International Journal of Automotive Technology, Vol. 17, No. 1, pp. 145−151 (2016)
DOI 10.1007/s12239−016−0014−0

pISSN 1229−9138/ eISSN 1976−3832

URBAN DRIVING CYCLE FOR PERFORMANCE EVALUATION OF ELECTRIC VEHICLES

N. T. JEONG[1)], S. M. YANG[1)], K. S. KIM[1)], M. S. WANG[1)], H. S. KIM[2)] and M. W. SUH[2)*]

[1)]Graduate School of Mechanical Engineering, Sungkyunkwan University, Gyeonggi 16419, Korea
[2)]Department of Mechanical Engineering, Sungkyunkwan University, Gyeonggi 16419, Korea

(Received 12 December 2014; Revised 10 April 2015; Accepted 24 April 2015)

ABSTRACT−Nowadays, a number of environmental issues have seriously come to the fore. For this reason, the R & D spending on eco-friendly vehicles that use electric power has been gradually increasing. In general, fuel economy and pollutant emissions of both conventional and eco-friendly vehicles are measured through chassis dynamometer tests that are performed on a variety of driving cycles before an actual driving test. There are a number of driving cycles that have been developed for the for performance evaluation of conventional vehicles. However, there is a lack of research into driving cycle for EV. Because large differences exist between the drive system and driving charateristics of EV and that of CV, a study on driving cycle for EV should be conducted. In this study, the necessity of an urban driving cycle for the performance evaluation of electric vehicles is confirmed by developing the driving cycle. First, the Gwacheon-city Urban Driving Cycle for Electric Vehicles (GUDC-EV) is developed by using driving data obtained through actual driving experiments and statistical analysis. Second, GUDC-EV is verified by constructing EV simulators and performing simulations that use the actual driving data. The simulation results are then compared against existing urban driving cycles, such as FTP-72, NEDC, and Japan 10−15. These results confirm that GUDC-EV can be used as an urban driving cycle to evaluate the performance of electric vehicles and validate the necessity of development of the driving cycle for electric vehicles.

KEY WORDS : Electric vehicles, Driving cycle, e-Vsim, EV simulator, Electricity performance

1. INTRODUCTION

Recently, a variety of environmental problems have surfaced, including global warming, increase in international oil prices, and the exhaustion of resources, and these have caused the a paradigm of the world automobile market to rapidly change from conventional vehicles (CV) that use internal combustion engines to eco-friendly vehicles that use electric power, including electric vehicles (EV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV) and fuel cell electric vehicles (FCEV) (Yang *et al*., 2007). Accordingly, automakers and components manufacturers around the world have made efforts to develop eco-friendly vehicles, and many countries have established policies to this end (Speidel and Bräunl, 2014).

Generally, vehicle performance is evaluated during development by performing chassis dynamometer tests over various dring cycles before the actual driving tests take place (André, 2004). From the 1970s onward, Many countries have developed a variety of urban driving cycles, such as the Federal Test Procedure-72 (FTP-72), the New European Driving Cycle (NEDC), Japan 10−15 mode and highway driving cyles like the US 06, the HighWay Fuel Economy Test (HWFET), etc.. The automakers have used these driving cycles for automobile development (André, 2004).

However, there is lack of research into the driving cycles for EVs (Kim *et al*., 2012). The above-mentioned driving cycles are not appropriate to evaluate the performance of EVs that have different characteristics from CV because these cycles have been developed to evaluate the performance and measure the pollutant emissions of CVs (Yang *et al*., 2014).

Great differences exist between the drive system of EVs and that of CVs that use an internal combustion engine (Park *et al*., 2011). An EV uses electric motor instead of an internal combustion engine, and electric power is supplied through a battery instead of through fossil fuel energy. Furthermore, power conversion systems, such as an inverter and a converter, are equipped in EVs. The powertrain system of an EV, consists of an electric motor, a battery, an inverter, a converter, and so on, and has a direct effect on the driving performance and dynamics of the vehicle (Park *et al*., 2011). In particular, pure electric vehicles that only use an electric motor power have a higher acceleration performance relative to CVs because EVs motors deliver maximum torque even at a stop state by motor characteristics.

In general, a large proportion of an urban driving cycle consists of acceleration, deceleration and stop section at a

**Corresponding author.* e-mail: suhmw@skku.edu

low speed. However, since existing urban driving cycles have been developed by using driving data from CV, the acceleration performance of an EV cannot be fully reflected. Currently, performance tests for EVs are being conducted according to existing urban driving cycles, which can then generate inaccurate results. Therefore, it is important to develop urban driving cycle by using driving data from EVs (Yang *et al*., 2014).

Accordingly, this study has developed Gwacheon city Urban Driving Cycle for Electric Vehicles (GUDC-EV) to fulfill the necessity for an urban driving cycle for EV. The driving cycle was developed through actual driving tests that were performed to collect driving data. Then, the collected data were processed and synthesized into one-speed profile that can represent all of the driving data through a statistical analysis (Yang *et al*., 2014).

Furthermore, the GUDC-EV and the development method were verified with the use of EV simulators that were constructed by e-Vsim. e-Vsim was also used for the simulations performed on GUDC-EV with actual driving data. In addition, the simulation results were compared against those of existing driving cycles; including FTP-72, NEDC and Japan 10-15 mode. These results validated the development of the urban driving cycle for the performance evaluation of electric vehicles.

2. URBAN DRIVING CYCLES FOR CHASSIS DYNAMOMETER TEST

Many driving cycles have been developed for to evaluate the performance and the pollutant emissions of light-duty or heavy-duty vehicles through a chassis or an engine dynamometer. Such cycles can be classified for urban transportation, rural loads, highway, or military operation area. Especially, urban driving cycles are the most-used and most important cycles of chassis dynamometer tests. In this study, the FTP-72, NEDC, and Japan 10−15 mode which are representative urban driving cycles, are compared with proposed GUDC-EV. The informations on these cycles is as follows.

2.1. FTP-72 (Federal Test Procedure-72)

FTP-72 is a mandated dynamometer test for tailpipe emissions of a car that represents city driving conditions. It is defined in 40 US Code of Federal Regulations (CFR) 86 Appendix I. It is also known as Urban Dynamometer Driving Schedule (UDDS) or LA-4 mode, and it is also used in Sweden as the A10 or Constant Volume Sampler (CVS) cycle. In Australia, it is used as the Australian Design Rules 27 (ADR 27) cycle and in South Korea as the CVS-72 (US Environmental Protection Agency, 1991).

The cycle simulates a 12.07-km urban route with frequent stops. The maximum speed is 91.2 km/h, and the average speed is 31.5 km/h. The cycle has two phases: a "cold start" phase of 505 seconds over a projected distance of 5.78 km with an average speed of 41.2 km/h, and a "transient phase" of 864 seconds. The total duration of 1369 seconds (US Environmental Protection Agency, 1991), and the speed profile of FTP-72 is shown in the Figure 1.

2.2. NEDC (New European Driving Cycle)

NEDC is a driving cycle that is designed to assess the emission levels and the fuel economy of passenger vehicles (excluding light trucks and commercial vehicles). NEDC is supposed to represent the typical usage of a car in Europe and consists of four repeated Economic Commission for Europe-15 (ECE-15) urban driving cycles and one Extra-Urban Driving Cycle (EUDC). The total distance for NEDC is 10.93 km, total time is 1190 seconds, and the maximum speed is 120 km/h with an average speed is 43.10 km/h (Barlow *et al*., 2009). The speed profile NEDC is shown in the Figure 2.

2.3. Japan 10−15 Mode

The 10−15 mode has been used in Japan to evaluate the emissions and the fuel economy in light duty vehicles. The 10−15 mode test is derived from the three 10 mode segment by adding another 15-mode segment including a high speed section. Pollutant emissions and fuel economy are measured over the last four segments, and the distance of the cycle is 4.16 km with an average speed of 22.7 km/h, a maximum speed of 70 km/h, and a duration of 660s (Barlow *et al*., 2009). The speed profile of the Japan 10−15 mode is shown in the Figure 3.

3. DEVELOPMENT OF GUDC-EV

In previous studies, the urban driving cycle for performance evaluation of EVs was developed. A police car's patrol route in the Gwacheon, South Korea, was selected as the test driving course, and the actual driving tests were performed with both an EV and a CV. The data acquisition

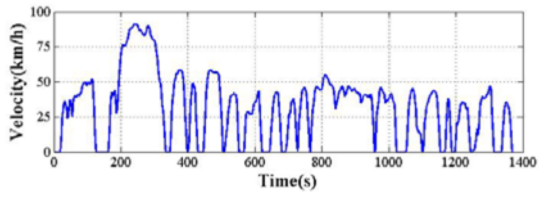

Figure 1. Speed profile of FTP-72.

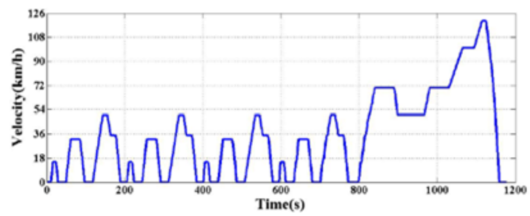

Figure 2. Speed profile of NEDC.

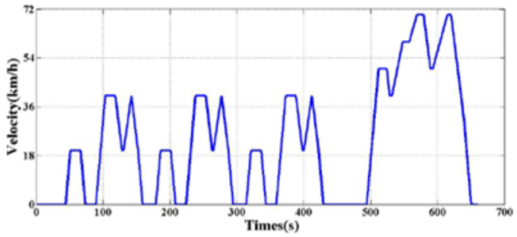

Figure 3. Speed profile of the Japan 10–15 mode.

equipment installed on vehicles collected the driving data and the reason for such an experiment was to compare the EV data and CV data (Yang *et al*., 2014).

The actual driving data are synthesized into one speed profile to represent all of the driving data by using a statistical analysis. After the speed profile was synthesized, the driving cycle for EV was named GUDC-EV and the driving cycle for CVs is called GUDC-CV (Yang *et al*., 2014). The speed profile and characteristics of each of the cycles are shown in Figures 4 and 5, and Tables 1 and 2.

The results of the analysis provided some parameters of the cycles such as the driving time, the driving distance and the average speed which were similar because the two test cars were driven on the same test course for the experiments. However, the result for the average acceleration showed that GUDC-EV had a higher average acceleration than a GUDC-CV, which indicated that EVs have a higher torque and a higher acceleration, which are applied in GUDC-EV (Yang *et al*., 2014).

4. EVALUATION AND VERIFICATION OF THE GUDC-EV

In this chapter, GUDC-EV is verified by using e-Vsim, which is a virtual driving simulation software, to perform

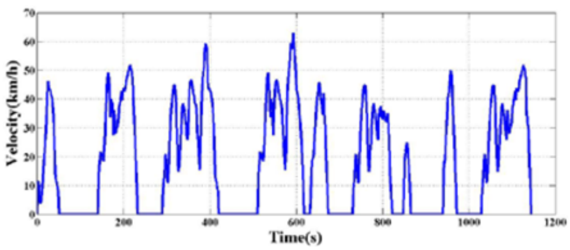

Figure 4. Speed profile of GUDC-EV.

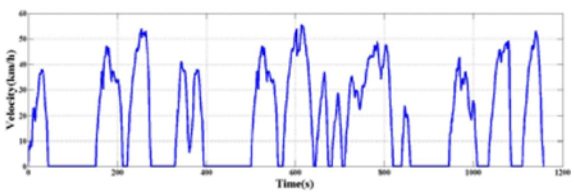

Figure 5. Speed profile of GUDC-CV.

Table 1. Characteristics of GUDC-EV.

Time (s)	1144
Distance (m)	5777
Average velocity (km/h)	18.16
Average velocity without stop duration (km/h)	31.13
Maximum velocity (km/h)	62.99
Stop duration fraction (%)	41.70
Averager acceleration (m/s^2)	0.578

Table 2. Characteristics of GUDC-CV.

Time (s)	1157
Distance (m)	5781
Average velocity (km/h)	17.97
Average velocity without stop duration (km/h)	30.74
Maximum velocity (km/h)	55.50
Stop duration fraction (%)	41.57
Averager acceleration (m/s^2)	0.454

simulations. In addition, the results of the simulation on the GUDC-EV are compared with those for existing driving cycles, and the results are analyzed.

4.1. Configuration of the Virtual EV Simulators Using e-Vsim

To evaluate GUDC-EV, the EV simulators are configured using e-Vsim. e-Vsim is a modeling and simulation program based on MATLAB/Simulink which is developed to design key components for eco-friendly vehicles such as EV, HEV and PHEV through design parameter alteration using GUI (Graphic User Interface) for user convenience. Moreover, e-Vsim can analyze and evaluate driving performance like accelerating ability, hill climbing abailty, motor operating line according to many driving modes, EV range, fuel economy and so on (KATECH, 2014).

The simulator for EV#1 and EV#2, which are the most representative electric vehicles in the world and South Korea respectivley, consists of a motor-generator, a battery, an inverter, a controller, a final reduction gear, a driver model, and the vehicle model, as shown in the Figures 6 ~ 7 (SKKU, 2012). A driving cycle are inserted in the Driver model of EV simulator. In the Driver model, input parameter is “Actual vehicle speed” and the outputs are “Accelerate pedal signal”, “Brake pedal signal” and “Demanded speed in cycles”. A “Actual vehicle speed” is inputted then, it is compared with “Demanded speed in cycles” in a PI controller. After calculating error value in the PI controller, “Aceelerate pedal signal” or “Brake pedal

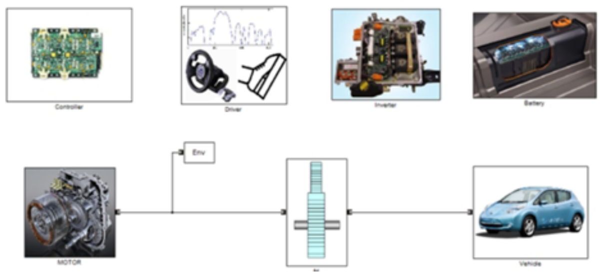

Figure 6. EV simulator.

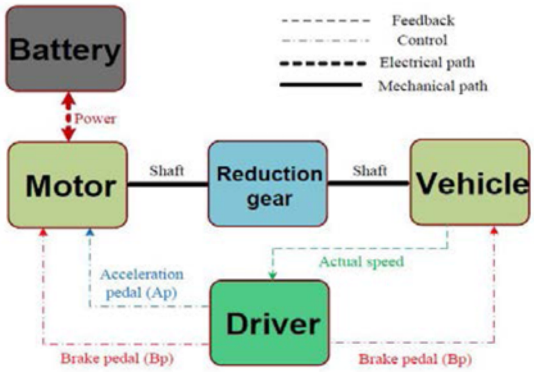

Figure 7. Block diagram of EV simulator.

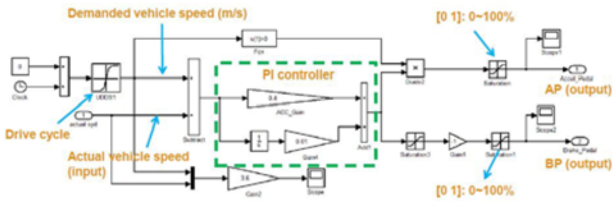

Figure 8. Driver model of EV simulator.

signal" is outputted as shown in Figure 8.

Two EV simulators were constructed for various analyses, and the specifications of each vehicle are shown in Tables 3 and 4. The validity of the EV simulators had been verified in a previous study (SKKU, 2012). It can be expected that representable and reliable simulation results can be obtained using these vehicles.

4.2. Comparison between GUDC-EV and Existing Urban Driving Cycles

In this section, GUDC is evaluated and verified through comparison with actual driving data and existing urban driving cycles. The existing urban driving cycles used for the comparison are FTP-72, NEDC and Japan 10 ~ 15 mode. After constructing the EV simulators, the simulations for each cycle were performed, and Electricity Performance (EP), which is the metric that replaces fuel economy in an EV, was measured. Unlike GUDC-EV, FTP-72 has a high-speed section after first waiting for a signal, and NEDC also has high-speed driving conditions after four ECE-15 cycles. Accordingly, a direct comparison of each driving cycles was performed by removing the high-speed sections in the existing urban driving cycles to conduct the simulations. The results of each simulator are shown in Tables 5 and 6.

Table 3. Vehicle specifications for EV#1.

EV#1	Item	Specifications
Motor	Max. Output (kW)	50
	Max. Torque (Nm)	164.6
Battery	Type	Lithium-ion
	Capacity (kWh)	16.4
Vehicle	Max. Speed (km/h)	130
	Drive range (km)	140
	Weight (kg)	1247

Table 4. Vehicle specifications for EV#2.

EV#2	Item	Specifications
Motor	Max. Output (kW)	80
	Max. Torque (Nm)	280
Battery	Type	Lithium-ion
	Capacity (kWh)	24
Vehicle	Max. Speed (km/h)	145
	Drive range (km)	160
	Weight (kg)	1520

The results of the comparison between GUDC-EV and the actual driving data of the EV show that EV#1 has a 0.5 % error and EV#2 has a 0.3 % error. In the case for the CV, each error is calculated as 0.12 % and 0.16 %. The results indicate that the development method for the driving cycle is reliable enough.

In addition, the results also indicate that GUDC-EV has similar values as those of actual driving data, but the existing urban driving cycles have a remarkably lower average acceleration and a higher EP than the actual driving data for EV in both EV#1 and EV#2. The modified driving cycles produced simulation results show that exhibited a similar tendency as the original cycles. The average accelerations are slightly higher than those of previous simulations, but large differences between both results are not observed. Moreover, the average EP on a modified driving cycles are larger than that on original cycles because the high-speed sections were eliminated. These results suggest that the existing urban driving cycles do not reflect the acceleration performance of EV due to motor characteristics and regenerative braking.

Generally, an EV can generate a maximum torque from

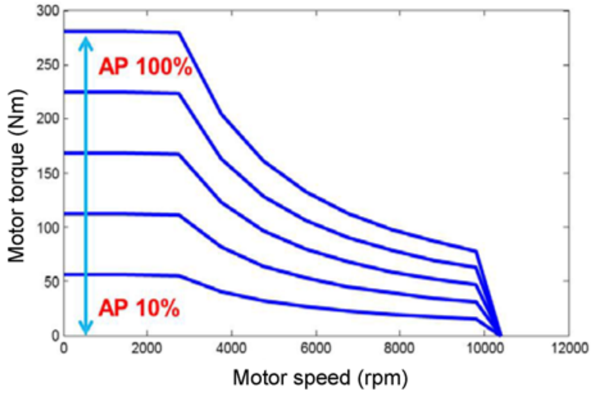

Figure 9. Motor characteristics curve of EV (example).

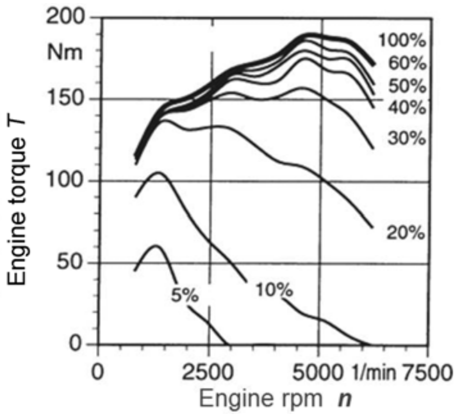

Figure 10. Gasoline engine characteristics curve (example).

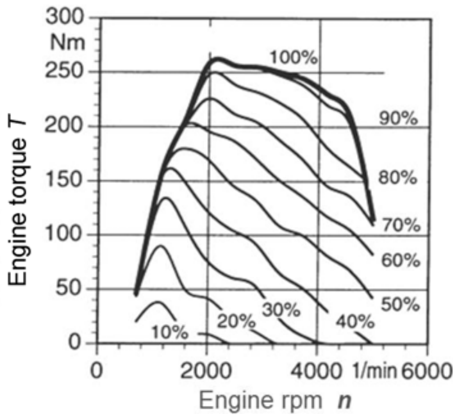

Figure 11. Diesel engine characteristics curve (example).

a stop state, but conventional vehicles with gasoline or diesel engines generate a relatively lower torque, as shown in the Figure 9 ~ Figure 11 (Ehsani *et al*., 2010; Lechner *et al*., 1999). Therefore, EVs have higher acceleration than CVs at a low speed. Stop sections are frequent in urban driving in particular, and as a result, drivers accelerate from a low speed or a stop state quite often. Therefore, it is possible for the driving characteristics of an EV to not be reflected in existing urban driving cycles. As a result, inaccurate simulation results or dynamometer test results can be obtained.

In addition, an EV "CAN" accelerate faster than the CV with its higher torque characteristic from a stop state, but an EV "DOESN'T NEED TO" accelerate faster than a CV. However, because the driving cycles were developed by statistical method with actual driving data of aggressive and defensive drivers, therefore, a variety of accelerating patterns are included in not only GUDC-EV but also GUDC-CV and average accelerating patterns of EV drivers are applied to that cycle. Therefore, it can be verified statistically that higher acceleration should be applied to urban driving cycles for EV and the necessity of that is validated.

Table 5. Simulation results of EV#1 on GUDC with actual driving data and existing urban driving cycles.

Cycles	Initial SOC (%)	Time (s)	Distance (m)	Average acceleration (m/s^2)	Average deceleration (m/s^2)	Average speed (km/h)	Average EP (km/kWh)
GUDC-EV	88	1144	5654.0	0.579	-0.551	17.784	8.17
GUDC-CV	88	1157	5657.2	0.455	-0.599	17.604	8.48
Actual driving data (EV)	88	1130	5565.9	0.599	-0.547	18.031	8.21
Actual driving data (CV)	88	1178	5586.3	0.462	-0.588	17.052	8.47
FTP-72	88	1369	11788.0	0.444	-0.473	31.507	8.66
Modified - FTP-72	88	1257	9287.5	0.465	-0.510	26.5	9.11
NEDC	88	1180	10790.0	0.282	-0.493	42.330	7.87
Modified - NEDC	88	866	4388.6	0.330	-0.508	18.252	9.21
Japan 10 ~ 15 mode	88	660	4088.6	0.315	-0.526	25.360	8.96

Table 6. Simulation results of EV#2 on GUDC with actual driving data and existing urban driving cycles.

Cycles	Initial SOC (%)	Time (s)	Distance (m)	Average acceleration (m/s^2)	Average deceleration (m/s^2)	Average speed (km/h)	Average EP (km/kWh)
GUDC-EV	80	1144	5667.1	0.576	-0.570	17.820	5.94
GUDC-CV	80	1157	5674.4	0.452	-0.632	17.654	6.25
Actual driving data (EV)	80	1130	5581.7	0.597	-0.572	18.077	5.96
Actual driving data (CV)	80	1178	5612.1	0.458	-0.624	17.130	6.24
FTP-72	80	1369	11816.1	0.445	-0.489	31.507	6.58
Modified - FTP-72	80	1257	9261.9	0.465	-0.530	26.532	6.60
NEDC	80	1180	10846.5	0.274	-0.516	42.330	6.51
Modified - NEDC	80	866	4408.8	0.327	-0.540	18.324	7.36
Japan 10 ~ 15 mode	80	660	4101.8	0.316	-0.550	25.360	7.14

5. CONCLUSION

This study investigated the necessity for developing an urban driving cycle for the performance evaluation of electric vehicles by examming the proposed driving cycle and comparing its results against those of exiting driving cycles.

First, GUDC-EV, which had been developed as part of a prior study, was validated through the use of two EV simulators that consisted of a motor, a battery, a controller, an inverter and the final reduction gear. The simulators were designed using e-Vsim which is a virtual driving simulation software. Second, simulations were compared. The results indicated that the driving characteristics of an EV are not reflected in the existing urban driving cycles, such as FTP-72, NEDC and Japan 10–15 mode with modified driving cycles, which indicates the necessity to develop urban driving cycles to perform an evaluation of electric vehicles.

In the future, the simulations will be performed using a greater variety of urban driving cycles, and a chassis dynamometer test will be conducted, which will allow further verification of GUDC-EV and of the necessity of developing an urban driving cycle to evauate the performance of electric vehicles.

ACKNOWLEDGEMENT–This paper received the support of the industry convergence infrastructure project ‘Development of virtual integrated development environment (VIDE) for commercialization supporting of green car’ conducted by the Ministry of Trade, Industry & Energy.

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