APPLICATION OF SYSTEM POWER CONCEPT ON HYBRID ELECTRIC VEHICLES AND ELECTRIC VEHICLES

Dongseok CHOI
Kwangbum LEE, Kihyeon Ryu, Haeboung KWON, Jonghyun LEE
Korea Automobile Testing and Research Institute
Republic of KOREA
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ABSTRACT

The concept of system power for motor vehicles becomes necessary because multi energy converters and higher efficiency drivetrain are being adapted in advanced motor vehicles for the energy savings and the precise emission controls. This concept is very important in hybrid vehicles due to two different energy converters such as an internal combustion engine and an electric motor. This concept is also applicable to electric vehicles for the efficiency of energy transfer from energy sources to vehicle wheels.

The system power is measured on the powertrain test bed at the state of whole vehicle. It is possible to measure the wheel torque precisely by the direct connection between the power absorber and the end of drivetrain without tires. Two different test methods were developed for the measurement of system power. One is the acceleration at full load under road load (i.e., Method I); the other is the acceleration at full load under the constant vehicle speed (i.e., Method II). Three HEVs and two EVs were tested using the developed test methods. The different types of drivetrain such as an automatic transmission (AT), a continuously variable transmission (CVT) and reduction gear (RG) were equipped in the test vehicles respectively.

Engine speed, coolant temperature, and SOC condition were very important factors for this test in order to produce the maximum power. Method I was much better one for the measurement of system power despite of transient characteristics. The analysis of standard deviation was used for the determination of transient system power at the specific vehicle speed. The criterion for this analysis is the standard deviation of one value, which means that each power value is within +/- two percent of averaged power value.

By measuring system power at the constant vehicle speed, it is shown that the transient power by method I could be maintained during at least 30s. The repeatability of method I was within +/- 5 percent. It is found that this concept and method are applicable and reasonable for the power test of HEVs and EVs.

INTRODUCTION

High efficiency and environmentally friendly vehicles have been developed since the reduction target of green house gases concentrates on the ground vehicles. An electric vehicle (EV) uses one or more traction motors for propulsion. Three main types of electric vehicles exist, those that are directly powered from an external power station, those that are powered by stored electricity originally from an external power sources, and those that are powered by an on-board electrical generator, such as an internal combustion engine or a hydrogen fuel cell. The mass production of those vehicles was started from hybrid electric vehicles (HEVs) and is being extended battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) [1, 2].

Hybrid electric vehicles are possible to drive efficiently by adapting an internal combustion engine and an electric motor. However, much confusion arises in defining which power is used as the maximum power of the engines. Much more electrified hybrid vehicles were inevitably faced with this problem.

Therefore, the concept of system power in terms of power measurement becomes necessary because multi energy converters and different types of drivetrain are adapted in hybrid electric vehicles. This concept of system power in terms of energy saving is applicable to electric vehicles. It shows how much energy transfers from a power source to a vehicle wheels.

System power means the power measured at the vehicle wheels in the powertrain test bed. It is possible to evaluate the power in a whole vehicle state using this concept. In other words, system power is equal to powertrain power because the definition of powertrain contains with energy storage and/or source, an engine, and a drivetrain. Moreover, this concept is irrelevant to an energy source or storage, an engine type, and a drivetrain type.

Meanwhile, it is difficult to conduct the test of maximum engine power due to the adaptation of the security system and the active safety system. Therefore, it is necessary to introduce the concept of system power on high efficiency and

environmentally friendly vehicles such as HEVs and EVs.

OBJECTIVES

This study has two objectives. One is to apply to the concept of system power on HEVs and EVs. The other is to evaluate the energy transfer efficiency for HEVs and EVs using this concept.

EXPERIMENTAL SETUP AND METHOD

Experimental setup

Figure 1 shows schematic of powertrain test bed [3]. The powertrain test bed is possible to measure the wheel torque precisely through the direct connection between the power absorbers and the ends of drivetrain without tires. It consists of four dynamometers, its control and I/O system, a pedal jig for acceleration, and a cooling fan. Each dynamometer as load absorber is a synchronous one with low inertia, maximum power of 290kW, maximum torque of 2500Nm. It is possible to install the vehicle with the wheelbase ranging from 1.8m to 3.8m and the wheel track ranging from 1.2m to 2.2m in this test bed. A pedal jig for acceleration equipped in a driver's seat is specially made in order to adjust an acceleration pedal. The speed of a fan for the vehicle cooling is adjustable with a vehicle speed.

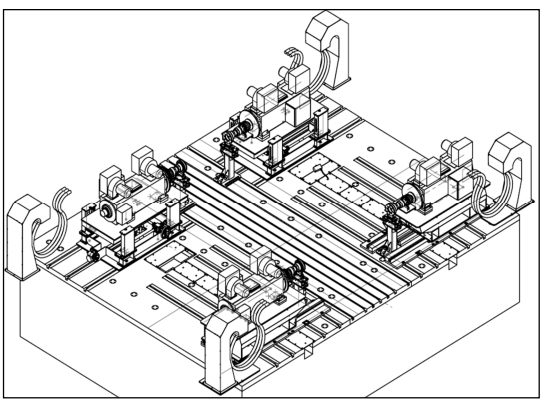

***Figure 1*. Schematic of powertrain test bed**

Methodology

Two different test methods as shown in figure 2 were suggested for the measurement of system power. One is the measurement under road load (i.e., method I); the other is the measurement at the constant vehicle speed (i.e., method II).

Method I rapidly accelerates at full load from the minimum vehicle speed or vehicle standstill to the predefined maximum speed or 60s. This method should measure the friction of drivetratin in the state of neutral gear in order to set the road load properly. Dyno adaptation is completed by subtracting this frictional resistance from actual road load. This method could be shown dynamic characteristics of powertrain. Due to the nature of the method I, the maximum power is produced within a few minutes. Method I could be had a noise problem due to very short measurement time. For this reason, the determination process using a standard deviation was provided. In order to make easier determination of maximum system power, all data were recorded at 100Hz.

Method II put the full load after the stabilization period of 60s at the constant vehicle speed by the speed control of dynamometer. All data were recorded at 100Hz like method I. This method do not consider the road load. Due to this difference between two methods, the power value by method I is smaller than that by method II.

These methods were also developed using a conventional vehicle with a gasoline engine and a 6-gear automatic transmission [4, 5]. In testing both methods, test vehicles were fully warmed up by running the vehicles at a moderate speed (90-100 km/h) for at least 10 minutes before beginning test.

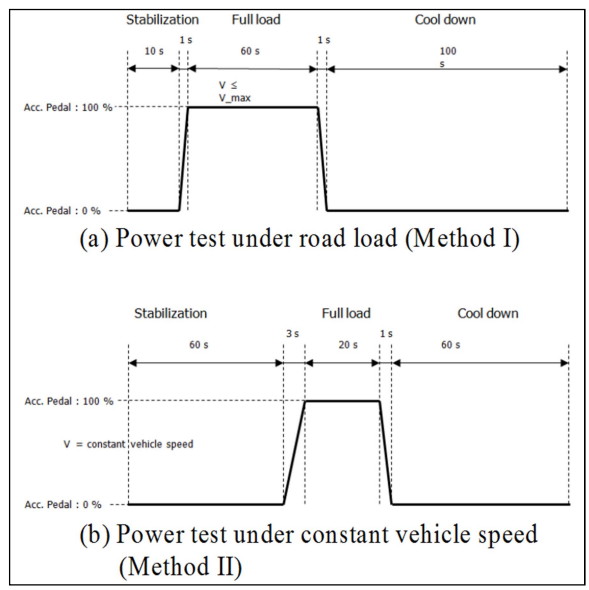

***Figure 2*. Experimental method**

Test vehicles

Five vehicles were tested using Method I and II. Test vehicles were consisted of three different hybrid vehicles and two electric vehicles. Each vehicle had different power of a traction motor and different type of a drivetrain such as an automatic transmission (AT), an electronically controlled continuously variable transmission (ECVT), and a reduction gear (RG). For the case of vehicle C, the system power value was provided by the manufacturer [6].

Table 1.
Specification of powertrain of test vehicles

Power / Test Vehicles	Internal Combustion Engine (kW)	Electric Motor (kW)	Drivetrain type
A	133.2	17.6	AT
B	110.4	30	AT
C	55.9	50	ECVT
	System power : 74 kW		
D	-	50	RG
E	-	70	RG

RESULTS AND DISCUSSION

Figure 3 shows the measurement result of system power on vehicle A by method I. Vehicle A is the hybrid electric vehicle, which has the layout connected by the belt between an internal combustion engine and a traction motor. The powertrain consists of a compact electric motor powered by a lithium-ion battery, a 2.4L gasoline engine, and a 6 gear automatic transmission.

Wheel torque shows the typical trend of rapid acceleration at full load. High wheel torque transits to low wheel torque as the gear shifts up. Two jerk points appears in the vehicle speed ranging from 60km/h to 110km/h due to the gear-shift shock. The maximum system power appears around 140km/h. Engine speed is also around 5700rpm at this vehicle speed.

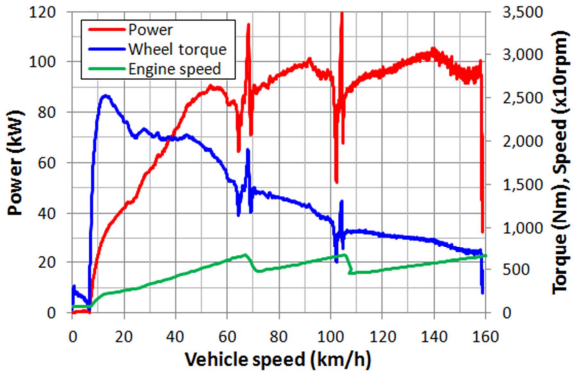

***Figure 3*. Test result of system power on vehicle A by method I**

Each power value was averaged with the vehicle speed. Each vehicle speed was calculated down to the first decimal place. In order to determine the maximum system power, the analysis of standard deviation was used. The criterion for this analysis is the standard deviation of one value, which means that each power value is within +/- two percent of the averaged power value.

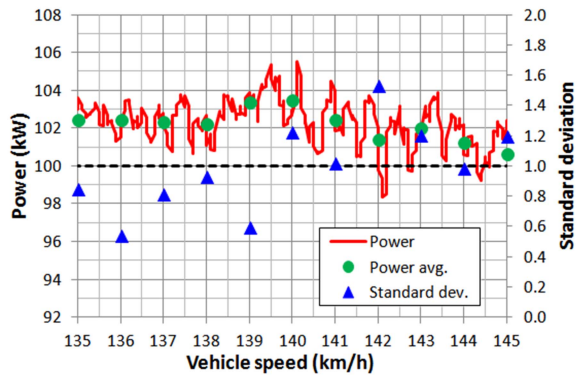

***Figure 4*. Determination of max. system power by analysis of standard deviation**

Figure 4 shows the result of this analysis. Two candidate values at the vehicle speed of 139 and 140 kilometers per hour were shown in figure 4. The standard deviations were 0.6 and 1.2 respectively. Thus, the maximum power value was 103.4kW at 139km/h. This test conducted three times and then the averaged value was 103.8kW at 138km/h.

For the case of method II, the vehicle speed was set in 140km/h and the load was given full within three seconds. The result by method II showed 105.3kW at 140km/h. The difference between two power values is whether road load is considered or not, which is the characteristics of test method. From these results, the transient power measurement by method I is also possible to represent the power performance of the vehicle.

Figure 5 shows the measurement result of the system power on vehicle B by method I. Vehicle B is a parallel type of hybrid vehicle, which has two ways for the power transfer to the wheels. This parallel hybrid system features the clutch and the electric motor positioned between the engine and the transmission. The powertrain consists of a 2.0L gasoline engine, a clutch, an electric motor powered by lithium polymer battery, and a 6 gear automatic transmission.

The wheel torque is a little different with that of the vehicle A due to the different hybrid feature. No jerk point appears in the vehicle B. The first peak of the wheel torque shows the engine torque due to a rapid acceleration. After this peak, the torque by the electric motor affects dominantly by the vehicle speed of 40km/h. The wheel torque is similar with that of the vehicle with a conventional 2.0L gasoline engine [5]. The maximum system power appears around 115km/h. Engine speed was also around 5700rpm at this vehicle speed. Through the analysis of standard deviation for the system power values in the test three times, the maximum system power was 101.6kW at 113km/h.

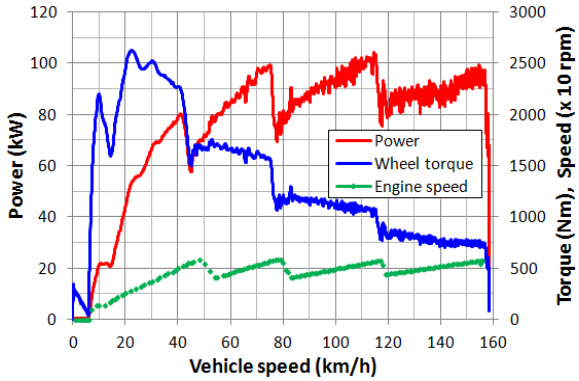

***Figure 5*. Test result of system power on vehicle B by method I**

The test result of vehicle B by method II had significantly different with that of the others. The measurement of system power by method II was conducted at the vehicle speed of 110km/h, 115km/h, and 120km/h. Engine speed at full load was around 4400rpm. Maximum system power was about 90kW at three vehicle speeds above. Thus, vehicle B did not reach the maximum power value measured by method I due to the effect of the control logic on the engine and the electric motor.

Figure 6 shows the measurement result of system power on vehicle C by method I. Vehicle C is also a parallel type of hybrid vehicle. The powertrain consists of a 1.6L gasoline engine, an electric motor of 50kW powered by Ni-MH battery, and an electronically controlled continuously variable transmission.

The wheel torque is quite different with those of the vehicle A and B due to the different hybrid types and transmission features. No step of wheel torque by gearshift appears in vehicle C. The shape of wheel torque until the vehicle speed of 50km/h is similar with the torque shape of the traction motor. Wheel torque below 50km/h has a significant effect on the motor torque, while the wheel torque over 50km/h has a dominant effect on the engine torque. The engine speed of 5000rpm for the maximum engine power was achieved over 90km/h, which means that the maximum system power also outputs over this speed. This power value was approximately 65kW. Through the analysis of standard deviation for the system power values in the test three times, the maximum system power was 68.1kW at 92km/h.

Figure 7 shows the measurement result of the system power on vehicle C by method II. Three candidates for the maximum system power on vehicle C was at the vehicle speed of 90km/h, 100km/h, and 110km/h. Engine speed also reached about 5000rpm over 90km/h. With a little difference, the maximum system power was 70.3kW at 100km/h. The difference between method I and method II is due to the consideration of road load.

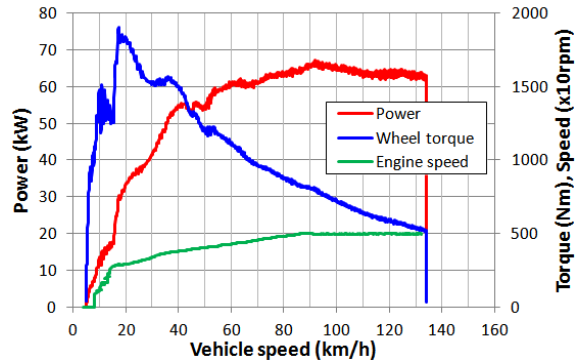

***Figure 6*. Test result of system power on vehicle C by method I**

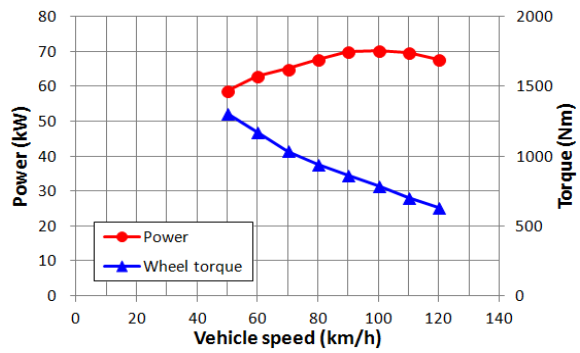

***Figure 7*. Test result of system power on vehicle C by method II**

Figure 8 shows the measurement result of the system power on vehicle D by method I. Vehicle D is an electric vehicle powered by a battery. The powertrain layout of this vehicle is very simple comparing with other test vehicles. The electric power from a lithium polymer battery transfers to the wheel via an electric motor and a reduction gear.

The rapid acceleration at full load was performed at the minimum vehicle speed of 7km/h. Wheel torque shows typical shape of the motor torque due to the simple reduction gear. The motor speed is also proportional to the vehicle speed directly due to the same reason. Wheel torque could be converted into traction force by multiplying a tire radius.

The region below 30km/h shows the operation of continuous wheel torque, which can be produced the maximum wheel torque. The region ranging from 30km/h to 100km/h shows the operation of continuous power, which can be maintained the maximum power continuously. The region over 100km/h shows the operation of weak magnetic field for higher vehicle speed.

The maximum system power could be expected in the vehicle speed ranging from 60km/h to 90km/h. Through the analysis of standard deviation for system power values in the test three times, the maximum system power was 47.6kW at 64km/h.

Figure 9 shows the measurement result of the system power on vehicle D by method II. Four candidates for maximum system power on vehicle D is at the vehicle speed of 60km/h, 70km/h, 80km/h, and 90km/h. With a little difference, the maximum system power was 48.1kW at 80km/h.

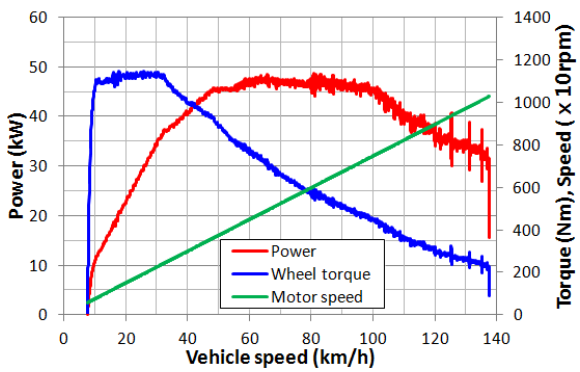

***Figure 8*. Test result of system power on vehicle D by method I**

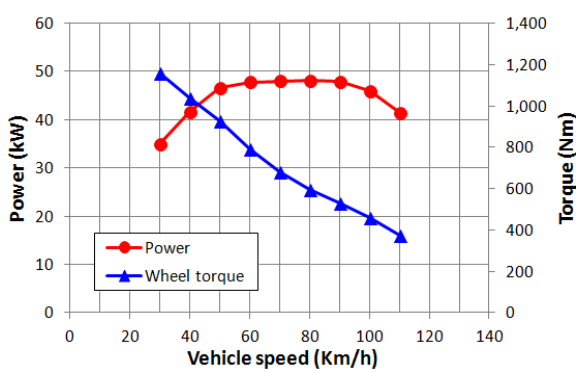

***Figure 9*. Test result of system power on vehicle D by method II**

Figure 10 shows the measurement result of the system power on vehicle E by method I. Vehicle E is also an electric vehicle powered by a battery like vehicle D. The powertrain of this vehicle has very simple layout consisting of a lithium polymer battery, a 70kW electric motor, and a reduction gear.
The rapid acceleration at full load was performed at the standstill. The motor speed is also proportional to the vehicle speed directly due to a simple reduction gear. The region of continuous torque was maintained until around 37km/h. The region of continuous power could be shown until around 110km/h. For higher vehicle speed, the operation of weak magnetic field was conducted over 110km/h. Each characteristic region of vehicle E is much more definite than that of vehicle D. The maximum system power could be expected in the vehicle speed ranging from 37km/h to 50km/h. Through the analysis of standard deviation for system power values in the test three times, the maximum system power was 68.7kW at 47km/h.

Figure 11 shows the measurement result of the system power on vehicle E by method II. Two candidates for the maximum system power on vehicle E is at the vehicle speed of 40km/h and 50km/h. With a little difference, the maximum system power was 69.3kW at 50km/h.

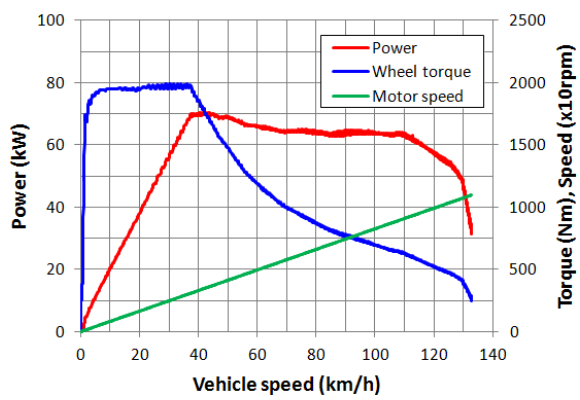

***Figure 10*. Test result of system power on vehicle E by method I**

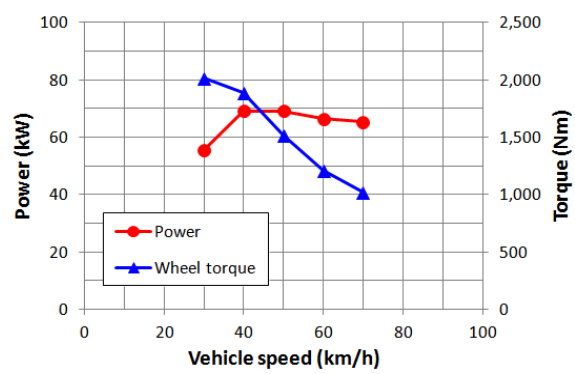

***Figure 11*. Test result of system power on vehicle E by method II**

Table 2 shows the summary of the test results by both methods. The repeatability of method I is within +/- 5 percent of average value. The test values by method II could be considered as reference values without the drivetrain loss in spite of no value on vehicle B. The difference between system power values by method I and those by method II was within +/-5 percent. Thus, method I could be used as

the measurement method for system power on HEVs and EVs.

The efficiency of energy transfer was calculated as follows: For HEVs, the measured value was divided by the power value of an internal combustion engines (ICE) as shown in Table 1. If the specification value of system power is provided by a manufacturer, the specification value was used instead of the power value of an ICE. For EVs, the measured value was divided by the power value of electric motors.

It was found that EVs have high efficiency of more than 95 percent comparing with their motor powers due to simple path of drivetrain. For the case of some HEVs, there was a big gap between the engine power and the system power due to complex drivetrains and different operating regions. It is important that which energy converters such as engines and electric motors are adapted to which drivetrain for higher energy transfer efficiency. Therefore, test method I is available to estimate the energy transfer efficiency for both complex HEVs and simple EVs. In the viewpoint of evaluation of energy transfer efficiency and energy saving such as well-to-wheel efficiency, the concept of system power is very important. Especially, vehicles with multi energy converters such as HEVs are positively necessary this concept.

Table 2.
Test results of system power for test vehicles

Items / Test Vehicles	Method I		Method II
	System power [kW/(km/h)]	Efficiency of energy transfer [%]	System power [kW/(km/h)]
A	103.8 / 138	76.7	105.3 / 140
B	101.6 / 113	92.0	-
C	68.1 / 92	121.8, 92.0[1)]	70.3 / 100
D	47.6 / 64	95.2	48.1 / 80
E	68.7 / 47	98.1	69.3 / 50

1) measured value divided by specification value of system power

CONCLUSIONS

The concept of system power was introduced in this paper. This concept was applied to HEVs and EVs for the determination of powers in whole vehicle state. The efficiency of energy transfer was evaluated for these vehicles. Main findings are as follows.

- System power on the vehicles means the power that is measured at the end side of the powertrain without a tier.
- The method of power measurement under road load (method I) was suggested and had the repeatability within +/- 5percent.
- For higher repeatability, it is important to the cooling condition and initial SOC for hybrid electric vehicles.
- The method of power measurement at a constant vehicle speed was used for the confirmation of method I.
- It was possible to apply the concept of system power by method I to HEVs and EVs for the power measurement and the energy transfer efficiency.

ACKKNOWLEDGEMENT

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