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Consideration and vote by AC.3 of draft gtrs and/or draft amendments to established gtrs - Proposal for Amendment 3 to global technical regulation No. 4 (Worldwide Heavy-Duty Certification procedure (WHDC))

Proposal for the Technical Report on the development of Amendment 3 to global technical regulation (gtr) No. 4

Submitted by the Working Party on Pollution and Energy *

The text reproduced below was adopted by GRPE at its sixty-ninth session (ECE/TRANS/WP.29/GRPE/69, para. 18 and Addendum 2). It is based on Addendum 2 to the report. It is submitted to the World Forum for Harmonization of Vehicle Regulations (WP.29) and to the Administrative Committee AC.3 for consideration.

* In accordance with the programme of work of the Inland Transport Committee for 2012–2016 (ECE/TRANS/224, para. 94 and ECE/TRANS/2012/12, programme activity 02.4), the World Forum will develop, harmonize and update Regulations in order to enhance the performance of vehicles. The present document is submitted in conformity with that mandate.

I. Introduction

1. The application of gtr No. 4 on engines installed in conventional vehicles can be characterized as a vehicle independent certification procedure. When developing the Worldwide harmonized Heavy-Duty Certification procedure (WHDC test procedure), worldwide patterns of heavy-duty vehicles were used for creating a representative vehicle cycle (WHVC). The engine test cycles World Harmonized Transient Cycle (WHTC) and World Harmonized Stationary Cycle (WHSC) derived from the WHVC are vehicle independent and aim to and are proven to represent typical driving conditions in Australia, Japan, the United States of America and Europe.

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

3. Consequently, this results in a less vehicle independent certification as for engines installed in conventional heavy-duty vehicles. A vehicle dependent certification as performed for passenger cars is not appropriate for heavy-duty vehicle vehicles due to the high number of vehicle configurations. Chassis dyno testing is, therefore, not considered a desirable certification or type-approval procedure, and two alternative test procedures considering the entire hybrid vehicle setup have been developed. To lower test burden and to avoid the introduction of vehicle classes, the required vehicle parameters have been made a function of the rated power of the hybrid system assuming that there is a good correlation between propulsion power, vehicle mass and other vehicle parameters. Data of conventional vehicles was therefore used to establish this approach.

4. Even though the WHTC engine dynamometer schedule is not considered representative for engines installed in hybrid vehicles, the WHVC vehicle schedule was modified to be closely linked to the propulsion power demands of the WHTC. This was enabled by introducing vehicle parameters as a function of hybrid rated power. This will result in comparable system loads between conventional and hybrid vehicles.

5. The test procedures developed are specified in Annexes 9 and 10, respectively. Both test procedures need to consider the entire hybrid vehicle within the type approval or certification test to reflect the engine behaviour during real-world operation. Therefore, both aim to reflect a vehicle chassis dyno test whereby:

(a) For the Hardware In the Loop Simulation (HILS) method the vehicle and its components are simulated and the simulation model is connected to actual Electronic Control Unit(s) (ECUs); and

(b) For the powertrain test all components are present in hardware and just missing components downstream of the powertrain (e.g. final drive, tires and chassis) are simulated by the test bed control to derive the operation pattern for the engine type approval or certification.

II. Vehicle parameters

6. The engine operation for engines installed in hybrid vehicles depends on the entire vehicle setup and, therefore, only the complete vehicle setup is reasonable to determine the engine operation profile. As indicated previously, heavy-duty vehicles can vary quite a lot

even though the power rating of the powertrain stays the same. Testing and certification of each vehicle derivative (different final drive ratio, tire radius, aerodynamics etc.) is not considered feasible, and thus representative vehicle parameters needed to be established. It was agreed at the fifteenth Heavy-Duty Hybrids informal working group meeting (HDH) (see HDH-15-06e.pdf)[1] that these generic vehicle parameters would depend on the power rating of the hybrid powertrain. This offers the key possibility to align the system demands for conventional and hybrid engine testing as described in chapter IV.

7. The equation describing the relation of power to vehicle mass is derived from the Japanese standard vehicle specifications. Curb mass, frontal area, drag and rolling resistance are calculated according to the equations in Kokujikan No. 281. Beside these parameters defining the road load, a generic tire radius and final drive ratio as a function of tire radius and engine full load were established to complete the generic vehicle definitions. They may not be representative for each individual vehicle but due to different vehicle categories in each region (Japan / United States of America (USA) / European Union (EU)) the harmonization of vehicle categories was considered very challenging and would probably have led to different categories for each region, which would in fact have increased the complexity and certification effort.

8. Since the hybrid related WHVC vehicle schedule was developed as a function of the rated power of the hybrid system, the vehicle parameters do not primarily define the system load. A deviation between generic and actual vehicle has no adverse effect for the certification. For the proposed test procedures the interaction of vehicle parameters, WHVC vehicle speed profile and road gradient defines the system load and they are designed to match the WHTC system load for an equally powered engine of a conventional vehicle (see chapter IV).

9. The benefits of introducing generic vehicle parameter can be summarized, as follows:

(a) The system load for hybrid vehicle testing can be aligned with conventional engine testing with reasonable effort in this gtr. Deviations between actual and generic vehicle parameters have no impact on the certification procedure. Therefore, pollutant emissions and limits of engine and vehicle test schedule are considered comparable under the premises of chapter IV.

(b) A vehicle independent certification similar to the WHTC test schedule and engines in conventional vehicles can be enabled for hybrid powertrains as well. This allows the manufacturer to mount certified powertrains in any vehicle and reduces test effort.

III. Development of WHVC vehicle schedule

10. It had been agreed within HDH that the pollutant emission type approval and certification procedure for engines installed in hybrid vehicles shall be, as far as reasonable, aligned with the test procedure specified for engines installed in conventional vehicles. This requires an alignment of the WHTC engine schedule and the WHVC vehicle schedule since the engine schedule is neither directly applicable nor reasonable for a hybrid vehicle's powertrain.

[1] Available at: https://www2.unece.org/wiki/download/attachments/12943378/HDH-15-06e.pdf?api=v2

11. Therefore, the vehicle schedule was developed with the premise that a conventional vehicle could be tested either using the engine or the vehicle schedule and both emission results would be comparable. Even though generic vehicle parameters were established, the power demand of WHTC and WHVC were still different and thus no comparable emission results could be expected. Directly aligning the power time curve had to be rejected, since the WHTC power pattern includes predefined sequences of gearshifts at specific times. Demanding the same gearshift sequences from hybrid vehicles as used for conventional vehicles at the WHTC generation was not considered reasonable, since the gearshifts should be executed according to the real-world operation. The proposed test methods for hybrids would be able to reflect those actual gearshift strategies.

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

13. To align WHVC and WHTC work, time curves of a normalized reference WHTC need to be available which can easily be de-normalized by using the rated power of the respective system. Common WHTC de-normalization considers the shape of the engine full load and, therefore, gives different results even though the rated power would be the same. Since neither a full load curve is easily available for hybrid vehicles nor the WHTC de-normalization be reasonable due to speeds below engine idle speed, a reference WHTC dependent only on the rated power was needed.

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

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

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

17. Data from twelve different worldwide representative vehicles were used for generating WHTC. Each data set is represented in one specific subsection of the cycle, called mini-cycle and lasting from vehicle stand still to the stand still on the WHVC vehicle schedule. During measurement, the recorded propulsion power demand for each vehicle was normalized to its engine rated power and combined to the WHVC normalized power time curve. Since all vehicles had different engine power to vehicle mass (and other parameter defining the road load) ratios and this power time curve served as basis for the WHTC, each engine tested on the engine dynamometer behaves as it would propel a vehicle where the payload is changed twelve times during the test cycle (at each stand still). This is of course reasonable since the WHTC test cycle covers typical engine operations representative of a large number of vehicles.

18. Generic vehicle parameters were defined which give one specific data set defining the road load (vehicle mass, curb mass, etc.) and this obviously does not include the change of payloads within the definition. Since adding payload and adding a positive road gradient both increase system load, the road gradients were chosen to imitate the different payloads as one of their tasks. Following the described correlations this would result in twelve different road gradients, a specific one for each mini-cycle, but the first adaption has to be made during vehicle deceleration to provide the correct amount of energy available for recuperation of hybrid vehicles.

19. Considering that the road gradient represents additional (or less) payload during vehicle propulsion it needs to be adapted during deceleration. An example is given, as follows:

20. A positive road gradient represents a heavier vehicle, which demands more propulsion power during acceleration. During braking the heavier vehicle would also be able to recuperate more energy but if the positive road gradient, which only represents the additional payload, would still be applied the potential for energy recuperation during braking would be lowered. Contrary to vehicle propulsion a heavier vehicle is represented by a negative road gradient during deceleration and since the value applied is representative for the payload the road gradient just needs to change its algebraic sign from plus to minus. The sections where inversed road gradients need to be applied can be identified by negative or zero propulsion power demand in the average WHTC and the WHVC (using vehicle longitudinal dynamics, the WHVC speed profile and the generic vehicle parameters). Sections less or equal to 3 seconds are not considered or aligned to avoid a shaky road gradient pattern, which would harm the drivability without any energetic impact.

21. Applying the described road gradient leads to alignment of WHTC and WHVC cycle work but with partial insufficient alignments. This is not because the road gradient could not address the correction of payloads, which works very well, but because certain sections during the WHVC speed and power profile recordings have not been driven on a flat road and in addition to the payload a real road gradient also needs to be considered for WHVC and WHTC alignment.

22. Sections where road gradients appeared during the measurements in the WHTC design process, although there is no information available, can be determined through a power mismatch between average WHTC and WHVC with applied road gradients representative for the different payloads (using vehicle longitudinal dynamics, the WHVC speed profile and the generic vehicle parameters). To be able to reflect them some of the twelve mini-cycles needed to be further divided in subsections. This occurs in sections where the average WHTC and WHVC power profile clearly differs.

23. To derive the road gradient (different payload), the twelve mini-cycle concept stays valid. To cope with real road gradients, the different power demand between the average WHTC and the WHVC with payload representing road gradients is again transferred into

an additional road gradient for the respective sections. This procedure gives a very good alignment of WHTC and WHVC, but implies to adapt the principle of the inversed slope for those specific sections to provide a representative amount of recuperation energy for hybrid vehicles. Since the road gradient now reflects combined payload and real road gradients, it cannot be as easily inversed directly as before for those specific sections. Under the assumption that the road condition unlikely changes every time the vehicle starts to decelerate just the mass-representing road gradient is inversed. The results achieved by this method demonstrated that a representative amount of recuperation energy is provided by the test cycle and that the work time curve could be very well aligned with WHTC.

24. The described method demands a calculation of the road gradient pattern for each power rating specifically to correctly align WHTC and WHVC. Investigations for a fixed slope calculated out of an average among different power ratings had to be rejected. A modified fixed slope concept was nevertheless introduced to simplify the calculation procedure, avoid the need for additional software and to ensure a practical handling for the gtr. It is based on an average slope calculated from power ratings between 60 and 560 kW, which represents 3.5 to 60 ton vehicles according to the generic vehicle parameters.

25. To compensate for the error in power and work alignment of different WHTCs and WHVCs when an average slope is used, a polynomial approach was developed. Since WHTC, vehicle parameter and WHVC road gradients depend on rated power, the error caused by the fixed slope follows. Introducing a second order polynomial to compensate this error enables an easy handling in the gtr without the need of additional software and without a significant loss of accuracy.

IV. System work concept

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

27. As explained above, the basis for the development of the hybrid load cycle of the vehicle as a combination of speed cycle, vehicle parameters and road gradients was that the propulsion power demand of the resulting load cycle is very close to the demand of the WHTC engine cycle. However, hybrid vehicles can provide the necessary propulsion power by two separate energy converters. Hybrid vehicles can recuperate a fraction of this propulsion energy by storing energy during decelerations of the vehicle. To be in line with testing of engines used in conventional heavy-duty vehicles where the engine work equals the vehicle propulsion work, also for heavy-duty hybrid vehicles the work for propelling the vehicle over the duty cycle and not only the engine work has to be used.

28. It was agreed within HDH that the propulsion work delivered by the hybrid system over the duty cycle shall be used as basis for calculating the emission values, since this approach allows a fair comparison between conventional and hybrid powertrains. This propulsion work delivered by the hybrid system over the duty cycle is referred to as system work.

29. Since there is no universal reference point for the determination of the propulsion power similar to the crankshaft of a conventional engine that is valid for all different layouts of hybrid systems, the wheel hub was defined as the common reference point valid for the hybrid systems. To be coherent with testing of engines used in conventional heavy-duty vehicles, where the propulsion power is measured at the engine crankshaft directly but

would need to be corrected for the efficiencies of the gearbox and the final drive to get the propulsion power at the wheel hub, the concept of a virtual combustion engine was introduced.

30. This means that the basic reference values of power demand are defined at the virtual engine crankshaft and two generic efficiency values of 0.95 are used to get the power demand at the wheel hub. Otherwise, the comparison between engines used in conventional heavy-duty vehicles and hybrid powertrains would be unfair, since two different reference points in the vehicle drivetrain would be used and the propulsion work at the wheel hub would be lower than the propulsion work at the engine crankshaft for conventional vehicles. This concept of the virtual engine crankshaft and the generic efficiencies is used throughout the whole procedure from the definition of the road gradients of the driving cycle, the determination of the hybrid system rated power and similar calculations and thus ensures that testing of engines used in conventional heavy-duty vehicles is in line with testing of engines used in heavy-duty hybrid vehicles.

31. For the HILS method (Annex 9), the propulsion power at the wheel hub is a standard output of the simulation model that has to be converted to the virtual engine crankshaft point by dividing it by the two generic efficiencies. Furthermore, this value is corrected for deviations between the reference engine work over the duty cycle from simulation output and the actual engine work measured on the engine test bed.

32. For the powertrain method (Annex 10), the propulsion power at the wheel hub is the same standard output of the simulation model that has to be converted to the virtual engine crankshaft point by dividing it by the two generic efficiencies. The propulsion power values do not need any further correction like for the HILS method, since in this case the engine is directly driven over the duty cycle with the whole hybrid system installed on the test bed and there is no additional step in between where a simulation output is used as a reference input cycle for the engine test bed.

33. The basis of the development of the concept from the test cycle at the beginning to the system work used for calculating the emissions in the final step was that the propulsion power demand of the test cycle is very close to the demand of the WHTC engine cycle. Therefore, existing emission limit values should also be considered as valid and should allow a comparison of emissions between engines and hybrid powertrains of a similar power rating used to propel the same vehicle.

34. The developed concept ensures comparability of different types of hybrid systems and also delivers reasonable results for different types of hybrid systems. Nevertheless, the underlying reference vehicle speed cycle WHVC, which represents an average worldwide mission profile of heavy-duty vehicles, may lead to disadvantages concerning emissions for some hybrid vehicles with primarily urban mission profiles.

35. Potential solutions for this problem would lead to a higher complexity of the emission type approval process, since they would require a mission specific testing of the hybrid powertrain or weighting of certain parts of the test cycle, and limit the application of the hybrid powertrain to one specific type of vehicle instead of allowing vehicle independent application. Additionally, a set of vehicle classes with specific limitations, e.g. only inner city driving, maximum vehicle speed, maximum vehicle mass, would need to be defined for application in gtr No. 4.

36. Furthermore, if mission specific testing or weighting of certain parts of the test cycle would be introduced for hybrid powertrains, the power demand of the driving cycle and the whole procedure for hybrid powertrains would not be comparable to the one for engines used in conventional heavy-duty vehicles any more. Consequently, mission specific testing or weighting of certain parts of the test cycle was not considered a viable solution by HDH.

V. Rated power determination

37. The test procedures for engines installed in conventional vehicles (WHTC engine schedule) and for hybrid systems (WHVC vehicle schedule) have been aligned in terms of power and work demand. To be able to do so, vehicle parameter and road gradients as a function of rated power described in chapters II and III have been established. This ensures that hybrid systems and conventional engines with the same power rating are loaded with the same load during the respective test procedure.

38. While the rated power of a combustion engine is a well-known and determinable parameter, the hybrid systems power can differ with test time depending on parameters like Rechargeable Energy Storage System (REESS) size, peak power capability, State of Charge (SOC) level, thermal restrictions of components and so on. Just summarizing component power ratings to derive the hybrid system power rating is not considered reasonable for multiple reasons and, therefore, the rated power test procedure shall determine a representative power rating for the respective hybrid system. It shall reflect its performance during in-use vehicle operation. In addition, the procedure needs to be applicable for both hybrid system test methods as regulated in Annexes 9 and 10 and performing the test with a conventional vehicle should give the power rating of the combustion engine installed.

39. An array of standard drive maneuvers was chosen to determine the capabilities of a hybrid system. It consists of full load accelerations starting from different speeds and applying different loads. This is representative for in-vehicle operation scenarios and for scenarios driven in the WHTC/WHVC. In line with the system work concept and the way the WHVC vehicle schedule was developed, the common reference point to determine the rated power for all vehicle concepts is the wheel hub. Considering a conventional vehicle, the power recorded at the wheel hub would, due to efficiency losses in the drivetrain, be lower than the combustion engine power and, therefore, standard efficiencies in line with chapters III and IV have to be used to correct this circumstance.

40. The recorded power at the wheel hub is thus divided by 0.95^2 to calculate the characteristic hybrid rated power for any hybrid configuration. Even though 0.95 may not be representative for each vehicle, this does not matter, since all alignments regarding test schedule and system work are based on the reference point at the wheel. The generic efficiencies have only been introduced to be able to transfer the WHTC power demands to the wheel for a conventional vehicle as a reference basis.

41. To determine the maximum performance of the hybrid system, it was agreed to be in warm initial condition and sufficient energy needs to be available (SOC level > 90 per cent of used range) before the start of each test scenario. However, performing a test where the maximum performance is considered as the characteristic rated power can result in a power rating where the WHVC vehicle schedule so derived can demand more power than the vehicle can deliver at a certain time in the cycle. This can be due to limitations of the hybrid system which take place depending on e.g. thermal restrictions or insufficient SOC level during the cycle and cannot be covered by the rated power test procedure which lasts shorter than the WHVC vehicle schedule. As a result, the vehicle may probably no longer be able to follow the desired vehicle speed in certain sections when the road gradient pattern is calculated using the hybrid power rating as described.

42. Consequently, only an iteration process where the vehicle schedule and the vehicle parameters are calculated with different power ratings would serve to identify the power rating where the vehicle is able to follow the test schedule, its full load capacities are tested and the frequency distribution of power in relation to its full load capacities is similar to the WHTC test schedule. However, depending on the design of a hybrid system, limitations may occur even when a different test scenario is used and the fulfillment of all three

demands may be not possible. It was agreed by the HDH informal group that the rated power test scenario is considered as reasonable for this amendment.

43. Due to limited availability of hybrid energy and design properties of the hybrid systems the determination of a representative power rating is more complex than for conventional engines. Nevertheless, a test method was developed where the hybrid system can be rated in a way that the test cycle demands its full load capacities in any case. The agreed method allows the alignment of conventional engine and hybrid system testing in terms of test cycle, system work for emission calculation and power determination and is valid and applicable for the powertrain and the HILS method without any changes to be made on a validated model.

VI. HILS Method

44. The HILS method (Annex 9) developed for this gtr is based on the Japanese regulation Kokujikan No. 281. To properly reflect the in-use engine operation for engines installed in hybrid vehicles for the certification or type approval, the main goal of the HILS procedure is to transfer a vehicle speed cycle into an engine test cycle, which is representative for the application in a specific hybrid system. Instead of a high number of actual vehicle test runs for different vehicle configurations, HILS enables the possibility to simulate a hybrid vehicle driving a transient vehicle speed cycle. During this simulation, engine operation is recorded, thus creating a hybrid system specific engine cycle. This engine cycle can then be used to test the engine's emissions on a conventional engine dynamometer.

45. The operation of the engine in a hybrid vehicle is highly dependent on the manufacturer's proprietary hybrid control strategies. Those strategies are part of the hybrid Electronic Control Unit(s) (hybrid ECUs). To be able to include these control strategies in the simulation loop, the hybrid ECU(s) are kept as hardware and are connected to the simulation, which is run in real-time. This process is called 'hardware in the loop simulation'. By means of the simulation model (consisting of sub-models for the driving resistances, the different powertrain components and the driver) corresponding to the real hybrid system and the real hybrid system control units as hardware, the vehicle speed cycle is transformed into a specific load cycle for the combustion engine. Operating the HILS system clearly reduces the practical test effort when variations on the hybrid system are made compared to actual testing of each system configuration. Annex 9 to this gtr includes figures and flowcharts illustrating the HILS test procedure in detail.

A. HILS model library

46. The structure and data flow from the models used in Kokujikan No. 281 was adapted to provide a simulation environment, which allows a well-defined selection and combination of components. The structure now follows a bus system with defined interactions of each module of the developed HILS model library. The design simplifies adaptations of the HILS simulator to different hybrid systems in future type approval applications.

47. For the complete vehicle simulation, it is preferable when the component models can be connected together in a straightforward manner to form a complete vehicle model. The modelling philosophy that is suitable for HILS or Software In the Loop Simulation (SILS) applications is called forwarding, which means that the powertrain is described by models described by differential equations. To achieve this, the model interfaces between the powertrain components need to be determined.

48. Two types of interfaces are needed where a port-based modelling paradigm was used:

(a) The physical interface is related to how different components are connected together physically and represents energy flows;

(b) The signal interface is related to control/sensor signals needed to control the components for an ECU.

49. For automotive powertrains, four (five) different physical interfaces are necessary. Those interfaces are: electrical, mechanical (rotational and translational), chemical and fluid. The following naming convention for the interface signals is used:

(a) Physical interface: phys_description_Unit

Where phys is fixed to indicate that it is a physical signal, description is a description of the signal, e.g. torque, voltage and Unit is the unit of the signal in SI-units, e.g. Nm, V, A, etc.

An example: phys_torque_Nm, which is the physical torque in a component model.

(b) Signal interface: Component_description_Unit

Where Component is the component short name, e.g. Clu, Engine, ElecMac, etc., description is a description of the signal, e.g. actual torque tqAct, voltage u and Unit is the unit of the signal in SI-units, e.g. Nm, V, A, rad/s, etc. As an example, ElecMac_nAct_radps means the actual rotational speed of an electric machine with the speed expressed in rad/s.

50. The model structure itself is divided into two parts, the physical model and the local controller. Every model includes a local controller, which converts the control signals from the control system (if existing) into local control signals, the block also sends sensor signal values to the control system, i.e. it handles the communication between the ECU and the physical model. The physical model block includes the implementation of the model equations. As forwarding is used, feedback signals that go into a block come from the block in front of the current component block. This means that from an energy perspective the energy that goes into a component block is given as the product of the input signal and the feedback output signal. Similarly, the energy that goes out from a component block is given as the product of the output signal and the feedback input signal.

51. Providing the library in MATLAB® Simulink®, which is a well-established software tool in the automotive area ensures the best usability for all participating parties. Nevertheless, the model descriptions as part of Annex 9 also allow using any software other than MATLAB® to set up a HILS simulator.

B. Component test procedures

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

C. Predicted temperature method

53. As cold start is part of the certification and type approval procedure for engines installed in conventional vehicles it was agreed that this scenario should also be applied on hybrid powertrains. Since cold start temperature is set to 25 °C for these test procedures and to avoid an unjustifiable effort where component data would need to be derived dependent on temperature, it is assumed that 25 °C cold start temperature will not influence the performance of the hybrid powertrain components. Nevertheless, the temperature could influence the operation strategy of the hybrid powertrain, which would lead to a different combustion engine operation. To be able to reflect this behaviour without implementing the mandatory use of accurate thermodynamic temperature models in the HILS library, where parameterization is considered as excessive effort, the hybrid control units shall be supplied with temperature data following the predicted temperature method.

54. For the cold start HILS run, temperature signals of elements affecting the hybrid control strategy need to be provided to the connected ECU(s). Regardless of their profile and origin they are used for the HILS simulation to generate the Hybrid Engine Cycle (HEC). To proof the correctness of the predicted temperature profiles the respective actual measured temperatures during emission measurements on the engine test bed (e.g. coolant temperature, specific temperature of after treatment system etc.) are recorded and compared to the predicted ones. Using linear regression analysis it shall be demonstrated that the predicted profiles have been correct and reflect actual temperature behaviour.

55. A validation of this method was performed by National Traffic Safety and Environment Laboratory (NTSEL) with available data of a Japanese vehicle, which was not part of the validation test programme as described in chapter VIII.

VII. Powertrain method

56. The powertrain test method proposed in Annex 10 is intended to delivers results relevant for certification or type approval comparable to the results obtained by the HILS procedure specified in Annex 9. Instead of using simulation models to derive the combustion engine's operation pattern, the powertrain method requires all components of the hybrid powertrain to be present in hardware and emission measurement is directly executed. Effectively, it reflects a chassis dyno test where chassis and most likely the final drive (and possibly the gearbox) are simulated by the test bed controller. The components simulated are subject to the same provisions as specified for the HILS method in Annex 9.

VIII. Validation of the methods

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

58. Since the emission measurement for the resulting engine duty cycle in Annex 9 is performed according to the provisions already included in gtr No. 4, the primary focus was laid on the HILS model validation. Therefore, chassis dyno tests were performed with all three vehicles. The developed WHVC schedule was applied according to its actual stage of

development at the respective test time, and thus the experience gained could be used for further development in terms of test schedule alignment with the WHTC and drivability on a chassis dyno. In the absence of other available validation criteria, the Japanese criteria of Kokujikan No. 281 were taken for assessing the HILS approach.

59. Real HILS model validation was not possible for all participating manufacturers within the validation test programme and therefore the validation results have been achieved using one HIL (hardware in the loop) system, one SIL (software in the loop) system and one MIL (model in the loop) system setup. As the chassis dyno measurements produce the reference data for the model validation, the accuracy of the dyno measurements turned out to be a key enabler for a successful model validation.

60. Independent of the use of HILS, SILS or MILS, it was demonstrated that an increased hybrid system complexity increases the model validation effort significantly. Consequently, the model validation for the serial hybrid system, which is the most complex of all systems tested, was not successful when applying the Japanese validation criteria. Of the two parallel hybrids, one vehicle passed all the Japanese criteria, the second one only part of them.

61. Therefore, alternative HILS model validation criteria have been considered but could not be further investigated within the timeframe of the HDH mandate. It was agreed at the seventeenth meeting of the HDH informal group to adopt the validation criteria as laid down in Kokujikan No. 281 and consider a modification of the criteria or the validation method in a potential amendment later on.

62. The powertrain method could not be specifically tested within the validation test programmes as part of the development process to this proposal of the amendment of gtr No. 4. However, a validation programme was conducted by the US Environment Protection Agency and Environment Canada, which demonstrated the general feasibility of the method.