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D4400.3 & D4500.3

Report of hybrid effects on emissions, noise and fuel consumption

Log of changes

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2013-06-27	First revision	Martin Sanfridson
2015-06-20	Added information regarding fuel consumption and noise as response to reviewer comments.	Robert Svensson

Summary

Rig tests have been performed in HCV sub-project SP4000 during 2012 to validate components, to make an integration test of the complete driveline and to estimate fuel consumption and emissions in order to make an intermediate evaluation of the goals of the sub-project. This report summarizes objectives, briefly describes the rig setups, and presents some of the results related to project aims on fuel consumption and emissions.

The energy storage system was tested and the results satisfy the requirements. An energy efficiency map of the DC/DC converter was constructed from measurements; the converter works according to specifications. The electric machine and its inverter were tuned and tested successfully.

The driveline test in the rig was a good test of the complete driveline and showed that the integration of components intended for the advanced second generation hybrid city bus was feasible. Emission levels are low but unfortunately, there was too little time to repeat the measurements to verify the preliminary results; the rig test could not confirm earlier simulations showing that the fuel consumption target of SP4000 will be reached. On-road measurements of fuel consumption and emissions are planned when the vehicle has been commissioned.

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Introduction

This document contains a summary on the effort to make a driveline integration test and to obtain intermediary results on fuel consumption and emissions targets by rig tests. This is a public compilation of confidential and restricted deliverables D4400.2 [1] and D4400.4 [2] and D4400.5 [3] covering the work carried out in FP7 Hybrid Commercial Vehicle (HCV) [4] work package 4400 by consortium partners Volvo, Kollmorgen and Magna.

The report provides an overview of objectives for the rig tests, a brief description of setups, and finally it reveals some results concerning fuel consumption and emissions.

Some explanation of the contents of related reports is necessary here. Deliverables D4400.3 “Report of hybrid effects on emissions, noise and fuel consumption” and D4500.3 “Report on the optimised hybrid drivetrain with results of fuel consumption gains for electrified auxiliaries, hybrid propulsion system and emission reduction” have been lumped together in this report. This does not constitute any reduction in the total amount of material presented in deliverables belonging to WP4400 and WP4500. The reason for the concatenation is that no fuel consumption or emission measurement activity is performed in WP4500. Measurements is performed in WP4600 and subsequently reported in D4600.1 [5] and D4600.2 [6]. Also, reports on the commissioning of the optimized hybrid drivetrain (without fuel consumption and emission measurements) when installed in the vehicle is found in D4500.4 [7].

Rig test objectives and plans

In sub-project SP4000 the advanced second generation hybrid city bus is designed and built. The main objectives in SP4000 “Advanced 2nd generation bus demonstrator” are to demonstrate improvements of a second generation hybrid city bus by

- 5% fuel consumption,
- 500 kg weight reduction
- 40% cost reduction of hybrid components

Further non-quantified objectives are to improve driveability, reduce noise and reduce emissions. The advanced second generation hybrid bus is compared with the early second generation.

Fuel consumption and emissions of the early second generation hybrid have been measured on a city bus route called CBR85 and reported in [7] and [8]. This measurement will be repeated with the advanced second generation bus, but before that there are a couple of activities to perform intermediate evaluations of targets. First, evaluation of the fuel consumption target has been carried out by desktop simulation. Likewise the weight reduction and cost reduction have been analysed. Second, the driveline of the advanced second generation bus has been put in a driveline rig. This rig test provides evidence of system integration of individual hybrid components developed within in the project and gives some indications (but no proof) of the fuel consumption, emission and noise levels.

Compared to the time plan in the project’s description of work, the time plan has been stretched as much as possible to allow time for installing and testing of individual components in the rigs used. The component tests were carried out during spring 2012 and the subsequent driveline test during autumn 2012 in Göteborg, Sweden.

Verification of components

Energy storage verification and characterization

The energy storage system is a battery connected to the higher voltage part of the electrical system together with the electric machine, used for propelling the vehicle, and a few other components. A characterization of the electrical performance of the developed Li-Ion energy storage system in Figure 1 has been done.

The characterization comprised of the following four tests

- Capacity test. The procedure was a discharge to zero percentage state-of-charge, a short pause, followed by a charge up to 100 % state-of-charge. The capacity calculated by coulomb counting is 8,06 Ah.
- Energy efficiency test. The procedure was a series of charge, pause and discharge sequences at three different current loads. The quotient between energy output and input gives an efficiency between 91,5 % and 97,2 %.
- Power capability test. The procedure was a discharge, pause and charge pulse at different operating temperature and state-of-charge set points. The result shows sufficient module charge and discharge power, i.e. according to specifications.
- CBR85 cycle test. The procedure was to run the city bus cycle's recorded usage of the battery system. The result shows that the steady state operating temperature is within the optimal operating temperature of the cells. Further, there is enough power capability and the cooling performance is sufficient.

The results verify that the desired electrical specifications of the energy storage system prototype as specified within HCV Task 4210 are fulfilled [12].

Figure 1 Energy storage system prototype for the HCV bus

DC/DC verification and characterization

The DC/DC unit converts electric energy from the higher voltage level (used to get enough power to propel the vehicle) to the lower voltage (24V) typically used for auxiliaries such as lamps and embedded electronic units.

A characterization of the efficiency was performed for the prototype DC/DC units shown in Figure 2. Air cooled resistive load banks were used on the low voltage side. The measurement equipment was a wideband power analyser. On the DC-link side a battery simulator was used instead of the real energy storage system in order to conveniently change operating conditions for the studied DC/DC units, see Figure 3.

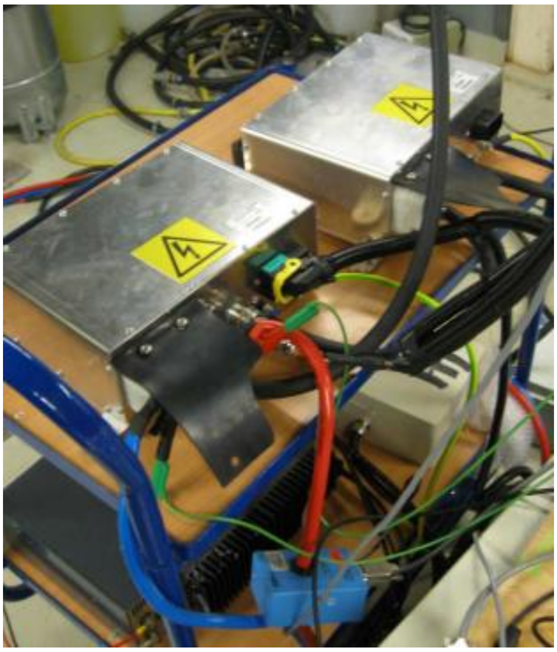

Figure 2 DC/DC test setup

The result of the characterization was a map of the DC/DC unit's efficiency at different operating points. The efficiency depends on the DC link supply (high side) voltage and the load's power consumption at the low side. The efficiency of the DC/DC units reaches 94 %. A likely average efficiency over a typical drive cycle with a typical load is about 91 %. Large current steps on the low side show responses that settle within 1 millisecond. The result is within specifications.

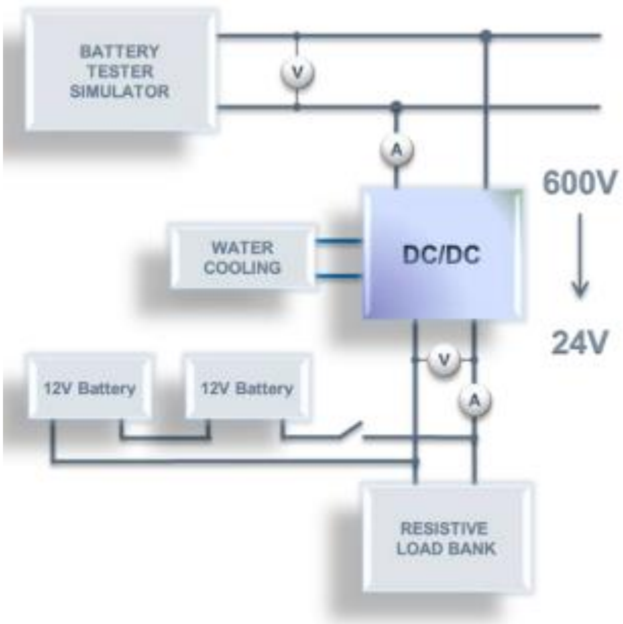

Figure 3 DC/DC unit test setup

The CAN communication was also tested to make sure the new DC/DC unit would fit with the control system later to be used in the driveline integration test.

Verification of the inverter for the electric motor

The electric motor is connected to the higher voltage system by an inverter. This power electronics controls the electric machine and electric energy can flow from the energy storage system to the electric machine and vice versa. The electric machine and its inverter were installed in a rig according to Figure 4. In motoring mode, the electric power is supplied in the rig by the battery tester simulator and the mechanical power is taken by the dynamometer load. The inverter shown in Figure 5 was a prototype developed in the project. A slightly upgraded inverter was later used in the driveline rig.

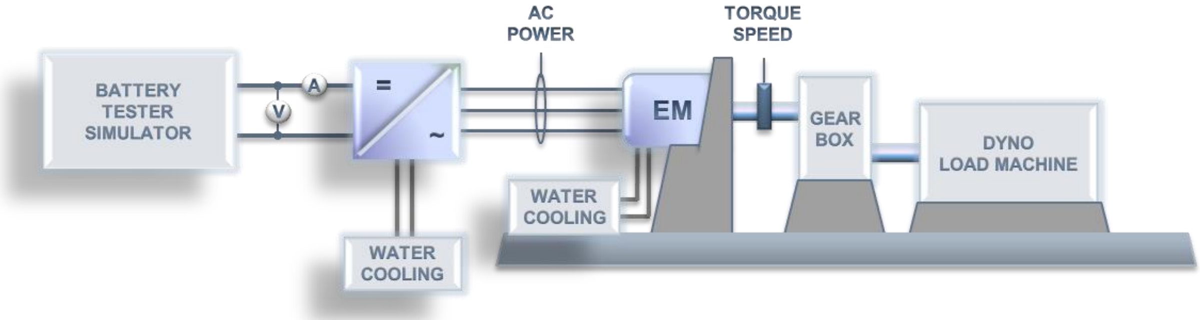

Figure 4 Test setup of electric motor (EM) and its inverter (=/~)

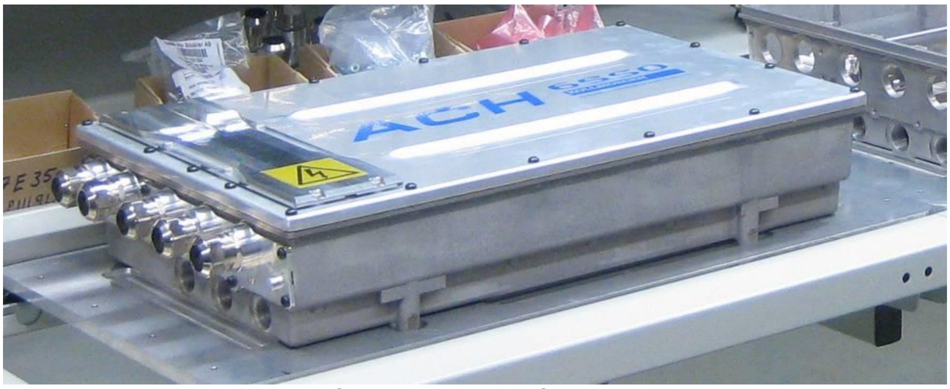

Figure 5 Prototype inverter

A functional test of the prototype motor drive system was carried out prior to complete driveline rig tests and demonstrator vehicle tests. In addition to stationary performance evaluation, an important part of the test was to verify the cooling of the electric machine.

The collected data showed that the performance of the electric machine and inverter was good and that the cooling of the electric machine was sufficient.

System integration of the driveline components

The hybrid driveline intended for the advanced second generation hybrid bus has been installed and tested in a driveline rig. It consists of the following components colour marked in Figure 6:

- combustion engine, a 5 litre diesel, with its electronic control unit EECU
- exhaust after treatment system
- transmission, 6 speed gearbox, with its electronic control unit TECU
- electric motor with its inverter (called EMD) and electronic control unit MCU
- energy storage system, ESS
- daisy chain configuration of higher voltage circuits
- converters from higher to lower voltage, DC/DC
- lower side voltage load (not shown in the figure)
- mock-up air compressor as higher voltage load (not shown in the figure)

The control system of the hybrid vehicle, which includes control units for the engine (EECU), transmission (TECU) and motor drive system (EMD and MCU), was integrated with the rig control depicted at the bottom of Figure 6.

The combustion engine and the exhaust after treatment system were of Euro VI emission class.

Five cooling circuits were used to control the temperature for the driveline components and also for the loads of the rig equipment.

The purpose of the lower voltage side load was to simulate auxiliary loads in the vehicle. The purpose of the air compressor at the higher voltage side was likewise to add the realistic load but also to add realistic characteristic electrical disturbances.

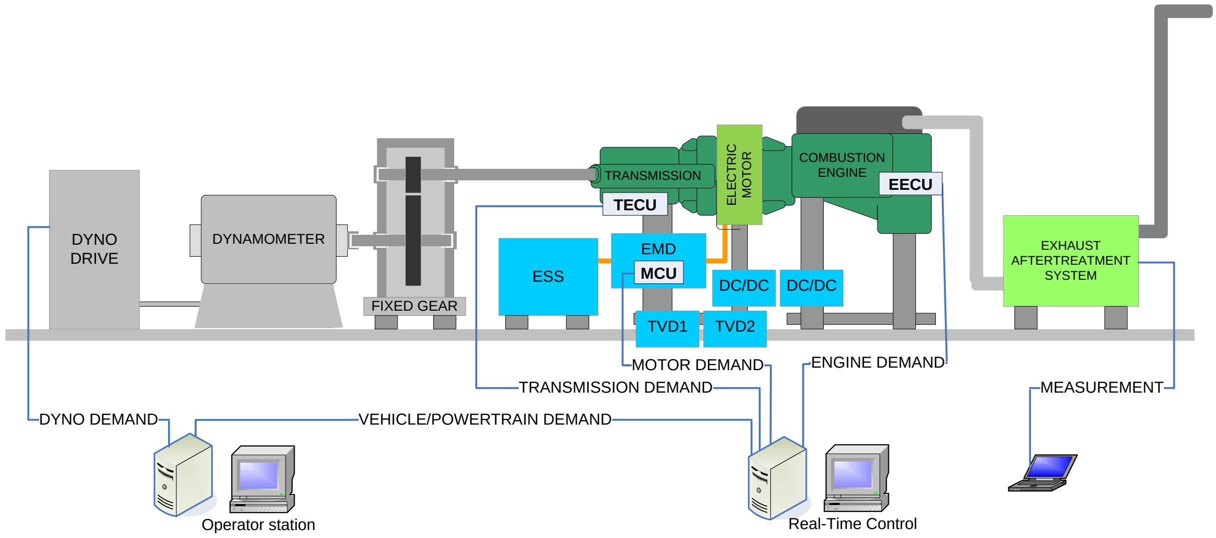

Figure 6 Driveline rig test set up with combustion engine, transmission (gearbox), dynamometer and the hybrid components (ESS, electric motor, EMD).

The output shaft of the hybrid driveline is connected via a fixed gear to a dynamometer which through its drive is connected to the rig's control system. This rig equipment, marked with grey colour in Figure 6, together with a simulation program to simulate the rest of the vehicle, environment and driver, completes the setup. The simulated chassis add important aspects such as vehicle weight and tires-road friction. The driver simulation affects the acceleration and braking behaviour during execution of drive cycles. The purpose of this setup is to make the driveline work, with as few modifications as possible, as if it was operating in a real vehicle by a real driver.

The simulated bus and environment with the real driveline were controlled from the operator station, see Figure 7 where a dashboard with vehicle and engine speed gauges are found on the left screen and plot of speed etc. including a graphical presentation of the bus with speed signs along the road are found on the right screen. The simulated vehicle, environment and driver offer repeatability which is beneficial for certain testing and evaluation.

Fuel consumption, emission and a multitude of internal variables in the embedded computer control system have been logged for all experiments that were carried out.


Figure 7 A snap shot of the operator station.

The test cycles were put into the operating control system in the form of speed limit signs that the simulated driver then tries to follow. The drive cycles tested were:

- SORT1, SORT2, SORT3 which are short synthetic cycles described in [14]
- TNO hybrid city bus cycle, which was developed within SP6000, see [11] for more information
- Three city bus cycles which are frequently used internally at Volvo for simulation and evaluation. One of these drive cycles is CBR85 that was used previously in the HCV project, for example during the initial measurements [8] in SP4000.

The combustion engine was also run as if it was alone in the test cell. By disconnecting the electrical parts of the hybrid driveline, an opportunity was created to run WHTC (the world harmonized transient cycle) which is an engine cycle, see e.g. [13] for its definition.

The overall testing worked fine. The driveline and the rig equipment, worked together without any major problems. The test in the rig was a good test of the whole driveline and showed that the integration of hybrid components worked. See result report [1] for more information.

Fuel consumption, emissions and noise

Functional development of the transmission application has been performed for the new driveline. This includes adaptation of existing functionalities for torque split, gear selection, engine start/stop, regeneration and electric only drive for the new driveline. These functionalities have successfully been verified in the driveline rig. The gear selection had to be made to work with six gears.

The fuel consumption during the test in test cell can be seen in Table 1 and Table 2 and this result is not showing a fuel saving of 5% and this can be due to several reasons. It has not been possible to point at any specific reason at the time of writing this report. The rig and its test object constitute a very complex system and many parameters have to be set correctly during a very limited time frame in the rig. It is positive that the rig test has triggered further investigations in order to arrive to a conclusion and, depending on the cause, perform corrective actions before the bus is declared completely commissioned. The driveline rig test could not confirm that the fuel consumption target of SP4000 is reached. However, refined simulation [10] confirms that the target will be reached but results from the planned WP4600 measurements in the bus have to be awaited.

The NOx emissions are lower with new engine aftertreatment system and have a NOx conversion of 80-95% which is higher than the earlier generation of hybrid system tested. The other emissions are within the legal limits for euro 6, for more information regarding fuel and emission testing see [1].

In the report HCV-D4600.2 & D4600.3 an explanation on the SOC difference can be seen and the information is shown here.
For the traction battery, the state-of-charge (SOC) difference before and after test run are presented. The SOC difference shows if the battery has been charged or discharged over the cycle which has an impact of the fuel consumption. With a negative SOC difference the battery has been discharged over the cycle. To compensate for this SOC difference it would have been necessary to have the diesel engine running at stand still at the end of the cycle in order to increase the SOC level to the original value. The fuel consumption is approximately affected 1% with a SOC diff of -5.4% and thereby neglected in this study.

Table 1 Average cycle data and fuel consumption from the measurements for all cycles

Measurement	Distance [km]	Cycle time [s]	Time at stand still [%]	Nbr. of stops	Nbr. of engine shut off	Avg speed (zero speed excl.) [km/h]	Avg. SOC [%]	SOC diff [%]	E-tp [kWh/h]	Fuel cons. [l]	Fuel cons. [l/100km]	Energy [kWh]
CITY2	19.0	3701	20	45	0 and 13	18.4 (22.9)	33.1	-4.6	NA	7.29	38.43	24.57
TNO	7.7	1135	11	0	0 and 1	20.3 (27.6)	30.6	-1.3	NA	3.03	40.40	10.65
SORT1	0.5	152	40	3	0	12.3 (20.4)	31.4	0.0	NA	0.24	46.36	0.77
SORT2	0.9	175	32	3	0	18.9 (28.0)	30.1	0.7	NA	0.34	36.67	1.14
SORT3	1.5	200	23	3	0	26.1 (33.7)	29.9	-0.4	NA	0.51	35.37	1.85

Table 2 Average emission and fuel consumption from the measurements for all cycles

Measurement	NOx [g/km]	NOx red [%]	NOx [g/kWh]	NOx red [%]	Inj. urea [g]	Inj. urea [g/km]	Inj. urea [g/kWh]	Inj. urea [l/kWh]	CO [g/km]	CO [g/kWh]	CO2 [g/km]	CO2 [g/kWh]	Fuel [kg/km]	Fuel [g/kWh]	Fuel [l/kWh]	Urea/ Diesel [%]	Urea dosing compared to NOx Ratio	NO2 [ppm]
CITY2, BEFORE SCR	5.17		3.99		265	14.0	10.8	0.010	0.81	0.62	821	634	0.33	252.17	0.30	3.3	2.7	15
CITY2, AFTER SCR	0.97	80.7	0.75	80.7					0.04	0.03	882	681						16
TNO, BEFORE SCR	5.87	0.0	4.14	0.0	129	14.7	10.6	0.010	0.70	0.49	871	615	0.34	242.34	0.29	3.4	2.6	16
TNO, AFTER SCR	0.28	95.4	0.19	95.4					0.03	0.02	950	670						1
SORT1, BEFORE SCR	5.99		4.04		5	10.4	7.1	0.007	0.95	0.64	889	598	0.39	265.27	0.31	2.1	1.6	16
SORT1, AFTER SCR	0.83	85.1	0.56	85.1					0.04	0.03	960	646						5
SORT2, BEFORE SCR	5.03		4.07		10	10.9	9.0	0.008	0.72	0.58	807	651	0.31	251.42	0.30	2.8	2.0	17

SORT2, AFTER SCR	0.59	87.7	0.48	87.7					0.03	0.02	864	697						4
SORT3, BEFORE SCR	5.89		4.63		30	20.9	16.5	0.015	0.63	0.50	864	679	0.30	236.26	0.28	5.5	3.5	18
SORT3, AFTER SCR	0.26	95.6	0.20	95.6					0.03	0.02	907	713						1

The acoustic noise was considered as being harsh in the high-pitch region. However, no conclusions can be made without further evaluation and considering the acoustic environment the bus chassis constitutes and also mounting specific details of the electric machine. Noise will be measured on a test track when the bus has been commissioned.

Noise measurements have been done in test cell on a similar hybrid drivetrain but at another time. The measurements were done when running in electric only and were made during two cases as can be seen in Figure 8.

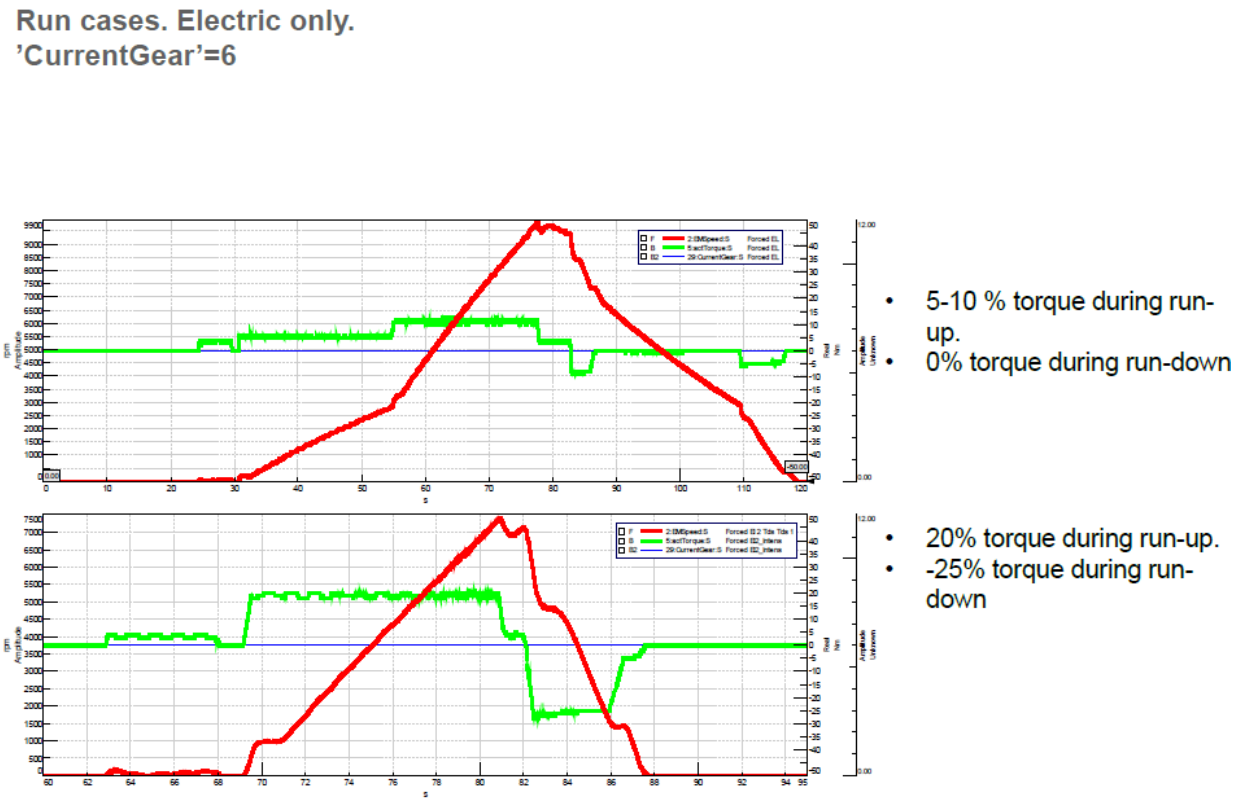

Figure 8 Two test cases for noise, showing speed, torque and gear.

The results from the measurements are shown in Figure 9.

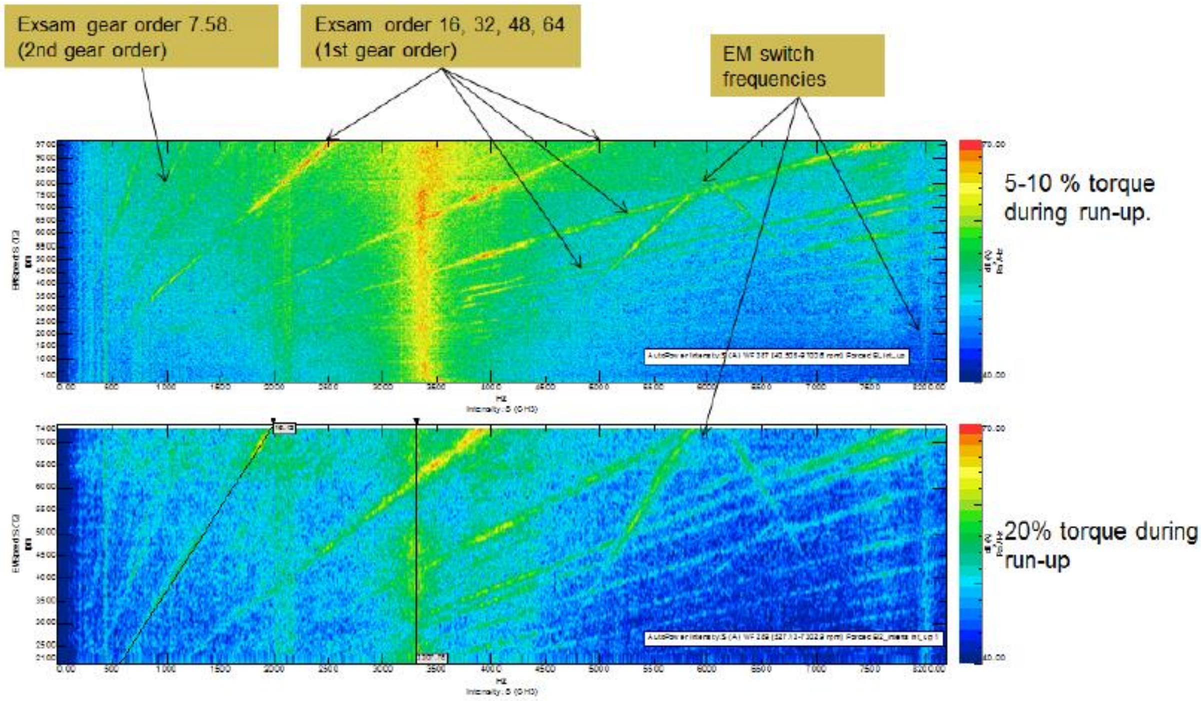

Figure 9 Sound intensity spectra for two run-ups.

The results presented are from running the driveline in ‘electric only’ mode. Note that the upper graph goes up to a maximum EM-shaft speed of 9700rpm, and the lower up to 7400rpm.
As can be seen in the graph above there are some tonal components which are from the gear meshes in the exSAM. The most prominent orders are 16, 32 and 48 which is the gear order and harmonics generated from the gear mesh between exSAM shaft and intermediate shaft. Looking at the second gear-mesh in the exSAM, order 7.58, between intermediate shaft and gearbox shaft the levels are much lower. The tonal components seen from ~5-7kHz origins from the switch frequency for the EM.

Conclusions

The components installed in the driveline rig were all prototypes not yet tested in production vehicles, i.e. on very low technology readiness levels. This turned the driveline integration rig test into a great challenge. With a limited number of weeks of rig time available the amount of experience gained through driving the virtual vehicle in the driveline rig became limited. The integration proved successful in the end. However, there was too little time to cross examine the results and perform repetitive development and measurement cycles, which means that the obtained result is difficult to verify. As a consequence, some of the interesting data concerning fuel consumption and emissions is not revealed in this report. However, the results have led to a further examination and understanding of the system. The next fuel and emission measurement will be carried out on-road when the vehicle has been commissioned.

The quality of the electric current of the higher voltage part did not cause any problems. High speed sampling measurements on individual components were also carried out.

The cost reduction target of the electrical hybrid components has been an important aspect. This can of course not be demonstrated in the rig but it is important to show the feasibility of the redesigned components when it comes to functional requirements. The DC/DC, the energy storage system and the electric motor drive worked according to specifications. The electric motor drive had to be retuned in the rig to damp certain frequencies found in the combined driveline and rig equipment. The daisy chain topology used for the higher voltage system worked well.

All components in the driveline were on prototype maturity level, i.e. basically between TRL5 and TRL6 according to [15]. Of course with that much equipment being on prototype level, several minor issues were encountered and a number of topics to continue working on were identified.

From a rough compare the sound levels of the orders are high enough to risk complaints.

References

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[8] D4100.1 “Early second generation hybrid vehicle equipped with logging devices for emissions and fuel consumption”
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