Working Paper No. **HDH-17-07e**
(17th HDH meeting, 08/09 April 2014)

GRPE-HDH Research Project

17th meeting of the GRPE informal group on heavy duty hybrids (HDH)

TU Graz

IFA
Institut für Fahrzeugantriebe & Automobiltechnik

CHALMERS

TU WIEN
TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

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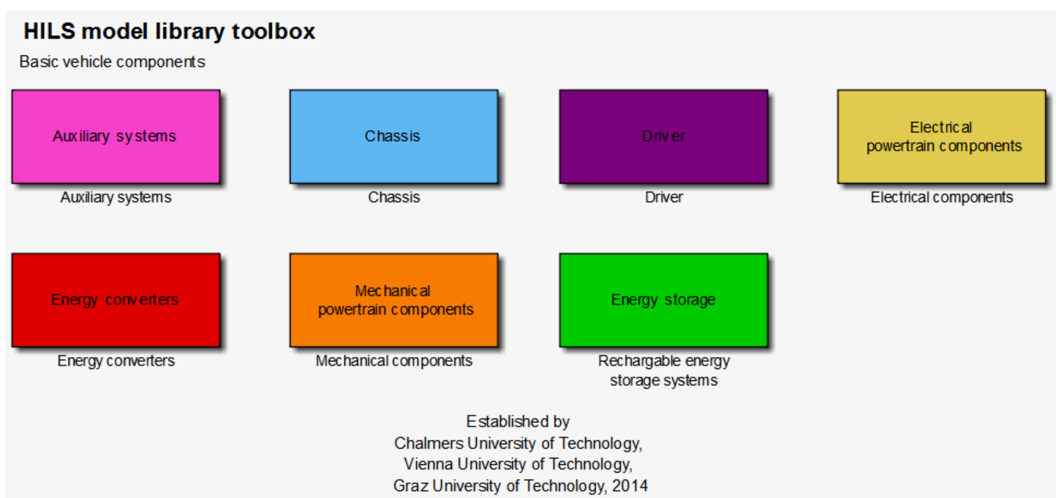
08/09.04.2014 - Madrid

Content

- HILS Model Library
- WHVC Test Cycle
- System Work Concept
- Rated Power Determination for a Hybrid Vehicle
- Family Concept – Validity of Certification
- VTP2 Validation Results
  - Sub-presentations of VOLVO, MAN and IVECO
- VTP2 conclusions & discussion of further actions

HILS Model Library

- HILS Model Library v1.0 has been released
  - Available at UNECE website (HDH general files)
  - Supports MATLAB 2008a and higher
  - Includes:
    - Library with component models
    - Example models for parallel and serial hybrid vehicles
    - Reference Hybrid Vehicle Model for HILS hardware check
- OEM feedback was implemented according to GTR applicability



WHVC Test Cycle

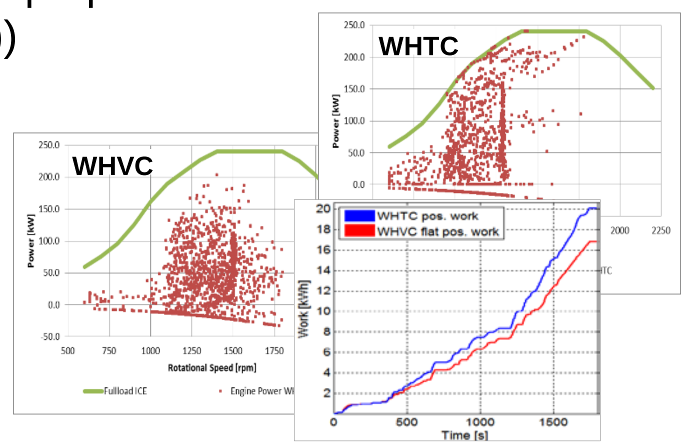
- Status update
  - Joint meetings (Japanese delegation, Institutes) were held beside HDH IG/DG meetings to boost test cycle development
  - Enhanced „Minicycle“ method was internally agreed (technically most reasonable and as well easily applicable for the GTR)
  - Final adoption at 17th HDH IG meeting planned

- Content
  - Background
  - Concept of basic Minicycle method
  - Concept of enhanced Minicycle method
  - Results and application
  - Summary

WHVC Test Cycle
Background

- Emission test method for hybrid vehicles should be – as far as reasonable – aligned with the test procedure for conventional engines
  - Alignment of engine (WHTC) and vehicle (WHVC) cycle is needed (power demand over time and cycle work)

- Generic vehicle parameter have been established to allow a vehicle-independent approach (OICA proposal)
  - Rated power of hybrid system specifies vehicle properties (mass, rolling and drag resistance,… = $f(P_{rated})$)
  - Reduces vehicle diversity -> One specific vehicle for each power rating
  - Nevertheless power demand over time and cycle work is not aligned with WHTC
  - Road gradients have been established to adapt power time curve and cycle work of WHVC to WHTC

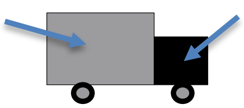


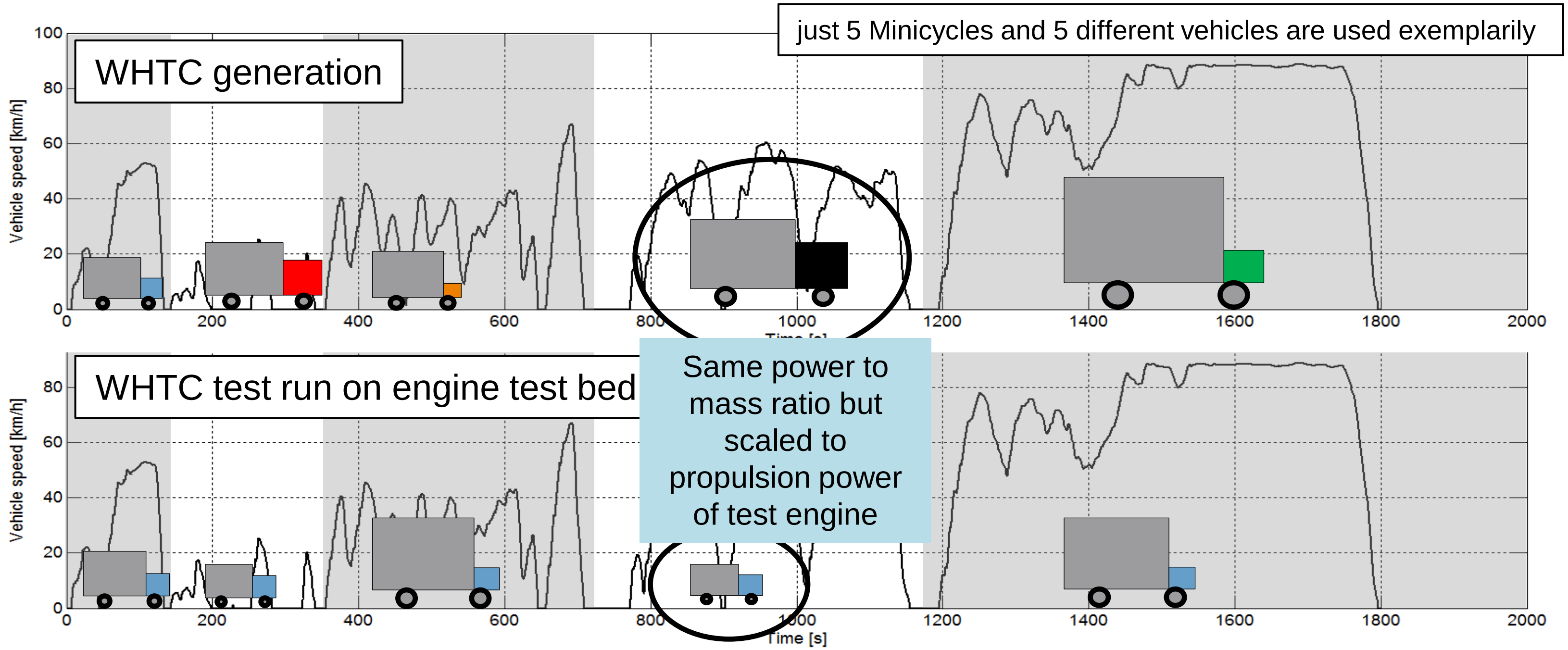
Comparison for a conventional HD vehicle (14 ton / 240 kW)

WHVC Test Cycle

Background

- ☐ WHVC consists of 12 Minicycles, power time curve derived from 12 different vehicles with different power to mass ratios (normalized and combined to WHTC)
- ☐ Conv. engine test:
  Engine is operated as it would propel a vehicle with 12 different payloads

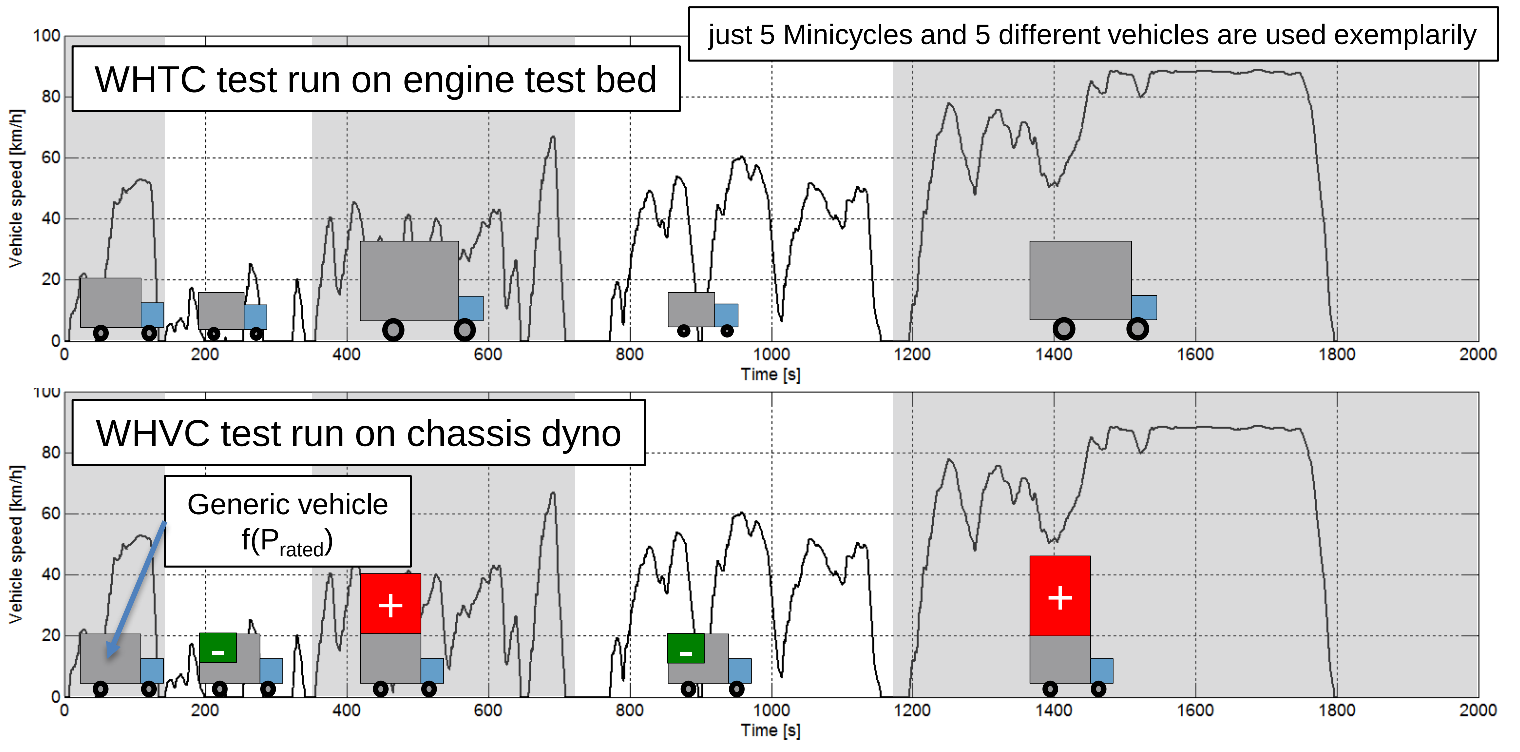




WHVC Test Cycle

Concept of Minicycle method

- ☐ Basic concept of Minicycle method (12 Minicycles)
- ☐ Road gradient has been chosen to represent different payloads

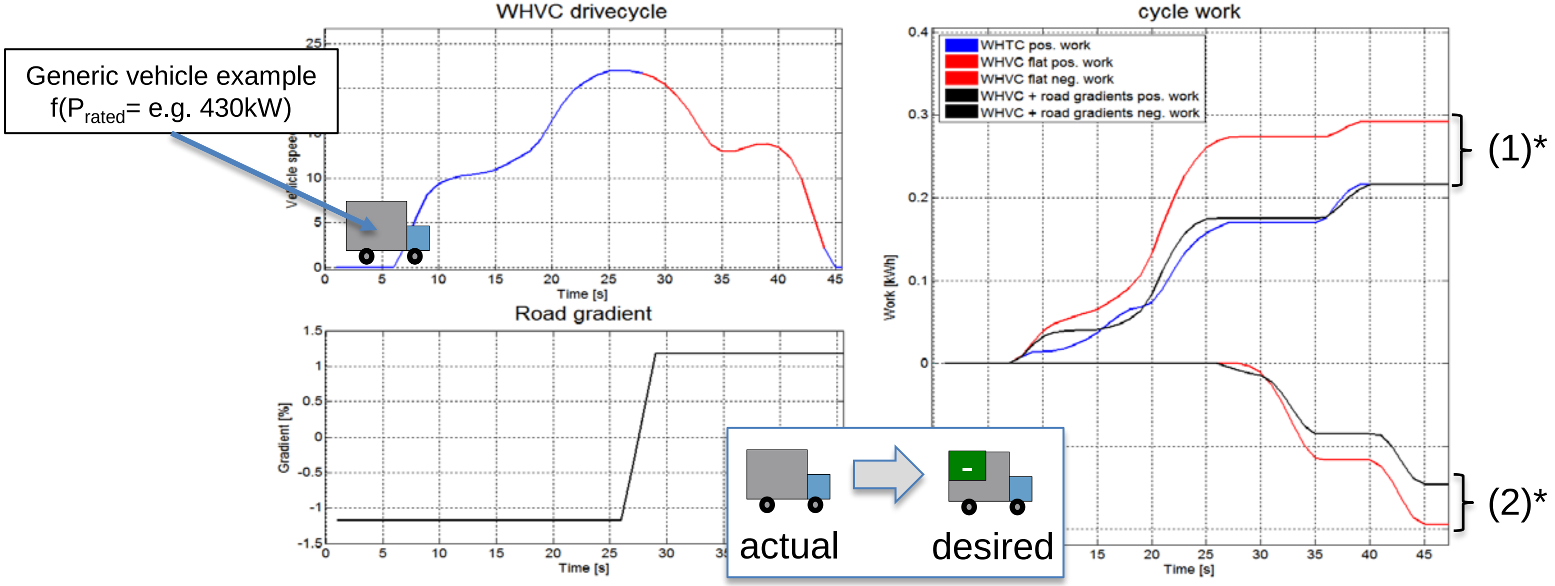


+ Higher mass = positive road gradient
- Lower mass = negative road gradient

WHVC Test Cycle

Concept of Minicycle method

- Road gradient is calculated to meet positive WHTC cycle work
- For correct negative work
  - Mass representing slope needs to be inversed during braking

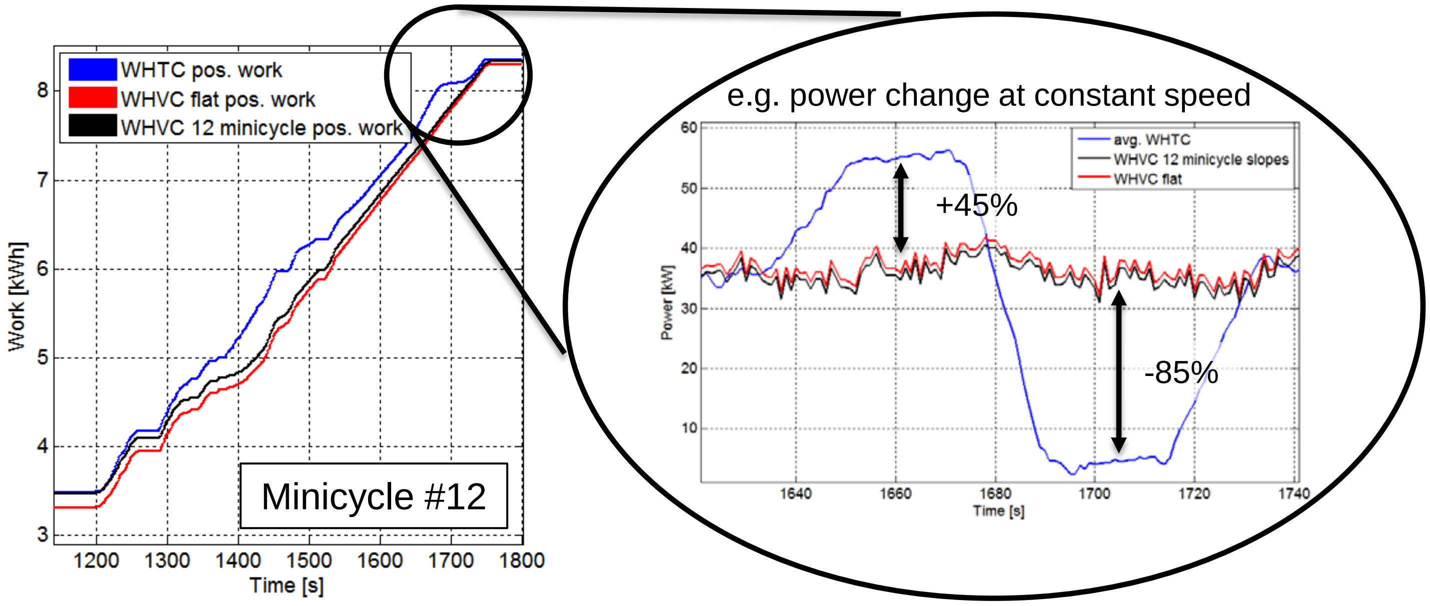


- WHTC vehicle was lighter than generic vehicle
  - (1)* Generic vehicle's weight reduced by negative road gradient during propulsion, running downhill demands less propulsion power
  - (2)* Generic vehicle's weight reduced by positive road gradient during braking, braking uphill delivers less recuperation energy

WHVC Test Cycle

Concept of Minicycle method

- Results of 12 Minicycle method (e.g. 100kW vehicle)
  - Perfect alignment of WHVC and WHTC cycle work at each Minicycle end
  - Partial insufficient alignment of power time curve due to real road gradients during WHTC measurements (no information available)



  - Alignment on a shorter time span by introducing sub-sections in relevant Minicycles

WHVC Test Cycle
Concept of enhanced Minicycle method

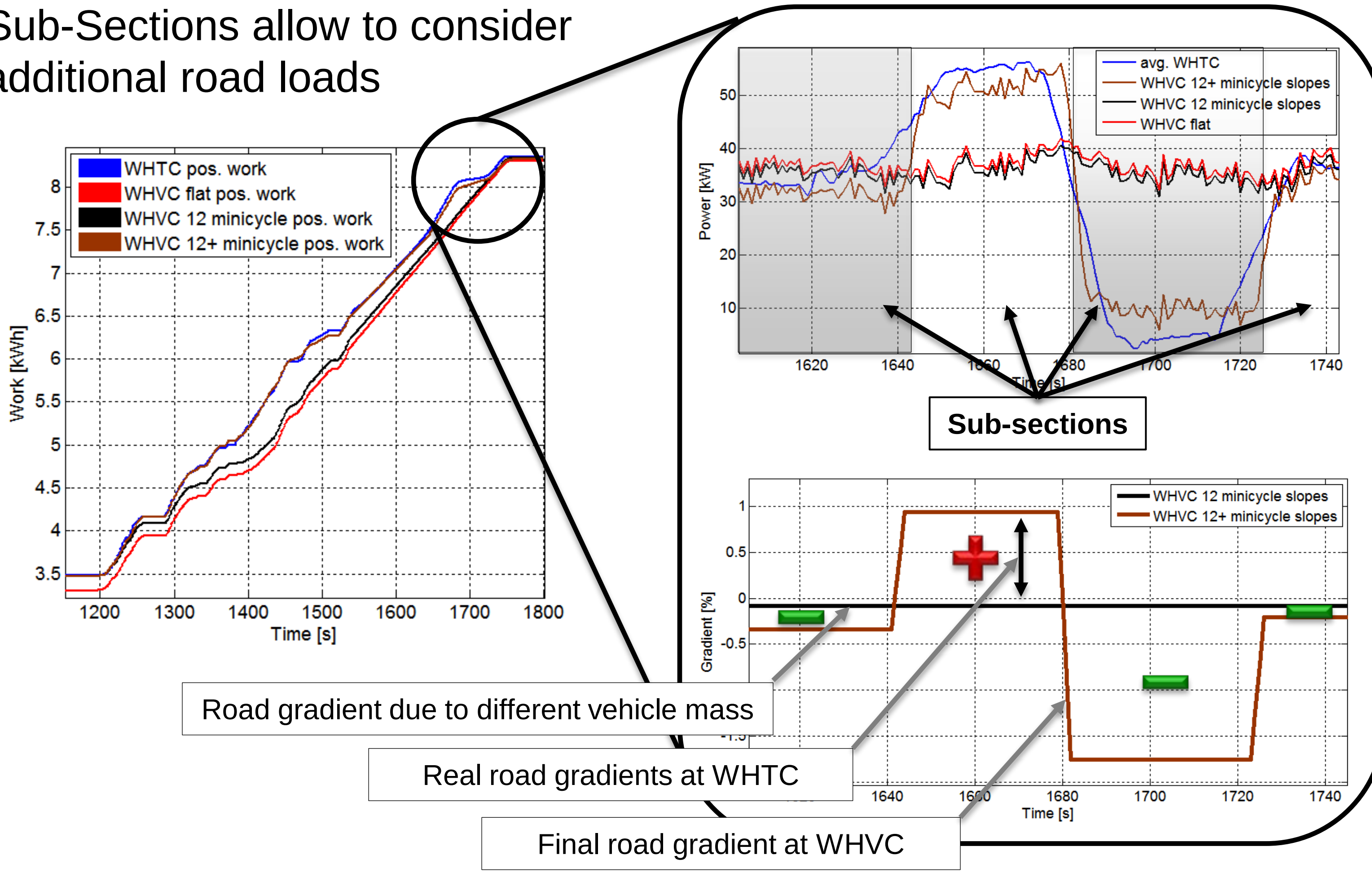
- ☐ Two effects to be considered:
  Different power/work demand (WHVC vs. WHTC) due to
  - Different vehicle mass
  - Real road gradients during WHTC measurements

- ☐ Solution:
  Keep 12 vehicle concept but consider real road gradients where relevant
  - Different vehicle mass
    - Basic Minicycle concept will adapt vehicle mass by applying 12 different road gradients
  - Real road gradients during WHTC measurements
    - Real road gradient is additionally applied where work time curve clearly differs
    - Improves accuracy of power and work time curve due to higher discretization

WHVC Test Cycle

Concept of enhanced Minicycle method

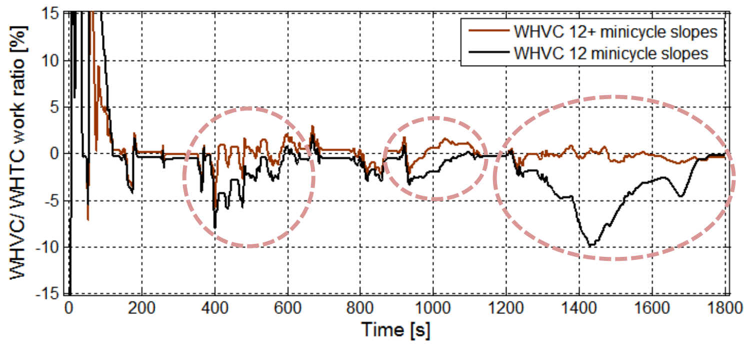
- Very good results of enhanced (12+) Minicycle method (e.g. 100kW vehicle)
- Sub-Sections allow to consider additional road loads

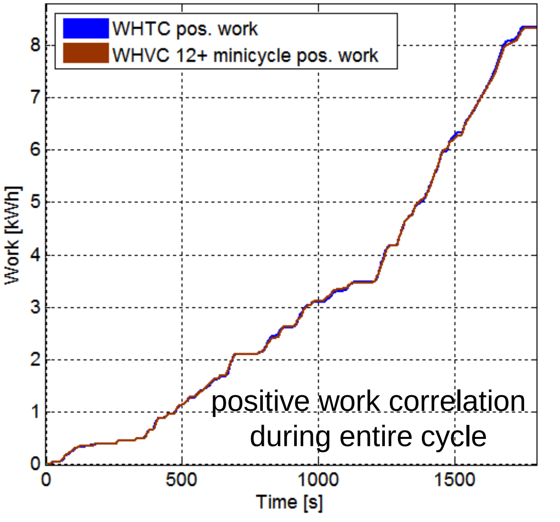


WHVC Test Cycle

Concept of enhanced Minicycle method

- ☐ Sub-sections included at highest work deviation





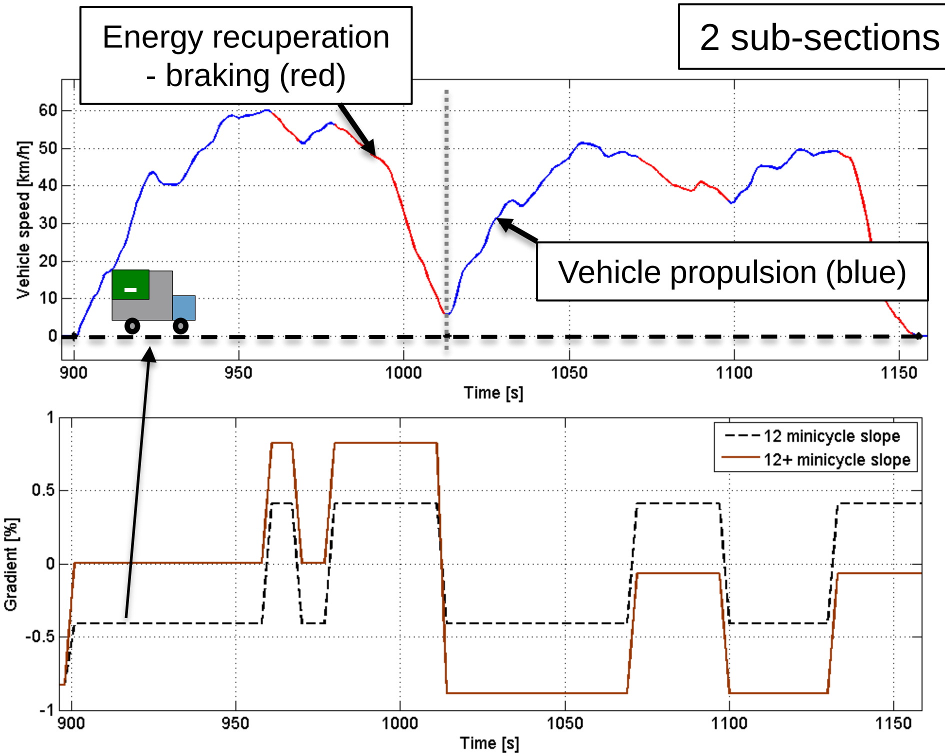
- ☐ Concept of inversed slope needs to be adapted at sub-divided sections to deliver correct negative energy
  - – Sub-divided sections consider slopes due to vehicle mass and real road slopes
  - – Just vehicle mass representing slope needs to be inversed, road conditions will most likely not change

WHVC Test Cycle

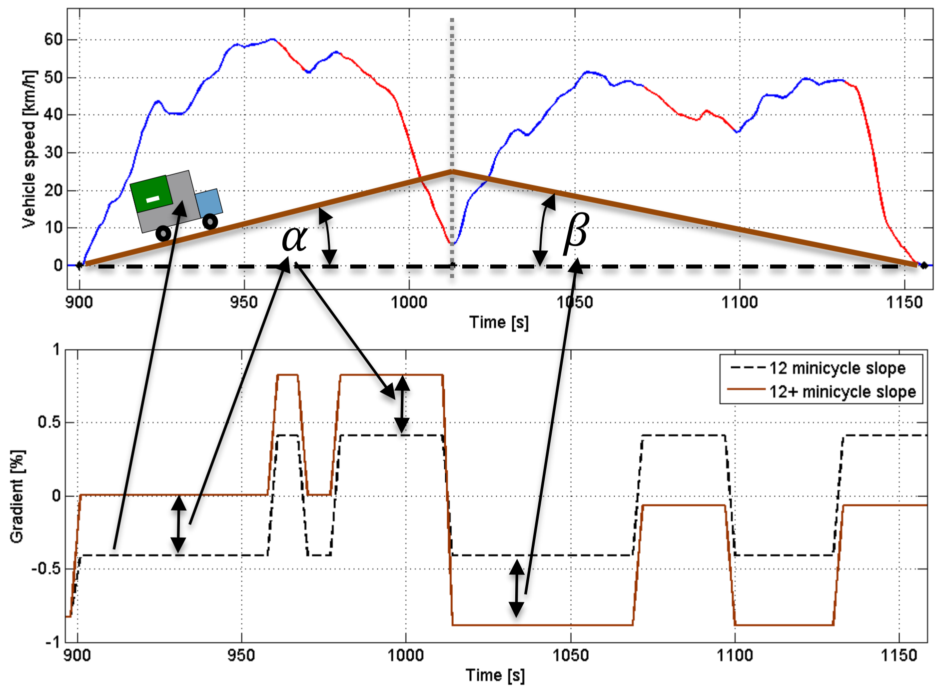
Concept of enhanced Minicycle method

- ☐ During propulsion: positive WHTC power gives information on real road gradient (difference of actual vs. desired power)
- ☐ During braking: no negative power available at WHTC - just ICE motoring
  Assumption needed: road condition will not change at brake operation

2 sub-sections at Minicycle #11



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

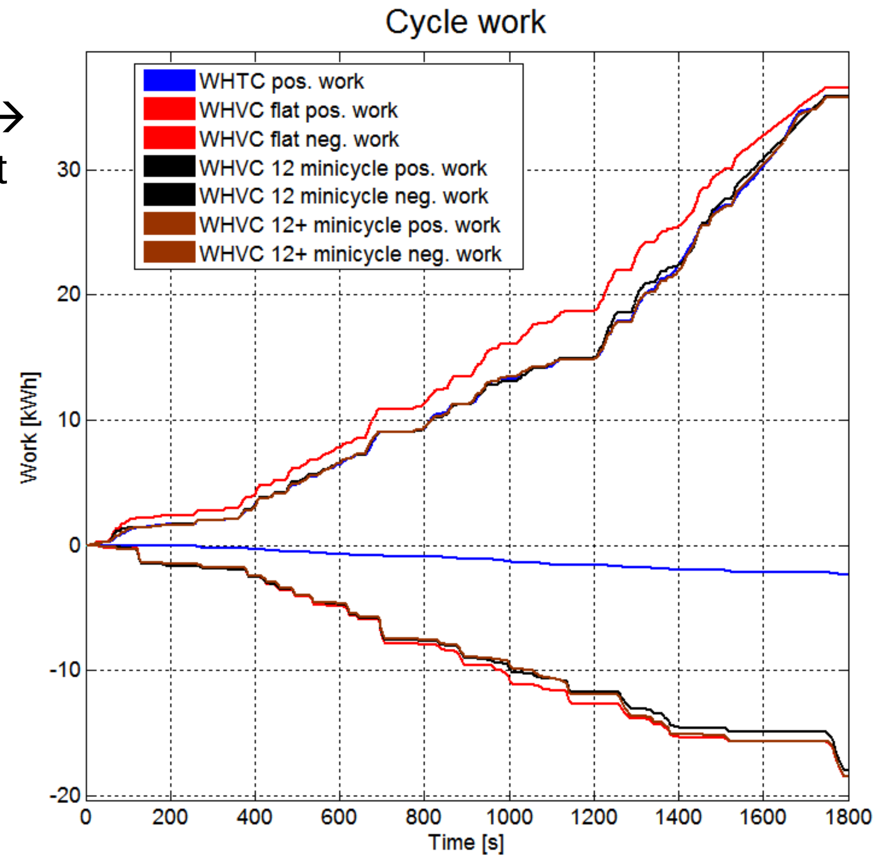


Enhanced Minicycle concept – slopes compensate different vehicle weight and real road gradients

WHVC Test Cycle

Concept of enhanced Minicycle method

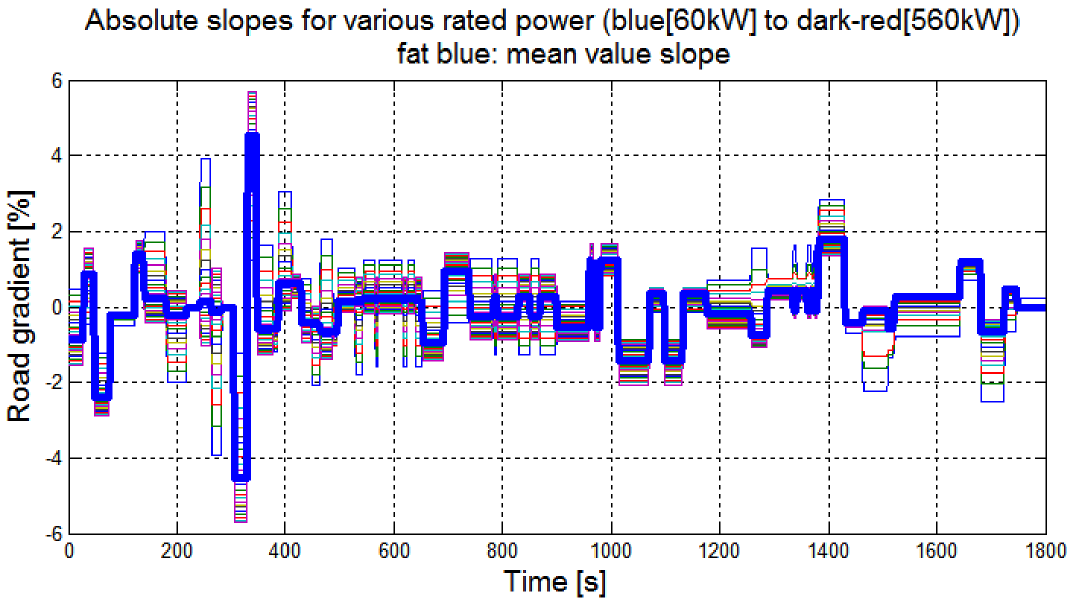
- ☐ Results of enhanced Minicylce method for positive and negative cycle work (e.g. P_{rated}=430kW)
  - Positive work well aligned
  - Negative work similar to flat road → time characteristics slightly different → cycle provides representative amount of recuperation energy
- ☐ Road gradients calculated for each vehicle (f=(P_{rated})) individually
  - Individual slope not feasible for GTR
  - Complex calculation
  - Software needed
- ☐ Solution: Fixed slope with polynomial approach for error compensation



WHVC Test Cycle

Fixed slope with polynomial approach

- Fixed slope with polynomial approach for error compensation
  - Calculate slopes for each rated power 60 to 560kW (aligns WHVC and WHTC)
  - Define an average fixed slope (blue)
  - Polynomial approach for error compensation

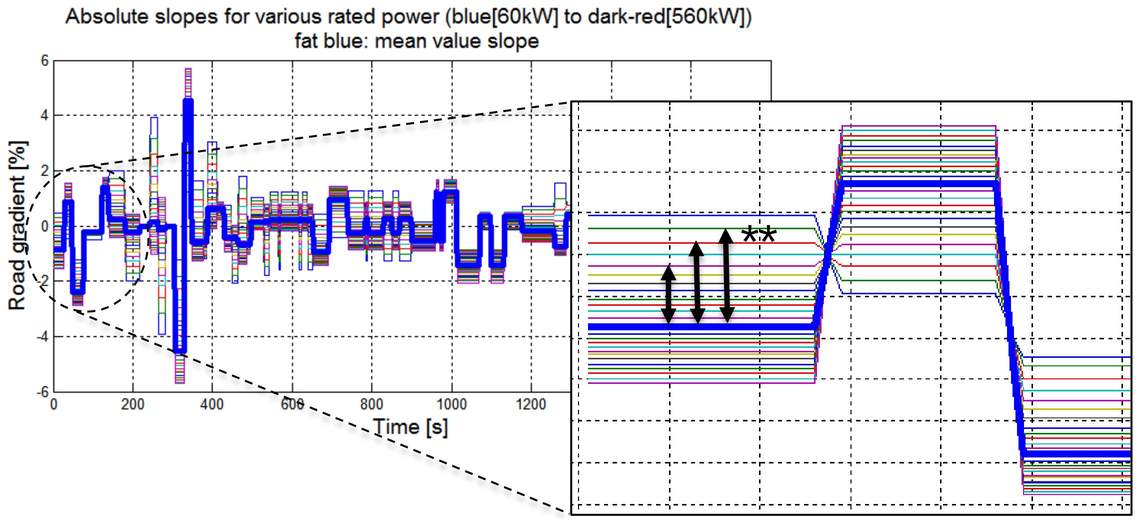


- High deviations in power and work for fixed slope
  - Error compensation via polynomial approach

WHVC Test Cycle

Fixed slope with polynomial approach

- ☐ Fixed correlation between fixed and individual slope depending on P_{rated}
  - – Individual slopes = f (P_{rated})
  - – [Fixed slope (blue) – individual slope]** = f (P_{rated})
- ☐ 2nd order polynomial chosen to describe correlation
  - – $Road\ gradient = (a * P_{rated}^2 + b * P_{rated}) + c$
- ☐ Enables accurate cycle power/work alignment for all vehicles with WHTC
  → Easy calculation without additional software



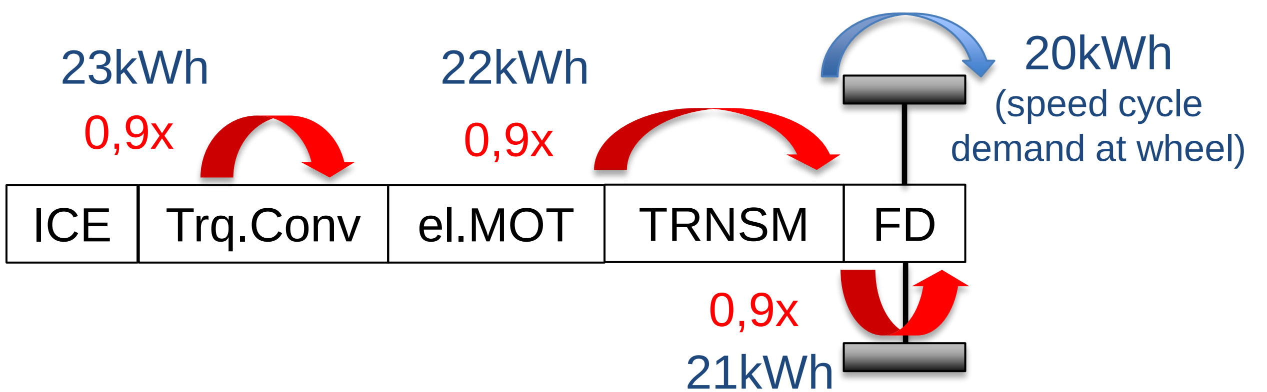
WHVC Test Cycle
Summary

- ☐ Introducing generic vehicle parameter enables vehicle independent certification (like WHTC)
- ☐ Alignment of cycle work and power could be achieved by enhanced Minicycle approach
  - – Ensures very similar system load compared to WHTC
  - – Recommended method of Japanese experts and Universities
- ☐ Easy handling of WHVC test schedule in GTR by polynomial approach
  - – Accurate results without the need of additional software
- ☐ Approval on CD with different vehicles recommended
  - – Final approach successfully proofed at Iveco measurements (speed within limits)

Hybrid System Work Concept

Background

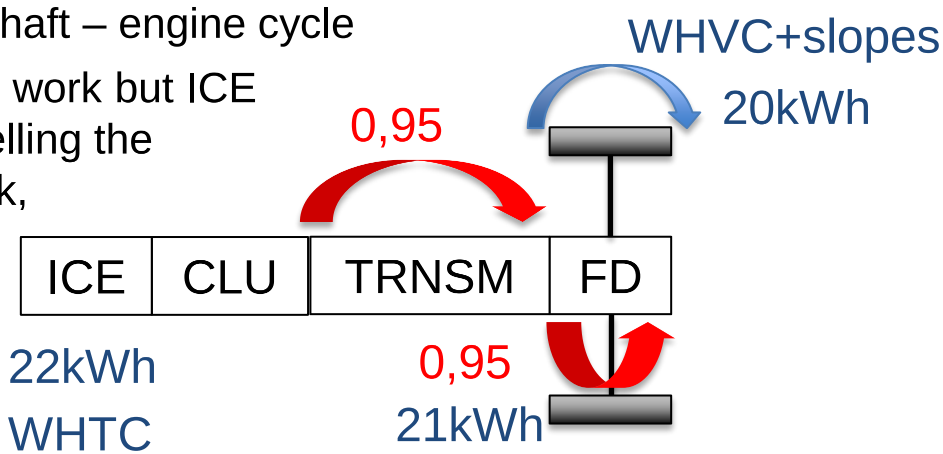
- Definition of hybrid system work is needed for emission calculation
  - Needs to be valid for different hybrid topologies, e.g.
    - One common propelling shaft
    - Distributed propulsion motors
    - Future drivetrains….
- Different locations in the drivetrain will give different work results
  - Running a defined test cycle will demand a certain amount of propulsion work to propel the vehicle e.g. 20kWh at the wheel
- Question: Which value to be used for emission calculation?
  What is the hybrid system's output shaft?



Hybrid System Work Concept

Background

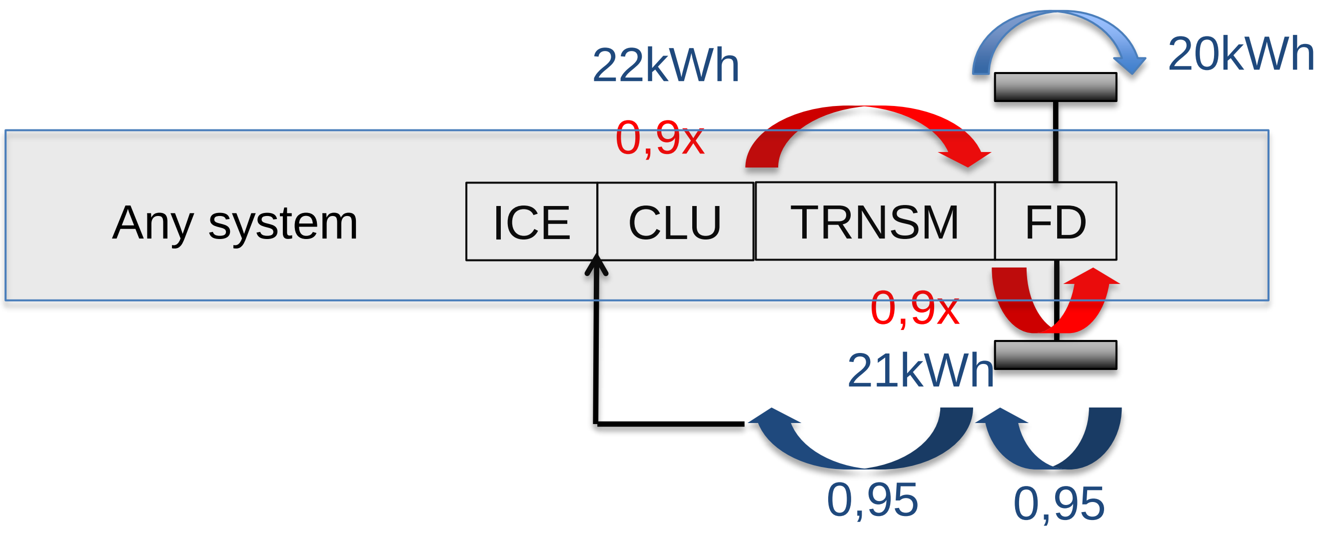
- Nearly impossible to specify system output shaft for different topologies → Considering different hybrid topologies **the only common reference point** for all **is** at the **wheel/hub <u>but</u>**
- Directly using work at wheel is not reasonable
  - Not in-line with conventional engine testing (uses ICE work though mounted in a conv. drivetrain)
  - Not in-line with developed WHVC+slopes test cycle
- Alignment is needed (example for a conventional drivetrain)
  - WHVC+slopes demands work at wheels – vehicle cycle
  - WHTC demands ICE work at crankshaft – engine cycle
  - Work at wheel hub is lower than ICE work but ICE work needs to be delivered for propelling the vehicle → emissions due to ICE work, emission calculation due to system work at wheel → **would lead to higher burden** (using system work at wheel)



Hybrid System Work Concept

General valid definition

- System work needs to be defined at the wheel
  - Ensures independency of system topology
- In order to be in-line with conv. engine testing & test cycle development
  - System work has to be transferred to a "virtual ICE's crankshaft" (considering standardized final drive- and gearbox efficiencies)
  - Same standard efficiencies have also been used to transfer average WHTC to wheels for reference work calculation of WHVC drive cycle (vehicle cycle)



Hybrid System Work Concept
Summary

- Most robust to define system work at wheel, valid for
  - all vehicle topologies
  - HILS and powertrain test method
- System work for emission calculation (W_{Sys}) is defined as

$$W_{Sys} = \frac{W_{Wheel}}{0.95^2}$$

- W_{Wheel} can easily be read out / calculated from chassis model
  - Integrating positive power (torque times rot. speed) at wheel
  - Valid for HILS and powertrain test
- In-line with
  - Conventional engine testing
  - Test cycle development
  - Rated power determination (see upcoming slides)

Rated Power Determination for a Hybrid Vehicle
Background

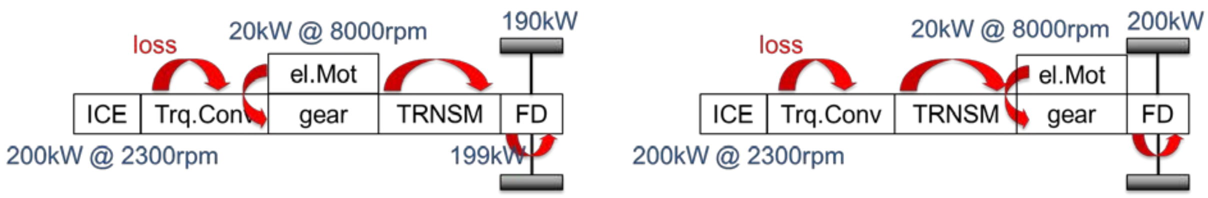
- ☐ Rated power of hybrid system defines system load during test via
  - – Vehicle parameter (mass, drag- and rolling res.,….)
  - – Test cycle and cycle work demand (like full load curve for WHTC)
  - → <u>Important parameter for entire certification procedure</u>

- ☐ Initial situation
  - – No definition of Rated Power available which is valid for all hybrid systems
  - – <u>Conventional vehicle</u> (one energy storage – a lot of energy stored)
    - – Rated (max) power clearly defined
    - – Always available (at sufficient fuel level)
  - – <u>Hybrid vehicle</u> (multiple energy storage systems – big and small one)
    - – (max) power differs over time (not in any case available!)
    - – Depending on RESS size, peak power capability, actual SOC level, temperature level of component…

- ☐ Question: What is the appropriate rated power for a hybrid system?

Rated Power Determination for a Hybrid Vehicle
Background

- ☐ Demand
  - Robust procedure where result reflects vehicle performance (power) during real driving
  - Procedure needs to be applicable on test bed (measured) and in HILS environment (simulated) with same results
  - Comparability to conventional vehicles, procedure should deliver ICE rated power for conventional vehicles/engines
- ☐ HILS requires definition without full hybrid system compound measurement
  - Rated power determinable without modifications on a valid HILS model
  - Sum of all power converters can not be used directly
    - Rated power of single components at different speeds
    - Mounted in different locations in the drivetrain (efficiencies in between)
    - Where to measure the power (see system work) → case to case negation with authority depending on topology would be needed → not desirable

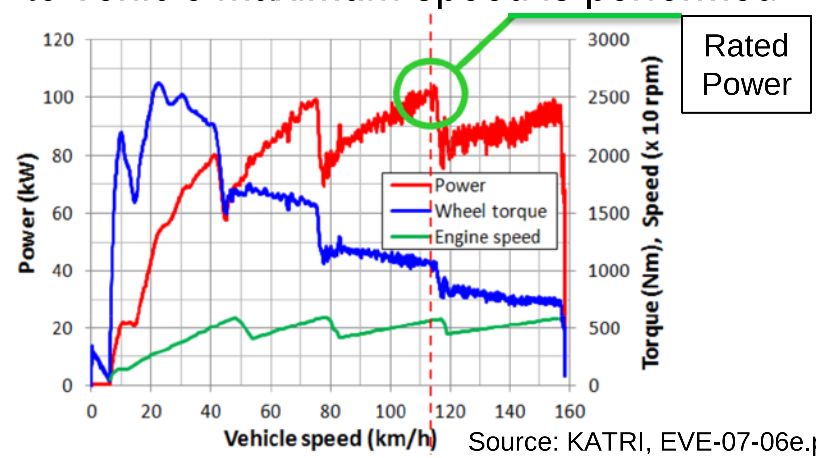


Rated Power Determination for a Hybrid Vehicle

Proposal

- ☐ Robust method
  - – Considers maximum vehicle performance during standard drive manoeuvre (comparability between all (incl. conventional) vehicles)
  - – Defines rated power at the wheel
    - – Common reference point for all vehicles
    - → Power would be too low and not comparable with conventional vehicles
    - → Therefore application of efficiency correction

- ☐ Concept based on KATRI system power concept (EVE-07-06e.pdf)
  - – Full load acceleration from standstill to vehicle maximum speed is performed (will demand maximum power)
    - – Using a powertrain test bed
    - – Using a verified HILS model
  - – Power at wheel is recorded
  - – Representative manoeuvre for real world driving and WHVC test cycle



Source: KATRI, EVE-07-06e.pdf

Rated Power Determination for a Hybrid Vehicle

Proposal

- Data processing
  - Recorded power needs to be corrected using standard efficiencies (GB & FD)
    - Due to comparability with conventional vehicles and test cycle conformity

$$P_{Sys} = \frac{P_{Wheel}}{0.95^2}$$

- Boundary conditions for full load acceleration
  - Maximum power will be demanded (no short shifting is expected)
    - Even if, lower power then is representative for vehicle performance
  - Road gradient should be increased until vehicle can not reach its maximum speed
    - Especially reasonable for vehicles with speed and acceleration limiters (e.g. city buses)
  - Default SOC level should be set (e.g. $\frac{SOC_{min}+SOC_{max}}{2}$ of used SOC level)
    - Vehicle is built to have energy for an acceleration available most of the time (desired SOC level between min and max)
    - 0% and 100% SOC level not considered as representative

Rated Power Determination for a Hybrid Vehicle
Summary

- Benefit of proposed method
  - Alignment of/with
    - Developed Test Cycle
    - System Work concept
    - Rated Power determination
  - Comprehensive compatibility with conventional vehicles/engine testing (conventional vehicle is expected to deliver ICE rated power)
  - Valid for HILS and powertrain method
  - Easily applicable on HILS system without any changes in the model
  - Approach of comparable driving performance avoids discussion on definition of electric(hybrid) peak vs. continuous power

- Approach was tested by Volvo and Daimler using HILS(SILS) simulation
  - Reasonable results and positive feedback
  - Further testing/comparison with actual vehicles is recommended for OEMs
    - No actual powertrain test result available

Hybrid family concept

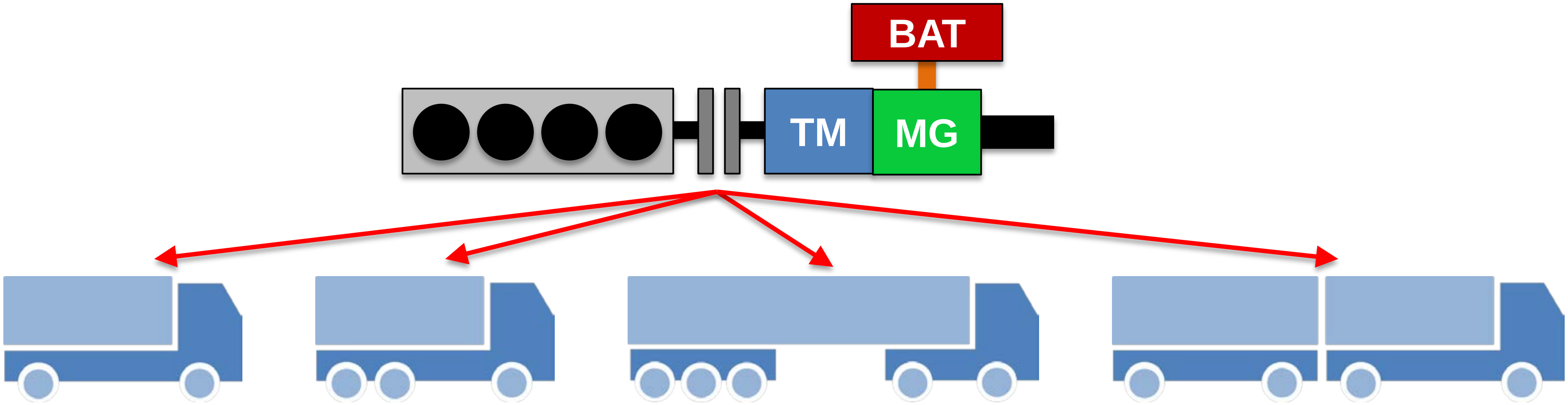
- Hybrid families could be defined on two different levels
  - Vehicle family
  - Powerpack family

- Vehicle family approach
  - Same hybrid powerpack(+transm.) could be mounted in different vehicles
  - Emission testing is done with a generic vehicle (defined by rated power of hybrid powerpack), generic driving resistances, drivetrain efficiencies and inertias
  - Only one testcycle for one specific powerpack(+transm.)

- Powerpack family approach
  - Components (ICE, 2nd energy converter, storage) in a powerpack could vary within a certain range
  - Emission testing is done for one specific combination of components
  - Only one testcycle for several different combinations of components

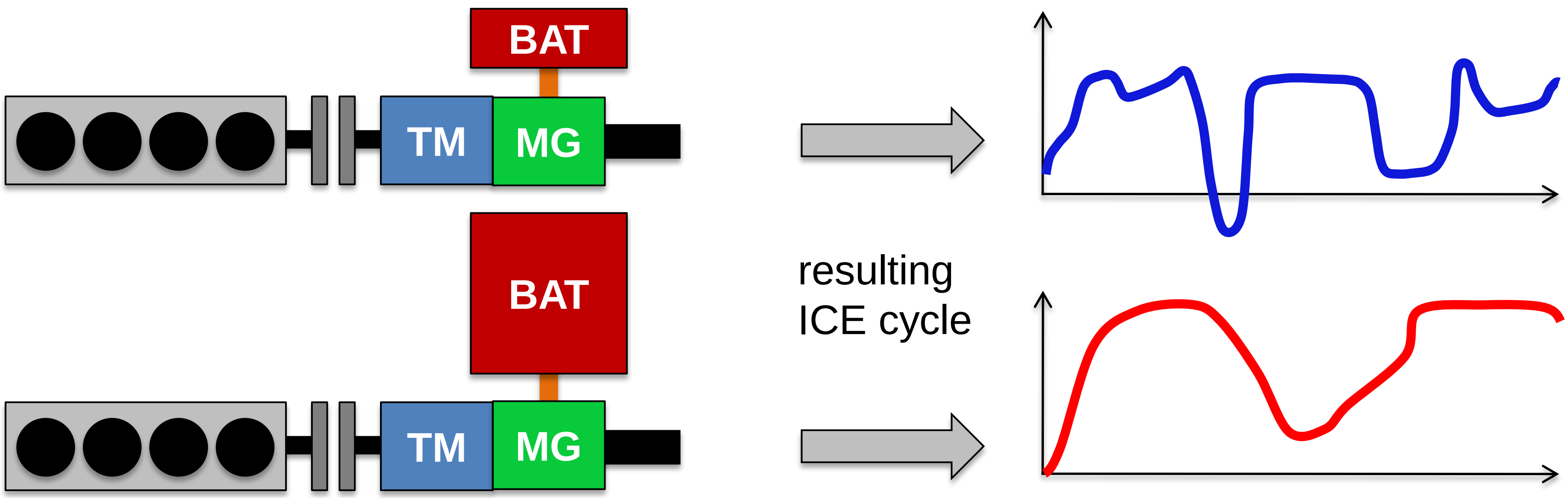
Hybrid family concept

- Vehicle family approach
  - Only one testcycle for one specific powerpack
  - Reduce testing burden for different variants of vehicles
  - Certification is independent of real vehicle variants
  - WHVC cycle is also defined as average driving behavior
    > Specific vehicle would also need specific mission profile
  - Same rationale and coherent with WHTC testing
    > Also only one engine cycle independent of vehicle
  - This approach was agreed in HDH-15 and is considered as reasonable



Hybrid family concept

- Powerpack family approach
  - Only one testcycle for several different combinations of components
  - Difficult to define a family for combination of powerpack components and to define the parent powerpack version based on rational basis
  - Each change in components will most likely influence ICE operation
  - Thus each different combination of components will most likely lead to a different ICE testcycle
  - How to define the representative cycle for emission certification?



Validation Test Program 2

Overview

- Kokujikan based validation procedure performed, including:
  - Chassis dyno testing
  - Application of HDH drive cycle (WHVC with road gradients – different proposals)
  - Application of generic vehicle parameter (where available)
  - HILS/SILS model verification

- Three OEMs participating (VOLVO, MAN, IVECO)

Volvo parallel hybrid bus

MAN serial hybrid bus

Iveco parallel hybrid truck

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Validation Test Program 2

Overview

- Successful validation not achieved for all test candidates
  - Increased system complexity compared to known vehicles which passed HILS certification in Japan
  - Additional DOF due to more complex systems make:
    - Validation criteria harder to be achieved
    - Reproducibility of reference measurement on chassis dyno more difficult
- Detailed analysis for each OEM on upcoming slides

OEM	Concept	Details	Setup	Validation passed
IVECO	Parallel Hybrid Truck	6 speed AMT	HILS	yes
VOLVO	Parallel Hybrid Bus	12 speed AMT	SILS	yes
MAN	Serial Hybrid Bus	Fixed gear, transient ICE operation	SIL(MIL)S	no

FPT Motorenforschung AG

HILS Validation

Tests, Simulations, Results and Conclusions of Validation Phase II

Michael Hensel, Leader Engineering Services
Oscar Chinellato,
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Arbon, Switzerland

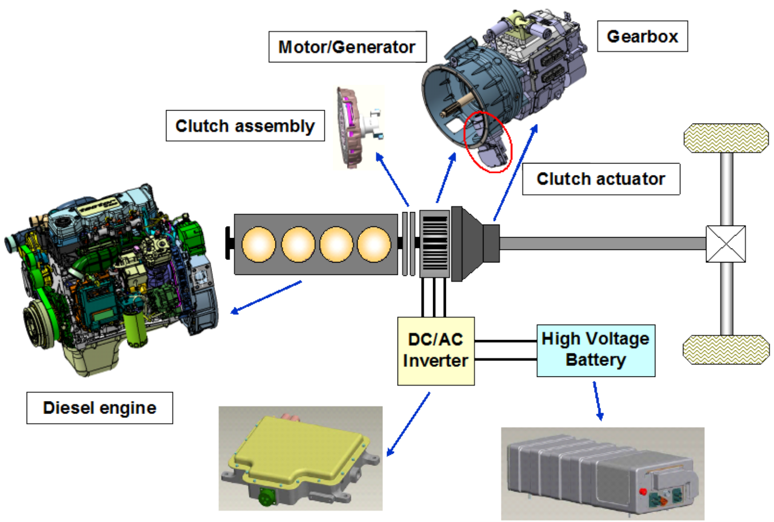
8./9. April 2014

Test Procedure

The Specimen

IVECO Eurocargo 120EL18 (Parallel Hybrid)

- Electric motor/generator with 44 kW, 420 Nm peak
- Lithium-Ion battery pack with 340 V (nom.), 5.5 Ah
- Diesel engine (FPT NEF4a, 3.9 litre, 4 cylinder, in-line) with 130 kW, 570 Nm peak
- Vehicle weight on chassis dynamometer bench: ~8’900kg
- Automated Manual Transmission (6 speeds)
- Electric Clutch Actuator
- *Additional drive-shaft torque measurement (at gearbox output) installed*



Preliminary Measurements, Validation Cycles and Supplementary Tests

In order to properly parameterise the vehicle model, dedicated measurements have been conducted …

- coast-down curves on the chassis dyno, enabling a validation of friction related quantities and (some) inertias
- "steady state" test runs, allowing for the calibration of (in)efficiencies and other losses
- the effective torque measurement on the gearbox output shaft, enabling the validation of (some other) inertias

Subsequently, WHVC (minicycle slopes, polynomial) cycles have been driven, logging …

- Diesel operation (speed, torque and injection quantity)
- electric motor operation (speed, torque and torque command)
- battery operation (current, voltage and state of charge)
- vehicle velocity and slopes
- accelerator pedal position
- brake pedal switch (standstill of front wheels required ABS module to be bypassed, thus no pedal position value exists)
- actual and requested gear
- clutch actuator position
- effective torque on gearbox output shaft (using a custom-equipped drive shaft)

To ascertain a high quality of the engine model and to reproduce fuel consumption and emission behaviour …

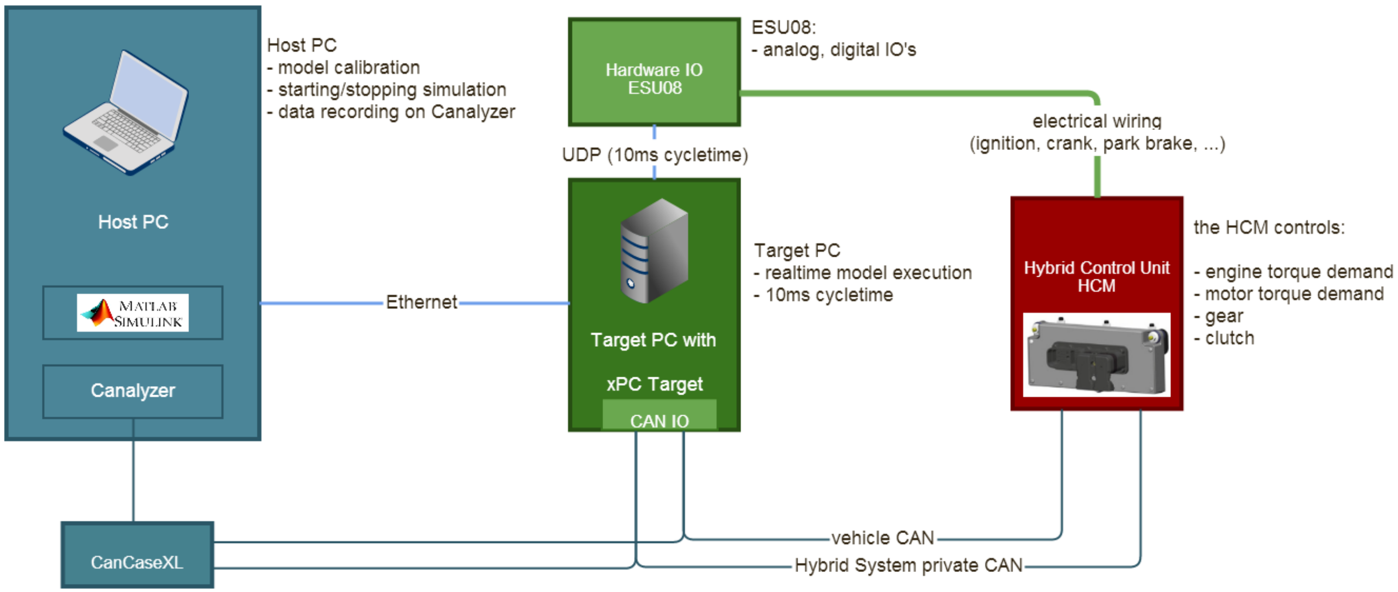
- all chassis dyno test runs have been reproduced on the engine test bench
- detailed engine maps and dedicated response time characteristics have been measured

The HILS Simulator

Setup of the Simulator

We assembled a HILS simulator by …

- running the compiled (Simulink) vehicle model on a xPC Target real-time platform from SpeedGoat
- embedding the real HCM of the vehicle in our simulator environment (ESU08 ↔ HCM ↔ xPC Target ↔ CANalyzer)
- emulating all necessary control units (Simulink)
- assembling additional analogue circuitry needed to satisfy the HCM (relays, switches, etc.)



Model Calibration, Interface Adaptation, Degree of Automation

Using component supplier data and dedicated measurements, we calibrated the model and observed …

- a constant torque loss through the gearbox
- a limitation of the battery power flow under certain circumstances
- a load-dependent gear shifting behaviour
- a slight deviation of the torque transfer from/to the electric motor at low loads

Therefore, the following (interface) adaptations[1] have been implemented …

- inclusion of a constant friction contribution at gearbox input (which can naturally be handled by newer library versions)
- implementation of an adaptive battery power flow limitation according to EATON
- implementation of a proprietary gear-shifting timing according to EATON

To assess the stability of the entire system (HCM & Model), we ran tests at several degrees of automation …

- closed loop (CLD) driving, i.e. limiters modelled, gear-shifting induced by HCM, virtual driver actuates accelerator/brake
- open loop (OLD) driving, i.e. limiters modelled, gear-shifting induced by HCM, driver is played back from recordings
- truly open loop (TOL)[2] driving, i.e. limiters, gear-shifting and driver are played back from recordings

[1] Due to time limitations, we worked with the library version 1.55.

[2] Measurements have shown, that putting the vehicle in manual shifting mode alters the energy management strategy behaviour of the HCM. We therefore refrain from showing any comparison results in this mode.

Formulae, Regulation and Expectation

As required by Kokujikan, we …

- compare the speeds, torques and powers calculated by evaluating the maps
- compute the coefficient of determination r^2 as described in the regulation
- consider removing …
  … no points at all [none]
  … points one second before and after a gear shifting event [shift]
  … all engine idle points, additionally [idle]
- compare the traces over both the initial 140s fraction and the entire WHVC cycle, respectively

Considering that the verification criteria are mainly based on r^2 limits, we …

- compare two WHVC cycles measured on the chassis dyno and driven by a human driver on consecutive days, in order to gain a notion on what to expect from a cycle comparison

Comparison of two measured (sloped) WHVC Cycles: The Numbers

Among the cycles measured on the chassis dyno, we compare two (sloped) WHVC runs (poly. minicycles) …

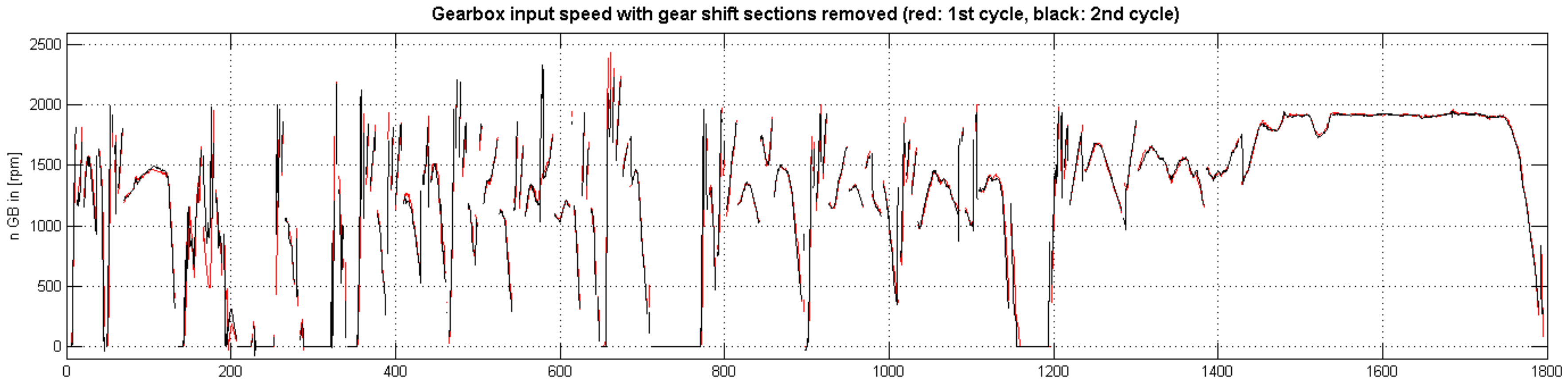
- in terms of the r^2 criteria used for comparisons between measured and simulated test runs

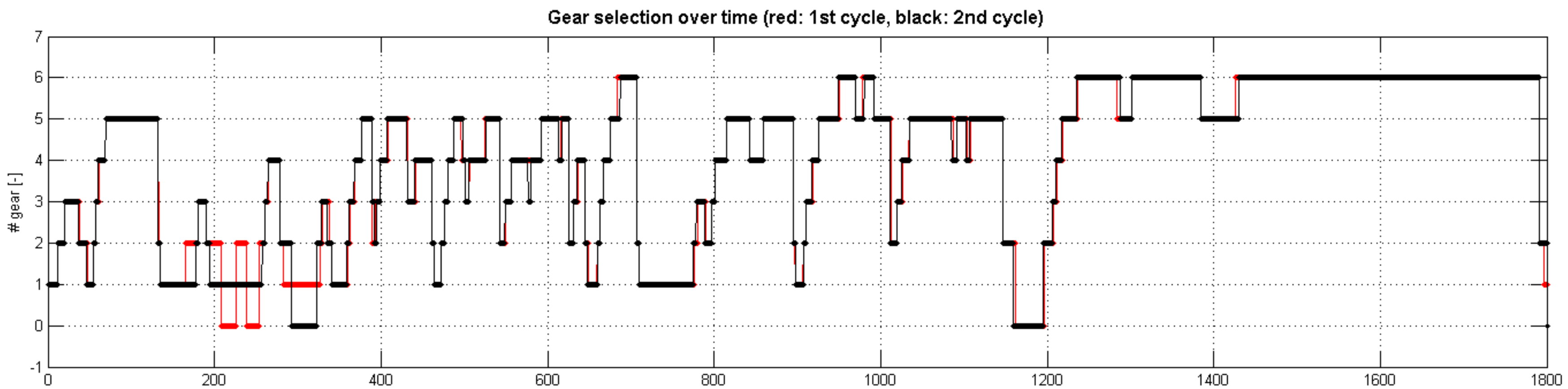
140s	Vehicle	Electric Motor		Diesel Engine		Battery
	Velocity	Torque	Power	Torque	Power	Power
Kokujikan (r^2>…)	*0.97*	*0.88*	*0.88*	*0.88*	*0.88*	*0.88*
IVECO [none]	**1.00**	0.31	0.26	0.65	0.69	0.27
IVECO [shift]	**1.00**	0.51	0.47	0.73	0.76	0.51
IVECO [idle]	**1.00**	0.51	0.47	0.69	0.70	0.51

1800s	Vehicle	Diesel Engine	
	Velocity	Torque	Positive Engine Work
Kokujikan (r^2>…)	*0.97*	*0.88*	*>0.97*
IVECO [none]	**1.00**	0.75	**0.98**
IVECO [shift]	**1.00**	0.82	**0.98**
IVECO [idle]	**1.00**	0.78	**0.98**

… and apart from vehicle speed and engine work, *none* of the regression criteria is satisfied!

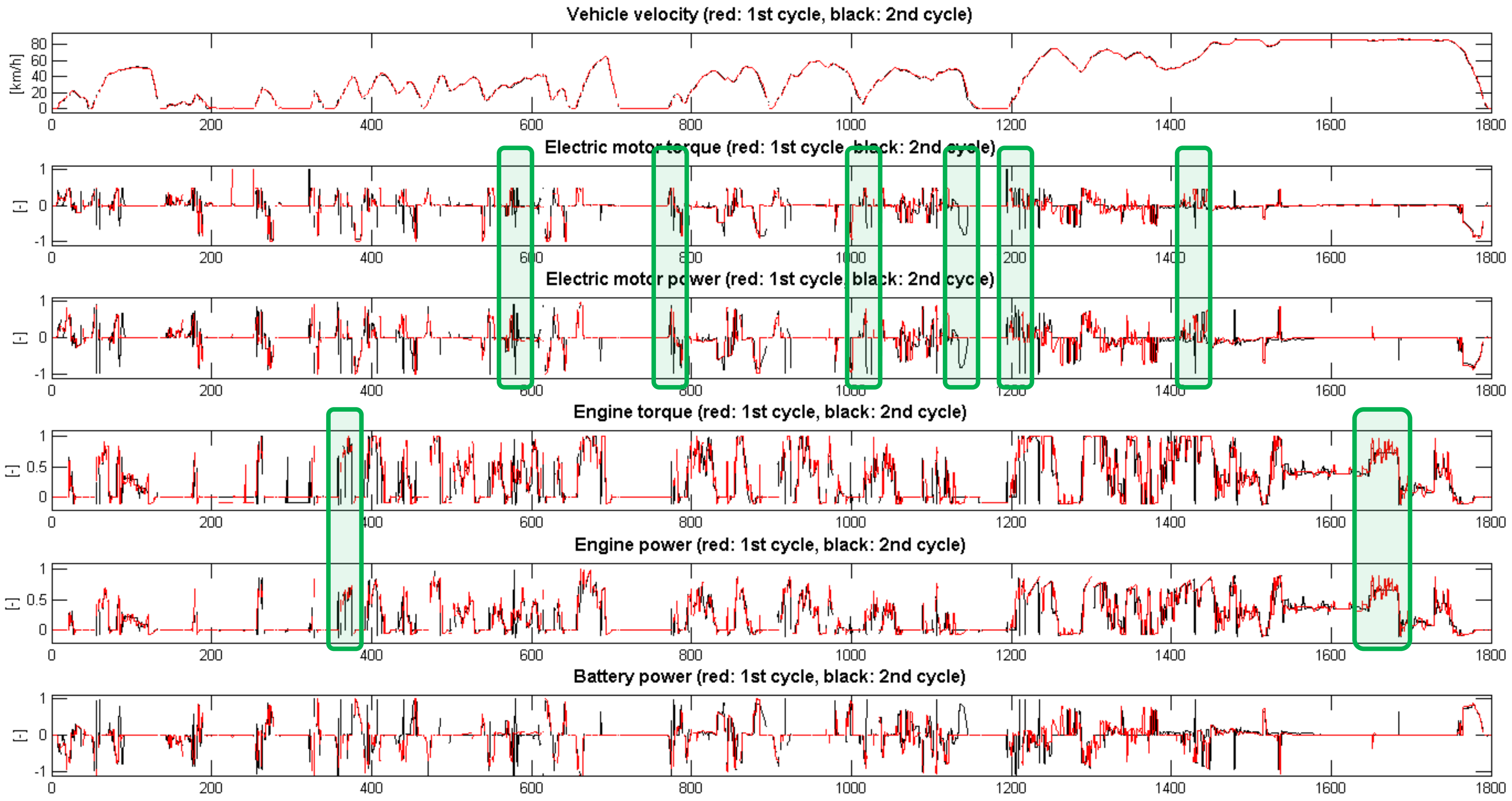
Comparison of two measured (sloped) WHVC Cycles: The Gears





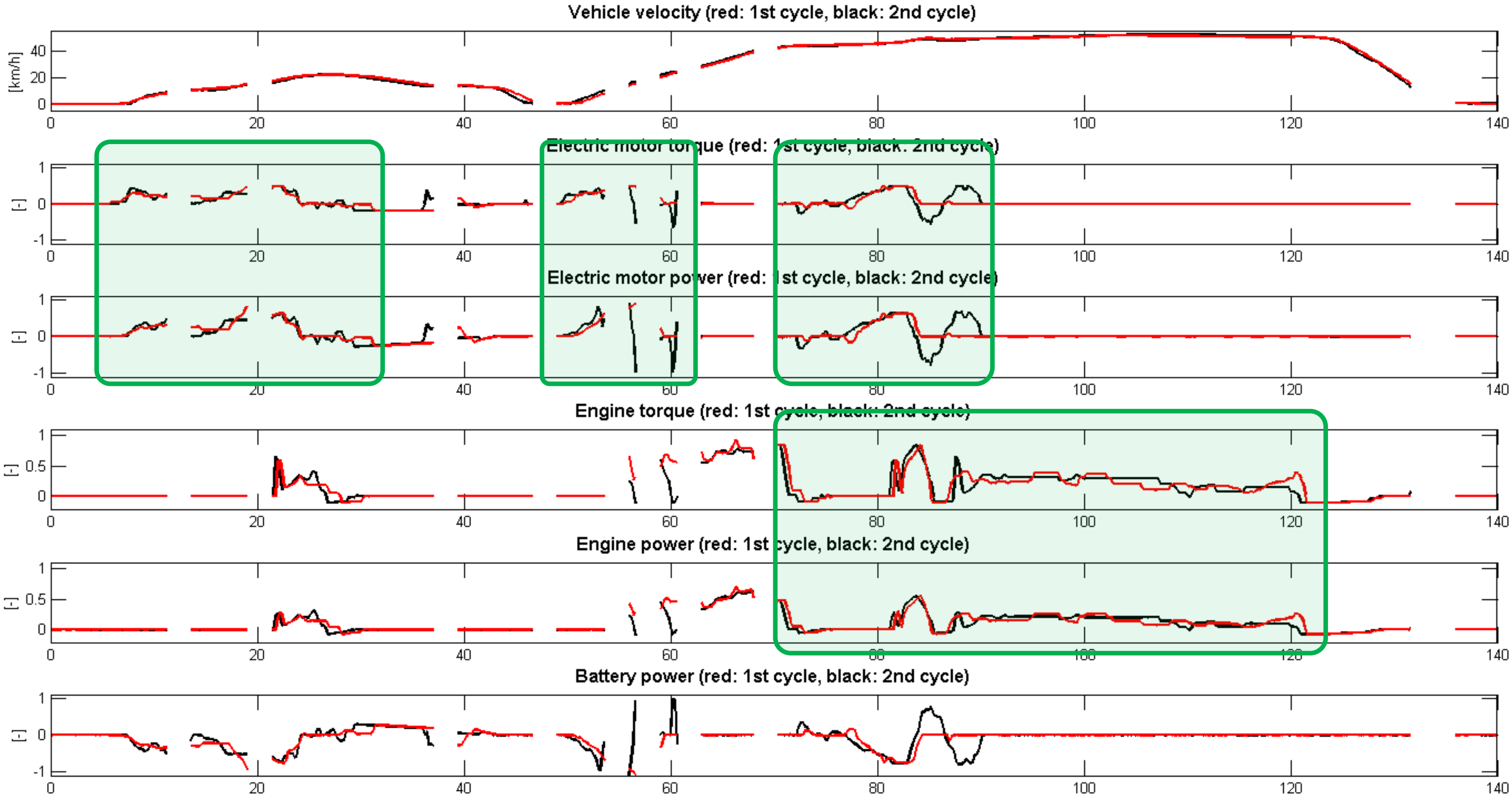
Results

Comparison of two measured (sloped) WHVC Cycles: The Traces



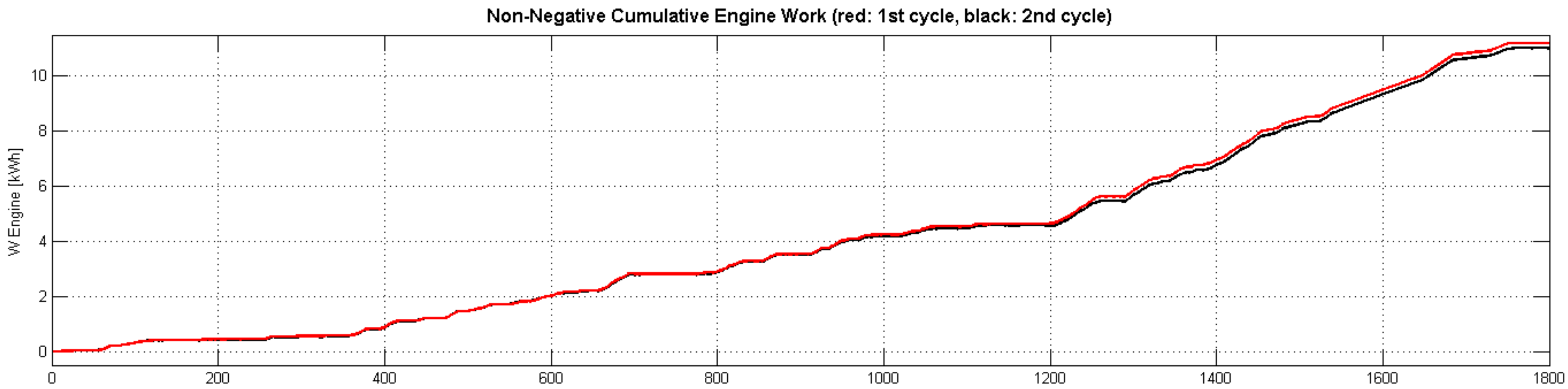
- Although the overall system power is comparable, the instantaneous single powers need not be

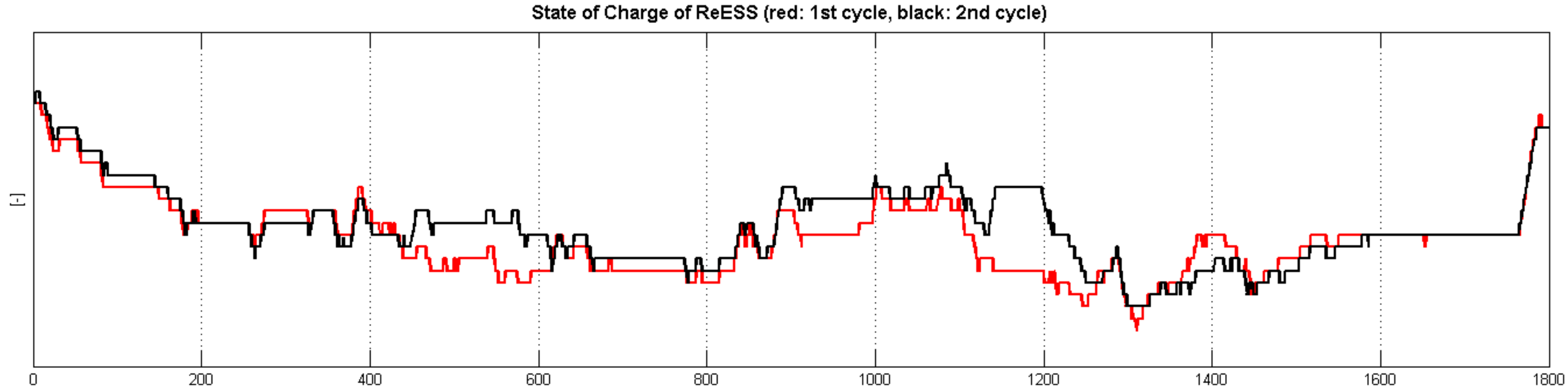
Comparison of two measured (sloped) WHVC Cycles: The Close-Up



Results

Comparison of two measured (sloped) WHVC Cycles: The Energies





- **The net works delivered by the systems and the initial/final states of the ReESS are comparable**

Results

1st Sloped WHVC Cycle, HILS vs. Dyno: The Numbers

After having calibrated the simulator, we …

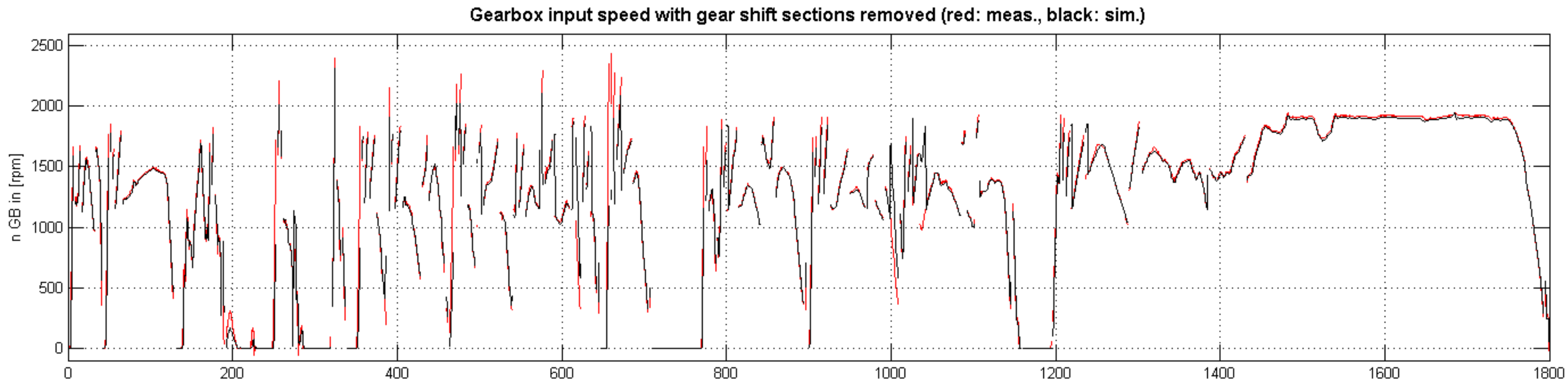
- performed some final adjustments on the simulator parameterisation by comparing simulated traces with traces taken from the first sloped WHVC cycle measured on the chassis dyno
- then simulated the vehicle in open/closed loop fashion
- finally compared the traces in terms of r^2 as required by Kokujikan

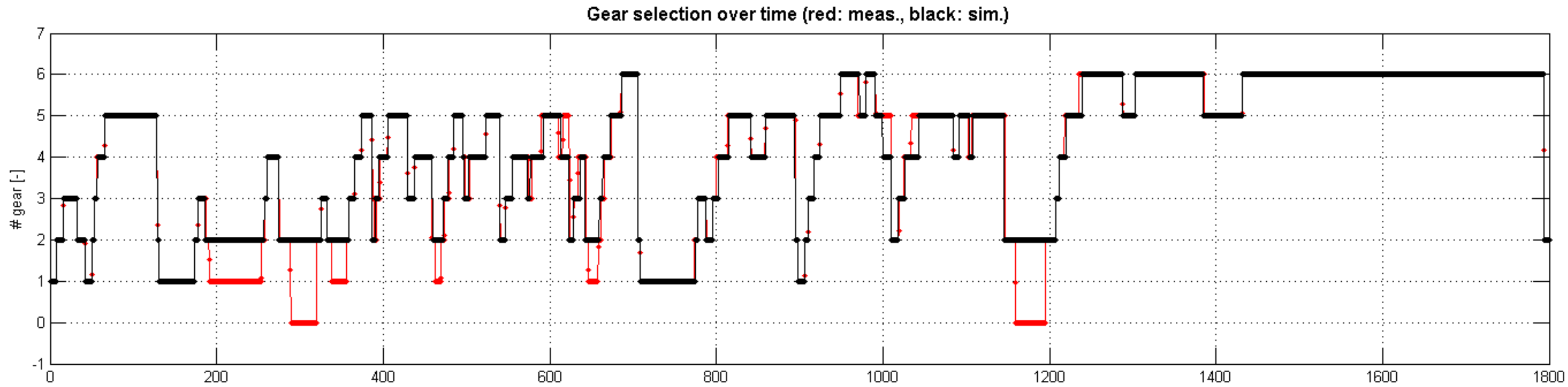
140s (OLD)	**Vehicle**	**Electric Motor**		**Diesel Engine**		**Battery**
	Velocity	Torque	Power	Torque	Power	Power
Kokujikan (r^2>…)	*0.97*	*0.88*	*0.88*	*0.88*	*0.88*	*0.88*
IVECO [none]	**1.00**	0.84	0.82	**0.93**	**0.94**	0.75
IVECO [shift]	**1.00**	**0.96**	**0.95**	**0.95**	**0.96**	**0.96**
IVECO [idle]	**1.00**	**0.96**	**0.95**	**0.94**	**0.95**	**0.96**

1800s (CLD)	**Vehicle**	**Diesel Engine**	
	Velocity	Torque	Positive Engine Work
Kokujikan (r^2>…)	*0.97*	*0.88*	*>0.97*
IVECO [none]	**1.00**	0.83	**1.03**
IVECO [shift]	**1.00**	**0.89**	**1.03**
IVECO [idle]	**1.00**	0.85	**1.03**

Results

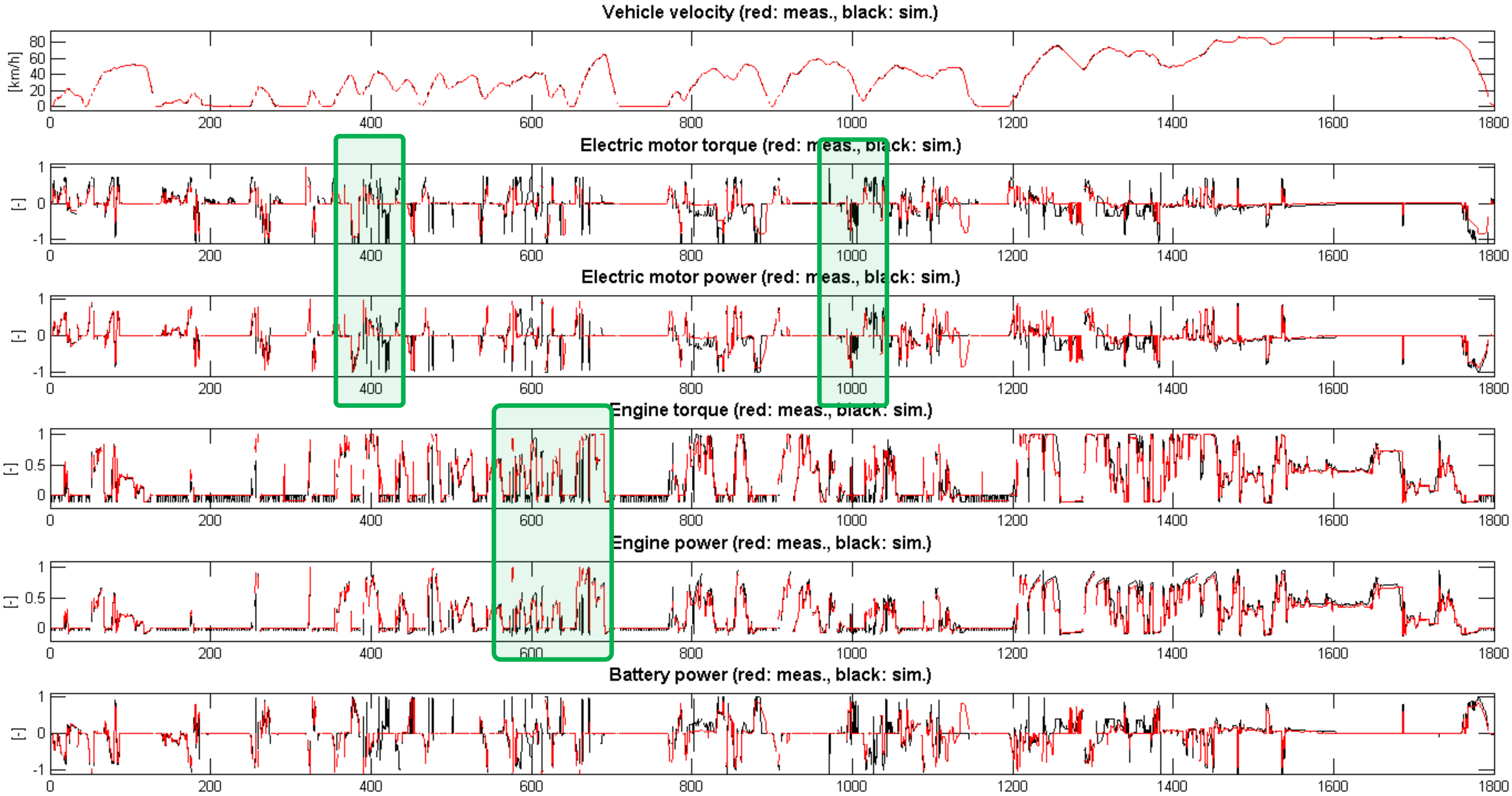
1st Sloped WHVC Cycle , HILS vs. Dyno: The Gears





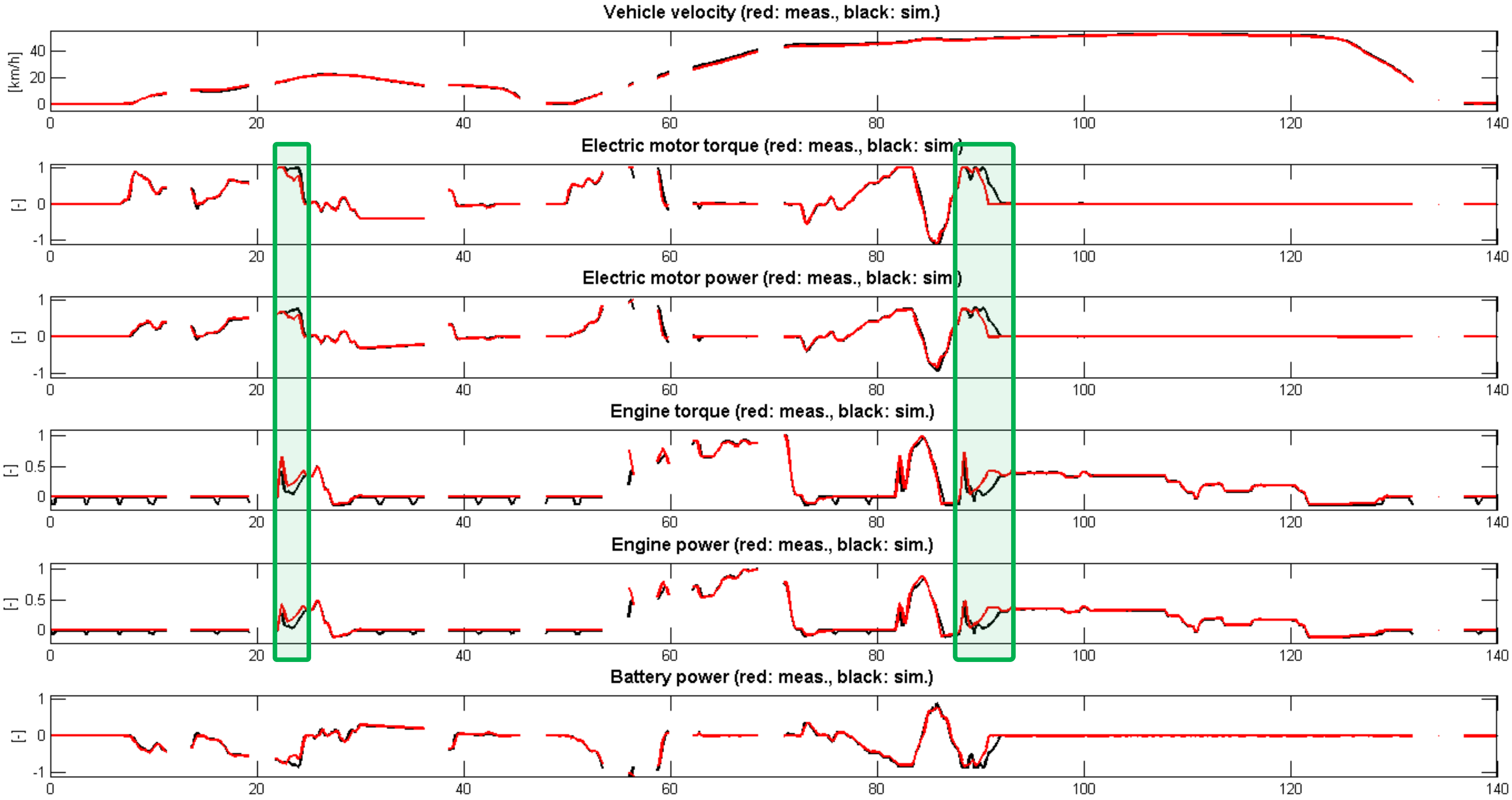
Results

1st Sloped WHVC Cycle, HILS vs. Dyno: The Traces



Results

1st Sloped WHVC Cycle, HILS vs. Dyno: The Close-Up

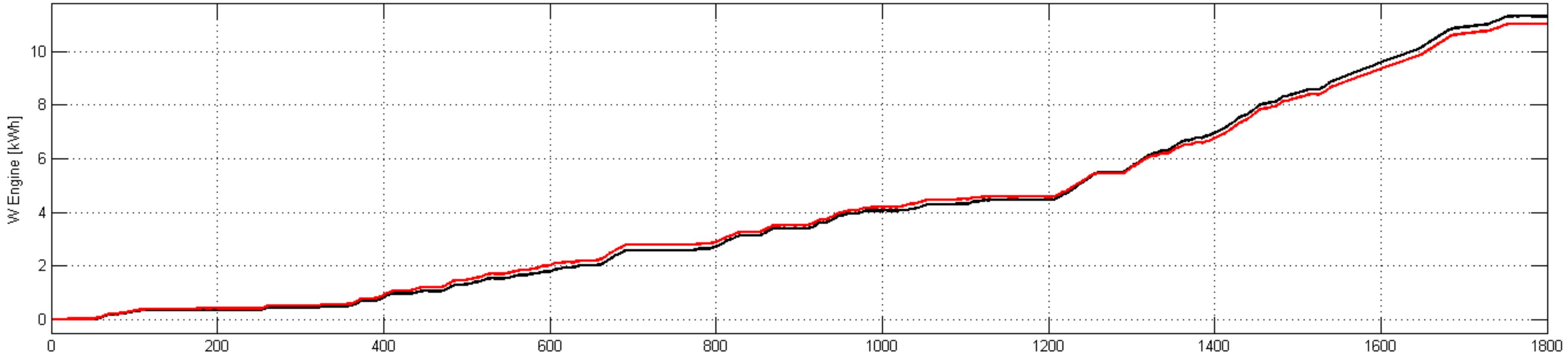


- Given the open loop driving of the 140s cycle, the discrepancies between the meas./sim. traces are minor

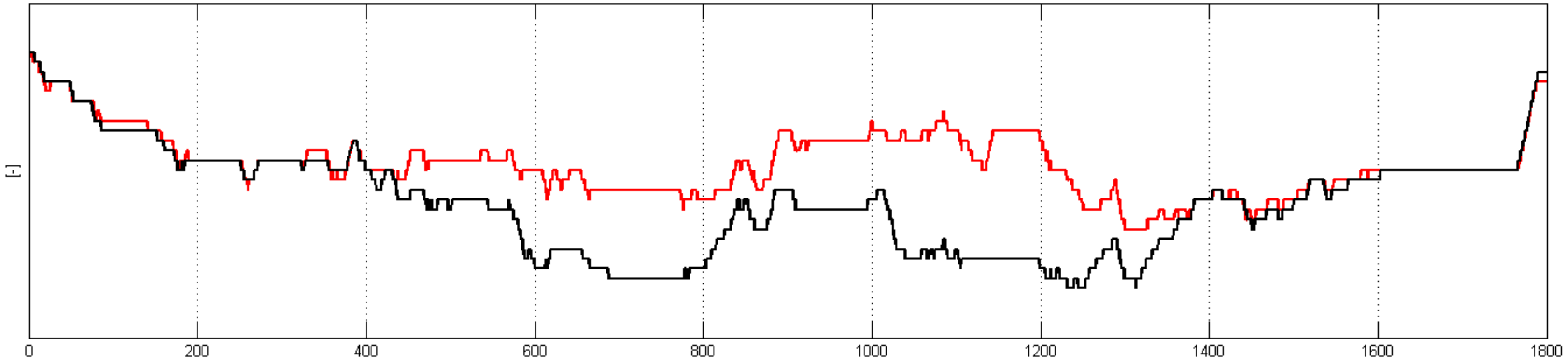
Results

1st Sloped WHVC Cycle, HILS vs. Dyno: The Energies

Non-Negative Cumulative Engine Work (red: meas., black: sim.)



State of Charge of ReESS (red: meas., black: sim.)



2^{nd} Sloped WHVC Cycle, HILS vs. Dyno: The Numbers

Once the simulations for the first comparison were done, we …

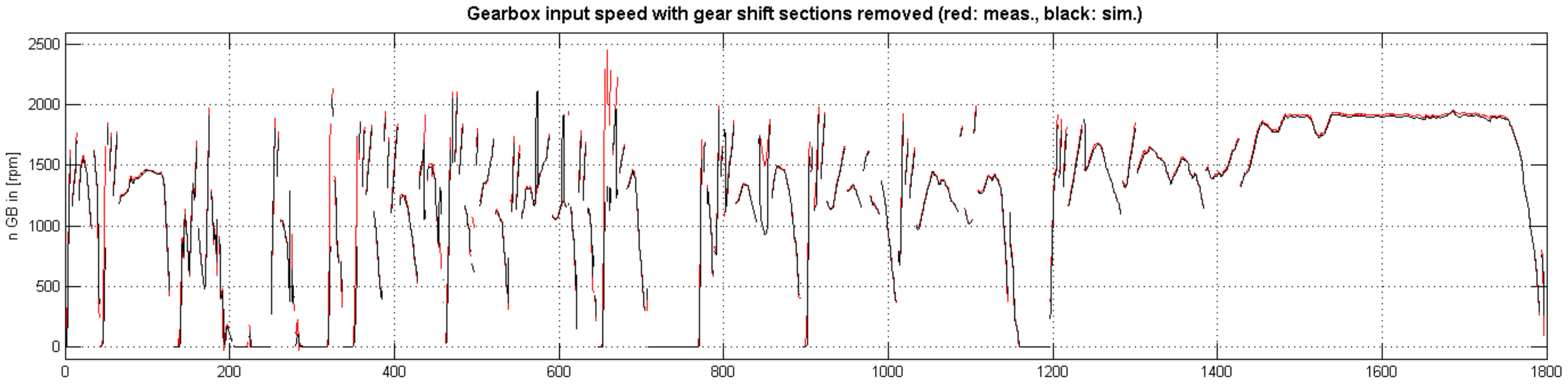
- ran the simulations again, this time, however, we compared the traces of the simulated and the measured second sloped WHVC cycle measured on the chassis dyno. No parameters have been changed in the simulator!
- then simulated the vehicle in open/closed loop fashion
- finally compared the traces in terms of r^2 as required by Kokujikan

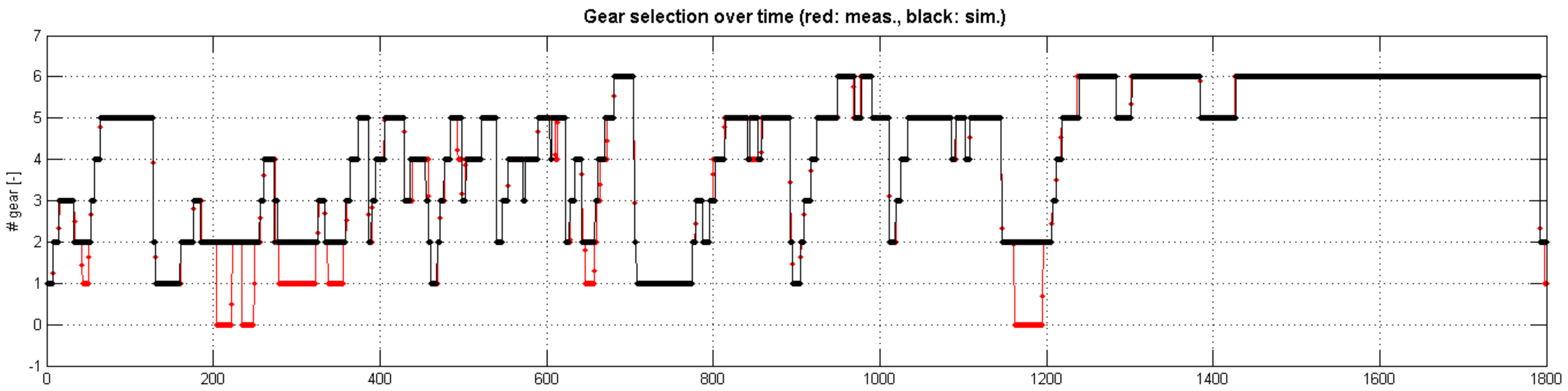
140s (OLD)	Vehicle	Electric Motor		Diesel Engine		Battery
	Velocity	Torque	Power	Torque	Power	Power
Kokujikan (r^2>…)	*0.97*	*0.88*	*0.88*	*0.88*	*0.88*	*0.88*
IVECO [none]	**1.00**	0.86	0.83	**0.93**	**0.94**	0.83
IVECO [shift]	**1.00**	**0.94**	**0.90**	**0.92**	**0.93**	**0.91**
IVECO [idle]	**1.00**	**0.94**	**0.90**	**0.91**	**0.92**	**0.91**

1800s (CLD)	Vehicle	Diesel Engine	
	Velocity	Torque	Positive Engine Work
Kokujikan (r^2>…)	*0.97*	*0.88*	*>0.97*
IVECO [none]	**1.00**	0.87	**1.00**
IVECO [shift]	**1.00**	**0.93**	**1.00**
IVECO [idle]	**1.00**	**0.91**	**1.00**

Results

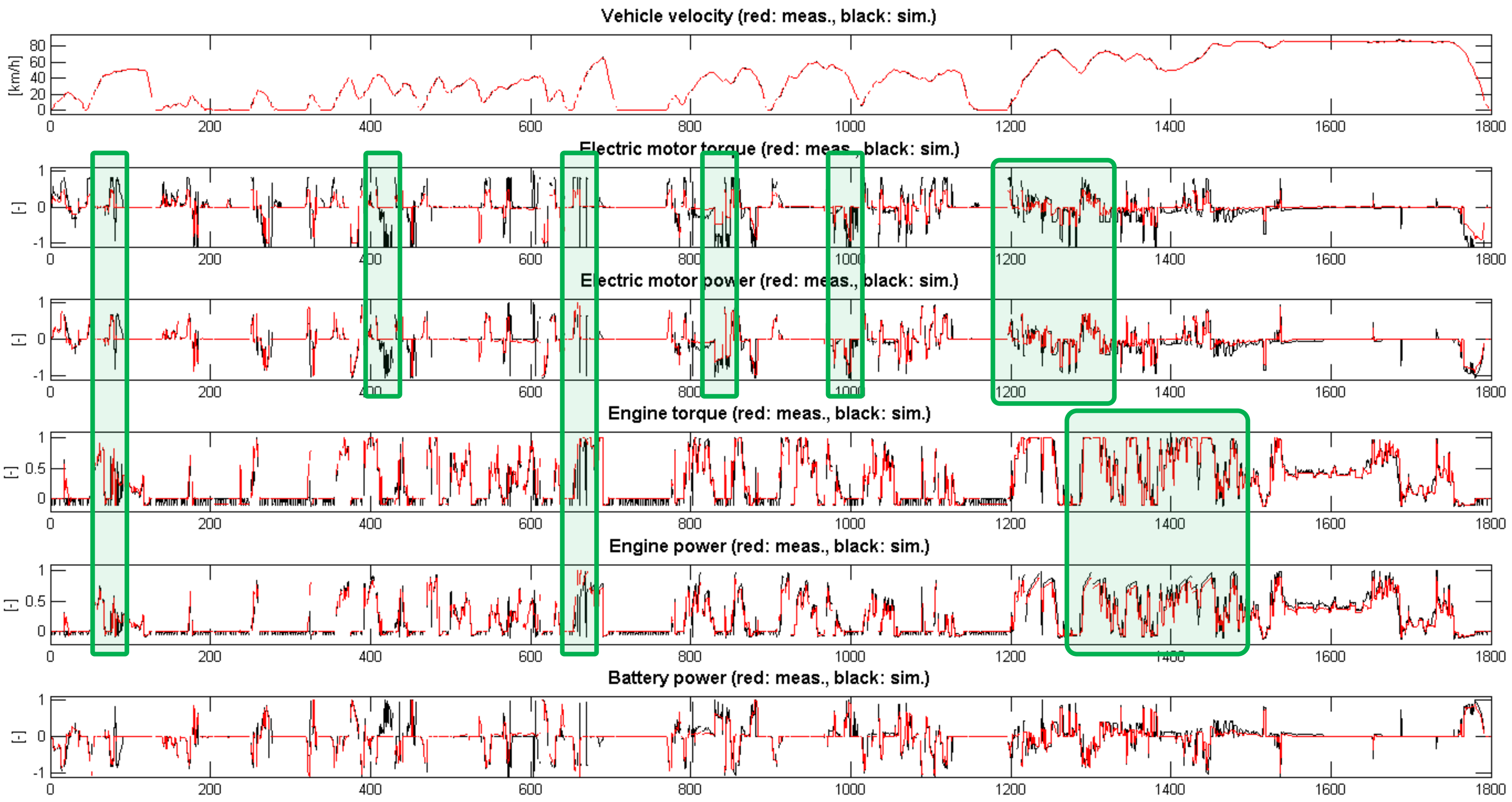
2nd Sloped WHVC Cycle, HILS vs. Dyno: The Gears





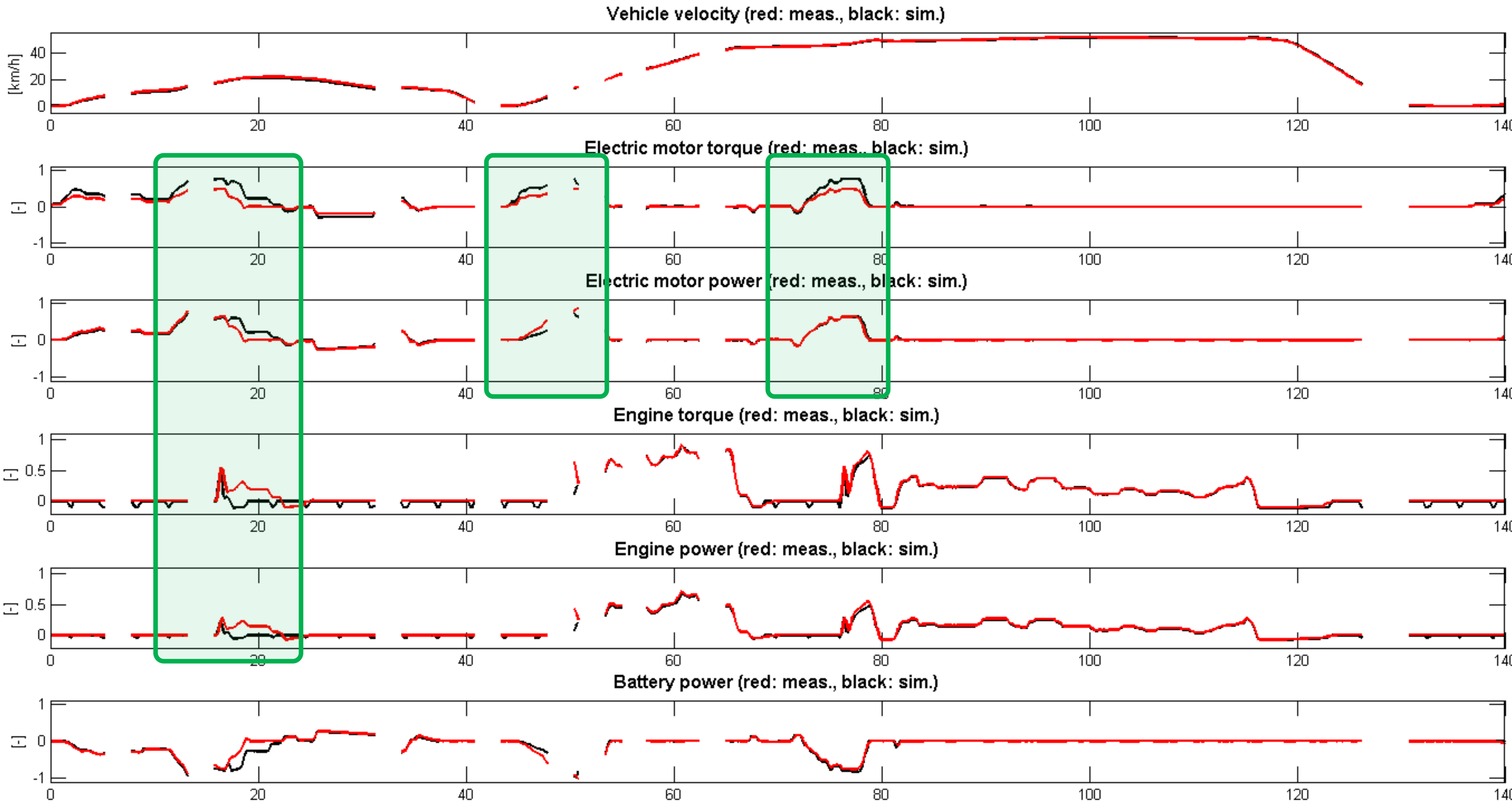
Results

2nd Sloped WHVC Cycle, HILS vs. Dyno: The Traces



Results

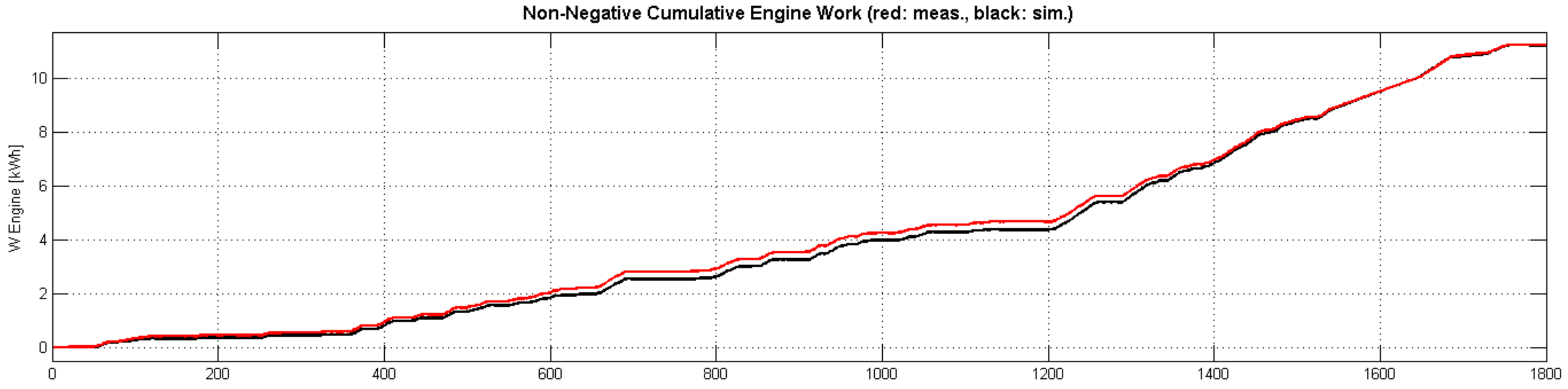
2nd Sloped WHVC Cycle, HILS vs. Dyno: The Close-Up

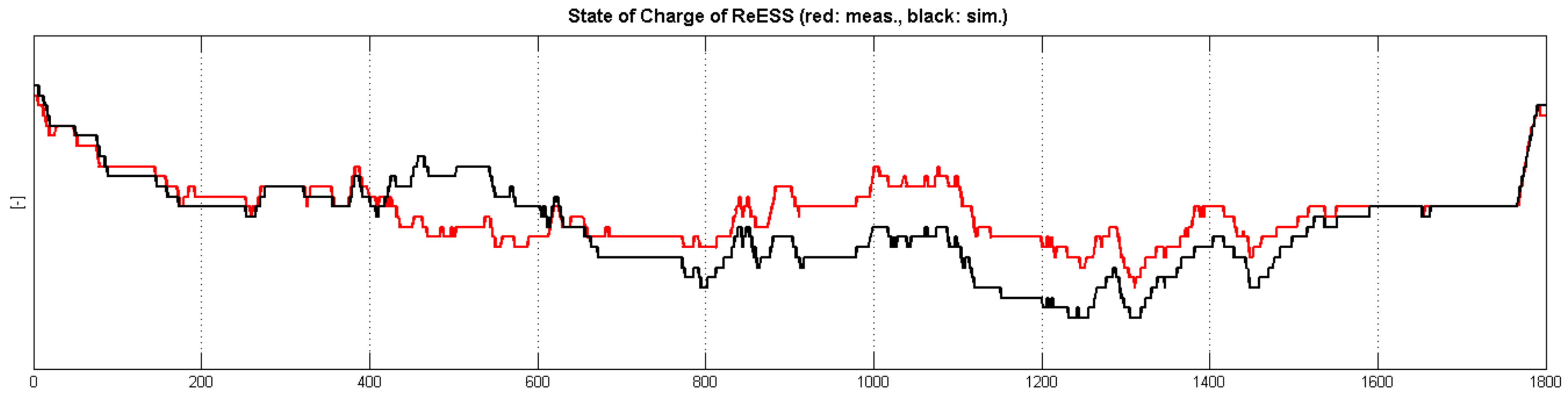


- **Given the open loop driving of the 140s cycle, the discrepancies between the meas./sim. traces are minor**

Results

2nd Sloped WHVC Cycle, HILS vs. Dyno: The Energies





Conclusions

Model related comments

- The model is sufficiently flexible and can easily be extended where necessary
- Interfacing the model with the HCM is ok, I/O channels suffice
- Thermal model was not needed (i.e. assume a warm vehicle). However, energy flow management is crucial (e.g. battery, compressors, etc.)

Approach related comments

- Replication of vehicle behaviour is challenging when simulation horizon is large. A small deviation (SOC, gear shifting) will accumulate and lead to an appreciably different behaviour
- More measurements (in order to isolate the model subcomponents) would be useful
- Some validation criteria appear not to be appropriate (torque, instantaneous powers, etc.) Instead, a holistic consideration of the propulsion system could be preferable

- Although the model based approach is sound and desirable, more focus needs to be put on the elaboration of new acceptance criteria. During our measurement campaign, we obtained chassis dyno measurements which do not satisfy the verification criteria imposed by Kokujikan

HILS Analysis

TF-HILS

2013-04-08/09

Model validation procedure

1. Run WHVC on chassis dyno and log CAN data
   - Engine, Electric motor, Vehicle speed, SOC level, Brake and accelerator pedal position, Current gear, Battery
2. Configure the SILS model to match chassis dyno
   - Set mass, resistances and inertia of rotating sections similar to the ones on the dyno (e.g. consider that the front axle was not driven)
   - Estimates the auxiliary loads. (mechanical, low voltage, high voltage).
3. Run the SILS model
   - For the 140sec verification and for the entire verification, measured brake and accelerator pedal position from the test are used as model input. (Open loop)
4. Validate the model
   - Optional to ignore validation data one second before/after a gearshift (when calculating the R^2)

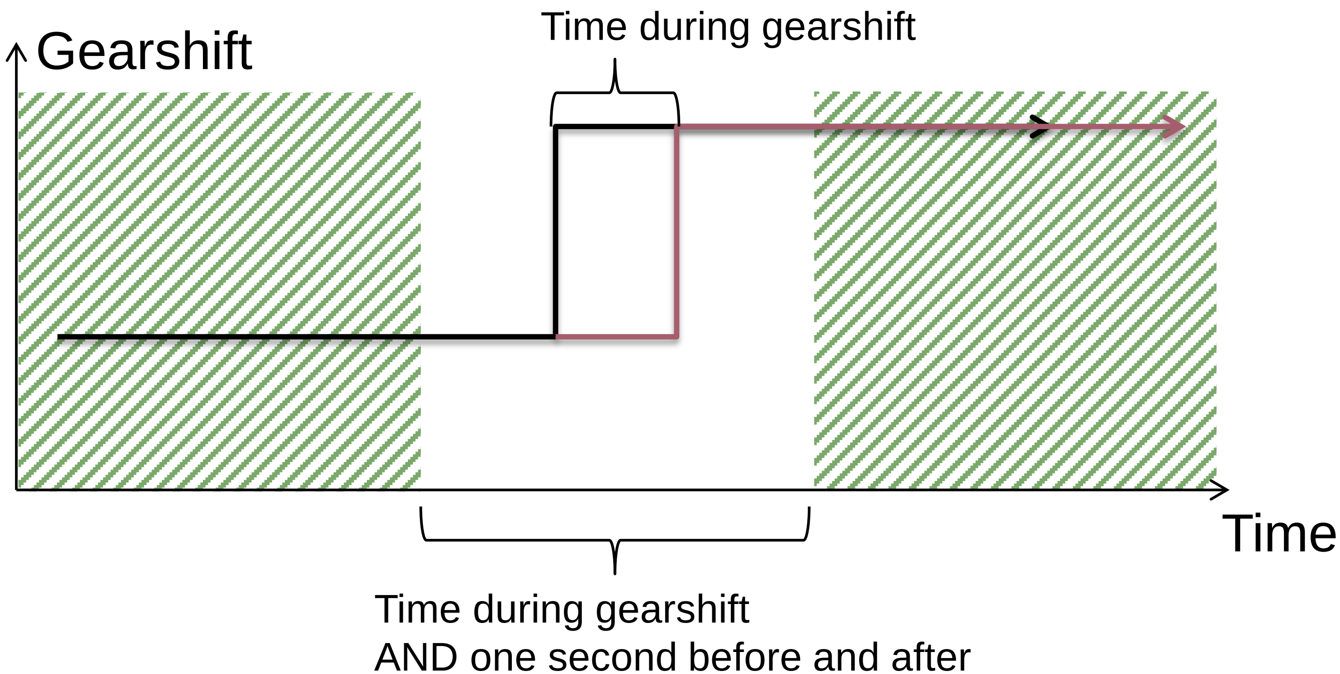
Model validation – Kokujikan criteria

WHVC short cycle	Vehicle	Electric motor		Engine		Battery
	Speed	Torque	Power	Torque	Power	Power
Kokujikan desired R^2	0.97	0.88	0.88	0.88	0.88	0.88
WHVC 2sec + gearshift removed	0.99	0.90	0.88	0.92	0.89	0.88
WHVC + Mini cycle 2sec + gearshift removed	0.99	0.96	0.94	0.94	0.91	0.93
WHVC nothing removed	0.99	0.80	0.76	0.74	0.75	0.76

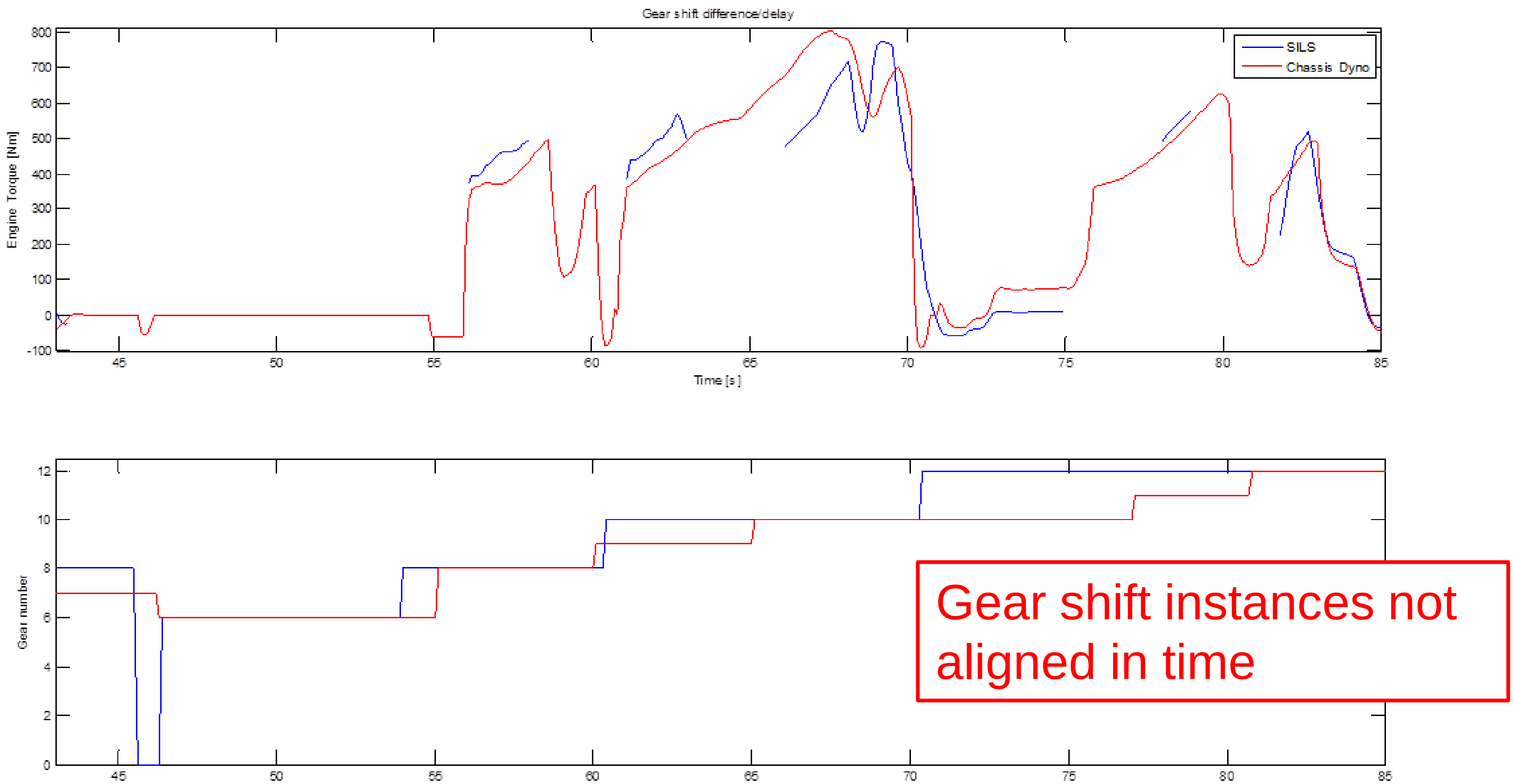
WHVC full cycle	Vehicle speed	Engine Torque	Positive engine work	Fuel economy value
	R^2	R^2	$W_{eng\_HILS}/W_{eng\_vehicle}$	$FE_{SILS}/FE_{vehicle}$
Kokujikan	0.97	0.88	>0.97	<1.03
WHVC 2 sec + gearshift removed	0.99	0.88	1.07	0.90
WHVC + Mini cycle 2sec + gearshift removed	0.99	0.89	1.07	0.97

Ignoring data during gearshifting

- It is suggested in the Kokujikan that the OEM can remove one second before and after gearshifting + during the gearshifting event itself.
- Only keep the green area when calculating R^2



Example of sequences comparing CD test and simulation with gear shift instances removed



Investigated possibility to force gear shifts in simulation model based on recorded test data

- Didn’t work because of many technical problems.
- Our virtual transmission ECU does not support manual shifting.

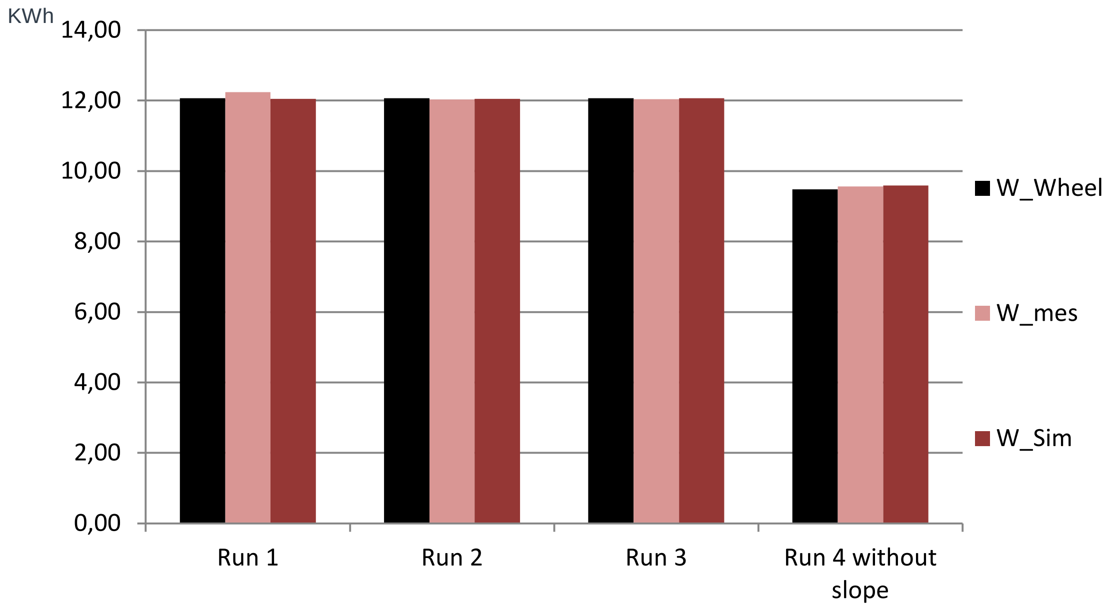
Procedure for validation of HILS test environment
Summary of Issues

Issues on repeatability and robustness of test and simulation procedures	Proposal
CD test with slopes added to WHVC: It has not been demonstrated that is is possible to follow a speed+slope profile with sufficient accuracy and repeatability in CD.	Relax speed criteria for verification run according to vehicle capability
Repeatability of test procedure: It has not been demonstrated that the test is repeatable at the level required by the proposed validation criteria.	Investigate repeatability of CD test procedure. Relax validation criteria accordingly.
We find it not possible to get good correlation between simulation and test with second-by-second accuracy. Small errors will accumulate so that gear shifts and engine on/off will be shifted in time.	Use validation critera <u>not</u> sensitive to time shifts in switch events. Maybe sufficient to use only total energy and cycle average criteria for verfication of HILS system.
Our results show that the only way to pass proposed validation criteria is to remove most of data in urban and rural part. With 12 speed gear box or with frequent gear shifts too litle data remain.	Keep gear shifts in data but use validation criteria less sensitive to actual gear and minor time shifts in actual gear shifts.

TF HILS

1. Chassi Dyno

Work comparison measurement, simulated and calculated work



Wheel force based comparison

- Good comparison between measured and calculated work
- Good repeat accuracy

2. Simulation Parameters

Validation - Overview

- Using measured CAN-data from roll bench tests in February 2014 in Munich
- Implementation with model library V0.5
- Realisation serial hybrid only with HILS model library toolbox components
- Using the measured “WHVC cycle with slopes”
- “140sec” Verification with measured AP/BP
    - Determination Coefficient for: vehicle speed, torque (e-motor, engine), power (e-motor, engine, e-storage)
- “Overall” Verification with HILS driver model and measured vehicle speed
    - Determination Coefficient for: vehicle speed, engine torque
    - Positive engine work
- Validation signals and tolerance in tables 1 and 2

HILS Verification

Table 1 Tolerance in Correlation (Determination Coefficient) of Actually-Measured Verification Values and HILS Simulated Running Values

Test condition	Vehicle speed or engine revolution speed	Electric motor		Engine		Electric storage device output
		Torque	Output	Torque	Output	
One heap in JE05-mode	0.97 or more	0.88 or more	0.88 or more	0.88 or more	0.88 or more	0.88 or more

Table 2 Tolerances in Overall Verification

Test condition	Vehicle speed or engine revolution speed	Engine torque	Positive engine work	Fuel economy value
	Determination coefficient	Determination coefficient	W_{eng_HILS} / $W_{eng\_vehicle}$	FE_{HILS} / $FE_{vehicle}$
Entire JE05-mode	0.97 or more	0.88 or more	0.97 or more	1.03 or less

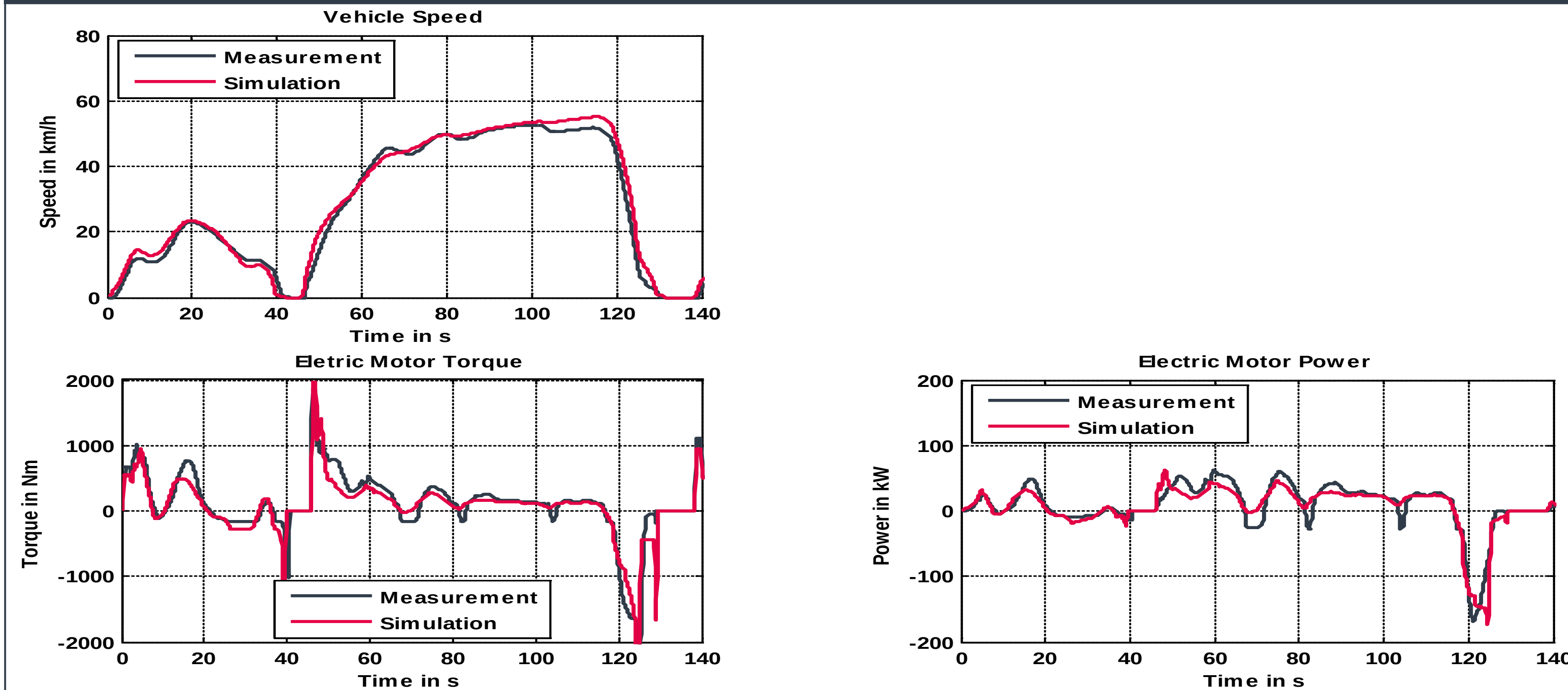
determination coefficient

$$r^2 = \left(\frac{n \times \sum x_i y_i - \sum x_i \times \sum y_i}{\sqrt{\left[n \times \sum x_i^2 - (\sum x_i)^2\right] \times \left[n \times \sum y_i^2 - (\sum y_i)^2\right]}} \right)^2$$

3. Results

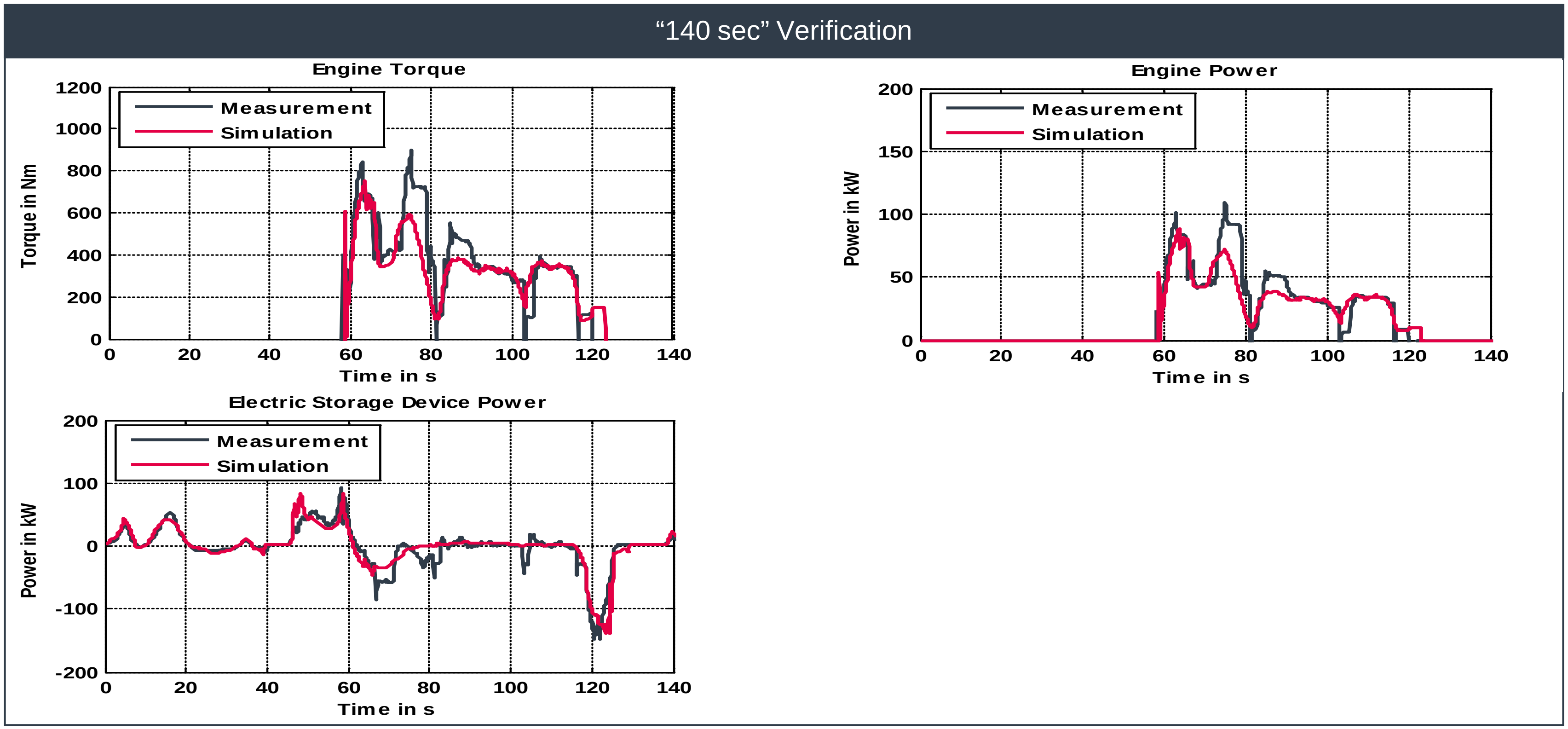
Status Validation

“140 sec” Verification



3. Results

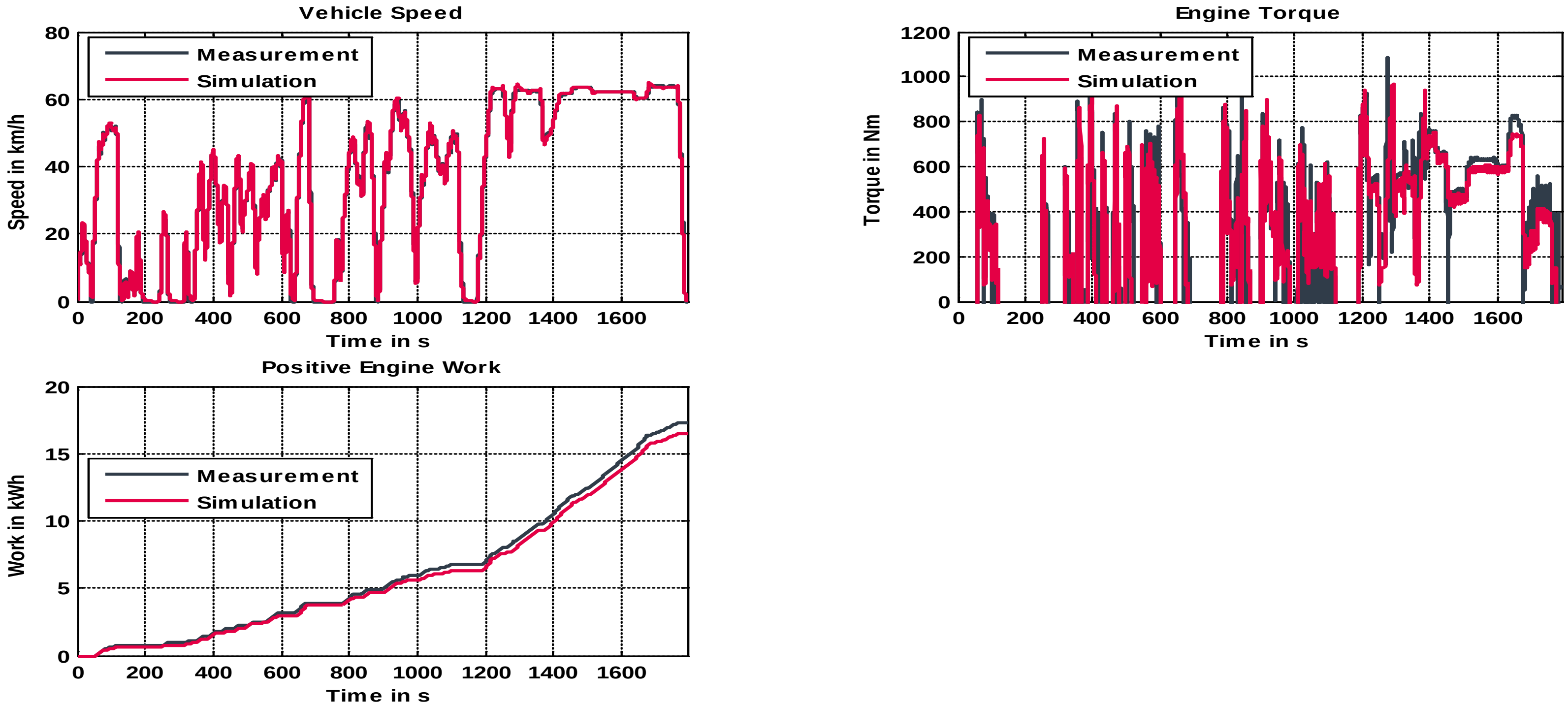
Status Validation



3. Results

Status Validation

“Overall” Verification



3. Results

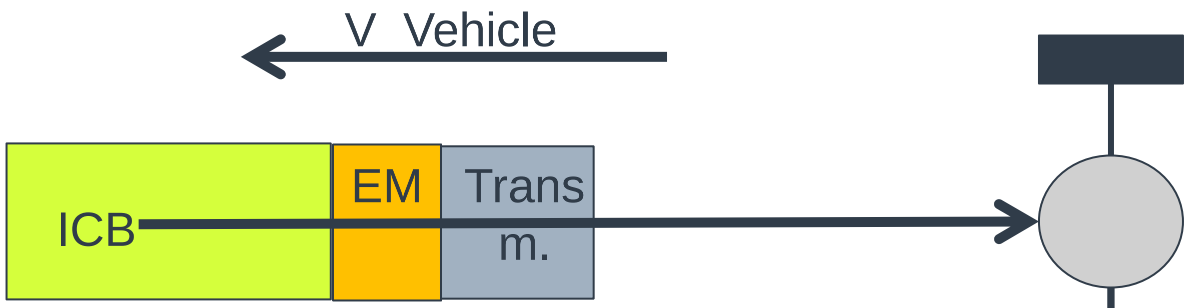
Status Validation

Verification

WHVC 0s-140s	Vehicle	Electric motor		Engine		UltraCap
	Speed	Torque	Power	Torque	Power	Power
Required	0,97	0,88	0,88	0,88	0,88	0,88
Achieved	0,988	0,814	0,855	0,882	0,883	0,826

WHVC full	Vehicle Speed	Engine Torque	Positive Engine Work
	R^2	R^2	$W_{eng\_HILS} / W_{eng\_vehicle}$
Required	0,97	0,88	0,97
Achieved	0,999	0,755	0,952

Link ICB Speed to Vehicle Speed



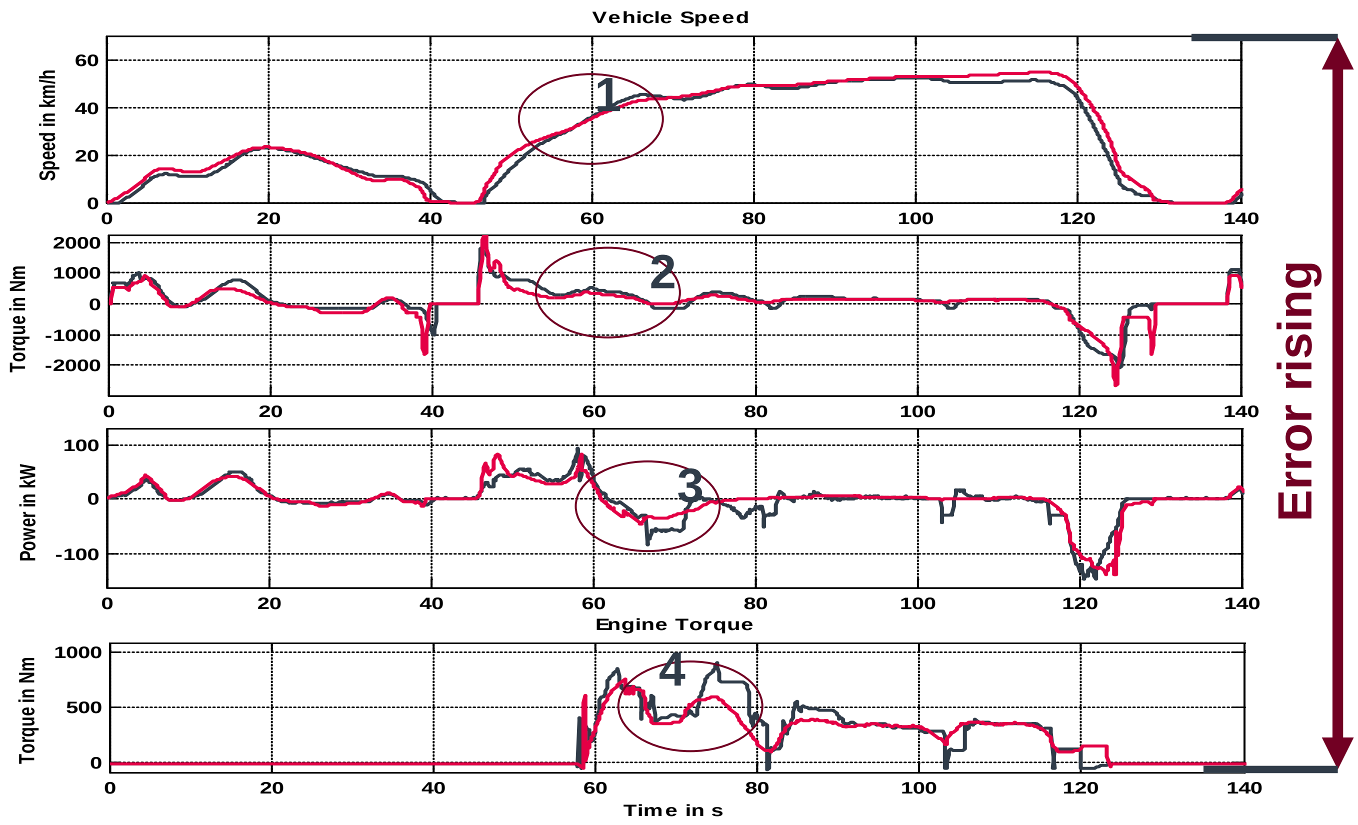
N_ICB = N_EM = N_Trans = i x N_Wheel = Fact. x V_veh

One more degree of Freedom in Serial Hybrids

N_ICB = N_GEN ≠ N_EM = Fact. x N_Wheel = Fact. x V_veh

4. Reasons for Results

Status Validation



red: Simulation

black: Measurement

No direct link between vehicle speed and engine speed

5. Conclusions and next Steps

- R^2 criteria or rather the limits are not reachable for Serial Hybrids because of error rising an no direct link between engine and vehicle speed.

→ checking differences in emission between measured and simulated speed and torque profiles

- Simulation Models must be improved slight, efficiency tables should be added

- Emission tests are planed with simulated and measured data

VTP2 conclusions & discussion

- Validation could be passed for parallel hybrid vehicles
  - IVECO
    - Vehicle and system similar to Japanese vehicles (6 speed GB, one HCU,…)
    - HILS setup according Kokujikan No.281 for validation
  - VOLVO
    - Vehicle and system different to Japanese vehicles (12 speed GB, more DOF…)
    - SILS setup for validation
- MAN Serial hybrid vehicle could not pass validation
  - Complexity of system makes validation more difficult
  - MILS setup

- **Even though validation could be passed for parallel hybrid vehicles there are some items for discussion regarding….**

VTP2 conclusions & discussion

Items for discussion regarding:

- ☐ Chassis dyno testing
  - – Variation of hybrid system behavior on chassis dyno/powertrain test bed
  - – Speed criteria for validation run on chassis dyno (independent of slopes)
- ☐ Model validation
  - – Validation criteria and application
    - – Suitability of criteria for all vehicle topologies and degrees of complexity
    - – Data omission during gear change
  - – What occurred beside…

VTP2 conclusions & discussion

Chassis dyno testing (Powertrain testing)

Variation of hybrid system behavior on chassis dyno/powertrain test bed

- ☐ Variation of system (and ICE) behavior during iterations of the same cycle on CD observed (vehicle speed within tolerances but human driver)
- ☐ No clearly representative load cycle for ICE for one specific vehicle cycle
  - Direct link between vehicle speed and engine load missing
  - Propulsion energy can be provided by two independent systems
  - More complex systems/degrees of freedom → less reproducible (valid for CD and powertrain test)
  - Impact on emissions not fully analyzed yet
- ☐ OEM would need to choose one specific cycle representatively for
  - Emission certification using a powertrain test
  - HILS model validation (validated model would in best case be able to depict also different CD test runs)

VTP2 conclusions & discussion

Chassis dyno testing

Speed criteria for validation run on chassis dyno (independent of slopes)

- ☐ CD test requires max. +/-2 km/h speed deviation from WHVC
  - Except Acc pedal is fully pressed and vehicle can still not follow
- ☐ Depending on vehicle concept criteria are harder to be met
  - Could cause high number of test iterations
  - Does not improve validation results/accuracy

- ☐ Speed criteria could be relaxed for validation run
  - No harm for model validation, anyway validated on actual speed profile
- ☐ Sufficient if +/-2 km/h speed criteria are met for the HEC cycle generation using the HILS model
  - Eases/accelerates CD test procedure
  - Easier and better handling with driver model in HILS

VTP2 conclusions & discussion

HILS model validation - Validation criteria and application

- ☐ Suitability of criteria for all vehicle topologies and degrees of complexity

- ☐ Requirements on validation criteria:
  - Characterize similarity between simulation model and real vehicle
  - Simulation model represents real vehicle in good approximation
  - Similarity regarding emissions means good approximation of emission relevant components (i.e. ICE speed and torque)
  - Engine load cycle influences emissions > chronological sequence of engine load points needs to be represented in good approximation
  - R-squared values of linear regression analysis check time-dependency

VTP2 conclusions & discussion

HILS model validation - Validation criteria and application

- Suitability of criteria for all vehicle topologies and degrees of complexity

- Validation for hybrid system with higher complexity is more difficult
  - For a more complex system ECU decisions depend on more parameters
  - Simulation model cannot reproduce exact behavior over time
  - The more complex the hybrid system (more DOF) the higher the possibility that an ECU in the simulation decides differently due to small deviations in parameters
  - Simulation model is able to reproduce vehicle behavior over a shorter timeframe
  - BUT: once a different decision occurs in the cycle the error will accumulate over the cycle since parameters for future decisions will never match (error propagation)
  - e.g. MAN series hybrid (different timing of ICE start)
- Loosening of R-squared limits is not considered as reasonable
  - Alternative criteria would be less stringent on time-dependent correlation
  - More variation in resulting ICE test cycle possible

VTP2 conclusions & discussion

HILS model validation - Validation criteria and application

- ☐ Suitability of criteria for all vehicle topologies and degrees of complexity

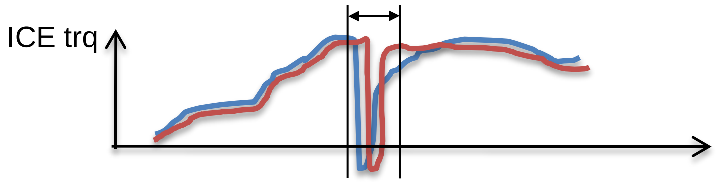
Consider: MAN model could not be validated, Volvo is partly close to the edge

- ☐ Putting either more effort in model validation or alternative data evaluation
  - Cut out error due to error propagation
  - Method to be analyzed and tested: Minicycle specific validation
    - Define initial conditions for each Minicycle according to the measurement data (accumulated error is reset)
    - Physical vehicle model and ECU control logics would be checked in the same way as in the current version of the validation process
    - R-squared values would be calculated for entire cycle
  - System behavior over time would be checked by Minicycle specific validation part
  - Additionally integrated values could be checked for entire cycle without resetting starting conditions in between
  - System behavior over 30min would not be exactly the same as in the measurement
    BUT also for repeated chassis dyno runs the behavior would be different

VTP2 conclusions & discussion

HILS model validation - Validation criteria and application

- Data omission during gear change
  - Necessary when using linear regression analysis
  - Bad R^2 result just because of slight differences (high gradients during gearshift)

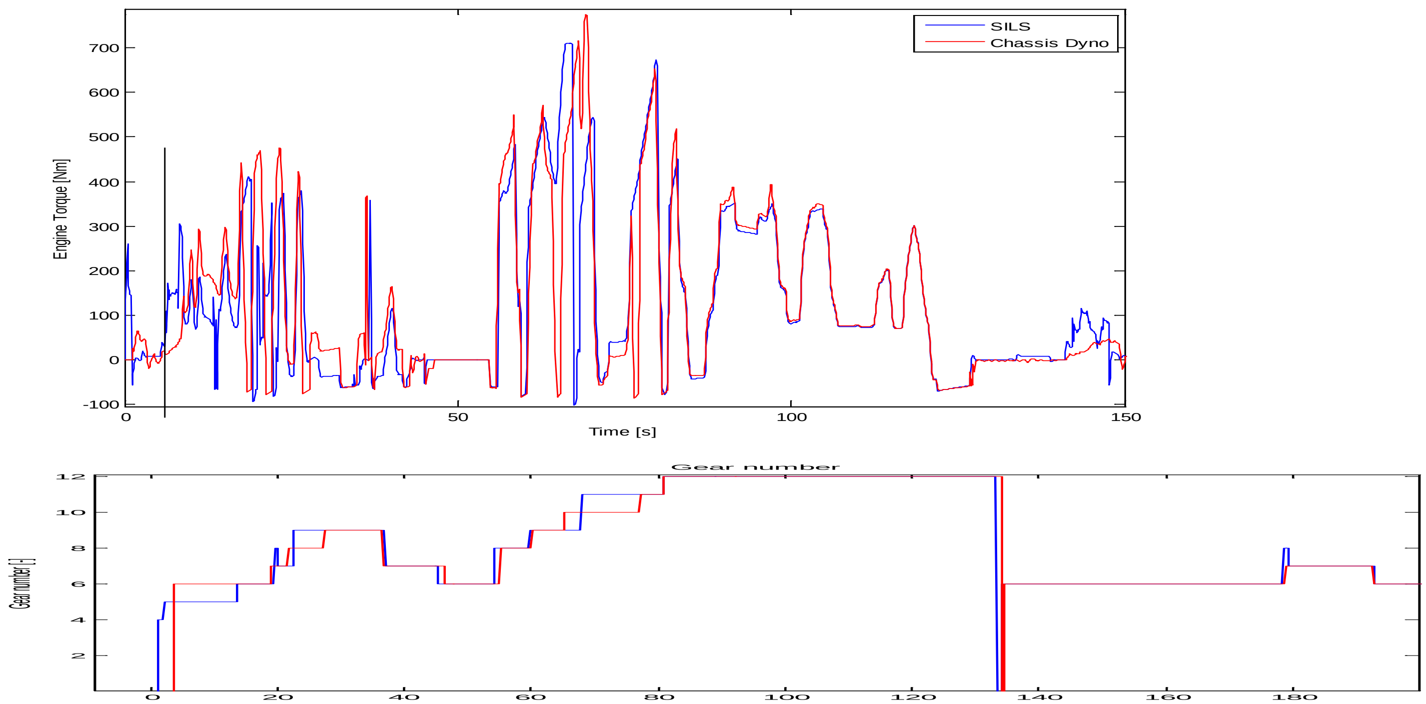


  - Not suitable to model behavior during gearshift accurately
- Data omitted increases with number of gears (…6,12,16 speed GB)
  - E.g. Volvo 12 speed GB:
    - 140 sec. validation: 75% of ICE torque data remains
    - Entire cycle validation: 85% of ICE torque data remains
- Nevertheless, data remaining needs to show similar behavior (using R^2)
  - Data omission is only valid for linear regression analysis
  - Omitting data is not allowed for work calculation (e.g. ICE work from trq/speed curve)

VTP2 conclusions & discussion

HILS model validation - Validation criteria and application

- ☐ Data omission during gear change
  - – Example of 140 sec. validation



- ☐ Data omission during gear change considered as reasonable

VTP2 conclusions & discussion
HILS model validation – What occurred beside…

- Occurred problems
  - Unavailability of data for components from external supplier
  - Restricted access to signals and values of components from external supplier
  - Control logics for components from external supplier
    - Case 1) control unit is needed as software version – availability of control logics
    - Case 2) control unit is needed as hardware version – detailed information for providing necessary dummy signals needed

VTP2 conclusions & discussion

Summary

- Though not all vehicles could fully pass validation, provisions in Kokujikan are considered as reasonable
- Considering the short timeframe in VTP2 and no experience with procedure at participating OEMs good results could be achieved
- Less complex vehicles were certified in Japan
  - Lower number of gears in shift transmission
  - No series hybrid with fully transient ICE operation
- For more complex hybrid systems (more DOF for operation) it is more difficult to pass the validation criteria (validity for future systems)
  - error propagation
  - Exact chronological alignment of system operation is a problem
  - May requires adaption of validation process and/or criteria
    - Additional analysis of data necessary
    - Additional HILS simulation runs necessary (test minicycle specific method)
- Regarding emissions the chronological sequence of engine load points is relevant and thus the R-squared criterion seems reasonable

VTP2 conclusions & discussion
Summary

- ☐ Validation procedure
  - Chassis dyno testruns will not be 100% reproducible
  - OEM is responsible to pick a representative testcycle (regarding emissions) for model validation
  - In best case the model can depict all measured test runs
    - Worked for at least 2 different test runs for Volvo and Iveco
    - Additional HILS/SILS simulation and data analysis would be suggested
  - Verifiability (repetition) of validation process may be difficult since chassis dyno testrun is not reproducible
- ☐ Simulation model should pass validation criteria for different testcycles
  - Experience of Japanese experts available?
  - Investigations needed (simulation runs with verified model and different chassis dyno testcycles)

Thank you for your attention!

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