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The Upcoming Global Technical Regulation for Determination of Electrified Vehicle Power (DEVP)

Michael J. Safoutin[1], Aaron Loiselle-Lapointe[2], Kieran Humphries[2], Elena Paffumi[3]

[1]*U.S. Environmental Protection Agency, 2000 Traverwood Drive, Ann Arbor, Michigan, U.S.A.*

[2]*Environment and Climate Change Canada, Ottawa, Ontario, Canada*

[3]*Joint Research Centre, European Commission, Ispra, Italy*

Summary

The United Nations Economic Commission for Europe (UN ECE) has proposed a Global Technical Regulation (GTR) for determining the rated power of electrified vehicles. Rated power is an input to the World Harmonized Light Vehicles Test Procedure (WLTP) and is also useful for other purposes such as customer information, insurance or taxation. The proposed procedure is applicable to electrified powertrains of all types and its power rating is comparable to the power ratings of conventional vehicles. This paper reports on the elements of the procedure, its technical basis and applicability to various electrified architectures, and a second phase of validation testing performed at Environment and Climate Change Canada (ECCC) and the European Commission's Joint Research Centre (JRC).

Keywords: testing processes, power, vehicle performance, regulation, HEV (hybrid electric vehicle)

1 Introduction

The United Nations Economic Commission for Europe (UN ECE) World Forum for Harmonization of Vehicle Regulations (WP.29) is a regulatory forum within the UNECE Inland Transport Committee. It includes many informal working groups (IWGs), including the IWG on Electric Vehicles and the Environment (EVE). EVE has been tasked with developing a Global Technical Regulation (GTR) for determining the rated power of hybrid electric vehicles (HEVs) and of pure electric vehicles (PEVs) powered by multiple motors.

This paper is a continuation of a paper presented at EVS32 [1] that described a first draft of the procedure and the findings of a first phase of validation testing. This paper describes the revisions to the procedure that resulted from additional research and a second phase of validation performed at Environment and Climate Change Canada (ECCC) and the European Commission's Joint Research Centre (JRC). It is intended to help users of the GTR understand the technical basis for the final procedure and how it can be applied to a wide range of electrified powertrain architectures.

1.1 Background

A vehicle power rating is useful for comparing the performance capabilities of passenger vehicles, and for other purposes such as vehicle classification, taxation, and insurance pricing. Additionally, the World Harmonized Light Vehicles Test Procedure (WLTP) [2] requires a vehicle power rating in order to classify test vehicles into power-to-mass ratio classes [3], and to allow low-powered vehicles to be tested on a downscaled cycle [4].

For conventional vehicles, the vehicle power rating used by WLTP and for most other purposes is simply the power rating of the engine, as determined by UN Regulation 85 ("R85") [5]. Losses downstream (e.g. transmission losses) are not considered. However, for electrified vehicles with both an engine and an electric machine, or multiple electric machines, no harmonized standard for determining a comparable power rating has been established. This complicates the downscaling and classification of electrified vehicles under WLTP, as well as the assignment of a power rating for other customary purposes.

1.2 Global Technical Regulation

In 2014 the EVE IWG was tasked with developing a harmonized test procedure for determining a system power rating for hybrid vehicles and for pure electric vehicles with more than one motor. A draft GTR proposal "Determination of Electrified Vehicle Power" (DEVP) [6] will be presented for consideration to WP.29 in June 2020 and will likely be established as a new UN GTR shortly thereafter.

2 Technical Basis

2.1 Requirements of a system power metric

The IWG identified several requirements for an electrified vehicle power rating. First, it should be qualitatively and quantitatively comparable to traditional engine-based power ratings, because these continue to be used for conventional vehicles under WLTP. It should also be verifiable, consistent, repeatable, impose a reasonable test burden, and be equitably applicable to all electrified architectures available now and conceivably in the future.

The IWG reviewed several concurrent research efforts [7], including: SAE J2908 [8]; research by Korea Automobile Testing & Research Institute (KATRI) [9]; and International Organization for Standardization (ISO) standard 20762 [10]. ISO 20762 was selected for its comparability to traditional measures and the flexibility offered by its two alternative test procedures, known as test procedure 1 (TP1) and test procedure 2 (TP2). The GTR proposal [6] provides more background on the selection of the draft procedure and its content.

2.1.1 Main modifications

As reported at EVS32 [1], the first phase of validation revealed significant differences between the results of TP1 and TP2 for many of the vehicles tested. EVE then focused on identifying the reasons for the differences and how to minimize them. This led to several modifications, the most significant of which are:

a) Default values for energy conversion efficiencies, a critical input to the power calculations, were replaced with a requirement for the manufacturer to provide efficiencies specific to the test vehicle.

b) Due to uncertainties in accounting for tire losses due to rolling resistance and slippage, the option to conduct TP2 using chassis dynamometer roller data was removed, in favor of axle or wheel hub instrumentation or use of a hub dynamometer.

c) To reduce variability, five repetitions are conducted, and an average taken of the last four.

d) A "reference point" concept was developed to confirm comparability and applicability of the procedure, and clear guidelines were developed for identifying the correct reference points for any architecture.

e) Rules were developed to determine applicability of TP1 and TP2 based on features of the powertrain.

f) To ensure that complex powertrains are correctly understood, the manufacturer is required to document the flow of power during the maximum power condition.

2.1.2 Reference point concept

The reference point concept ensures comparability to the power ratings of conventional vehicles, and consistency across diverse powertrains, by explicitly establishing a consistent measurement goal for TP1 and TP2.

Reference points are specific points in the mechanical power flow of an electrified powertrain that are analogous to the engine output shaft of a conventional vehicle. In general, they represent where mechanical power that propels the wheels (during maximum power output) is first produced from stored energy. The vehicle system power rating is the sum of the power transmitted through all of the reference points.

Considering a simple P2 parallel HEV (Figure 1), the reference points are at R1 (engine output shaft) and R2 (motor-generator MG output shaft). Because power at these points is not easy to measure directly, the procedure instead measures power flow at other points that are easier to instrument, and estimates the power at reference points R1 and R2 by accounting for the losses between the measuring points and the reference points.

Under ISO 20762, reference points are not explicitly defined. However, for a parallel P2 HEV, ISO's TP1 and TP2 define measuring points upstream or downstream of the reference points (respectively), and convert these to power at R1 and R2 by accounting for the relevant energy conversion losses.

Accordingly, both TP1 and TP2 as defined in ISO 20762 apply well to a parallel P2 HEV. ISO TP1 determines engine power at R1 by reference to engine speed and the engine maximum power curve (as determined by ISO 1585 [11]), and determines the power at R2 by measuring power from the rechargeable electrical energy storage system (REESS), i.e. the traction battery (subtracting accessory power) and multiplying by the electrical to mechanical conversion efficiency factor K1. Alternatively, TP2 determines the sum of the power at R1 and R2 by measuring power at the axle shafts and dividing by efficiency factor K2 to account for losses in the gearbox. If the applicable measurements and K factors are equally accurate, then for this powertrain architecture, TP1 and TP2 should always deliver the same answer for the sum of R1 and R2.

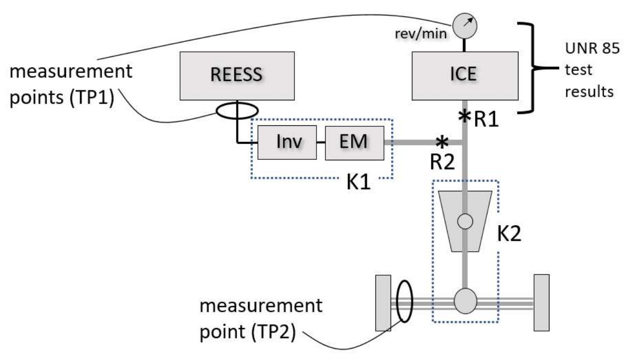

Figure 1. Reference and measurement points for parallel P2 hybrid
NOTE: measurement point for TP2 represents both axle shafts.

However, when EVE experts rigorously applied the concept of reference points to various HEV architectures, it was found that for some other powertrain architectures (for example, planetary power-split, pure series hybrids, and vehicles with two powered axles), the then-prescribed calculations for TP1 and TP2 may have been estimating power at slightly different reference points, leading to variation between the results.

For example, as shown in Figure 2, the Toyota Hybrid System (THS) utilizes a planetary gear set with multiple inputs and outputs. Under maximum power demand, engine power enters through the planet gear carrier (P), then is split between the ring gear (where it goes directly to the wheels) and the sun gear S (where it enters a series path that eventually delivers additional torque to the ring gear for delivery to the wheels).

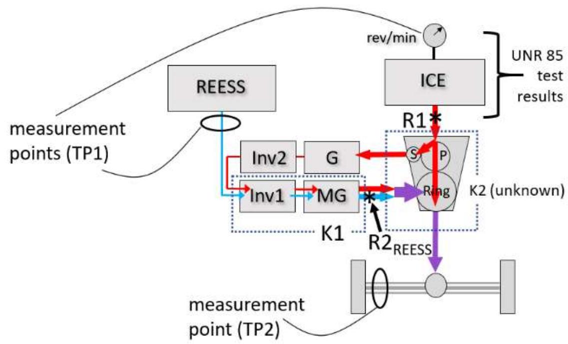

Figure 2. Power split hybrid, ambiguous under TP2
P = planet carrier and gears; S = sun gear; Ring = ring gear
NOTE: measurement point for TP2 represents both axle shafts.

One reference point is at R1 where mechanical power from the engine is first produced. From here, the engine power splits to a series path and a direct-to-wheels path, which together may be considered as a sort of electro-mechanical transmission. As with the transmission of a conventional vehicle, the losses (by convention) are not subject to accounting for the purpose of assigning a vehicle power rating.

Another reference point must be established to account for the contribution of the traction battery. Battery power is first produced as mechanical power at the output shaft of the motor-generator MG; however, at this point it has been combined with power contributed by the engine series path (which is already accounted for via R1). To prevent double counting, the second reference point is therefore called $R2_{REESS}$, and represents the portion of MG power that is attributable to the REESS (battery).

Once these reference points are defined, ISO TP1 is straightforward for this architecture. The power at R1 is determined from ISO 1585 results, and $R2_{REESS}$ is the measured battery power multiplied by K1 (where K1 is the electrical conversion efficiency of the total power flow through Inv1 and MG). System power is the sum of R1 and $R2_{REESS}$.

However, ISO TP2 has difficulty reconstructing the power at R1 and $R2_{REESS}$. ISO TP2 relies on a measure of total power at the axle shafts or wheel hubs, to which it seeks to apply a K2 efficiency factor to account for gearbox losses. But here, the power has arrived via two different paths from the engine, and a third path from the REESS (battery), all of which have experienced different conversion efficiencies. The combined power measurement at the axle does not identify the share of power along each path, so there is not enough information to reconstruct the power at R1 and $R2_{REESS}$ even if the conversion efficiency of each path is known. If the K2 factor were to represent just the efficiency of the mechanical direct drive path (as implied in the ISO procedure), then it would not be reconstructing the power at exactly the same designated reference points.

This is another way of saying that the original versions of TP1 and TP2, when applied to a power split hybrid, each determine the power at slightly different reference points. When considered individually, either of the results might be reasonable as a system power rating. However, they cannot be expected to be the same if they refer to different reference points.

This situation is seen more clearly in Figure 3, for a pure series hybrid. As before, the reference points are where mechanical power is first produced, at R1 and $R2_{REESS}$. ISO TP1 would determine the mechanical power from the engine (at R1) and the REESS contribution at motor MG (at $R2_{REESS}$). In contrast, ISO TP2 would measure the power at the axle shafts and apply a K2 factor to account for losses in the gearbox and differential, thereby reaching a different reference point (here called $R2_{TOT}$) and reporting that as the system power. The power at $R2_{TOT}$ is bound to be different than at ($R1 + R2_{REESS}$). Further, R_{TOT} is inconsistent with the concept of a reference point because it is not a point where mechanical power is first produced.

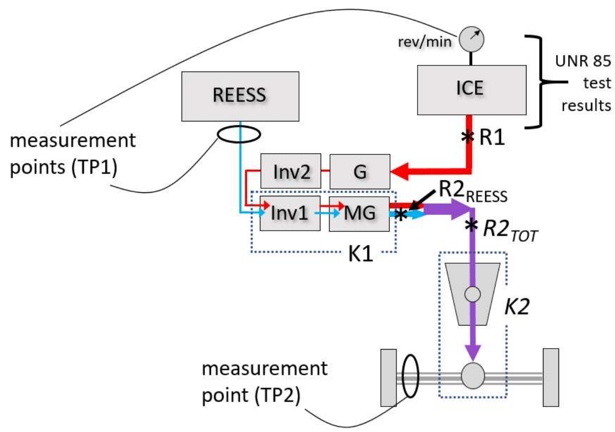

Figure 3. Inconsistent reference points for TP1 and TP2 for pure series HEV
NOTE: measurement point for TP2 represents both axle shafts.

Even when the reference points are harmonized, some powertrain architectures may pose special challenges to one or the other TP. As shown in Figure 4, a parallel P2 hybrid with two motors, TP2 would not have any difficulty determining the sum (R1+R2) from the measured power at the axle, given an accurate K2 factor. However, TP1 would measure power at the battery, without accounting for how this power is divided downstream, between the two parallel inverter/motors Inv1/MG1 and Inv2/MG2. Rather than measuring the battery power, it would be more effective to measure the power into each inverter, and apply a separate K1 factor for each inverter/motor combination. In some cases this would be very difficult to instrument, putting TP1 at a disadvantage.

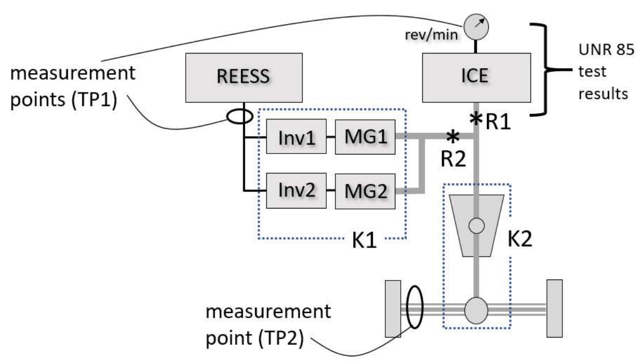

Figure 4. Parallel P2 hybrid with two motors, more difficult for TP1
NOTE: measurement point for TP2 represents both axle shafts.

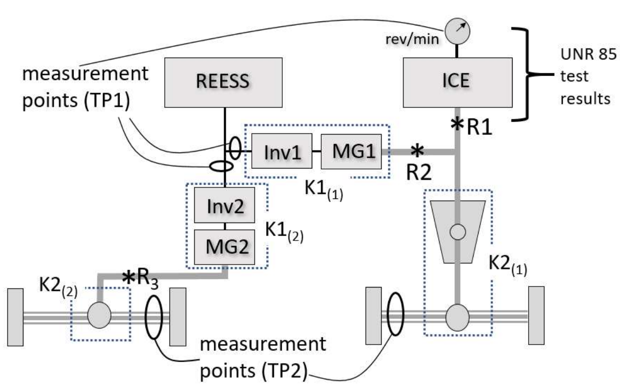

Figure 5. Parallel hybrid with two powered axles
NOTE: measurement points for TP2 represent both axle shafts.

Figure 5 (above) shows an HEV with two powered axles, where power must be measured at each axle. The reference points on the first (right) axle are R1 and R2, and on the second (left) axle, R3. TP2 is straightforward for each axle (although it does require a unique K2 factor for each axle). TP1 can determine R1, R2, and R3 if the electrical measurement points include the inputs to each inverter (Inv1 and Inv2) and factors $K1_{(1)}$ and $K1_{(2)}$ are provided. Alternatively, TP1 can determine R1 and the sum (R2+R3) if the electrical measurement is at the REESS and the conversion efficiency of the two electrical paths can be combined or are the same.

However, as shown in Figure 6 below, a small change to the architecture makes it very difficult to apply TP2. Here MG2 (R3) combines with ICE (R1) and MG1 (R2) by directly driving the axle. The power from R3 is likely to experience a very high efficiency $K2_{(2)}$, while that entering the gearbox/differential from (R1+R2) experiences a lower efficiency $K2_{(1)}$. TP2 measures only the combined power at the axle, and so cannot apply each K factor to the portion it represents.

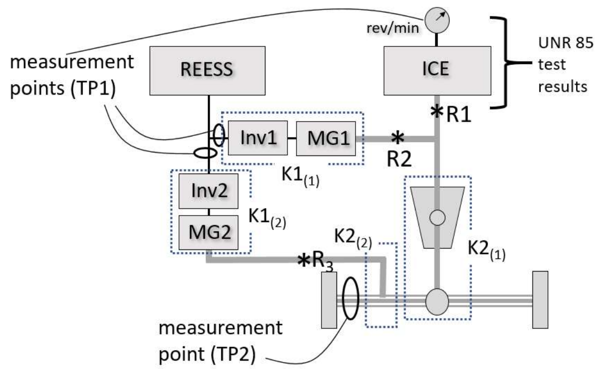

Figure 6. Parallel hybrid that presents difficulty for TP2
NOTE: measurement point for TP2 represents both axle shafts.

The applicability of TP1 and TP2 can depend not only on the physical configuration of the powertrain, but also on the driving mode. Figure 7 and Figure 8 show two high-power modes of the Generation 2 Chevrolet Volt powertrain, one a pure electric charge-depleting (CD) mode and another a blended charge-sustaining (CS) mode.

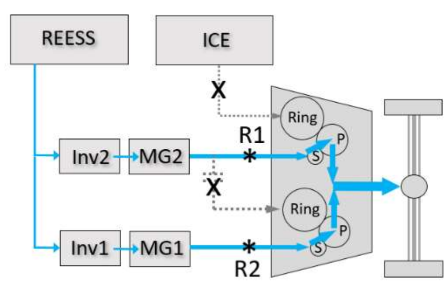

Figure 7. Volt Gen 2 charge-depleting Mode 2 (CD2)

In CD mode (Figure 7 above), both TP1 and TP2 can be performed (with certain assumptions). TP1 can determine both R1 and R2, assuming that the power into each inverter is measured, or the sum (R1+R2) if power from the REESS is measured and the conversion efficiency of both electrical conversion paths is the same and can thus be combined. TP2 can determine the sum (R1+R2) from the power measured at the axle, assuming that the efficiency of each sun-to-planet (S, P) gear path is the same.

However, in CS mode (Figure 8 below), the power flow paths are different. TP1 can still determine R1 and R2 from engine and REESS measurements. But for TP2 to determine the sum (R1+R2) as before, the efficiency of the Ring-to-planet and Sun-to-planet gear paths must be similar enough to be combined. Otherwise, the portions of power contributed by the engine and the motor must be determined, which are not collected by TP2.

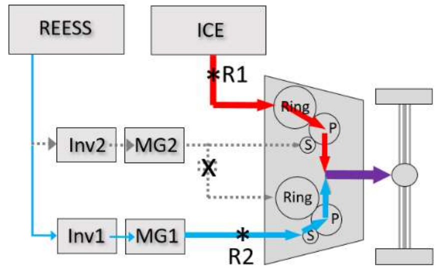

Figure 8. Volt Gen 2 charge-sustaining mode 2 (CS2)

It is thus necessary to consider powertrain architecture, mode, and the routing of power at maximum power demand in order to establish the correct reference points and determine applicability of TP1 and TP2. It should then be possible to determine the power at the reference points by means of the prescribed measurements and energy conversion "K" factors.

3 Second Phase of Validation Testing

A second phase of validation testing was conducted by ECCC and JRC, focused on evaluating the revisions to the procedure. ECCC tested four vehicles: a 2018 Toyota Prius Prime PHEV, a 2016 Chevrolet Volt PHEV, a 2018 BMW 530e PHEV, and a 2009 Saturn Vue BAS HEV. For TP2, Canada tested these vehicles using torque and speed sensors attached to the axle shafts. JRC investigated the use of an instrumented wheel assembly and a hub dynamometer as alternatives to the use of axle shaft sensors, and tested a rented parallel P2 HEV on a hub dynamometer to assess the agreement of TP1 and TP2.

Any research-level validation program can claim only a limited ability to reproduce an actual type approval situation. For type approval, the manufacturer would be expected to carefully prepare and provide all information required for conducting the procedure, such as K factors for TP1 or TP2, hybrid power flow descriptions, R85 engine test data, and technical consultation. Information of this type is often proprietary or costly to prepare and so was not always available, which limited the ability to perform some of the tests exactly as prescribed by the procedure. However, implementing the evolving procedure using available data and engineering judgment was very effective at identifying ambiguities in the procedure and further testing its ability to produce an effective characterization of system power.

The second phase of validation was initially intended to focus on reducing the difference between TP1 and TP2. However, this became less important as the procedure was revised with applicability requirements for TP1 and TP2, which meant that many of the vehicles could only properly be tested under TP1 or TP2, but not both.

For vehicles to which TP1 was applicable, technical issues with data collection and the unavailability of R85 engine test results for North American vehicles limited the ability for ECCC to perform TP1 exactly as prescribed. For vehicles to which TP2 was applicable, ECCC found that the use of torque and speed sensors is highly sensitive to calibration, temperature drift and difficulty zeroing the sensors once installed on the wheels. Issues with faulty sensors were reported to the manufacturer but could not be resolved in the short time frame available. However, the exercise helped resolve many open issues and ambiguities, and led to significant improvements in many areas of the procedure such as vehicle conditioning, instrumentation, and measurement accuracies.

JRC tested a parallel P2 HEV, for which both TP1 and TP2 were applicable, using a hub dynamometer for TP2. The hub dynamometer was more successful at delivering stable torque and speed measurements. As shown in Figure 9, the percentage difference between TP1 and TP2 averaged over the four repetitions was below 0.2% for both peak and sustained power. This strongly suggests that TP1 and TP2 deliver similar results when the measurements under both TPs are equally accurate.

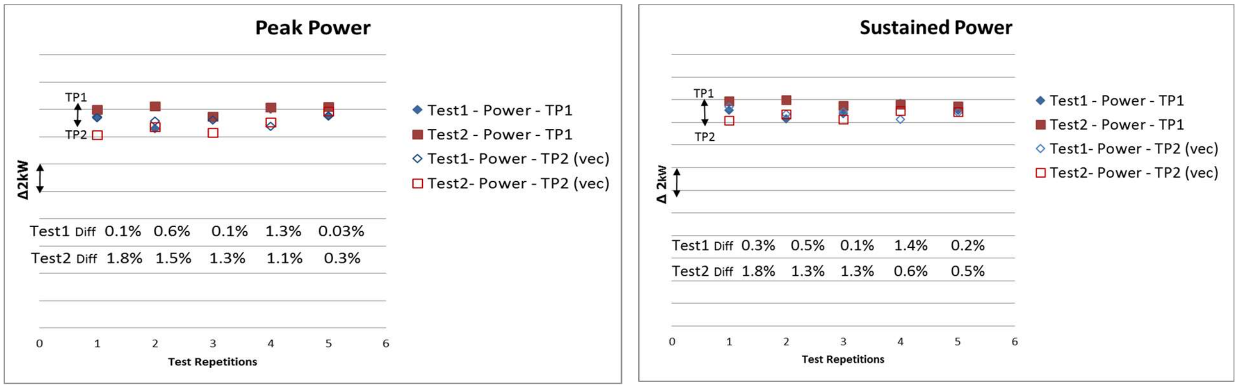

Figure 9. Agreement of TP1 and TP2 for P2 HEV using hub dynamometer

4 Overview of the revised DEVP GTR procedure

The validation exercises and proposed modifications led to the resolution of open issues and resulted in the version of the procedure proposed for the GTR. This section highlights the major features of the procedure. For a more complete description including all requirements and flexibilities, see the DEVP GTR proposal [6].

4.1 TP1 and TP2

The proposed GTR defines two equivalent methods to determine system power, TP1 and TP2. This serves to accommodate variations in powertrain architectures, vehicle instrumentation possibilities and laboratory capabilities. For some powertrain architectures or operating modes, only one of TP1 or TP2 is applicable. In theory, for vehicles where both TP1 and TP2 are applicable, they should deliver the same result if the source measurements and the efficiency factors are accurate. Onboard data may be used in place of physical measurements if their accuracy is shown to meet the requirements of the procedure.

In TP1, measurement occurs upstream of the reference points. Measurements include engine speed, intake air pressure, fuel flow rate, battery output voltage ($U_{battery}$), and battery output current ($I_{battery}$). Power to the DC-DC converter (P_{DCDC}) may optionally be measured, and power drawn by any high-voltage auxiliaries that cannot be turned off (P_{aux}) is measured or estimated. Efficiency factor(s) (K1), which represent the energy conversion efficiency between the electrical measurement point(s) and the output shaft(s) of the electric motor(s) during the power test, are provided by the manufacturer.

In TP2, measurement occurs downstream of the reference points. TP2 calls for measurement of power at the wheels (P_{wheels}), as measured by wheel torque and speed at each driven wheel or axle shaft, by appropriate sensors or a hub dynamometer. Efficiency factor(s) (K2), representing the mechanical efficiency between the reference point(s) and the measurement point(s) during the power test (i.e. gearbox efficiency), are provided by the manufacturer. If the test cannot be conducted at standard environmental conditions, then many of the measurements of TP1 may also apply, in order to determine and correct the engine portion of total power.

4.2 Reference points and applicability

The test authority examines the powertrain architecture and identifies the applicable reference points, based on manufacturer information and GTR guidelines. Applicability of TP1 and TP2 is then determined based on the architecture and the power flows that occur during maximum power output. If both TP1 and TP2 are applicable, the manufacturer may choose either.

4.3 Power test

After a vehicle conditioning cycle, the dynamometer is placed in fixed speed mode and set to a specific speed at which the vehicle has been determined to deliver maximum power. The accelerator pedal is then rapidly and fully depressed for at least ten seconds, while time series data is collected from the vehicle instrumentation and dynamometer. If the speed of maximum power is not known in advance, the power test is performed over a range of fixed dynamometer speeds until it is identified.

4.4 Power calculation

Under both TPs, vehicle system power is calculated as the sum of the power at each of the reference points:

$$Vehicle\ system\ power\ [kW] = \sum_{i=1}^{n} R_i \quad (1)$$

where

n is the number of reference points
R_i is the power at the i[th] reference point [kW]

The power calculations are performed on time series data collected during the 10-second power test. Two power ratings are calculated: a “peak” power rating, which is the maximum of a 2-second moving average over the 10 second window, and a “sustained” power rating, which is the average power between the 8th and 10th seconds.

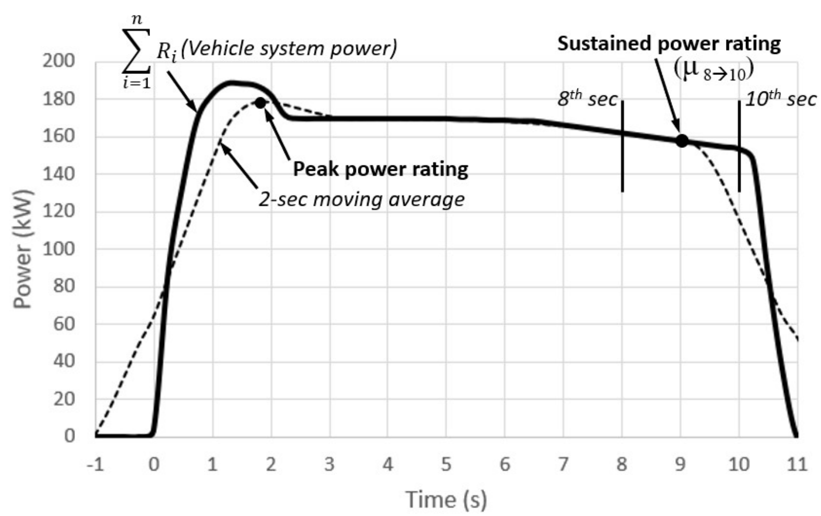

Figure 10. Determination of peak and sustained power

4.4.1 Calculation for TP1

In TP1, for reference points consisting of engine power, R_i is an engine power. derived from the measured engine speed, by reference to engine test results of UN Regulation No. 85 (“R85”), which reports engine output power, intake air pressure, and fuel flow rate at wide-open throttle (WOT) over the full range of engine operating speed. WOT is confirmed by comparing the measured intake air pressure and fuel flow rate to the test result at the observed engine speed. If WOT is not confirmed, options are to consult with the manufacturer or perform R85 under the observed conditions.

For reference points consisting of electric machine power, and where the measurement point is the battery output, R_i is determined by the equation:

$$R_i\,[kW] = \left(\frac{U \times I}{1000} - P_{DCDC} - P_{aux}\right) \times K1 \tag{2}$$

where

U and I are the measured battery current and voltage respectively (negative if flowing into battery)
P_{DCDC} is the power to DC/DC converter for 12V auxiliaries, if present (1.0 kW or measured value) [kW]
P_{aux} is the power to high-voltage auxiliaries powered by the REESS, other than P_{DCDC}, if present and operating during the test (measured or estimated value) [kW].
K1 is the energy conversion factor from DC electrical power to mechanical power.

For reference points consisting of electric machine power, and where the measurement point is the inverter input, R_i is determined by the equation:

$$R_i\,[kW] = \left(\frac{U_{Input} \times I_{Input}}{1000}\right) \times K1 \tag{3}$$

where

U_{Input} is the measured DC voltage at the inverter input [V]
I_{Input} is the measured current at the inverter input [A]
K1 is the conversion factor from DC electrical power to mechanical power.

4.4.2 Calculation for TP2

In TP2, the power at each reference point is calculated as:

$$R_i\,[kW] = \left(\frac{P_{axle}}{K2}\right) \tag{4}$$

where

K2 is the mechanical energy conversion efficiency factor K2 applicable to the axle
P_{axle} is the power measured at the respective powered axle [kW]:

$$P_{axle} = (2\pi \times n \times \tau)/1000 \tag{5}$$

where
n is the axle shaft or wheel speed [rev/s]
τ is the axle shaft or wheel torque [Nm].

5 Conclusions

This paper is meant to help stakeholders understand the technical basis for the upcoming DEVP GTR, the general structure of the test procedure, and its proper application to a variety of electrified powertrain architectures.

The second phase of validation provided a wealth of information on the practicability and effectiveness of the procedure. The results indicate that the revised procedure is practicable, and the resulting revisions have significantly reduced uncertainties in its application and the potential for variation between TP1 and TP2. The second phase also provided additional evidence that the maximum power of the vehicles tested can be reliably produced by the fixed-speed dynamometer method.

The availability of two test options, TP1 and TP2, provides flexibility to accommodate a diversity of powertrain architectures and the practical limitations of instrumentation. Differences between the results of TP1 and TP2 encountered in the first phase of validation led to a careful examination of the nature of the problem that the procedure seeks to solve, and the theoretical and physical requirements for a valid solution. This led to the reference point concept, which, when integrated with the procedure, provided (a) a clear technical basis for judging the applicability of TP1 or TP2 to various powertrain architectures, preventing the possibility of applying a TP for which the powertrain architecture cannot support its use, and (b) a strong theoretical basis for the expectation that TP1 and TP2 should yield similar results for powertrains to which both are applicable. These developments eliminate a primary source of the differences.

JRC's hub dynamometer tests confirmed very good agreement between TP1 and TP2 for a P2 parallel hybrid. Because the new applicability rules mean that not all vehicles can be evaluated by both TP1 and TP2, comparison between the results of TP1 and TP2 was often not possible nor relevant for other vehicles in the program.

The EVE IWG has good confidence in the ability of the revised procedure to deliver valid results. If the power flow is properly understood, reference points are correctly identified, and K factors and other manufacturer-provided inputs are accurate, the primary remaining source of potential error is measurement error. Requirements for measurement accuracy and frequency are clearly identified and align with similar requirements in ISO 20762 and GTR No. 15. If the test is conducted with care, the remaining potential for error should be small.

Acknowledgments

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Authors

Michael J. Safoutin is a Senior Mechanical Engineer with the US Environmental Protection Agency's (EPA) Assessment and Standards Division (ASD), part of the Office of Transportation and Air Quality (OTAQ) in Ann Arbor, Michigan, USA. As a subject matter specialist on electrified vehicles and advanced battery technologies, he has been a key technical contributor to U.S. EPA light-duty greenhouse gas standards and to United Nations Economic Commission for Europe informal working groups on global technical regulations. He holds a Ph.D. in Mechanical Engineering from the University of Washington and a Master of Science from the University of Illinois at Urbana-Champaign.

Kieran Humphries is a researcher in the Emissions Research and Measurement Section (ERMS) of Environment and Climate Change Canada (ECCC). He is involved with testing and evaluating electric and hybrid vehicles for use in Canadian climates. His recent activities include projects on electric bus range and energy consumption, alternative cabin heating methods for electric vehicles, and power determination for hybrid vehicles. Kieran holds a bachelor's degree and master's degree in Mechanical Engineering from McGill University in Montreal, Canada.

Aaron Loiselle-Lapointe is an engineer with Environment and Climate Change Canada (ECCC) and has 10 years of experience testing electric mobility technologies, both on the road and on chassis dynamometers. Previous to this, Aaron conducted in-use emission and fuel consumption tests on marine and locomotive engines. Aaron has a Masters of Applied Science degree in Environmental Engineering and a Bachelor's of Engineering degree in Aerospace engineering.

Elena Paffumi is a research scientist with the Joint Research Centre (JRC) located in Ispra, Italy. After years working in the nuclear field she moved to sustainable transport and she is in charge of the European pre-normative research for hybrid and electric vehicles and policy support. She is member of the UN ECE working groups related to hybrid and electric vehicles testing procedure definition. Her research focus includes e-mobility, big data analysis, experimental testing of vehicles and transport policy support. She is author of several scientific articles. Elena holds a Ph.D. in Engineering and a Nuclear and Sub-Nuclear Physics University degree.