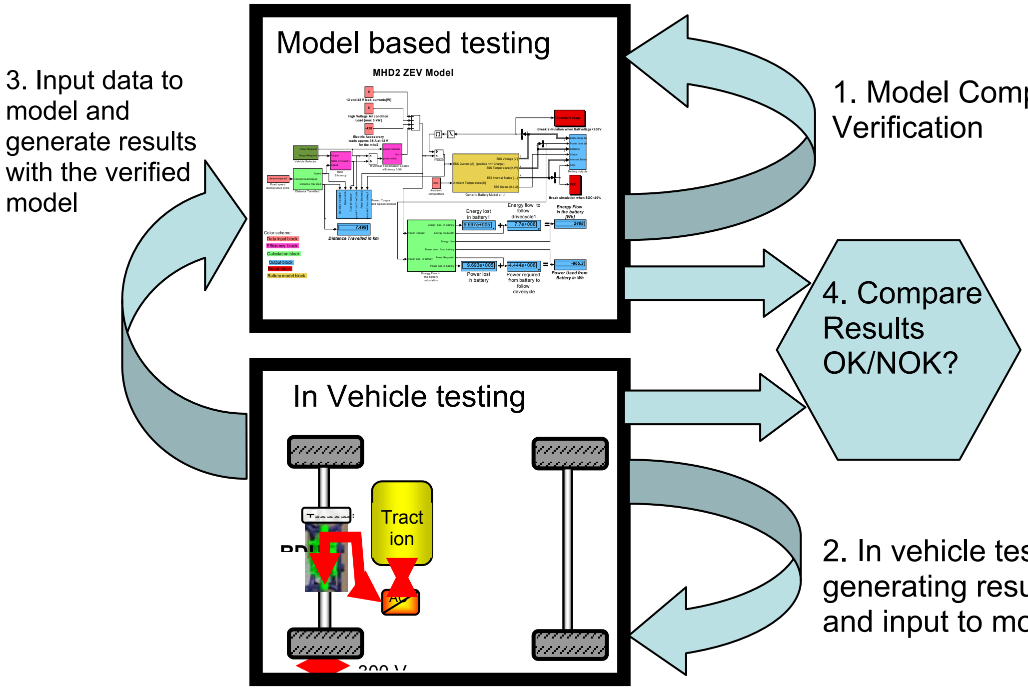

Figure 8. Workflow for validating the ZEV capability

4.2 Zero Emission Vehicle (ZEV) capability test procedure

Originated Date: April, 2006
Revised Date: NA
Approval Date: NA

4.2.1 Introduction

Note: Nothing in the specification, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

Purpose

To subject a test vehicle to operation similar to that experienced by customer vehicles in zero emission mode in urban type driving and thereby get a measure of its ZEV capability.

4.2.2 Definitions

Zero Emission Vehicle (ZEV): A vehicle that is certified to meet the most stringent emission standards established by the California Air Resources Board (CARB). The vehicle shall not produce emissions or pollution when stationary or operating. These standards require zero regulated emissions of particulate matter, that is soot, non methane organic gases, NMOGs, carbon monoxide, CO, and nitrogen oxides, NO_X. Although not considered an emission by the CARB definition, carbon dioxide is a greenhouse gas implicated in global warming scenarios.

Limp Home: In this context limp home means the vehicles capability to propel the vehicle in terms of speed and range in absence of a working ICE.

Foreword

The aim of the test is to obtain information about the range of the electric drive system in absence of the propelling power from the ICE. This information is used to evaluate the vehicle capability for ZEV functions. In extent of this it provides information regarding the vehicles capability to propel in case of a broken ICE, that is its limp home capability.

General Information

This procedure provides a method to simulate urban vehicle driving in ZEV mode, consisting of low speed driving at level grade, tarmac roads.

For Vehicle Validation

This procedure is intended as a capability test used in hybrid development in order to determine performance and capability of different drive systems.

Applicability

This test is applicable to all types of Hybrid Electric Vehicles, which have the ability to run in pure electric mode.

4.2.3 Resources

Facilities

Trollhättan - Stallbacka Proving Ground, Track alternatively a dynamometer

Facility conditions

The test site should have resources for sufficient ventilation and cooling for the vehicle and its batteries during charging. Moreover, is should preferably allow for off vehicle charging of the batteries as well. Protection from exposure to hazardous voltages should be available to grant personal safety. High voltage areas should be marked with high voltage signs for protection of non authorized personnel.

Equipment

The testing equipment is possible to use in three configurations depending on accuracy and conditioning demands:

- CAN bus logger, if the signals of interest are available through the bus. For example Starfrec or Frec 2000 from Combitech systems might be used for this data logging
- Measurements, described in Instrumentation paragraph below is used

Instrumentation

All instrumentation must be calibrated and prepared in accordance with applicable national standards. The following instruments are required for the tests outlined in this procedure

- DC Wideband Ampere-Hour Meter: An Ampere-hour meter using integration technique with an integration period of less than 0.05 s so that abrupt changes of current can be accommodated without introducing significant integration errors. Alternatively a Watt-time recorder might be used
- Vehicle speed versus time recorder

- Distance versus time recorder
- Ampere meter
- AC kilowatt-hour meter to measure AC recharge energy
- Tire pressure gauge
- Ambient temperature versus time meter
- Constant current discharge equipment for HIL tests, verifying battery model capability
- Multimeters for additional needed measurements
- An instrument to measure throttle pedal position

4.2.4 Test Vehicle

Conditioning of the vehicle

Vehicle Stabilization (Optional)

Before any testing is made the vehicle will be stabilized including mileage accumulation to a distance off at least 4000 miles (6437.376 kilometers)

Vehicle Appendages

The test vehicles will be equipped with normal appendages during the testing. For example bumpers, rails and mirrors that are mounted on the standard vehicle are to be mounted during the testing.

Vehicle Test Weight

Testing will be performed with the vehicle weighting curb weight plus additional fluids, full tank, test equipment and 2 test personnel approximately weighting:

$$\text{Test weight} \approx \text{curb weight} + 280kg$$

Lubricants

The lubricants specified by the manufacturer will be used.

Tires

The tires recommended by the manufacturer will be used.

Tire Pressure

The tire pressure is to be set in accordance with the manufacturer recommended level. Observe that the additional load, from curb weight, might generate an additional increase in the tire pressure. This pressure increase should be linearized between the normally two, from the manufacturer, given data points for tire pressure.

Tire Conditioning

Tires shall be conditioned as recommended by the vehicle manufacturer.

Gear Shifting

During the test driving the vehicles shall be operated as specified in 40 CFR Part 86.128-00 [31] and 40 CFR Part 86.128-179 [32] these specifications include descriptions of acceleration pace and gear shifting patterns. If an automatic transmission is used the only concern is to be taken to the acceleration pace description. This is given in the two above specifications.

Regenerative Braking

The testing of the vehicle should preferably be made on road or in an all wheel dynamometer, given that on a two wheel dynamometer the effect of the regenerative braking tends to be exaggerated, since all the braking is made on the driven axle.

ABS/TCS

If dynamometer testing is made on a two wheel dynamometer the ABS and/or TCS systems may need to be disabled, since the single axle interaction might be sensed as errors for these systems and as a result they might interrupt the testing.

Air condition settings

The air conditioning system shall be kept in the same mode at the same temperature and fan speed during the entire test. Preferably the test should be performed both with and without the air conditioning system on, in order to provide detailed information about the vehicles system capabilities and the effects on these from a large variation of the auxiliary loads.

Headlights

The headlights will be in normal mode during the entire test.

Test Time

Approximately X hours for conditioning the battery, Y hours for preparing the vehicle, installing and connecting measurement equipment. Then an additional Z hours for driving the test slope is required. Finally additional W hours for restoration of the vehicle
The total test time is then:

$$Total\ test\ time = 2X + Y + 2Z + W$$

The practical charging time of the battery is far longer than the theoretical due to several factors:

- Battery charger limitations
- Cooling limitations during charging
- Need to overcharge batteries to get 100% SOC

A more realistic estimation is that the charging time, X, is approximately 5 times the theoretical charging time.

The example figures are for the MHD 2 vehicle
Y=1 If the CAN bus is used for the measurements otherwise this value should be adjusted depending on the amount of instruments that are to be used.
Z = The test slope is maximum 1/3 hour but most probably the batteries will not last that long. Getting to test site 1/3 and from the test site 1/3 hour. That is a total of 1 hour
W=0.5 hours if the CAN bus was used otherwise depending on the amount and type of measurement equipment.

Personnel / Skills

The personnel involved in the installation and removal of test equipment and handling of the vehicle should be trained in accordance with the following GMU training procedures:

Hybrid Electrical Safety Level 1	CTIS#28674
Hybrid Electrical Safety Level 2	CTIS#30876
“Avdelning C”	
Basics of CPR- CardioPulmonary Resuscitation	

Preparation

The batteries should be conditioned in such a way that they have full State Of Charge and full State Of Health at the beginning of the test cycle. The charging should be made in accordance with the battery manufacturers recommendations.

Conditions

Environmental Conditions

Weather conditions shall be fairly good preferably within normal temperature range, 283-300 K. There shall not be any extreme wind conditions nor any downpour or snow, because the tests are to be performed on dry tarmac road.

Test Conditions.

Deviations from the requirements of this test procedure shall have been agreed upon. Such requirements shall be specified on component drawings, test certificates, reports, and so on.

Measurements

Measurements shall be made regarding the following quantities during the test drives:

- Current from the battery [A]
- Voltage across the battery terminals [V]
- Instantaneous speed logging [km/h]
- Distance versus time logging [m] and[s]
- Acceleration[m/s^2]
- RDU speed [rpm]
- RDU Torque(if possible) [Nm]
- Pedal position [%]

Interrupt conditions

Before the test is initiated interrupt conditions are to be determined:

- SOC – It is suitable to set an interruption condition if the SOC gets too low during discharging, since it will increase the tear on the battery if certain levels are reached, as well as a to high SOC might be hazardous to the batteries lifetime.
- Temperature- If the temperature gets too high it might be hazardous both for the components and for the passengers of the vehicle.
- Voltage level- When the terminal voltage gets lower than a predetermined value it may be a good idea to interrupt the simulations or driving tests, since the battery quite soon will have problems to deliver the desired power.
- Speed profile-When the vehicle is not able to follow the drive cycle anymore the test is to be terminated.

Procedure

The test is performed after the necessary conditioning of the vehicle has been performed and all measurement equipment has been attached to the vehicle. It must be ensured that all sensors are operational before the test driving is initiated, since the time it takes to condition the battery is rather substantial. The vehicle is to be towed or pushed to the test site or dynamometer where the test is made by following the driving schedule presented below as closely as possible. If a test track is unavailable a four wheel dynamometer can be used instead. In that case a driving robot may be used. The drive cycle to be followed is the standardized MVEG (Motor Vehicle Emissions Group) cycle minus the high speed part that is the first 800 seconds of the cycle. If necessary it is to be repeated, shown in the figure below. The shortened version of the MVEG drive cycle is the official ZEV testing cycle for General Motors Power Train Europe at the moment. A new drive cycle will be presented as a GM standard in a not too distant future. If there for some reason is a problem with following this cycle then any comparable driving scheme can be used.

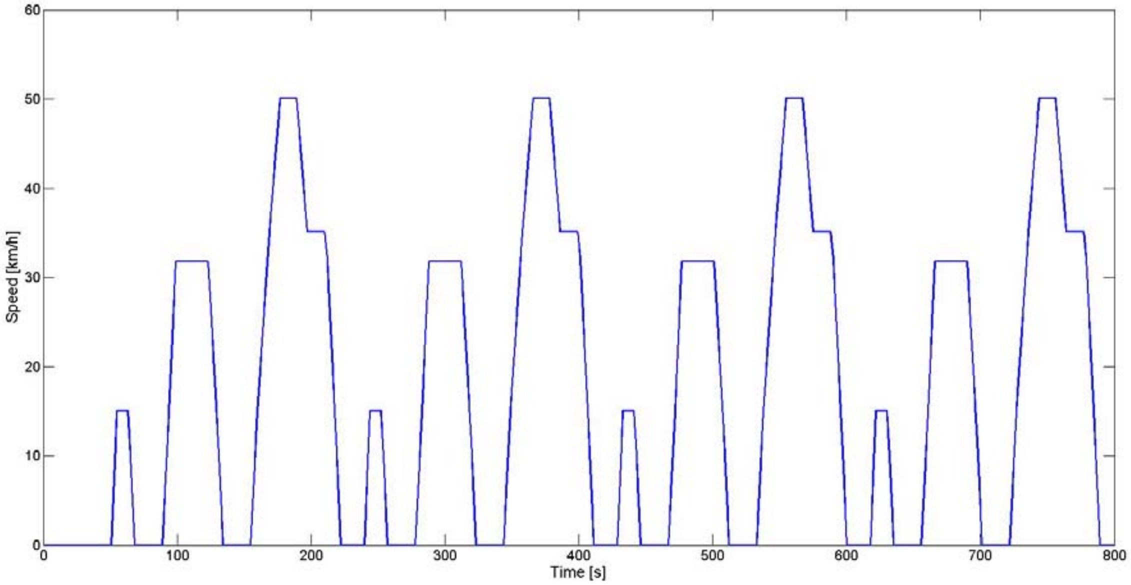

Figure 9. MVEG-A Drive Cycle minus the high speed part

Result analysis

The results from the test drive are to be analyzed and compared with the results yielded from simulations and potentially used to calibrate the simulation models. [33, 34]
The results give a good approximation of a best case scenario range for the vehicle driven in a pure electric while it also provide information regarding the possible limiting factor that forced us to interrupt the test. If there is stability or control problems with the vehicle other drive cycles can be used as long as the simulations and drive cycle are matched yielding comparable results.

References

[31] 40 CFR Part 86.128-00 Describing gear and driving strategies
[32] 40 CFR Part 86.128-179 Describing gear and driving strategies
[39] 40 CFR Part 86—Control of Air Pollution from New and In-Use Motor Vehicles and New and In-Use Motor Vehicle Engines; Certification and Test Procedure
[34] GM internal use only

4.3 The simulation model

The simulation model that was used in the ZEV capability test is presented below. The model is given input from the city part of the MVEG drive cycle.

An initial simulation using the first 800 seconds of the MVEG cycle is looped until satisfactory length of simulation is reached or one of the boundary conditions is met.

The model is primary used to calculate the vehicles range in ZEV mode, but also power and energy flow in the battery and battery thermal properties. The model also calculates the RDU efficiency, torque and power during the drive cycle. The different subsystems and equations for these are presented in appendix 5.

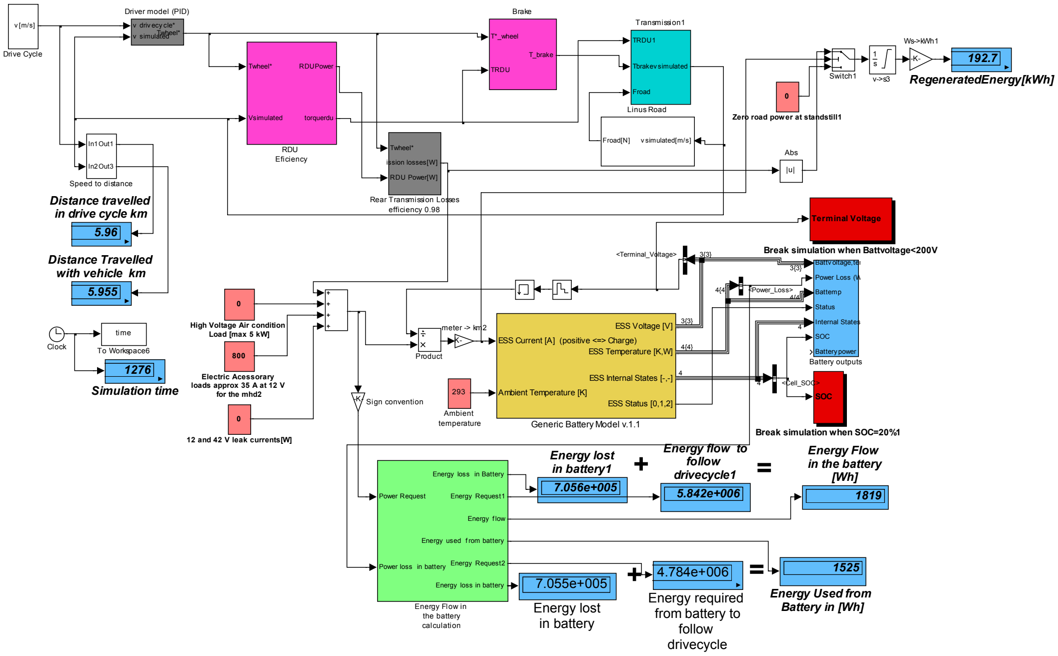

Figure 10. The model for the ZEV capability test

4.3.1 Auxiliary systems

In a modern vehicle there are approximately electric accessory loads at, P_{AUX} =0.8 kW, that are always on to supply vehicle vital functions. The High Voltage Air Conditioning systems maximum power demand from the battery is, P_{HVAC} =6 kW. However a more reasonable HVAC load case is an average of 3 kW. Thereby giving us two examples of load cases:

$$HVAC_{ON} \Rightarrow P_{AUX} = P_{HVAC} + P_{AUX} = 3.6\ kW$$
$$HVAC_{OFF} \Rightarrow P_{AUX} = P_{HVAC} + P_{AUX} = 0.6\ kW$$

In the simulations the HVAC is off since otherwise it lowers the battery voltage beyond boundary conditions.

4.3.2 Simulation model verification method

The data used in the simulation should be verified regarding the input data, efficiency maps for components and the battery model, to make the simulation model useful in reality. The verification is made starting at the input and proceeding through the model to the output:

Therefore it is natural to first run the drive cycle and to see how much the actual vehicle speed deviates from the drive cycle reference speed and if available against measured data.
A suitable measure is the Root Mean Square method which gives a measure on the speed deviation. Since the simulation and measurement values are discrete these deviations are squared then summed. Then the square root of the sum is calculated and divided by the number of sample points giving an average deviation. How well the drive cycle is followed is in this way shown as a coefficient of performance and the speed should not be allowed to deviate more than a predetermined value to make the simulations useful.

$$Deviation\ in\ speed = \frac{\sqrt{\sum_{1}^{n}\left(v_{drivecycle}(t) - v_{simulated}(t)\right)^2}}{n}$$

The distance traveled is an additional measure to verify the vehicles capability to follow the drive cycle or measured data. This is made by using the following calculation:

$$Deviation\ in\ dis\tan ce\ traveled = \int_{0}^{n} v_{drivecycle}(t)dt - \int_{0}^{n} v_{simulated}(t)dt$$

Once the deviation in speed has been controlled the next step is to measure deviation in torque and power comparing measured or drivecycle data with simulated. A large deviation will make the simulation useless. The data should also be checked to verify that it is reasonable values that are being used making sure that no erroneous input data is used or erroneous calculations are made. A scatter plot of torque and motor speed is combined with an RDU efficiency plot and a calculation of average RDU efficiency to check that results are reasonable. The efficiency maps for the RDU are checked in this way, both in generator and motoring mode:

$$Deviation\ in\ torque = \frac{\sqrt{\sum_{1}^{n}\left(T_{drivecycle}(t) - T_{RDU}(t)\right)^2}}{n}$$

$$Deviation\ in\ power = \frac{\sqrt{\sum_{1}^{n}\left(p_{drivecycle} - p_{RDU}\right)^2}}{n}$$

The battery current is checked by analyzing several variables:

1. Temperature- verifying that a physically reasonable temperature is calculated and that it follows the load case reasonably.
2. SOC- verifying that the size of the battery has been correctly set and that the SOC range stays within the physical limits, that is between 0 and 1 during simulations.
3. Current demand- Making sure that there are no non physical currents demanded from the battery.
4. Voltage level- To preempt the battery from being destroyed in the vehicle the voltage level should be controlled in simulations.

The calculations regarding energy and power flow and thermal losses should be controlled making sure that the utilization of the battery is reasonable with respect to its size.

Since the battery model has been validated thoroughly by VTEC in this particular case there is no need to explicitly verify the model of the battery to any further extent. Neither is there any need to further validate the efficiency maps for the electrical machines, since they have been measured professionally by LTH. However, a brief verification is made in the subsequent chapter, in accordance with the verification method presented in this chapter

4.3.3 Simulation model verification

By using the suggested scheme from the previous chapter the ZEV model of the MHD2 vehicle is verified in this chapter.

The deviation in average speed according to the calculation in the previous chapter is 0.0055 m/s and the deviation in distance traveled is 4.9604 m. This is to be considered as deviations small enough not to generate significant model accuracy problems. A verification for this fact is that the difference between the simulated and drive cycle distance is 5 m. The reasonability of the vehicle and RDU axle speed is verified by inspection of the figure of these quantities presented below:

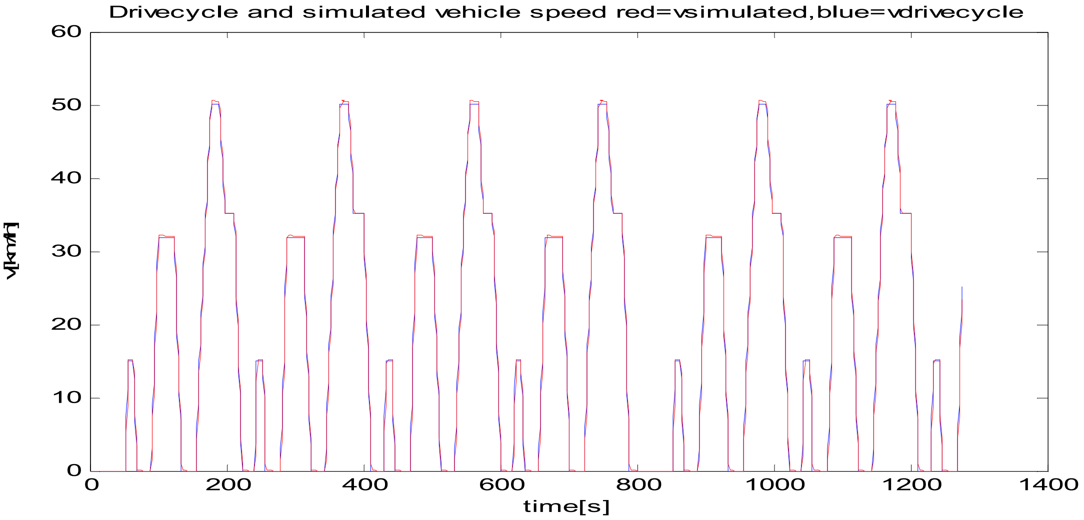

Figure 11. Vehicle speed

As can be seen the simulated speed follows the drive cycle speed very well only small deviations occur during the drive cycle.

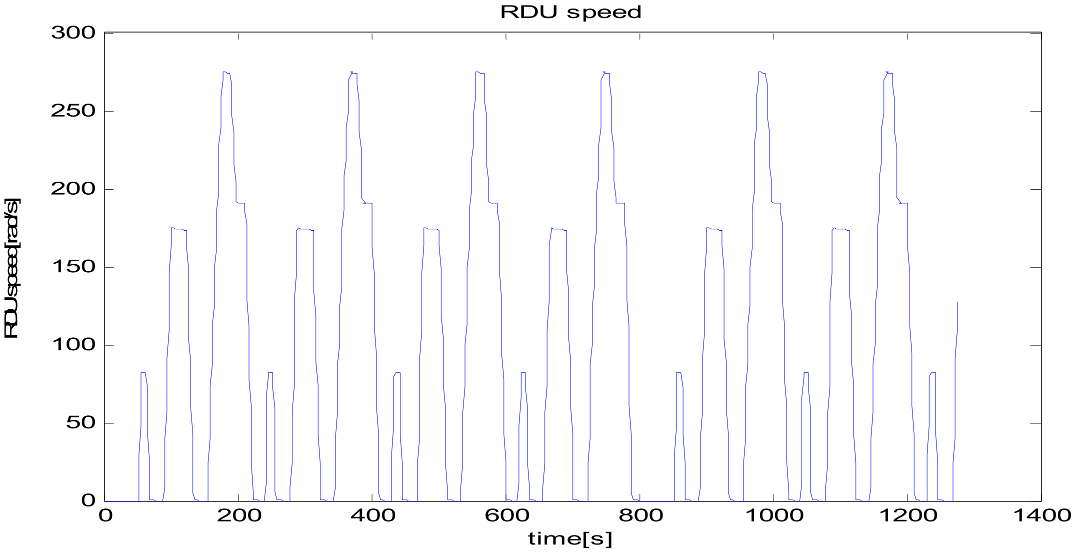

Figure 12. RDU axle speed

The RDU speed is well below the maximum speed of the RDU, (722 [rad/s]) and follows the drivecycle changes well.

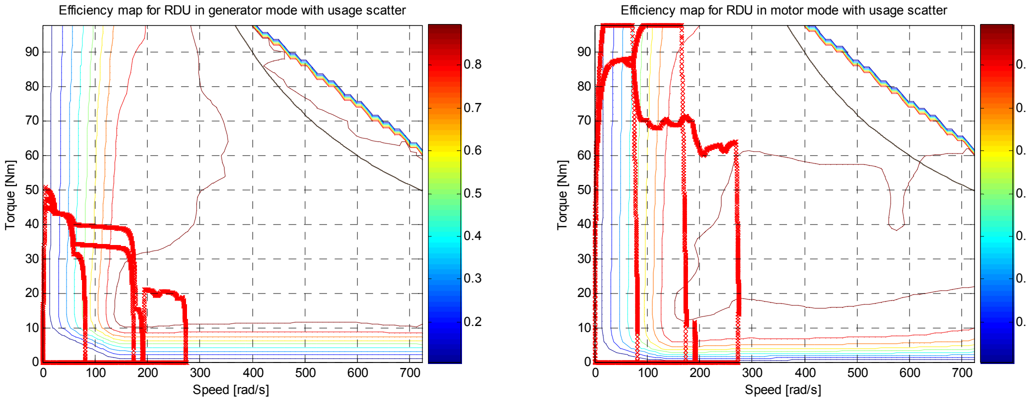

Figure 13. (left)RDU in motor mode efficiency map with usage scatter
(right) RDU in generator mode efficiency map with usage scatter

As can be seen in the plots above the low speed of the RDU during the drivecycle keeps the RDU efficiency at a rather low level. However, the situation is not as bad as it might seem since the average efficiency is actually 0.8614 due to the nature of the maps:

$$P_{mechanical}(t) = T_{RDU}(t) * \omega_{RDU}(t)$$

$$In\ motor\ \mathrm{mod}e:$$

$$P_{mechanical} < P_{electrical} \rightarrow \eta < 1$$

$$P_{RDUelectrical}(t) = \frac{P_{mechanical}(t)}{\eta}$$

$$In\ generator\ \mathrm{mod}e:$$

$$P_{mechanical} > P_{electrical} \rightarrow \eta > 1$$

$$P_{RDUelectrical}(t) = P_{mechanical}(t) * \eta(t)$$

In this model the only deviation of torque is the one between the torque calculated in the road load subsystem and the torque delivered by the RDU. This is to a great extent controlled by the settings of the PID.

The temperature of the battery in the model is verified by inspection of the battery temperature variable:

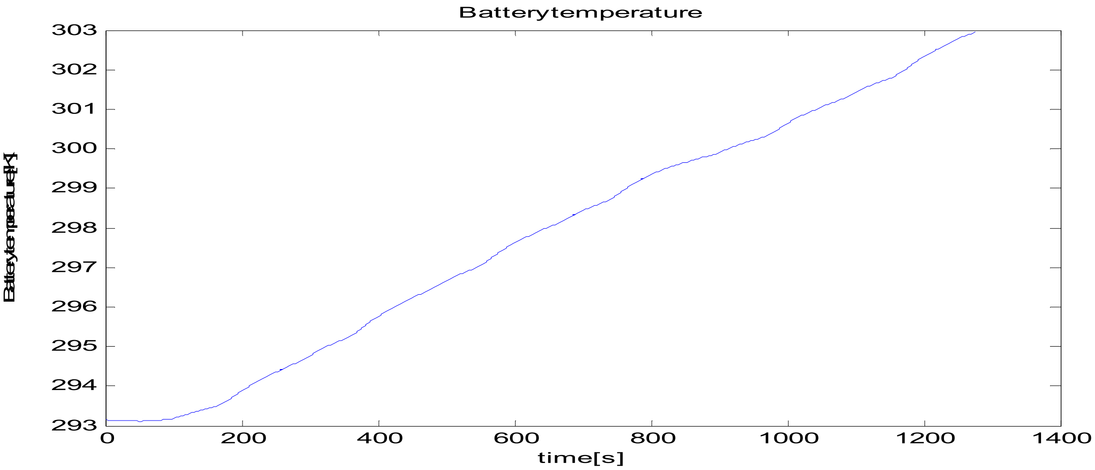

Figure 14. Battery temperature

The maximum battery temperature during the simulation is 303 K, which is well below the critical limit of 310 K, thus giving a positive indication for in-vehicle testing. However, it should be taken into consideration that the battery packaged in the vehicle may be exposed to other cooling demands to maintain the battery below the critical level than in simulation.

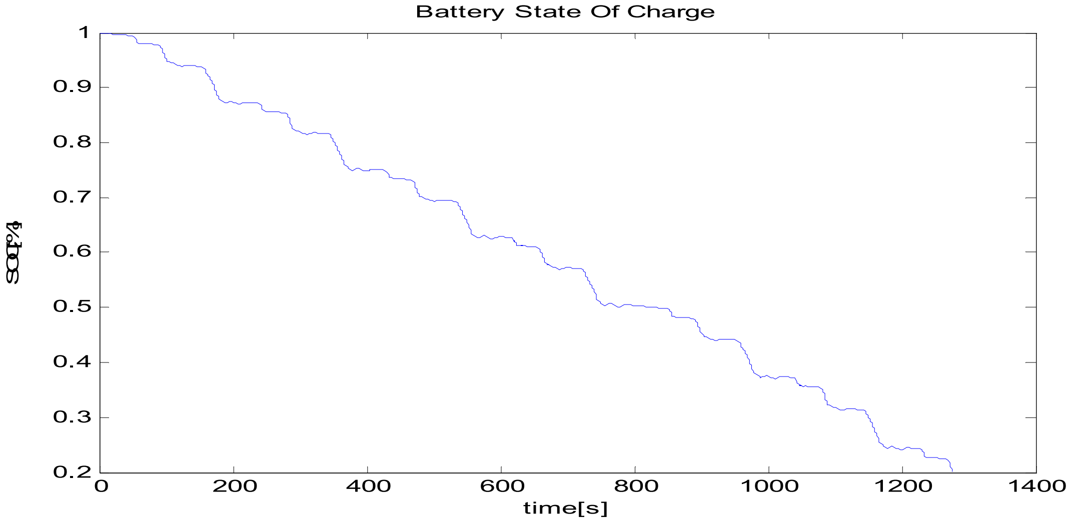

Figure 15. Battery SOC

The SOC range stays within the physical levels and the SOC follows the load case well.

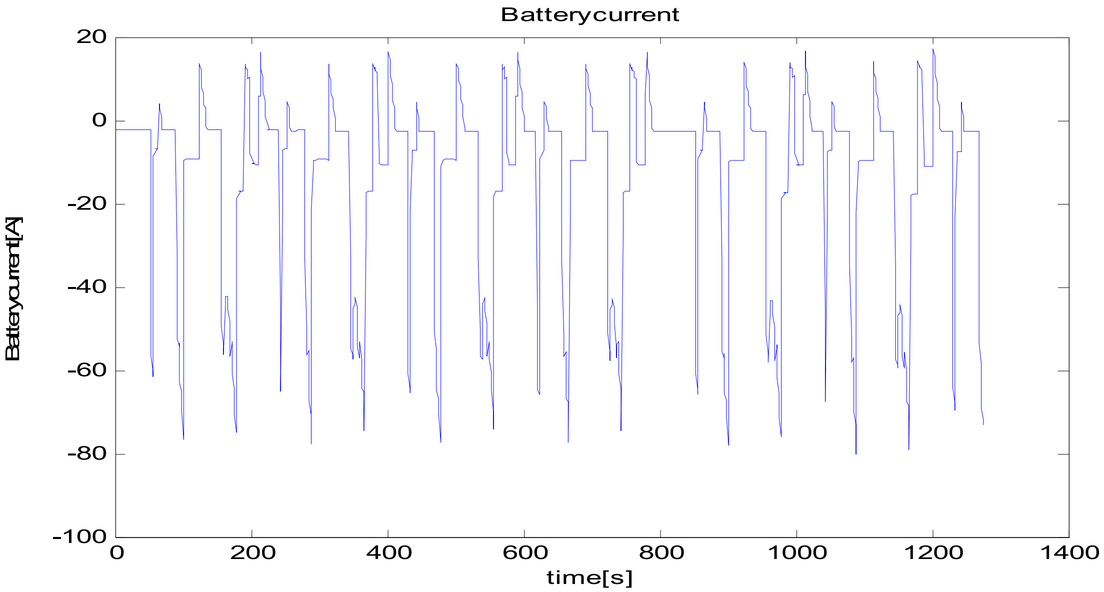

Figure 16. Current demanded from the battery

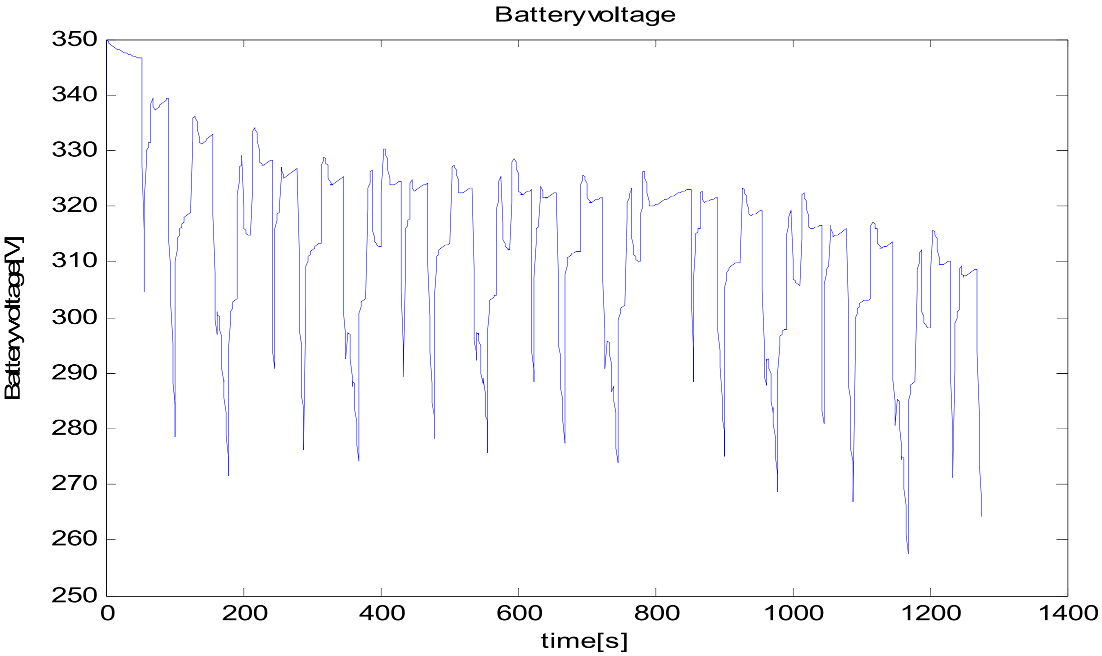

Figure 17. Battery terminal voltage

The battery voltage and current are reasonable in their deviations with respect to the load case from the drive cycle.

From the model it might be seen as the energy and power flows are reasonable with respect to the size of the battery.

For complete power train model validation in general the recommendation from the following quote forms a good basis:

"To sum it all up, a drive train model can be considered
validated if:

- The acceleration test gives comparable times.
- The steady-state tests, the tests used for tuning, and the cycles used to validate the tuning previously done have SOC, final consumption, intermediate torques, speed, current and voltage, and engine on/offs comparable with the real data. All these tests should finally be realized using different initial SOC". [27]

4.3.4 Simulation results

The RDU.

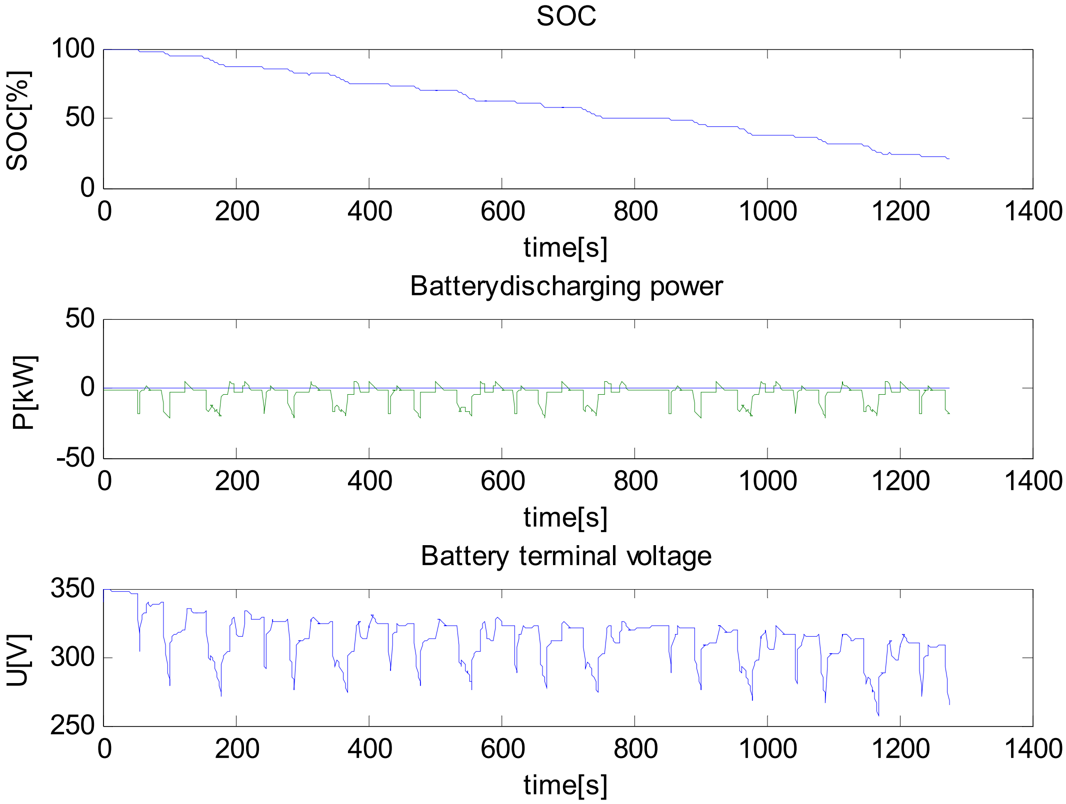

Figure 18. SOC , Power demanded from the battery and battery terminal voltage

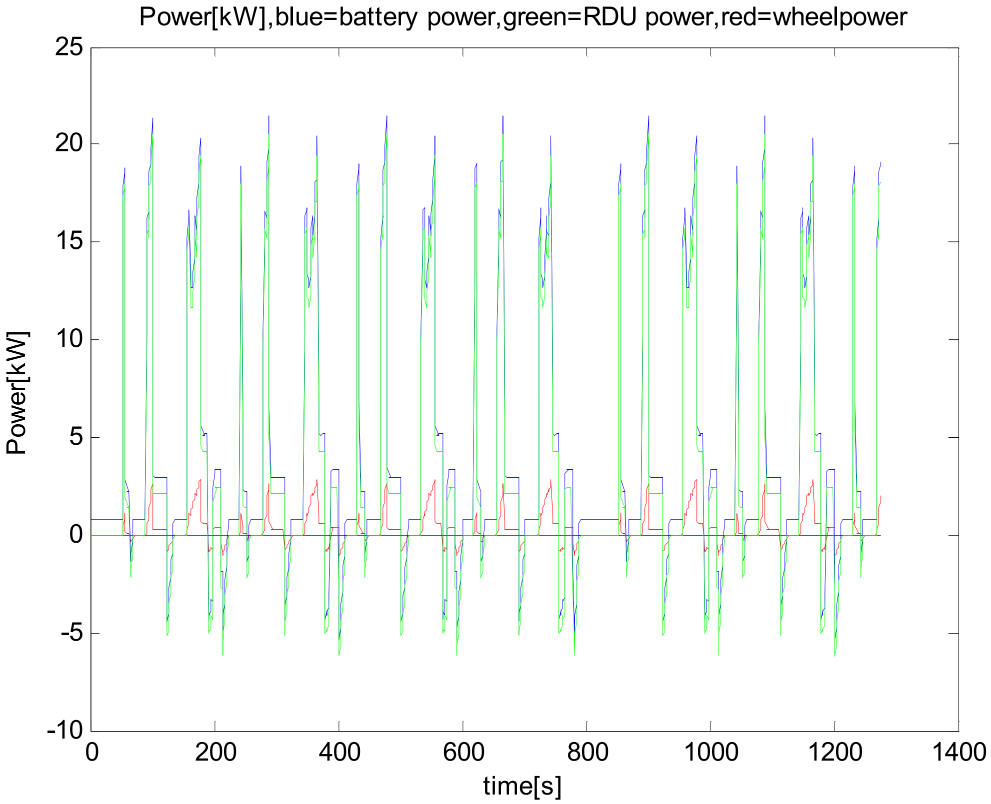

Figure 19. Battery-, RDU- and wheel power during the drive cycle

To conclude the simulation results in accordance with the original requirement:

- The distance that the MHD2 vehicle is capable of traveling in the MVEG A city part drive cycle, with a SOC swing between 100 and 20%, is 5.95 km with no AC on.

- The energy used from the battery is 1.525 kWh. This result corresponds well with the fact that the battery capacity is above 1.8 kWh in the battery model a SOC swing of 80% corresponds rather well to this result.

- The energy flow in the battery during this drive cycle is 1.819 kWh. This result is reasonable with a maximum battery energy content of approximately 1.8 kWh.

- The maximum battery temperature is 303 K, which is below the critical limit of 310 K, thus giving a positive indication for in vehicle testing. However, it should be considered that the battery packaged in the vehicle might need cooling to maintain the battery below the critical level.

- The electrical machine handles the drive cycle.

- ZEV range depends highly on the use of the HVAC no further results for the HVAC on are given.

- With respect to torque and rotational speed the RDU has no problem to handle the specified driving cycle.

4.3.5 Robin Hood Battery Management system charge equalization capability test

Requirement(s)

Determine whether or not the charge equalization capability of the Robin Hood Battery Management system gives a noticeable performance improvement.

Conventional drive line demands

Not applicable

Effect of the hybridization

The hybridization is the reason for having this feature, otherwise the vehicle would have been at a complete standstill, since in a conventional vehicle the sole source of propelling power is the ICE. A conventional vehicle differs from a hybrid, since it does not have a buffer to store excess or regenerated energy, which is virtually what the vehicle is driven on in this test.

The aim of the test is to obtain information about the difference in range of the electric drive system in absence of the ICE when using the system charge equalization capability and not.

Type

System performance identification

Validation

This test is to be performed using the Zero Emission Vehicle (ZEV) capability test procedure in two modes, with and without the Charge equalization System on.
Once the test has been conducted in both modes the results are to be compared, consequently evaluating if there are any substantial differences in the performance of the vehicle when the system is on respective off. The difference in performance should be larger than the measurement errors and discrepancies if anything is to be said regarding the improvement in performance with the charge equalization system in use or not.

4.3.6 Robin Hood Battery Management system charge equalization capability test procedure

Originated Date: April, 2006
Revised Date: NA
Approval Date: NA

Introduction

Note: Nothing in the specification, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

Purpose

To determine the performance of the Robin Hood Battery Management Systems during driving of the MVEG-A cycle minus the high speed part that is the first 800 seconds of the cycle. If necessary it is to be repeated.

Foreword

The aim of the test is to obtain information about the range of the electric drive system with and without the Robin Hood battery management systems charge equalization capability.

General Information

This procedure provides a method to simulate urban vehicle driving in ZEV mode consisting of low speed driving at level grade, tarmac roads.

For Vehicle Validation

This procedure is intended as a capability test used in hybrid development to determine performance and capability of the Battery Charge Equalization capability system.

Applicability

This test is only applicable on hybrid vehicles having the Robin Hood battery management system installed and the capability to run in pure electric mode.

Definitions

Zero Emission Vehicle (ZEV): A vehicle that is certified to meet the most stringent emission standards established by the California Air Resources Board (CARB). The vehicle shall not produce emissions or pollution when stationary or operating. These

standards require zero regulated emissions of particulate matter, that is soot, non-methane organic gases, NMOGs, carbon monoxide, CO, and nitrogen oxides, NO_X.
Although not considered an emission by the CARB definition, carbon dioxide is a greenhouse gas implicated in global warming scenarios.

Limp Home: In this context limp home means the vehicles capability to propel the vehicle in terms of speed and range in absence of a working ICE

Procedure

This test is to be performed using the Zero Emission Vehicle (ZEV) capability test procedure. The test is to be performed in two modes with and without the Charge equalization System on. Once the test has been performed in both modes the results will be compared and any substantial differences in the performance of the vehicle when the system is on respective off will be evaluated. The difference in performance should be larger than the measurement errors and discrepancies if any conclusions in benefit of the battery management system should be drawn or the opposite.

5 Future work

The validation methodologies presented in this thesis have been developed in an iterative process continuously improving the workflow and the possibilities to generate adequate results. This iterative process is to be continued as experience of hybrid electric vehicle validation grows.

Evaluating and performing the tests presented in this thesis should be made to improve quality, performance and security of future HEV products.

The simulations regarding ZEV driving should be improved especially with regards to the road model and driver model which are quite simple in their current form.

.

6 Conclusions

The validation of hybrid electric vehicles poses a complex problem, however by using the methodologies described in this thesis the work flow is made more natural and the work load is minimized. Nontheless, the methodology is a process that continuously should be updated as the experience in this field grows.

Zero Emission vehicle capability of the MHD2 vehicle in its current configuration clearly is below any commercially useful levels especially if battery wear is to be taken into consideration. In the simulations a range of 5.95 km was simulated during the MVEG-A city part drive cycle. This range was reached by using an extreme SOC swing of 80% (100-20%). The result may seem remarkable, but is to be compared to commercial vehicles having SOC swings of their batteries at +/- 10% to keep the life time requirements on the batteries.

7 References

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8 Appendices

8.1 Appendix 1 Thesis work proposal - Development of validation methods for HEV (Hybrid Electrical Vehicle)

Thesis work proposal - Development of validation methods for HEV (Hybrid Electrical Vehicle)

Leif Hermansson, 2005-11-28, E-mail: leif.hermansson @se.gm.com

Background

The complexity of vehicles is constantly rising and the introduction of hybrid power trains increases the complexity even further. This, in combination with the hybrid power train being a pilot project and not a well-known product that has been under development for mass production for a long time, creates a need for a systematic method for validation and verification of the power train. It is very expensive and time consuming to build real prototypes of HEVs. Computer simulation is therefore an almost necessary complement. Although, to be able to verify the HEV product quality and behavior some parts of the validation process needs to take part on real HW. It is for that reason essential to find the balance between quality, cost and time when deciding on how and when in the development HW testing should occur.

Studied power train

The study should be done in order to develop a generic validation plan for parallel and split HEV. One part of the work will be to apply the validation plan and perform a test on the power train in figure GM internal. It is a 4WD parallel hybrid car. The difference from a “classical” parallel vehicle is that an EM has been added on the rear axle. A NiMh battery is used as buffer and the engine is of gasoline type.

Problem Description

The scope of the master thesis includes:

- Identify and present the different parts of the hybrid power train and describe the different configurations that we are currently interested in
- Identify hybrid specific requirements regarding the power train
- Develop validation and verification methods for these requirements. The methods should be developed for testing on a vehicle level and when found necessary on a subsystem level. The methods should also decide what type of tests that are necessary to validate the respective requirement.
- Perform simulations of one of the tests from the generic validation plan on a specific vehicle namely a four wheel drive parallel hybrid vehicle (Figure 1).
- Prepare a test plan for the simulated requirement.

Desirable background

Suitable educational background is M, F, E, Z and Y. Experience from vehicle technology, simulation, object oriented programming and HEVs is merit. If interested, E-mail your application (CV, courses etc) to leif.hermansson@se.gm.com.

Supervisors

SAAB, Leif Hermansson, leif.hermansson@se.gm.com
LTH, Mats Alaküla, mats.alakula@iea.lth.se

Timeframe

Starting date 2006-01-16
Finishing date 2006-06-16

8.2 Appendix 2 The high level validation tests

8.2.1 Creep

Requirement(s)

To keep the creep speed within a limited speed range independent of road inclination and several other factors (see validation subchapter). These factors are to be determined depending on the demands on accuracy of the creep speed from different initial conditions. There is also a requirement to ensure a certain acceleration of the vehicle from standstill to creep speed the same constraints is valid for the acceleration.

Conventional drive line demand

The applicability of this demand is the same for the conventional vehicle as for the hybrid. However, the control of the conventional vehicles creep speed is only made by the idle controller having the ICE as the only actuator. The type of gear box affects the degree of difficulty to keep the creep speed: A manual transmission has a fixed gear ratio a CVT is able to vary the gear ratio continuously and an automatic transmission with fixed steps uses a torque converter.

Effect of the hybridization

The hybridization provides the vehicle with additional degrees of freedom since the ICE is not the only source for propulsion. In a hybrid it can be combined with the propelling power of the electrical machines thus generating additional possibilities regarding both control and performance for the creep behavior of the vehicle. There can be different driving modes implemented setting control parameters differently

Type

Technical Performance requirement

Validation

The requirement states that the speed and acceleration should be kept within a limited range an example of such a range for a typical production car is shown in the figure below:

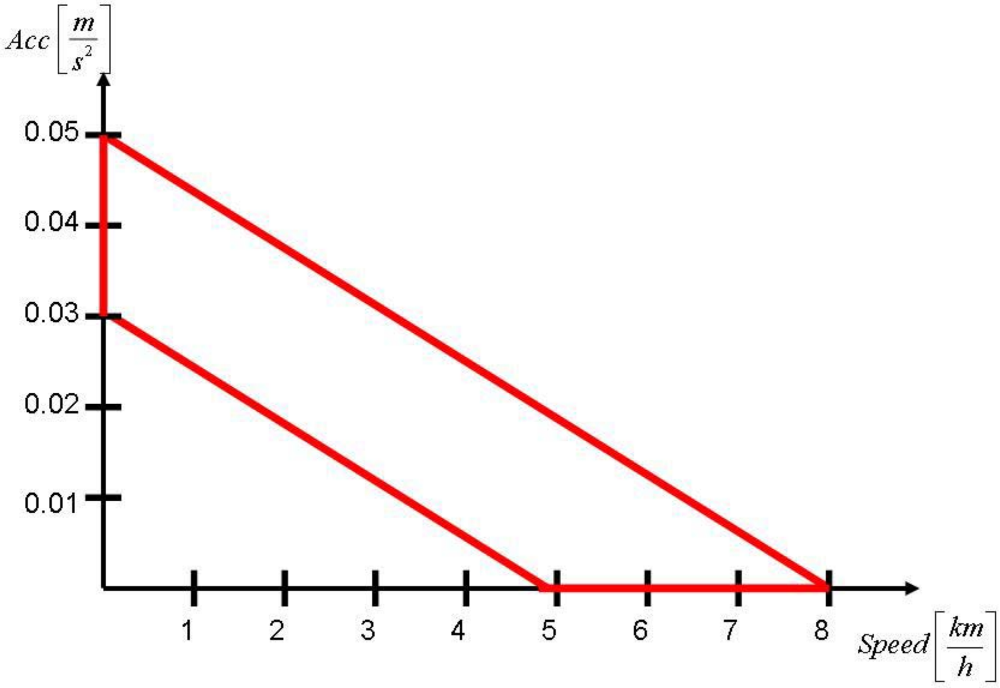


Figure 20. Speed-Acceleration requirements for creep driving

This demand is extremely sensitive to the initial conditions and constraints of the test that is differences in for example:

- Tire pressure
- Tire thread wear depth
- Gradient of the road
- Surface of the road
- Wind conditions
- Coolant temperature
- Frictional differences in the engine
- Idle controller performance
- SOC
- Temperature of the electrical machines

When developing the vehicle with regard to this requirement it is to be determined to what extent the vehicle should be allowed to deviate from the requirement depending on changes in the initial conditions and constraints. That is, there is a need to determine the stability conditions of the requirement regarding several factors before the validation can be initiated. This should already have been made in earlier development process stages but should be checked in the validation process.

The initial validation should be made in simulations determining an optimization on what combinations of electrical machines and ICE provided power that should be used at different road load cases and SOC levels.

The gear ratios to be used at different road load cases should also be determined if a CVT is used if there is an automatic gearbox with fixed steps is used the torque converter should be dimensioned to handle this requirement. Finally, if a manual transmission is used the clutch and gear ratio is controlled by the driver and the idle controller controls the vehicle to creep speed. In a HEV the electrical machines might add additional torque to ease the design constraints but making the control more complex.

During the simulations it is also suitable to find the limitations regarding initial conditions and constraints making sure that they are fulfilling the requirement.

Since there are numerous initial conditions that are to be applied the reliability of the simulation model and the correctness of this is the determining factor whether the simulations are enough for validation or if there is a need for further validation in vehicle. An example of a test scheme is proposed in "Subjective test drive Lexus RX400h regarding creep/coast behavior" [Appendix 9].

8.2.2 Coast

Requirement(s)

To maintain a predefined, stable deceleration behavior during coast without brake or accelerator pedal intervention.

Conventional drive line demand

The coast demand in a conventional vehicle is basically the same as in a hybrid; but in a conventional vehicle it solely depends on the ICE retardation in combination with the current gear ratio.

Effect of the hybridization

A HEV has far greater control authority on the coast behavior than a conventional vehicle. It has the capability to retard the vehicle with the electrical machines in addition to the ICE retardation. Making it possible to enable different driving modes where different amount of regenerative braking is used.

Type

Technical Performance requirement

Validation

The requirement states that the deceleration rate should be kept within a limited range an example of such a range for a typical production car is shown in the figure below:

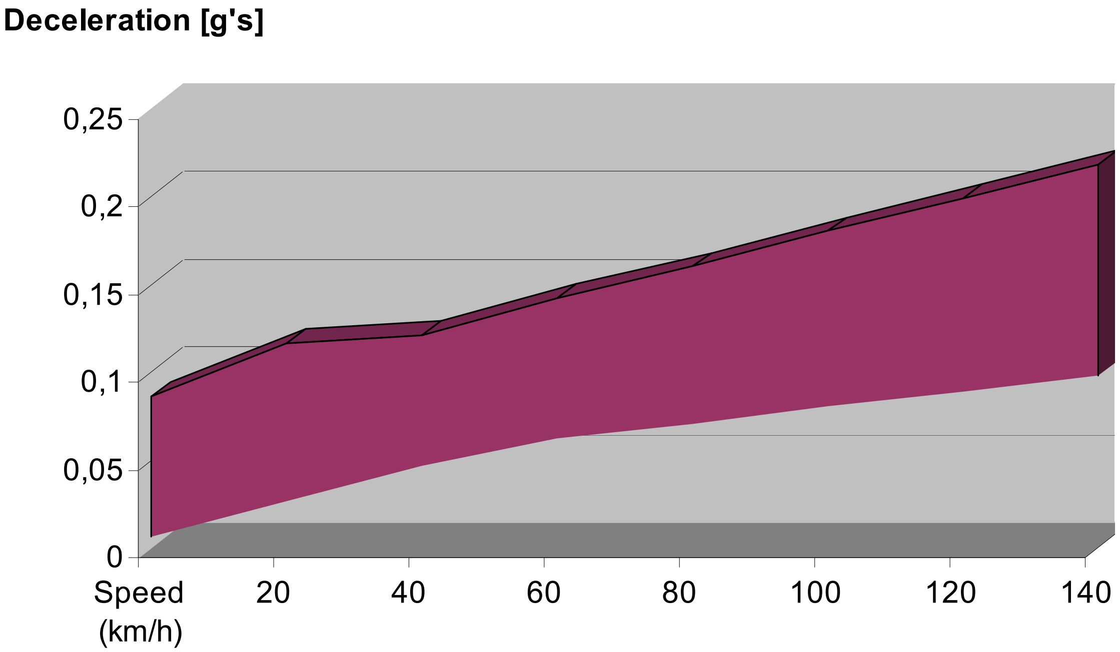


Figure 21. Example of maximum and minimum allowed deceleration in g’s during coast driving

The requirement regarding deceleration at different speeds is a designed requirement that should give the vehicle a feeling that appeals to the customers. This feeling is quantified by a driver quality group. Naturally regard is taken to stability and safety when designing the deceleration requirements.

This demand is extremely sensitive to the initial conditions and constraints of the test that is differences in for example:

- Tire pressure
- Tire thread wear depth
- Gradient of the road
- Surface of the road
- Wind conditions
- Coolant temperature
- Frictional differences in the engine
- Idle controller performance
- SOC
- Temperature of the electrical machines

When validating this demand it is important to remember that the hybrid vehicles additional coast decelerating capabilities is far greater and more controllable than for a conventional vehicle. The figure below shows a schematic sketch of the creep/coast axle torque where two different drive modes are shown Drive, D, and B, Brake. The D mode is the normal driving mode whereas the B mode is used to utilize the regenerative braking more aggressively, “Subjective test drive Lexus RX400h regarding creep/coast behavior” [Appendix 10].

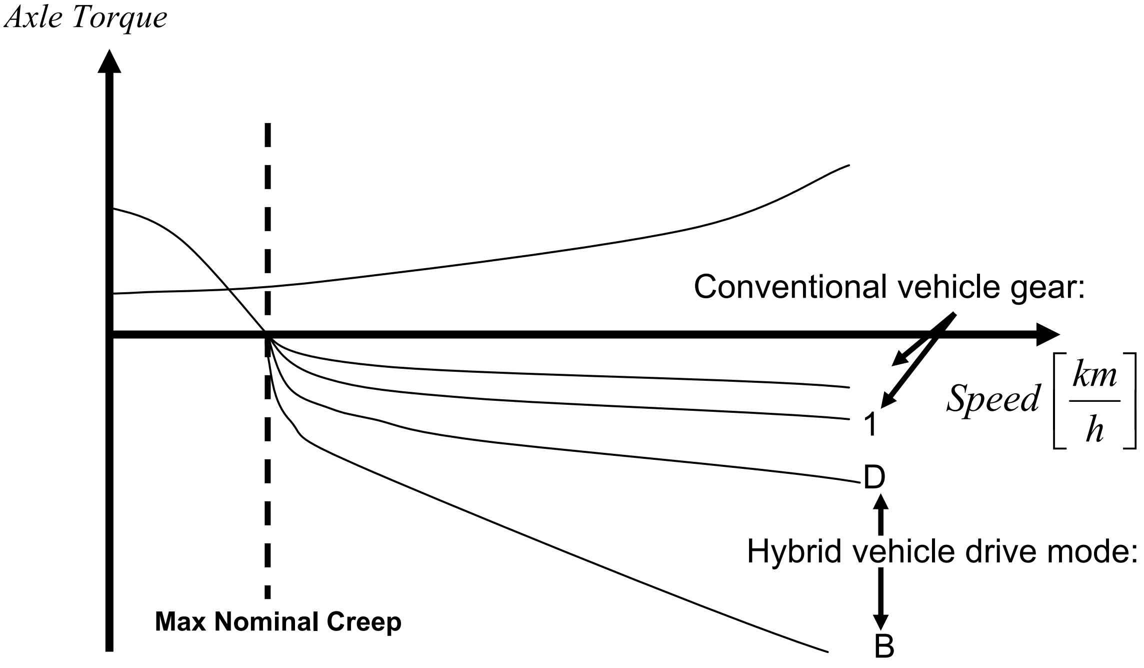


Figure 22. Creep/Coast Axle Torque

The validation of this requirement is made in simulations to verify that the control of the regenerative braking in combination with ICE retardation gives a deceleration pace that corresponds to the requirements given. As stated before the difference in the results for this requirement varies greatly depending on initial conditions and boundary conditions. Depending on the sensitivity and importance of the accuracy of the requirement the extent of the need to validate this demand in vehicle must be evaluated. At least there will be a need from the driver’s quality aspect to make in-vehicle testing.

8.2.3 Startup time of the Internal Combustion Engine, ICE

Requirement(s)

This requirement is set up to verify the vehicles ability to start at different temperatures and is divided into three parts:

- Cranking a cold engine from standstill, that is cold first start of the ICE.
- Restarting the ICE from driving modes that allow fuel to be cutoff or allow ICE speed to be reduced to less than preset speeds.
- Cranking the engine when having automatically stopped it for a short period of time, for example, during standstill at red lights, e.g. start stop capability.

Conventional drive line demand

The first two parts of the requirements are applicable to a conventional vehicle in which the cranking of the engine mostly is directly based on key signal to the starter relay.

Effect of the hybridization

In a Hybrid Electric Vehicle, HEV, the ICE is not necessarily required to crank when turning the key to start mode or pressing the start button. The engine should start when a control signal is given from the Engine Control Module, ECM. The start of the engine in a HEV can be based on several factors:

- The configuration of the hybrid driveline and the control of it.
- State Of Charge of the batteries.
- Which drive program that has been chosen for example the ICE is not to be started at all in Zero Emission Vehicle, mode.
- The power demand from the auxiliary loads.
- Forced start of the ICE for example for battery charging or service.
- Either starting the engine or prohibiting it from starting at hood opening and key input.

When in a hybrid vehicle, lacking ICE idling there should preferably be some sort of indication to the driver that the engine is ready. If the hybrid vehicle has start/stop capability there are increased performance demands on the starting of the ICE regarding noise and starting time.

Type

Technical performance requirement

Validation

The validation of the startup time for the ICE requirements is made in similar manner for the three parts of the requirements paragraph. First the time from key crank input or control module crank input to start of crank rotation should be determined and should typically be below 200 ms to not be experienced as a too long delay by the driver. When testing for Start/Stop capability the time should preferably be even lower to not be disturbing. In FAS/BAS applications this time depends on the capability of the EM. Once the start of crank has been initiated the time should be measured until the engine reaches 60% of its programmed idle speed for gasoline engines and 100% for diesel engines [31]. The start of crank should for the different parts of the requirements be performed at different coolant and oil temperatures. In the table below an example of typical test temperatures is presented. All of the tests except the one at -40° C should be unassisted. The cold start at -40° C should be assisted, "an assisted start is defined as 4 hours of block heater application or auxiliary battery boosting." [31]

Start Time
-40° C (assisted)
-30° C
-20° C
0° C
100° C
Hot Soak

Table 2. Suitable coolant and oil temperatures for ICE startup time test

The requirement for the total start time is to be defined separately for each vehicle being tested but it is defined as:

$$Total\ starttime = \text{crank input to start of crank rotation time} + \text{start of crank to}$$
$$\text{100 or 60\% of programmed idle speed}$$

During the starting of the vehicle the throttle is to be operated according to user instructions from the vehicle manufacturer and then during idling it is not to be used.

The time in which the vehicle should go from crank input to being motive capable should for a HEV typically be less than 600 ms where motive capable is "defined as the point at which the vehicle achieves an acceleration of 0.02g's at any throttle" [32].This time will give the driver a slight feeling of delay before the engine starts, but is short enough for it not to be irritating and inconvenient.

8.2.4 Stability problems due to Internal Combustion Engine, ICE, failure while charging the batteries with the Electrical Machines, EM.

Requirements

Evaluating the potential risk of stability problems if the electrical machines are being charged from the ICE and the ICE fails.

Conventional driveline demands

Not applicable

Hybrid specific demands

In a Hybrid Electric Vehicle, HEV, the electrical energy buffer is mainly charged in two ways, either by an electrical cord plugged in to a wall outlet that is a plug in hybrid or by utilizing the electrical machine(s) generator capability. Charging the electrical energy buffer from the electrical machines can be made in two ways: either by utilizing the electrical machines to generate energy from the vehicles kinetic energy to electrical energy stored in the batteries during braking, or by increasing the demand on the ICE beyond the road load power demand and directly ICE driven auxiliary components then using the electrical machines in generator mode generating energy that is stored in the vehicles electrical energy buffer most commonly batteries or/and super capacitors. The possibility to utilize the different capability modes depends on the hybrid configuration. The equation for the effective power generated by the electric machines to the electrical energy buffer from the additional power generated by the ICE is presented below:

$$P_{Buffer} = \left(P_{ICE} - P_{road} - P_{Aux}\right) \cdot \eta_{EM} \cdot \eta_{PE} \eta_{buffer}$$

P_{Buffer} = Effective power generated by the electric machines to the electrical energy buffer from the additional power generated by the ICE
P_{ICE} = Power generated by the ICE
P_{road} = Road load power demand
P_{Aux} = Power demand from auxiliary components that are directly driven from the ICE
η_{EM} = Generator efficiency of the electrical machine
η_{PE} = Charging Efficiency of the power electronics
η_{buffer} = Charging efficiency of the electrical energy buffer

When generating power with the electrical machines they impose a braking torque on the axle they are connected to:

$$T_{brake} = \frac{P_{EM}}{\omega} = \frac{\frac{dW}{dt}}{\omega} = \frac{\frac{dW}{dt}}{\frac{d\theta}{dt}}$$

T_{brake} = Braking torque of the electrical machine
P_{EM} = Power generated by the electrical machine
ω = Angular speed of the electrical machine
$\frac{dW}{dt}$ = Instantaneous power generated by the electrical machine

$\frac{d\theta}{dt}$ =Instantaneous angular speed of the electrical machine

If there is a transmission with a gear ratio between the electrical machine and the driven wheels it is connected to, the maximum brake torque that it might impose on the wheels is:

$$T_{brake\ on\ the\ wheels} = \frac{T_{brake} \cdot \omega_{axle}}{\omega_{wheel} \cdot Gear\ ratio}$$

$T_{brake\ on\ the\ wheels}$ = Brake torque imposed on the wheels by the electrical machine
ω_{axle} =Angular speed of the electrical machine
ω_{wheel} = Angular speed of the wheel axle
$Gear\ ratio$ = Ratio between the electrical machine and the wheel axle

While charging the buffer from the electrical machines that are driven from the excess power produced by the ICE it is critical for the vehicle stability if the ICE should fail. In a worst case scenario a complete failure of the ICE while charging at maximum capacity of the electrical machines might give a braking torque equal to the maximum torque generating capacity of the electrical machines. As a consequence this potentially might endanger vehicle stability.

Type

Risk scenario analysis

Validation

The risk of endangering vehicle stability if the ICE should fail should be validated by firstly analyzing the power train configuration for potential hazardous situations regarding EM charging during ICE failure and thereby evaluating the risk scenario. Once this first analysis has been made it is determined whether or not an ICE failure might risk transferring the braking torque of the electrical machines to the driven wheels and thereby endangering vehicle stability. If there is a risk of transferring this torque, simulations regarding the effects this torque might have on vehicle stability should be made. Since this is a serious safety issue, which can create a critical scenario, in-vehicle testing should be made, where the electrical machines are controlled to give maximum braking torque and then shutting down the ICE at different speeds, thus simulating an engine failure.

8.2.5 Repeated acceleration test from speed V_1 to speed V_2 within a time interval T and back again.

Requirement(s)

Determine the vehicles capability to perform repeated accelerations and decelerations in a short time without significant performance degradation. This is to be determined for different initial speeds, V_1 and V_2 but also for different relaxation times, $t_{relaxation}$ and rates of speed change, $\frac{dv}{dt}$ between starting speed, V_{Start} and final speed, V_{Final}.

Conventional drive line demands

This demand is applicable to a conventional driveline only in extreme situations, which does not resemble normal or even hard driving. The limit is either in overheating the vehicle or when it runs out of gas. However, the overheating problem is much less likely to occur than having the buffer discharged before acceleration as is the case in the hybrid vehicle

Effect of the hybridization

The hybridization might change the way the acceleration is performed, since it is not necessary to use the ICE to supply the entire power demand in a hybrid vehicle. Instead, the electric motors could be used to supply power. The batteries might become depleted due to hard usage of the electric motors, for example after several takeovers in a short amount of time. Depletion of the batteries means that the batteries have no more energy and can therefore not supply the electric machines, which in their turn are unable to supply any torque to the wheels.

It is important to have the desired road power delivered in a deterministic manner, or at least be well aware when we have a power shortage and inform the driver of this shortage. This can only be achieved if the control system has been set up correctly. In the control system one might consider options where special features such as launch control are used which is a function that is specially requested by the driver.
Another example is to utilize the possibility to let the electric motors run beyond the capacity of the cooling system and thereby being able to get a torque boost during a short time. The additional heat is absorbed by the casing of the electric motors. This potential is shown in the picture below as the marked field and the additional torque is shown as T_{boost}. The torque limit, T_{Limit}, is determined by thermal limitations and by field weakening, determined by the motor control system.

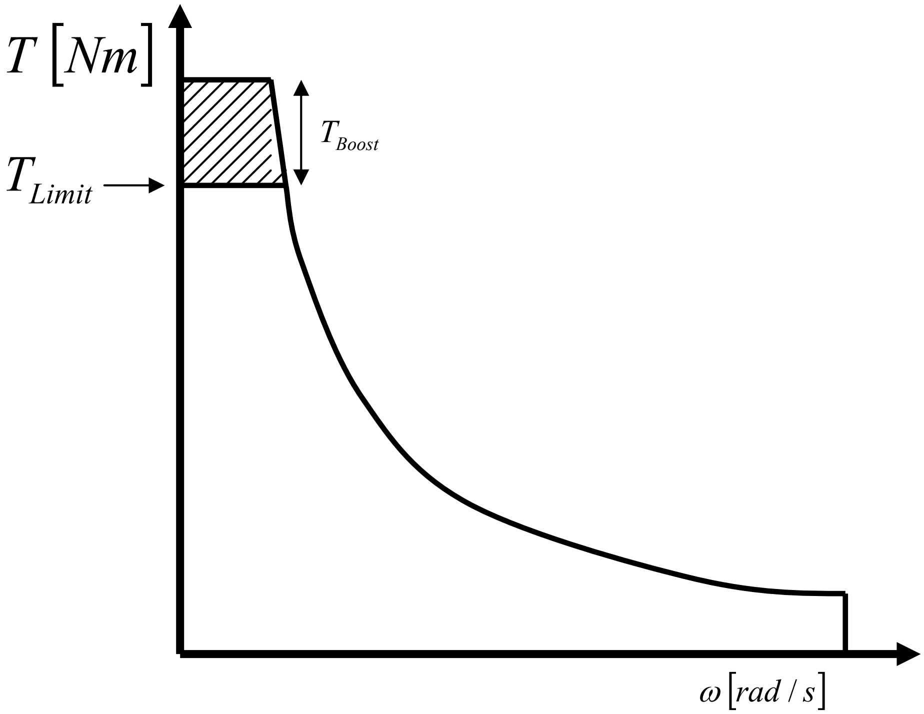


Figure 23. Potential for torque boost for an electrical machine.

These types of features can be used in a non-deterministic mode with smaller security margins for battery depletion, or even options where simply the driver is alerted when there, for example, only is 70% of maximum power available. The setup of these special functions and rules are to be determined before the test is to be performed.

Type

Technical performance requirement and risk scenario analysis.

Validation

The test being set up for this validation is an endurance test of the entire power train with special focus on the batteries and electrical machines capability. The test is to be performed as a predetermined number of cycles, n, of the drive cycle described by x in the figure below. The drive cycle starts at speed, V_{Start} , then an acceleration to, V_{Final} , is made and then deceleration back to, V_{Start} , again. The n repetitions of x are to be made within a specified preferably short time. It is somewhat likely that the hybrid vehicles energy management algorithm builds up the SOC as soon as there is enough power available from the ICE to charge the batteries.

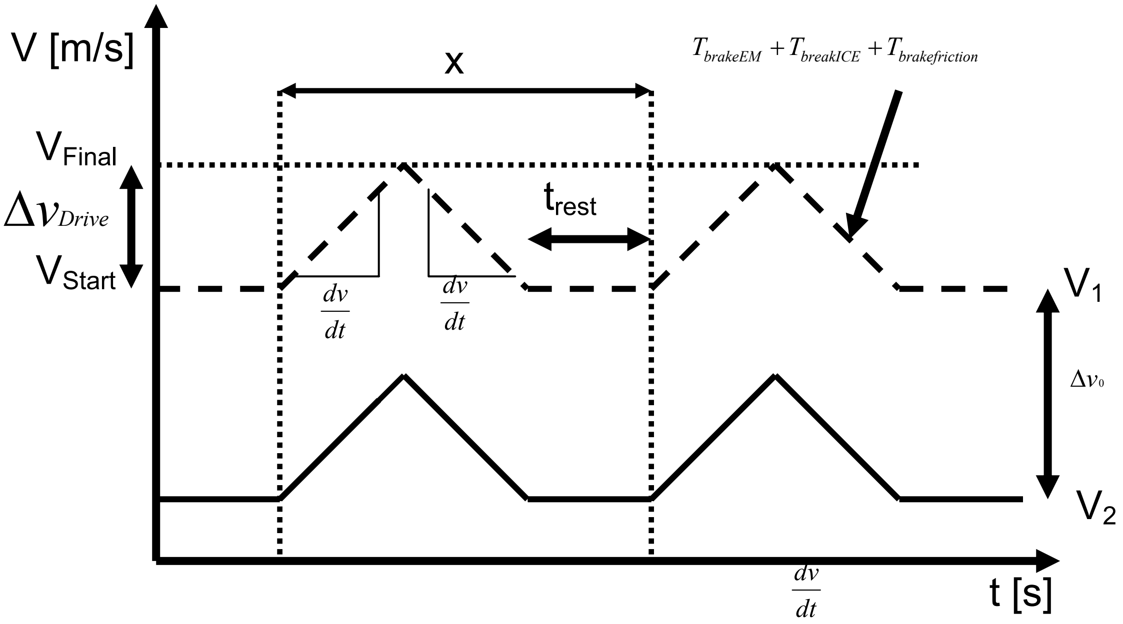


Figure 24. The test drive cycle

The test should be performed thoroughly in simulations where different scenarios can bee evaluated rather swiftly once the simulation environment setup has been made. The simulations should be complemented by hardware testing because of the need to check for model discrepancies and to check potentially critical areas discovered during simulations, but also to check the entire power train for potential problems, such as overheating in the power electronics or the electric motors.

The hardware tests should be separated into two parts. First Hardware In the Loop (HIL) tests should be made to examine potentially critical areas found in the simulations. Once these tests are providing satisfying results test drives should be conducted in order to search for critical areas that might have been missed in the simulations and HIL tests.

The reason behind this thorough testing is that the determinism regarding acceleration is a safety feature, which most drivers are used to from conventional vehicles and when absent it might pose the drivers to hazardous situations. This test is only applicable if the electrical motor is used to enhance the maximum acceleration beyond the capability of the ICE. If this feature is not used there is a great loss being made in the performance advantages gained by hybridization.

8.2.6 Stability problems during regenerative braking

Requirement(s)

To maintain physical and emotional vehicle stability during regenerative braking

Conventional drive line demands

This demand is somewhat comparable to the engine retardation used in conventional vehicles although the regenerative braking retardation is more practically controllable. The conventional engine retardation might be available in the hybrid vehicle, depending on configuration, and might be combined with the ordinary mechanical brakes and the regenerative braking to retard the vehicle.

Effect of the hybridization

When retarding the vehicle by means of running the electric motor(s) in generator mode and thus charging the battery (-ies) there is a retarding torque being imposed on the wheel axle and thus on the wheels. If this torque becomes too great compared to the available grip of the tires the physical stability of the vehicle is endangered. This feature is called regenerative braking and is one of the main advantages with a hybridization of a hybrid vehicle, since this feature regenerates some of the available energy that is stored in the movement energy of the vehicle instead of burning it in the mechanical brakes which then would be dissipated as heat and thereby being a pure loss. Furthermore, there is the factor of drive quality to reconsider, since it is utterly important that the driver maintains the feeling of being in control of the vehicle.
The emotional stability limit is likely to be reached well before the physical stability limit; however both are of interest for the validation. That the power generating limit for electrical machine(s) might be reached before there are stability problems is yet another factor. This limit is shown as P_{EM} in the figure below.

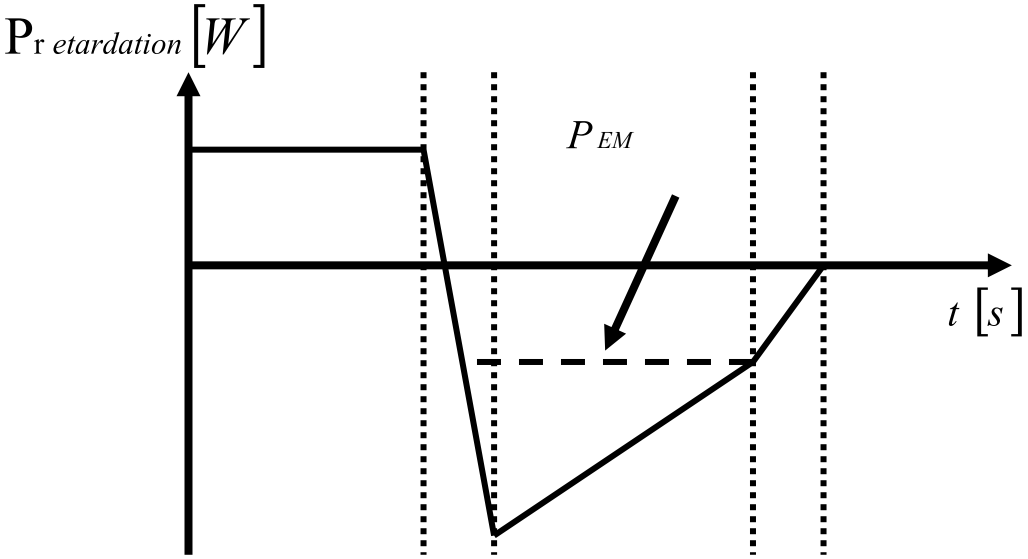


Figure 25. Regenerative braking power limit

Type

Technical performance requirement, drivers' quality demand and risk scenario analysis.

Validation

To be able to avoid stability problems during regenerative braking the control of this must be tested at the different road conditions and frictional interfaces that one might get in contact with in diverse driving situations. It is of importance that the test is made on split friction surfaces as well, in order to grant best possible results regarding vehicle stability.
The tests are to be performed in two steps:

- Simulations which possess the potential of testing several possible scenarios in a time and cost effective manner, as well as evaluating if the current control of the regenerative braking has been reasonably set up. Once the simulations are completed they are a good indication if the regenerative braking would be safe to use.

- In real vehicle it is of uttermost significance to perform these tests because the feeling of safety and control when using the brakes is of great importance. Especially since the driver only will be able to give a brake force command via the brake pedal and has no other way to control the distribution of this force between the different brake force generating components, at least not in a production car.

There is a difficult question regarding to what extent the regenerative braking should be used if it is to be maximized. There will have to be either some form of sensor, virtual or real, that approximates the friction and thereby controls the allowed degree of regenerative braking. Another alternative is using a wheel speed sensor that gives information about the rotational speed of the wheel from which it can be detected when the tire has lost its grip. This information combined with the emotional stability could be used to set the regenerative braking algorithm.

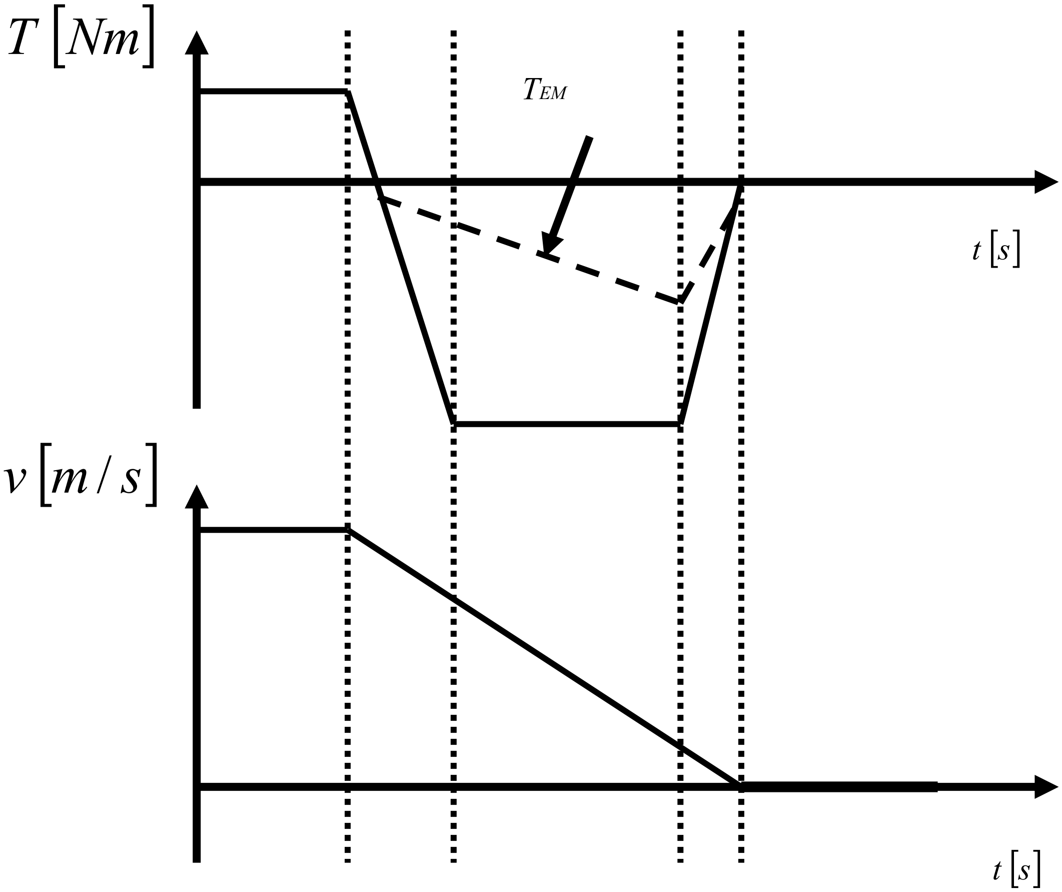


Figure 26. Regenerative braking profiles: Top: Regenerative torque profile with electrical machine torque limit, T_{EM} . Bottom: Corresponding speed profile during the braking.

8.2.7 Top speed test in pure electrical mode

Requirement(s)

This test is designed to test the maximum capability of the electrical machine(s) to propel the vehicle in the absence of having an operational ICE or when used in ZEV mode.

Conventional drive line demands

Not applicable

Effect of the hybridization

The hybridization is the reason for having this feature; otherwise the vehicle would have been at a complete standstill since the sole source of propulsion in a conventional vehicle is the ICE. Testing is made in order to determine the maximum performance of the electric drive system in absence of the ICE. This test is to be performed to check the vehicle for its capability in pure electric mode that is as a Zero Emissions Vehicle, ZEV. The ZEV capability of a hybrid vehicle is most advantageous to use in dense city traffic where the power demand is low and the engine idle times are long.

Type

Technical Performance Requirement

Validation

This test is to be performed in simulations at first, where the test is to be run on a level grade until the maximum capability of the vehicle in pure electric mode has been obtained with special control on not exceeding maximum currents, voltages and thermal limits for the different components.
If the vehicle is equipped with several electric motors the simulations should be run with the electric motors configured and controlled as they will be in the production car.

To obtain the proper conditions for this test all features involving the ICE must be turned off. The test should be run in two modes and optionally a third:

- Auxiliary equipment is off
- Auxiliary equipment at maximum load.
- Optional: Auxiliary equipment at intermediate load

It is most likely that when this feature is in use all auxiliary loads are off at least if the pure electric drive is considered as a limp home function.
If the test is made especially to evaluate the vehicles ZEV capability then an intermediate load representative for that particular car is to be used. In ZEV driving all normal in-car functions, such as air-conditioning, stereo, navigation and more should be fully operational thus the auxiliary loads should be added in excess of the road load in the simulations.

After the simulations tests should be made in a real vehicle to verify the accuracy of the model, but also to get a real numeric value of the top speed of the vehicle in pure electrical mode. The test in the real car is to be made in dry weather conditions with low or no wind. An average of the top speed from two drives one in each direction along a level road should be noted as top speed. This numeric value might then be used in a decision processes regarding limp home functions and ZEV ability for the vehicle.

8.2.8 Steady speed match

Requirement(s)

This test is made in order to gather information regarding the settings and the function of the control strategy primary regarding the following issues:

“At what SOC is the engine shut off or turned on?” [27]
“How is the engine operating point changed to meet the SOC demand?” [27]
“How are the engine torque, speed, and power adjusted to meet the demand?” [27]
“What is the battery current during these steady speeds?” [27]
“Is the battery current zeroed so that SOC is approximately held constant during steady speed operation?” [27]
Is the battery management strategy charge sustaining or charge depleting?
How large deviations in SOC does the control strategy allow?

Additionally this test is used to verify the models of the vehicle components thus determining the accuracy of the data, maps or look up tables used to describe the components in the model.

Conventional drive line demands

This test is to some extent applicable on a conventional drive line. Answering the question regarding: “How are the engine torque, speed, and power adjusted to meet the demand?” [27] However the questions regarding SOC are not applicable on a conventional power train. On a conventional vehicle it is enough to check gear ratio and torques of the Internal Combustion Engine, ICE.

Effect of the hybridization

The hybridization provides quite a substantial addition in complexity of the control strategy compared to a conventional vehicle. It has further degrees of freedom with its addition of electrical motors, batteries and power electronics to take into consideration when developing the strategy.
For some hybrids where engine torque and hybrids do not have a direct relationship this test is used to evaluate the effect of the different parameters of the control strategy and to understand the function of it.

Type

Control System behavior evaluation, Component map validation

Validation

This test is to be performed in-vehicle to validate the vehicle model regarding the parameters described in the previous requirements paragraph, but also to validate the control strategy settings. For this test there are two alternative paths depending on how the power train is configured:

- "There is a direct relationship between engine torque and speed and wheel torque and speed."[27]

- "Where the engine torque and speed do not bear a direct relationship to the wheel torque and speed, this phase is crucial for understanding the control strategy." [27]

For the first path there is merely a need to check the gear ratio and the torques of the ICE, as well as the electric motor to be able to evaluate the control strategy and the parameters in the requirement paragraph.

For the second path the controller has authority to control the ICE, electrical motors and generators independent of one another, as long as the road loads desired torque and speed requirements are fulfilled. This allows for running the vehicle in several modes, which is not possible in the first path:

- Pure electrical mode
- Increasing ICE load beyond road load to charge the batteries
- Splitting power demand freely between the different power sources.

The test is divided into two parts with the first one being an in-vehicle test where the steady speed drive cycle, shown later in this paragraph, is to be used. The test drive is to be made on a tarmac road with no grade changes, dry weather conditions and no, or low wind.

The first part is an in-vehicle test where the steady speed drive cycle presented below is to be used. This part is used to gather measurement results from the vehicle in order to be able to verify the simulation model.

Examples of suitable quantities to measure are:

- Battery terminal voltage
- Battery current
- Battery SOC
- Battery Temperature
- Electrical Machines voltages
- Electrical Machines Currents
- Electrical Machines Temperature
- Electrical Machines Torque
- Vehicle Speed
- Vehicle Acceleration
- Internal Combustion Engine Speed
- Internal Combustion Engine torque
- Wheel Torque

In the second part, the measurement results gathered during the test drive is used as comparative material to be matched with results gained in simulations for steady speed driving.
This is first made at a component level showing potential weaknesses and limitations of component look up tables, regarding accuracy and range, and parameter settings.
This gives an opportunity to adjust the component models to measured results gaining in model accuracy.

Once the component models have been adjusted the function and behavior of the Energy Management Algorithm, EMA can be verified and developed in simulations.
If the vehicle power demand is held constant, which is the case in a steady speed test, this gives opportunity to validate and optimize the EMA behavior with respect to SOC. The use of several steady speed levels gives the opportunity to identify the engine behavior at different constant loads and shows the dependence on the load in combination with SOC level for engine operating point. This test will unveil how the control strategy is set to react on vehicle speed, which is indirectly power demand and SOC during steady state behavior. These two are the primary factors used by the control strategy to determine the engine operating point. While additional factors are used, these are the main ones.
Depending on the used control strategy path for the SOC management algorithm, charge sustaining or charge depleting, the significance of the initial SOC is of varying importance. That is, if a charge sustaining algorithm is used the initial SOC has a greater impact on the vehicle behavior and furthermore it will show how aggressive the algorithm is if the initial SOC is varied.

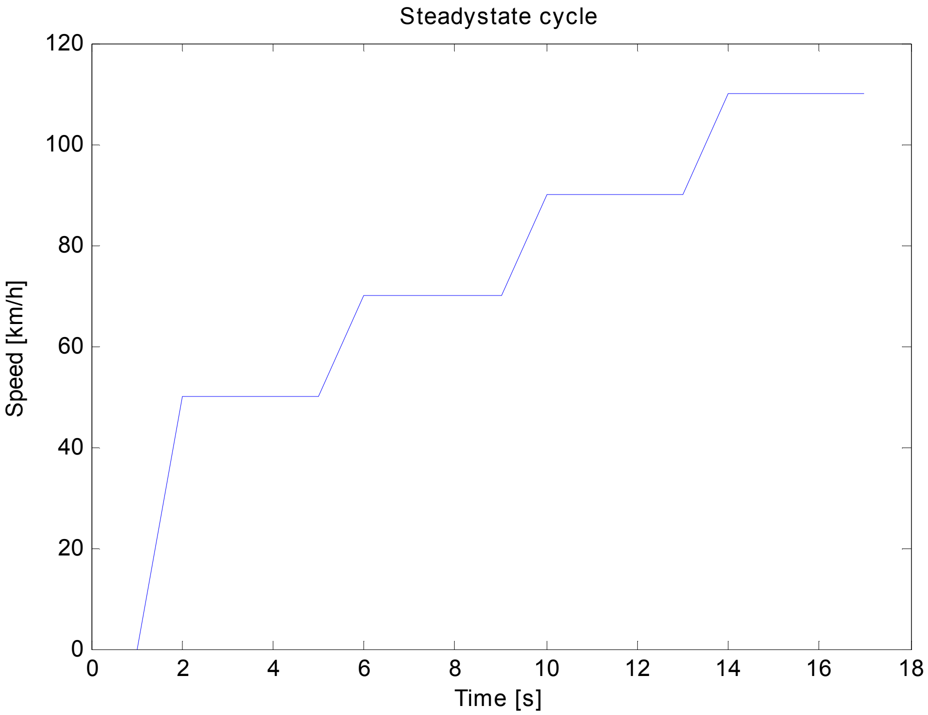


Figure 27. Steady speed match cycle

8.2.9 Maximum acceleration 0-100 km/h performance

Requirement(s)

Determining the maximum acceleration capability from 0 to 100 km/h of the vehicle and also matching the simulation model and the real vehicle regarding acceleration performance.

Conventional drive line demands

This test is one of the classic performance tests that are used to compare vehicle performance and is to be considered rather important at least from the customers' point of view, given that the result from this test combined with the top speed are the two performance measures generally used by customers to compare cars. This acceleration test is applicable on the conventional drive train and is fairly straightforward to test in a conventional car that gives us deterministic performance during repeated accelerations 0-100 km/h

Effect of the hybridization

The hybridization of the vehicle might change the way the acceleration is performed, since the ICE does not have to momentarily supply the entire desired load power, beacause the road load now can be supplied to some extent by the electrical machines. However, during this maximum acceleration the main target is to accelerate the vehicle as fast as possible thus the combination of the ICE and the electrical machines should be used to generate an as large tractive force as possible.

For example, the MHD 2 vehicles acceleration performance should most certainly be improved because the ICE gets help from the FAS in propelling the front wheels, but most important is that the rear drive unit, the electric motor mounted on the rear wheel axle, generates a propelling force on the rear wheels and gives the vehicle four wheel drive capability as a result. The possibilities to optimize and control the way the acceleration is to be performed is given several more degrees of freedom in the hybrid vehicle than in the conventional.

Type

Technical specification validation and model validation

Validation

The validation of the complete vehicle and drive train model should be done by first making several simple 0 to 100 km/h acceleration tests at different initial State Of Charge in order to gather data from the real vehicle. The data is used to calibrate the transient behavior of the drive train model and to check the inertias of the drive train [27]. Since the test is made with the intention of collecting information about the maximum acceleration capability of the vehicle the control strategy for the power train is indirectly checked in this test and shows potential weaknesses. Weaknesses for the involved components are also exploited showing the maximum constraints on the components, such as maximum engine and motor, torque and speed. The test also gives possibility to tune the simulated ICE, electrical motor and generator speeds to agree with their real counterparts [27]. Moreover, the shifting strategy models for the transmission might be adjusted to match those of the real vehicle. The effect of SOC on the extent of motor assist can also be determined and incorporated into the simulated control strategy. It is of great importance to make sure that when the validation of the model to measured data has been completed that the time required making the acceleration between 0 to 100 km/h match between the results from the data from the measured vehicle and the simulated vehicle.

8.2.10 Deceleration test

Requirement(s)

To establish how the braking strategy of the hybrid blends the friction and regenerative braking during a hard deceleration. Determine physical limits for the components in the regenerative braking chain to incorporate these in the model to make it more physically correct

Conventional drive line demands

This demand is in some sense comparable to the engine retardation used in conventional vehicles although the blended braking deceleration has further degrees of freedom to determine in what way the braking should be made. The conventional engine retardation might be available in the hybrid vehicle, depending on configuration, and might be combined with the ordinary mechanical brakes and the regenerative braking to retard the vehicle

Effect of the hybridization

The hybridization provides the vehicle with additional braking features compared with the conventional vehicle, which has engine retardation and mechanical brakes. In addition to these the hybrid also has the possibility to use its electric motors in generator mode to provide additional braking force. However, it should be remembered that it is the traction of the tires that is most likely to determine the maximum retardation even in a hybrid electric vehicle.
This means that there are two degrees of freedom added when optimizing the braking strategy.

Type

Technical performance and model validation

Validation

This requirement is validated by making several hard braking events from different speeds, which should be hard enough to max out both the friction and regenerative braking ability of the vehicle [27]. During the hard braking event data should be logged in order to make it possible to determine the distribution between friction brakes and between the two electric motors, but also physical parameters such as maximum current, voltage and temperature of the electrical motors, power electronics and the battery. This test will show the speed dependence of the regenerative braking thus giving the possibility to incorporate this into the model. It is important to perform this test not only from different speeds, but also from different initial SOC levels because the amount of regenerative braking could vary depending on current SOC level, especially when having very high SOC. A limit where the battery would not overcharge should be reached and as a result perhaps the regenerative braking would be disabled or the high SOC would be handled in another way according to the installed blended brake control strategy currently being used in the vehicle. Optionally additional tests might be made on the vehicle where the vehicle and the simulations are run on the same drive cycles for different SOC and thus giving the possibility to evaluate this battery parameter and incorporating this information into the simulation model.

8.2.11 Braking Performance – In general

Requirement(s)

The vehicle shall comply with the requirements of the EEC 71/320[28] document if the vehicle is intended for the European market and with SAE J135a [29] and SAEJ134 [30] if intended for the North American market.

Conventional drive line demand

Applicable according to the standards described in the requirements paragraph.

Effect of the hybridization

The Hybrid Electric Vehicle is, naturally, also to meet the requirements of the standards given in the requirements paragraph. However, what makes the hybrid validation a bit different than the validation of the conventional vehicle is the blended braking. The blended braking distributes the brake force between the different brake actuators of the vehicle depending on what brake mode is being used for a HEV these modes are:

- Regenerative braking utilizing the electrical machines as brake actuators
- Mechanical braking utilizing the brake calipers and discs as actuators
- Engine retardation using the frictional and pumping losses of the ICE as actuator

The blended braking in a hybrid is an electro-mechanical system, compared to the purely hydraulic system of a conventional vehicle.
The brake system in the vehicles of today has redundancy in the brake circuitry and the hybridization has the potential to increase the redundancy further, if controlled correctly. However, when using regenerative braking it is important that the mechanical brakes still can handle braking performance comparable to that of a conventional vehicle if the electrical machines or the power electronics fail.

Type

Technical Performance and safety requirement

Validation

The blended braking distributes the brake force between the different actuators of the brake system. Since there are several actuators available there is a need to control the distribution between these. This is, in particular, made to validate the accuracy of the blended brake algorithm and to verify the brake actuators quality, especially regarding temperature.

The validation is to be made in simulations where a thermal model of the electrical machines, power electronics, electrical energy buffer and mechanical brakes are given input from the blended brake algorithm for widely different braking performance scenarios ranging from mountain descent testing to high speed fading of the brake system, where multiple decelerations from near to maximum speed are made. Between the stops maximum acceleration is used.
The areas of interest during the validation are:

- Rate of deceleration at the different stops [$^{m}\!/_{s^2}$]
- Brake pedal force [N]
- Brake pedal travel [mm]
- Brake fluid temperature [°C]
- Brake rotor temperature[°C]
- Brake drum temperature[°C]

The simulations are made to swiftly to enable determination of the performance of the blended braking algorithm, given that having an algorithm with poor performance could, for example, put too much of the brake torque demand on the electrical machines and thus potentially overheating them. Since the braking system is a critical safety issue thorough control of the performance is necessary. Therefore, once the simulations are finished the validation is to be continued with in-vehicle testing validating the same areas as in the simulations making sure that none of the components gets overheated and as a consequence increases the risk of malfunctioning.

8.2.12 Fuel consumption

Requirement(s)

Determining fuel consumption of the vehicle according to the European drive cycle for City/highway/Combined driving in accordance to the 1999/100 EC directive.

Conventional drive line demands

The requirement is applicable to a conventional drive line and the fuel consumption demand is to be stated in l/100 km.

Effect of the hybridization

The hybridization of the vehicle makes it more difficult to evaluate the true energy consumption, since a hybrid can use both energy stored in the batteries and fuel from the gas tank to propel the vehicle. There is, therefore, a need to gain a measure of the fuel consumption for the HEV that is comparable to that of a conventional vehicle.

Type

Technical specification verification

Validation

The test is made by driving the European drive cycle according to the 1999/100 EC directive. The fuel consumptions should be measured during the test and for the hybrid vehicle the change in SOC of the batteries should be measured or if additional energy buffers are available the consumption from these should also be measured as well. Then refer to appendix 6 “The value of consumed electrical energy in the battery seen as conventional fuel” to calculate a measure of consumed fuel that is directly comparable to the fuel consumption of a conventional vehicle.

8.3 Appendix 3 Suggestion of contents for low level test plan

This appendix contains suggestions that might be suitable to add to the low level test plan:

Details about requirement being tested
Introduction
Purpose
Foreword
General Information
For Vehicle Validation
Applicability
Definitions
Resources
Facilities
Facility conditions
Equipment
Instrumentation
Test Vehicle
Conditioning of the vehicle
Vehicle Stabilization (Optional)
Vehicle Appendages
Vehicle Test Weight
Lubricants
Tires
Tire Pressure
Tire Conditioning
Gear Shifting
Regenerative Braking
ABS/TCS
Air condition settings
Headlights
Test Time
Personnel / Skills
Preparation
Conditions
Environmental Conditions
Test Conditions
Measurements
Procedure
References
Presenting the simulation model and simulation results
Performing the in vehicle tests
Conclusions

8.4 *Appendix 4 The data input and the subsystems of the MHD2, ZEV model*

In this appendix the subsystems and equations for the MHD2 vehicle ZEV model are presented.

8.4.1 The drivecycle

This subsystem is based on a subsystem created by Mats Alaküla, professor at the department for Industrial Electronics and Automation at LTH

This subsystem gives a time/speed vector as input to the model a variety of drive cycles are available and more can easily be added. In the simulations the city part of the MVEG-A drive cycle was used.

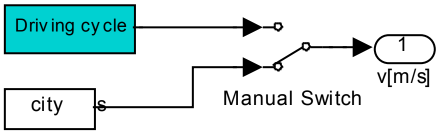


Figure 28. The Drivecycle subsystem

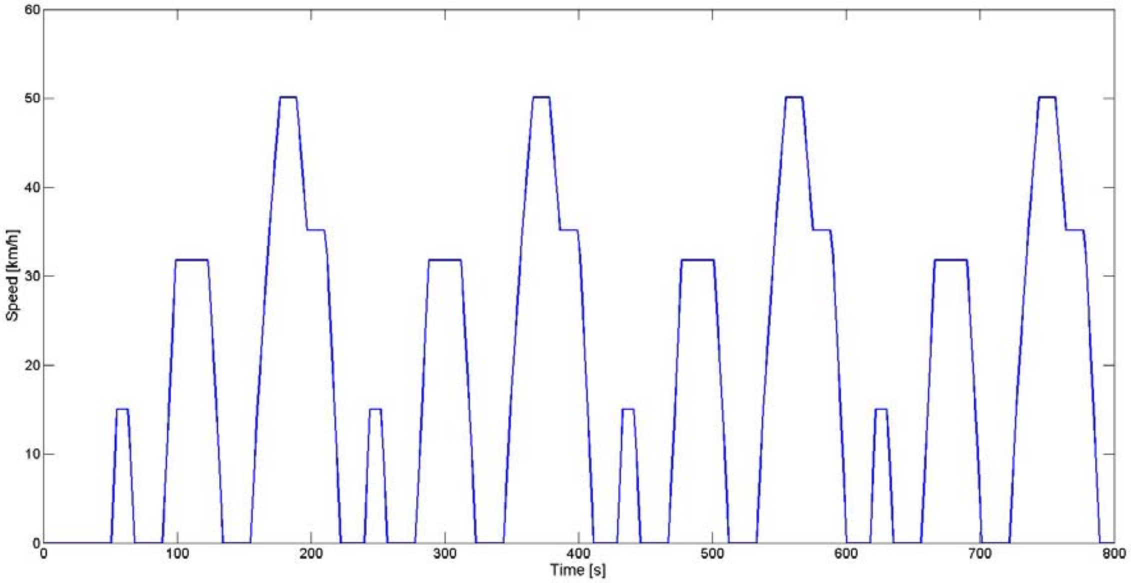


Figure 29. The MVEG-A city part drive cycle

8.4.2 The distance traveled subsystem

This subsystem converts the input data from m/s and then integrates the result with respect to time and then converts this distance from meter to kilo meter thereby generating the distance traveled both the reference speed from the drive cycle and the simulated vehicle distance is calculated according to the equation:

$$dis\tan ce\ traveled = \frac{\left(\int_0^t v(t)\right)}{1000}$$

$$t = simulation \quad time\ [s]$$

$$v = speed\ [m/s]$$

$$dis\tan ce\ traveled\ [km]$$

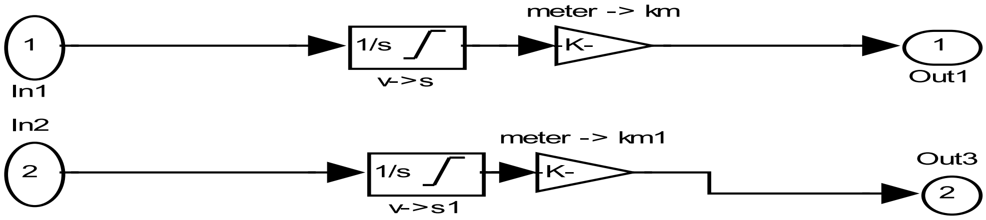


Figure 30. The Distance traveled subsystem

8.4.3 The driver model subsystem

This subsystem is based on a subsystem created by Mats Alaküla, professor at the department for Industrial Electronics and Automation at LTH

This subsystem uses a PI regulator with anti windup on the integrator to prevent saturation in the actuator. It is used to simulate a drivers behavior to follow the drive cycle using the difference in speed between drive-cycle speed and actual vehicle speed as input to the controller the output generated by the controller is desired wheel torque to achieve requested vehicle speed. The model is a simplification of driver behavior but it gives good results for comparative studies. The equations used are presented below together with the model (a derivative part in the controller is available but not used):

$$T^*_{wheel}(t) = K\left(\left(v_{drivecycle}(t) - v_{simulated}(t)\right) + \frac{1}{s\tau_i}\left(v_{drivecycle}(t) - v_{simulated}(t)\right)\right) * r_{wheel}$$

$T^*_{wheel}(t) = Total\ requested\ torque$

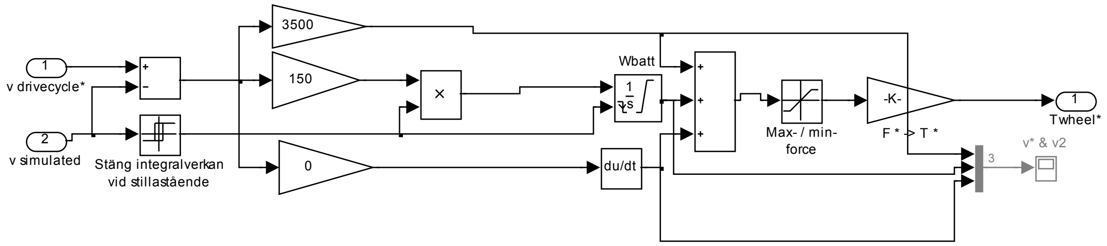
$v_{drivecycle}(t) = Speed\ \ from\ drivecycle[m/s]$

$v_{simulated}(t) = Simulated\ vehicle\ speed[m/s]$

$K = Controler\ gain$

$\tau_i = Integral\ time[s]$

$r_{wheel} = effective\ wheel\ radius[m]$



PID Regulator to simulate driver behavior to follow drive cycle
Controls on difference between drive cycle reference speed [km/h]
and actual vehicle speed [km/h]. Gives desired torque as output to RDU efficiency
calculation and to mechanical brake calculation

Figure 31. The Driver model subsystem

8.4.4 The Rear Drive Unit, RDU, efficiency subsystem

This subsystem uses two inputs the simulated vehicle road speed and the torque demand to follow the drive cycle from the driver model. These inputs are recalculated to RDU rotational speed and torque and used as input to two dimensional electrical motor efficiency look-up tables for the RDU. These look-up tables are based on data measured on the RDU; one being data for the generating mode of the electrical machine and one being data for the motoring mode. The torque demand input is then used to determine which of the maps to be used by evaluating the sign of the torque request thereby determining which efficiency map that should be used. The equations describing the physics of this subsystem are presented below together with the model:

$$T_{RDU}(t) = \left(\frac{T_{wheel} * (t)}{Gearratio_{RDU}} \right)$$

$$\omega_{RDU}(t) = \frac{v_{simulated}(t)}{r_{wheel}} * Gearratio_{RDU}$$

$T_{RDU}(t) = Torque\ delivered\ by\ the\ RDU [Nm]$
$\omega_{RDU}(t) = Speed\ of\ the\ RDU\ [rad / s]$
$Gearratio_{RDU} = 6.1$

These data are then limited according to the physical limits of the RDU, that is:

$T_{\max} = 98 Nm$
$T_{\min} = -98 Nm$
$\omega_{\max} = 722\ \text{rad/s}$
$\omega_{\min} = -722\ \text{rad/s}$

The resulting torque and speed is then used as input to the efficiency maps of the RDU thereby generating RDU efficiency for the correct load case. The limited RDU torque is given as output (used as input in the brake and transmission systems).

The calculation to calculate the electrical power is presented below together with the efficiency calculation:

$P_{mechanical}(t) = T_{RDU}(t) * \omega_{RDU}(t)$
$In\ motor\ \text{mod}e:$
$P_{mechanical} < P_{electrical} \rightarrow \eta < 1$
$$P_{RDUelectrical}(t) = \frac{P_{mechanical}(t)}{\eta}$$
$In\ generator\ \text{mod}e:$
$P_{mechanical} > P_{electrical} \rightarrow \eta > 1$
$P_{RDUelectrical}(t) = P_{mechanical}(t) * \eta(t)$

The subsystem chooses between these modes based on the sign of the torque and calculates the RDU power:

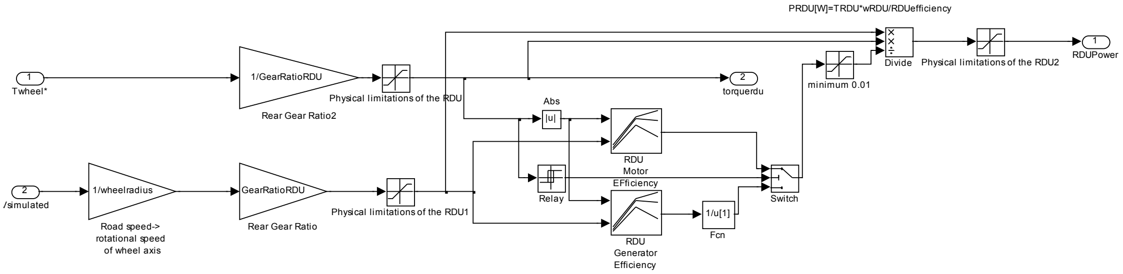
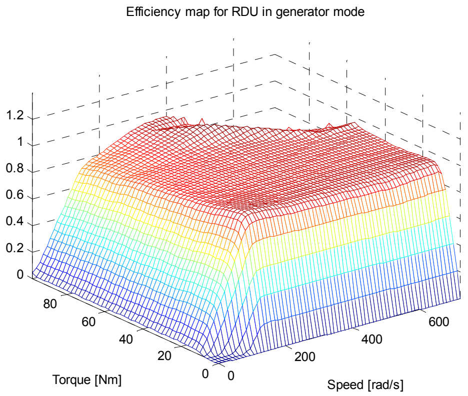


Figure 32. The RDU efficiency subsystem

The efficiency maps used in the simulations are presented below:



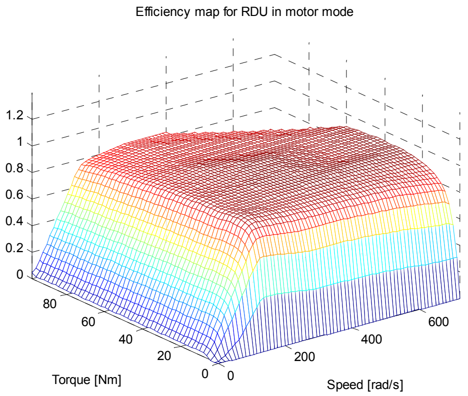


Figure 33. (left)Efficiency map for the RDU in generator mode.
Figure 34. (right)Efficiency map for the RDU in motor mode.

The difference between the maps are presented below

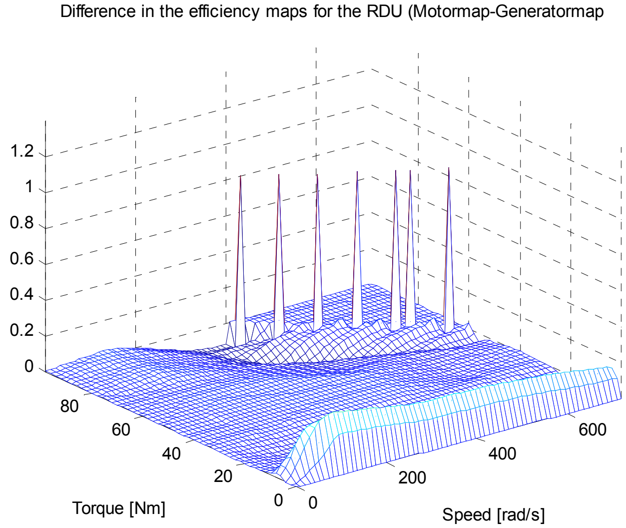


Figure 35. The difference between the efficiency maps

8.4.5 The rear transmission efficiency subsystem

This subsystem is used to allow for adding transmission losses by increasing the power demand in motoring mode and decreasing the power in generator mode by an efficiency factor that is determined by the transmission connecting the RDU with the wheels. The power demand from the battery is to be increased according to:

$$P_{RDUtrlosses}(t) = \frac{1}{\eta_{gear}} \cdot P_{RDUelectrical}(t)$$

$$\eta_{gear} = transmission\ efficiency$$

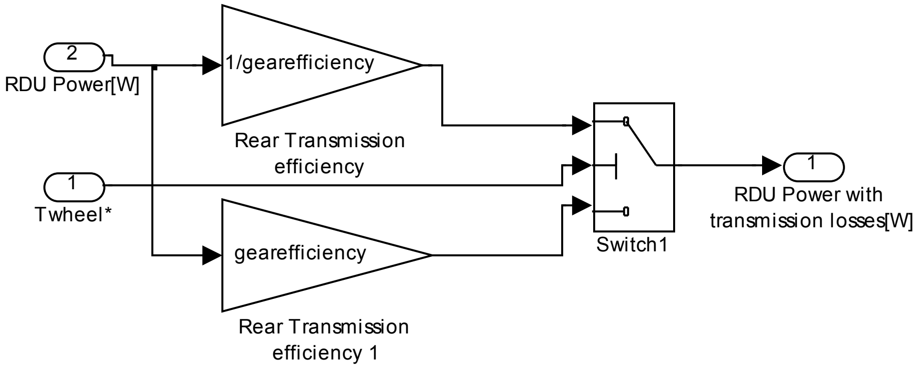
$$P_{RDUtrlosses}(t) = Power\ demand\ \ from\ RDU\ with\ transmission$$

$$losses\ included\ [W]$$

In motoring mode and in generator mode it is to be decreased to:

$$P_{RDUtrlosses}(t) = P_{RDUelectrical}(t) * \eta_{gear}$$

In the MHD2 ZEV simulation a constant efficiency of 98% is used this is considered to be an adequately good approximation.



Introduces transmission losses:
Puts through a larger power to withdraw from the battery
due to the losses in the transmission

Figure 36. The Rear transmission efficiency subsystem

8.4.6 The Energy Flow in the battery calculation subsystem

This subsystem calculates the energy loss in the battery and the energy requested by the vehicle by taking the absolute value of the power request and power loss in the battery and then integrating these. Finally, adding these and converting the value yielded from Ws to kWh gives the total energy flow in the battery during the drive cycle in kWh. A similar approach is used for the power flow calculation. The power lost in the battery is simply the integrated output power loss in battery signal from the battery model. The power request data is also integrated. Due to a sign convention the sign must be changed before it is to be added with the battery losses and thereby generating the power used from the battery which also is transformed from Ws to kWh

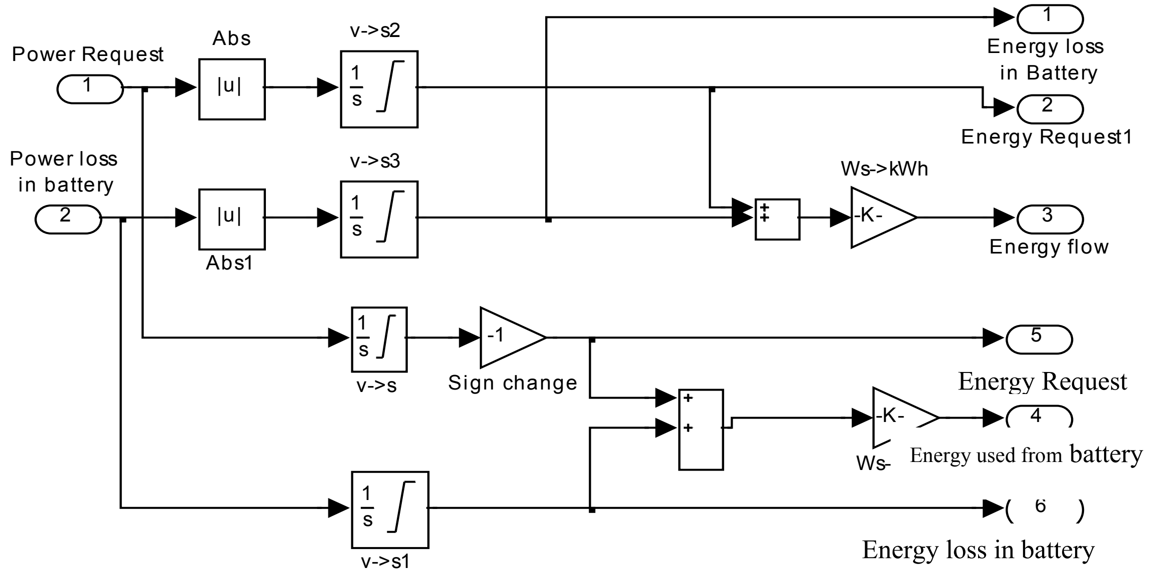


Figure 37. Energy Flow in the battery calculation

8.4.7 The mechanical brake subsystem

This subsystem is based on a subsystem created by Mats Alaküla, professor at the department for Industrial Electronics and Automation at LTH

This subsystem compares the torque delivered by the RDU with the requested wheel torque. If the torque is negative and the requested wheel braking torque is larger than the delivered RDU braking torque then the mechanical brakes are applied. They apply a torque equal to the difference between the requested wheel torque and the RDU delivered torque.

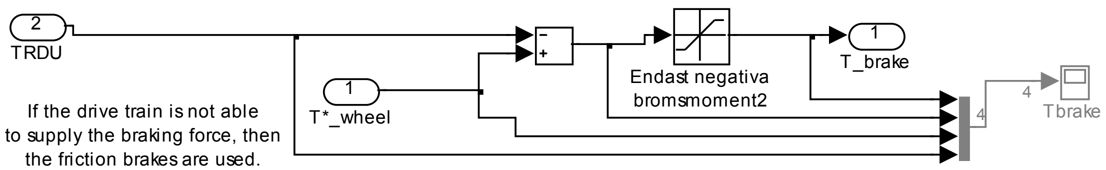


Figure 38. The mechanical brake subsystem

8.4.8 The road load subsystem

Road Load

This subsystem calculates the road load in N the formula coefficients and the components they are based on are given in the table below:

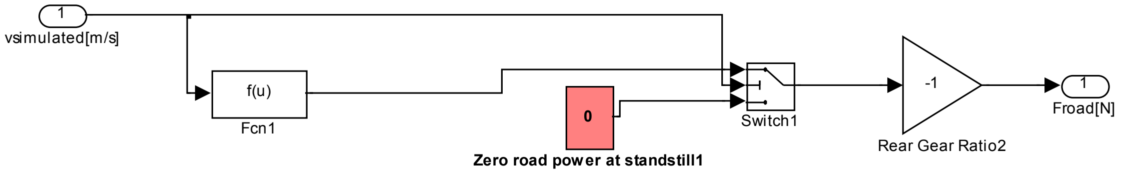
Vehicle type	**Saab 9-3 Sport Sedan**
EU/US	EU
Fuel	Gasoline
Engine	L850 2.0 T
Manual/Automatic transmission	A
Transmission name	AF33-5
Weight class	1590
Tire mark and model	Pirelli Zero Rosso
Tire size	225/45 R17
F0	GM internal use only
F1	GM internal use only
F2	GM internal use only

Table 3. Road load

The equation and the subsystem is presented below:

$$F_{road} = F0 + F1 * v_{simulated} * 3.6 + F2 * (v_{simulated} * 3.6)^2$$

$$F_{road} = Roadload(N)$$



8.4.9 The transmission subsystem

This subsystem is based on a subsystem created by Mats Alaküla, professor at the department for Industrial Electronics and Automation at LTH

This subsystem uses the braking torque from the mechanical brake subsystem together with the RDU torque from the RDU efficiency subsystem and also the road load force from the road model and calculates the speed of the simulated vehicle:

$$P_{simulated}(t) = \frac{\left(T_{brake}(t) + T_{RDU}(t) * Gearratio_{RDU}\right)}{r_{wheel}} + F_{road}(t)$$

$$a_{simulated}(t) = \frac{P_{simulated}(t)}{Mv}$$

$$v_{simulated}(t) = \int_{0}^{t} a_{simulated}(t)dt$$

$$P_{simulated}(t) = \mathrm{Re}\,sulting\ \ power\ acting\ on\ vehicle[N]$$

$$a_{simulated}(t) = Simulated\ vehicle\ acceleration[m/s^2]$$

$$Mv = VehicleMass[kg]$$

$$T_{brake} = Mechanical\ brake\ generated\ torque[Nm]$$

$$F_{road} = Road\ load[Nm]$$

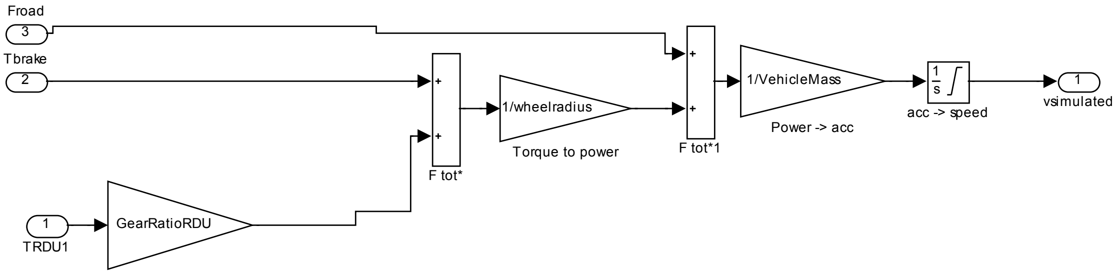


Figure 39. The transmission subsystem

8.4.10 The 300V battery subsystem

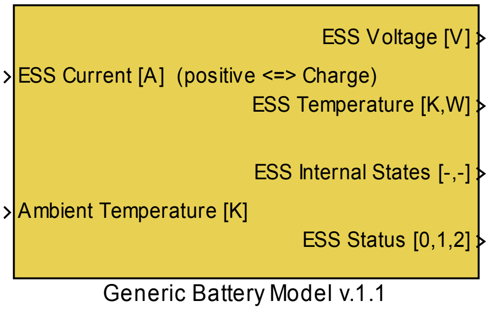


Figure 40. The 300V battery subsystem

For the battery cells used in the MHD2 vehicle there was an accurate model available; developed and verified by Volvo Technology. This model uses a current demand and the ambient temperature as inputs and generates the following outputs

- Terminal voltage[V]

- Max/min cell voltage[V]
- Power loss [W]
- Cell temperature[K]
- Max/min cell temperature[K]
- Cell State Of Charge, SOC
- Max/min cell SOC
- Cell State Of Health, SOH

The battery model was adjusted regarding the number of cells, no other modifications where made. The model is GM property and no further information is to be given about it.

8.4.11 The terminal voltage subsystem

This subsystem allows the user to determine at what terminal voltage the simulation is to be interrupted, 200 V was used in the simulations to protect the battery an over-voltage protection is built into the battery model.

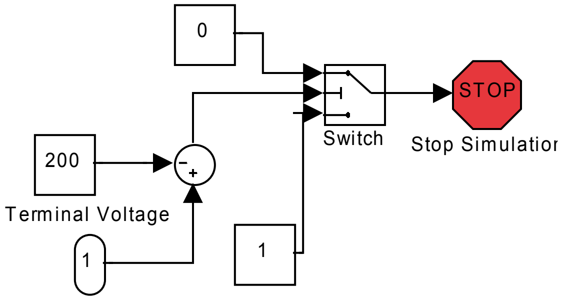


Figure 41. The terminal voltage subsystem

8.4.12 The terminal State Of Charge subsystem

This subsystem allows the user to determine at what State Of Charge the simulation is to be interrupted.

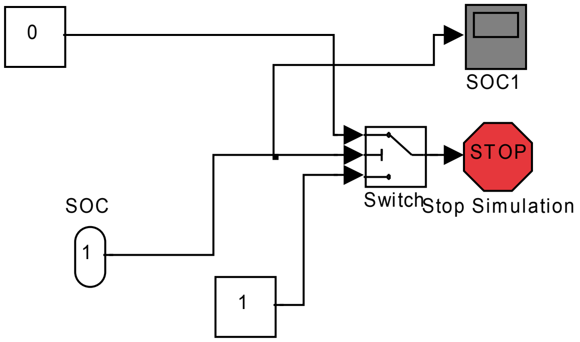


Figure 42. The terminal SOC subsystem

8.5 Appendix 5-Definition of important terms

8.5.1 Hybrid

The word hybrid has different meanings in different contexts. In the eyes of a biologist it means being offspring produced by parents of different races, breeds, species, or genera. However, this is also quite true for our application of the word. When we refer to a hybrid in this text it is a reference to a power train for a four wheeled vehicle that uses a combination of a conventional internal combustion engine and one or several electric motors combining their forces through one or several gearboxes to propel or retard the vehicle.

8.5.2 Validation/Verification

Validation is the confirmation that a requirement is met and verification is to establish the amount of accuracy for that requirement. Or as described in Wikipedia [35] on the web:
“Verification is one aspect of testing a product's fitness for purpose. Validation is the complementary aspect. Often one refers to the overall checking process as V & V.
Validation: "Are we building the right product?" that is does the product do what the user really requires.
Verification: "Are we building the product right?" that is does the product conform to the specifications.
The verification process consists of static and dynamic parts. E.g., for a software product one can inspect the source code (static) and run against specific test cases (dynamic).
Validation usually can only be done dynamically, i.e., the product is tested by putting it through typical usages and atypical usages ("Can we break it?").”[35]

8.6 Appendix 6-Abbreviations

ADV	Analysis Development and Validation
ADVMS	Analysis Development and Validation Management System
BAS	Belted Alternator Starter
CTS	Component Technical Specification
DCT	Dual Clutch Transmission
ECM	Engine Control Module
EHPS	Electro Hydraulic Power Steering
EM	Electric Machine
EMA	Energy Management Algorithm
ERD	Electric Rear Wheel Drive
FAS	Flywheel Alternator Starter
GPDP	Global Power train Development Process
HVAC	High Voltage Air Conditioning
HIL	Hardware In the Loop
HRV	Homeroom V Staff
HV	High Voltage
ICE	Internal Combustion Engine
MCU	Main Control Unit
MHD2	Mild Hybrid Demonstrator 2
MVEG	Motor Vehicle Emissions Group
MS	Market specification
PQMS	Performance Quality Management System
PTSSTS	Power Train Sub System Technical Specification
RDU	Rear Drive Unit
SAE	Society of Automotive Engineers
SOC	State Of Charge
SSTS	Sub System Technical Specification
SSVP	Sub System Validation Plan
VCC	Volvo Car Corporation
VOC	Voice Of Customer
VTS	Vehicle Technical Specification
VVP	Vehicle Validation Plan
ZEV	Zero Emissions Vehicle

8.7 Appendix 7 The basic problem

Today’s society is depleting the earth from its resources of fossil fuels in a tremendous and so far accelerating pace. There are various reports and articles (see for example references [2 to 12]) claiming different times, and scenarios, until these resources are depleted.
Although there is a disagreement between different interpretations regarding the time to depletion there is a consensus that it will occur in a foreseeable future.
The modern man constantly travels increasingly larger distances, at the same time as the number of people using vehicles for their transportation is growing rapidly, especially in previously underdeveloped countries with very large populations [13, 14].

To put further weight on this problem there is also the today well-known global warming scenario presented by Natural Resources Defense Council as: “Higher temperatures threaten dangerous consequences: drought, disease, floods, lost ecosystems. And from sweltering heat to rising seas, global warming's effects have already begun. But solutions are in sight. We know where most heat-trapping gases come from: power plants and vehicles. And we know how to curb their emissions: modern technologies and stronger laws.” [15], [36].

These facts combined most certainly pose a dark scenario. Depletion of one of the modern societies and economies’ most important resources, in combination with an increased degree of usage of vehicles for transportation, hence increasing the demand for oil even further, is certainly creating problems for the future and what is more, global warming is threatening with diversified natural disasters.

Keeping these facts in memory makes it quite logical and understandable that enormous resources are being put into research and development of fuel saving techniques, fuel cells and also into the use of alternative fuels such as ethanol. In the long-term the aim must be to only use renewable resources to supply fuel for our transportation needs.

An alternative to the technical development is to influence people’s transportation habits. Even better would a combined approach of these two approaches be, in order to solve the fundamental problem. However, the behavioral change does however not rime well with modern man’s desire for a more comfortable life and is also out of scope for this thesis.

8.8 Appendix 8 Subjective test drive Lexus RX400h regarding creep/coast behavior

It should be remembered that the Lexus RX400h has one ICE and one electrical machine driving the front wheels and one electrical machine driving the rear wheels. The power distribution between these is made by a planetary gear and the power is transmitted via a Continuously Variable Transmission, CVT.

In the Lexus RX400h there are two shift modes for propelling the vehicle in forward mode; namely Drive, D and Brake, B. The D mode is the normal drive mode with soft settings made for comfortable driving whereas the B mode is a mode that is using a more aggressive profile regarding the utilization of the capability of the regenerative braking. That is the gain for the regenerative braking has been increased greatly compared to the D drive mode. When this mode is used the pace of battery detoriation is increased greatly but under certain driving conditions it might improve the fuel economy by using the hybridization capabilities to greater extent than in the D mode.

Symptomatic for both modes is the fact that when releasing the gas pedal and entering coast mode there is a delay before the regenerative braking is initiated the reason for this delay is not certainly known however a couple of theories are presented below:

- The delay is there to get the same feeling as in a conventional vehicle when the fuel is cut of when releasing the gas pedal.

- The delay is there for drive quality reasons to not make the vehicle feel nervous. Especially when driving in the B mode with its higher gains on the regenerative braking an instant response could make the vehicle feel nervous and jumpy.

- The delay may be there for safety reasons, since when driving in dense traffic situations and releasing the gas pedal a too fast response of the regenerative braking could be hazardous, causing unintentional traffic accidents. The behavior of the Lexus RX400h is quite different from a conventional vehicle having a more intense coast deceleration.

- The power electronics, electrical machines or the control of these have slow response times however this theory is not likely.

  An optimization of the first three theories is most likely the answer to this behavior. Naturally there might be additional reasons for this behavior these are just basic theories

  The creep driving scenarios carried out in this test might be divided into 5 categories:

1. Creep driving on a level road: In this driving scenario the vehicle is driven with no throttle and no grade of the road. The vehicle reaches a nominal creep speed that is approximately 8 km/h. The acceleration to that speed is difficult to make a subjective measure of but it is low probably in the range of 0.02-0.05 m/s^2. However the way the creep speed is reached and maintained is strongly dependent on the SOC level. If the SOC level is approximately 40% or lower on the in vehicle SOC meter, which most probably corresponds to 40% of the allowed swing in the real battery, the vehicle uses the ICE for coast driving and also recharges the batteries. However when the SOC reaches approximately 50% the ICE is turned of and the propulsion is instead made by the front electric motor. If the creep behavior is kept for a long time the behavior repeats itself and starts the ICE to charge the batteries again. The use of auxiliary loads increases the repetition pace of this pattern.
2. In very slight grade uphill driving the creep speed gets very low and if there is SOC above approximately 50% the front electric motor is used for propulsion when the inclination is increased slightly the front and rear electric motors are used to together propel the vehicle until the SOC level gets too low and the propulsion is made by the ICE, which at the same time is used to charge the batteries.
3. In very slight downhill grade the propulsion is made solely by the front electric motor if the SOC is high enough and the speed is increased depending on the declination. The ICE is used in the same manner as in the other scenarios.
4. Strong uphill inclination, approximately 10%: When releasing the brake pedal the vehicle starts rolling back, in both B and D mode, and keeps rolling back until the slope is flat. That is, there has been no demand made on the maximum rollback distance of the vehicle. To make the vehicle move forward there is a need for a throttle input and once the throttle is released the speed is decreased to zero and then the vehicle starts rolling back as described above.
5. Strong downhill inclination, approximately 10%: When standing still in a downhill grade and releasing the brake pedal the speed is increased depending on the declination and the drive mode. If the B mode is used there is some retardation made with the electrical machines thus charging the batteries. When instead using the D mode the vehicle increases speed giving the feeling that the vehicle is free wheeling. In the particular test drive that was conducted the speed was above 80 km/h when the speed was decreased due to driver intervention.

The coast driving is tested from several initial speeds, ranging from 10 to 110 km/h all to get a description of the behavior of the deceleration slope towards creep speed. The feeling of deceleration and to quantify it in real numbers is very difficult and since no measuring equipment was available during the test drive the subjective feeling is described instead:

Independent of the initial speed the vehicle gives the driver a feeling of a linear and safe deceleration. The rate of deceleration depends on in what mode the vehicle is driven. In the B mode the rate is noticeable higher than in D mode giving a slightly less comfortable ride. The feeling of linearity and smoothness in both modes is probably due to the CVT giving an infinite number of gear ratios. During the coast deceleration the vehicle regenerates energy down to creep speed. Naturally the deceleration rate depends on road load and the drive mode being used.

8.9 Appendix 9 Methodology

8.10 Methodology

When making a study the focus should not be on what methods that should be used. The focus should be on the problem of interest and the purpose of the study. If it is possible the study should be divided into sub problems making the study easier to grasp and conduct. In the following subchapters the low and high level methodologies developed in this thesis are classified according to theoretical scientific methodology

8.10.1 Alignment of the validation and verification methods

Studies might be classified in several ways depending on their level of explanation ranging from explorative studies, with a rather brief informative part, to predictive studies which have the highest level of ambition and information.

The aim of the high level tests is to provide tools that are powerful enough to provide an explanatory level of description and the low level tests are to provide a predictable level. Every increase in level requires knowledge corresponding to the previous level.

8.10.2 The layout of the survey

There are three main dispositions that the study should be classified according to:

- **Case study**: Where a certain case is studied in depth making it possible to grasp the complexity of the situation being examined and also how different parts interact or affect each other. According to Denscombe [38] a case study encourages the researcher to use different sources, research methodologies and different types of data to be able to capture and research the complicated reality. A problem that often occurs when making case studies is that a unwanted bias is unintentionally imposed on the study by the researcher.

- **Cross section projection**: Where a wide perspective at different stages in development is researched in a shallow manner at a specific time. [39]

- **Time series analysis**: Where development is studied over time.

In this thesis the development of validation and verification methodologies and the application of these can be classified as case studies. Aiming at giving methodologies that can be applied on any HEV to give verification and validation plans. These plans are to be used as input when creating VTS and SSTS documents for the vehicle.

8.10.3 Qualitative and quantitative studies

A qualitative study is used to create an understanding of the problem being studied and is often used in research where the gathered data can not be quantified or coded in a meaningful manner. The qualitative study is more adaptable to data and leaves the result open-ended. Whereas a quantitative study is used trying to explain and prove, the results that might be yielded are predetermined by the quantization of the data.

In this thesis which has an open-ended solution space for both the low- and high-level methodology it is pointless to quantify any variables in a meaningful manner therefore the data gathered will be analyzed without being encoded. As a result a qualitative study is made in both cases.

8.10.4 Primary and secondary data

The data used in a study is divided into primary and secondary data. Where secondary data is previously gathered data and primary data is data from for example simulations or experiments. When generating the high level tests there are to be used both primary and secondary data. The secondary data used are:

- Generic identification of HEVs.
- Identification of a corporate specific vehicle. In this case the MHD2 vehicle
- Identification of a commercially available product, the Lexus RX400h, is made. The identification of the Lexus is made based on publicly available information
- Information found during search to find well-known critical areas and problems related to the hybrid power train.

For the high level tests the primary data used is from a benchmarking test drive of a commercially available Hybrid Electric Vehicle.

The low level plans use secondary data as input for generation of the methodology these data are:

1. High level test plan
2. Other test plans in similar field of requirements

When applying resulting test plans from both methodologies additional primary and secondary data is to be used and new data is generated

8.10.5 Validity, reliability and objectivity

The three terms from the heading might be defined as:

Validity: Is a measure of the how adequate the measurement method is.

Reliability: Is a measure of the measurement method to resist random influence that is repeatability and is determined by how the study is performed and how thoroughly the information is worked up.

Objectivity: Is the ability to gather data in an impartial and neutral way and reproduce it without bias.

A high reliability is a prerequisite for high validity but not a guarantee [40]

The validity of the thesis is controlled by one supervisor from the academic world and one from the industry reviewing the thesis and confirming the accuracy and correctness of it. The objectivity of the thesis might be influenced by external factors and previous experiences. However when writing the thesis an open mind was kept trying not to be influenced to a great extent.

8.10.6 Generalization

The results from the thesis might be used by any car manufacturer and the case studies are made on a generic basis making the results applicable on any HEV.

8.10.7 Deduction, induction and abduction

In research methodology there are three approaches to work out empirical facts:

Deduction: Is a conclusion gained by use of common principles on individual occurrences. That is theory is used as a basis point when assumptions are made about what reality looks like. [40]

Induction: Is when the researcher uses a limited amount of special cases to formulate a general law or principle. That is the empirical material is used as a basis for the general conclusions that are drawn [40].

Abduction: Is a combination of the previous two. That is the starting point is empirical facts but theory is used to explain them and draw conclusions. [40]

In this thesis an abductive approach is used, that is a combination of deduction and induction, since both individual occurrences and empirical tests and simulations are made and the conclusions drawn are based on both theory and empirical material.

8.10.8 Criticism of sources

The criticism of sources might be divided in two parts:

External criticism: Is regarding the authentity of a source and if it gives a true description.

Internal criticism: Is where the contents of the source is thoroughly examined [41].

It is important to examine the sources that are used and not uncritically accept the “facts” being presented. The examination should be both regarding content, making a judgment if the document primarily contains facts or opinions and values and the author, regarding his background and his intentions with the text.