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Series Hybrid Electric bus vehicle and its impacts on fuel consumption in European and Tehran driving cycle

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A B S T R A C T

In this article, the procedure of series hybridizing is fulfilled on the O457 city bus that is produced in Irankhodro Diesel Company. For simulation validation the bus with base diesel engine is simulated in European and Tehran compound urban–highway driving cycle and fuel consumption results compared. First the ECE_EUDC_LOW driving cycle simulation results compared with the results of the advisor software that was some difference between two software results. For deep validation bus with base engine was simulated in Tehran driving cycle and fuel consumption calculated 53.26 Lit/100Km that was near actual value that is 59.48 Lit/100Km. After verification, a bus with series hybrid electric-diesel powertrain was designed and simulated in the European and Tehran driving cycle. Simulation results and experimental data's shown that the series hybrid electric-diesel bus fuel consumption reduction in the ECE_EUDC_LOW driving cycle, is 30% and in Tehran driving cycle is 39% less in comparison to base power train that is base diesel engine.

1. Introduction

Tehran, the capital of the Islamic Republic of Iran, is located in the north of the country. Tehran with a population of 8.2 million urban residents and a daily greater population due to migration from vicinities, suffers from rapid urbanization in recent years resulting in severe air pollution [1]. There are more than 17 million vehicular trips per day in Tehran, and many of the vehicles have not outdated technology [2]. Thus, the air in Tehran is amongst the most polluted in the world. Topography and climate

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add to the pollution problem. Tehran is at a high altitude and is surrounded by the Alborz Mountain Range, which traps polluted air. Temperature inversion, a phenomenon particularly occurring during the winter months, prevents the pollutants from being diluted. Several recent trends indicate that reducing air pollution will not be straight forward: rapid population growth (partially due to migration from other cities), industrial development, urbanization, and increasing fuel consumption are pressure points for clean air in Tehran. On the other hand, a decrease in fossil fuel resources, an increase in air pollution; global warming, and an increase in oil prices have led to the fact that both governments and vehicle designers have an extreme tendency to decrease fuel consumption and air pollution.

For the above reasons, it is necessary to reduce the pollution of the city in solving its problems. In Iran, about 23.1% of total petroleum consumption is in the transportation [3]. In the statistical calendar book of Tehran, it is stated that 6,353 bus units, carry out passengers across the city of Tehran [4]. These buses use an internal combustion engine with diesel or CNG fuels that have toxicity for the urban environment. Generally, reduce losses and increase the efficiency of energy conversion are two main strategies for reducing vehicle fuel consumption. To reduce losses, researchers have efforts on factors such as losses due to aerodynamic drag, tire rolling resistance, and energy loss due to vehicle inertia, but recent studies show that the reduction in fuel consumption over a certain level with just mechanical approach is not possible. Hence, in recent years' researchers have been attracted to use electricity in the automobile. One of the essentials of expanding clean energy vehicles is to find the right energy storage system that can ensure high mileage and high acceleration for the car. Various batteries, including lead, nickel, sodium, and lithium batteries have been proposed for use in electric vehicles [5]. Due to problems in pure electric vehicles (EV), such as battery technology and its rapid depletion and Low battery life and long charging time. The electrical energy use with fossil energy has been focused on vehicles that are called hybrid vehicles [6].

The global approach to greenhouse gases and air pollution reduction has focused on clean energy vehicles, including electric and hybrid cars [7]. Anderson and colleagues have shown that the use of electric vehicles reduces greenhouse gases emissions by up to 40% [8].

"Significantly, such hybrid vehicles offer various benefits to drivers including fuel consumption efficiency, less expenditures on fuel, less risk on air pollution and health problems" [9].

There are many research activities for hybrid electric vehicles today in the world. Lajunen has studied on the evaluation of battery requirements for hybrid and electric city buses with simulation. Based on his evaluation, the battery overall costs, including replacements, and battery durability are practically the most important factors for hybrid and electric city buses [10]. Also, he has studied on a cost-benefit analysis (CBA) of hybrid and electric city buses in fleet operation. Based on his evaluation, the initial cost of the bus is a major factor for the charge sustaining parallel and series hybrid buses [11]. Esfahanian and his coworkers modeled an Irankhodro city bus (O457) in AVL-Cruise software [12]. Mirmohammadi and Tavakoli compute the fuel consumption in Tehran driving cycle for samand car using GT-Drive software [13]. Mirmohammadi and Rashtbarzadeh simulated a series Hybrid electric-dieselbus and studied its fuel consumption [14]. The result of this reference is used for verification.

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In this article, a series hybrid electric-diesel bus was designed and simulated in GT drive software, after data verification the results are presented.

2. Vehicle powertrain design

Hybrid electric vehicles combine the use of an electric motor with other power trains such as internal combustion engines, fuel cell, hydraulic power generators turbine and etc. to optimize the operation of the engines. In this study, an internal combustion diesel engine with an electric motor is used in a series layout for an urban bus. This design to a powertrain is to lowering the engine dependency from the vehicle operating conditions and allowing the engine to operate more efficiently. Because of the increased efficiency, the engine can be downsized to further reduce fuel consumption and still provide sufficient power.

2.1 The internal combustion engine and generator design

The selection of the engine in an HEV powertrain depends on the drivability requirements and the level of hybridization. Since micro and mild hybrids offer no or little assistance from the electrical machine to the propulsion of the vehicle, the engine must have similar specifications to that of an equivalent conventional vehicle in order to meet the same performance in terms of drivability. Also in the non-plug-in version, the engine is still the main source of energy, requiring the engine to produce sufficient power amount to avoid depletion of the batteries under normal driving conditions. Since hybrid electric buses have a series power train in more cases, so in this layout the engine and the generator should have the same power. Furthermore, in the bus with a series of the hybrid power trains, the internal combustion engine, and generator are used to prevent full discharge of batteries and the batteries are used to provide temporary power such as acceleration. According to traffic rules, the total power of the internal combustion engine and generator should be able to move the bus on the highway at speed of 130km/hr (36.1 m/s).

The average power provided by the internal combustion engine or a generator can be evaluated from a free diagram of forces acting on a vehicle as shown in Figure 1 that is (1).

$$P_{e/g} = \frac{V}{1000\eta_{te}}\left(M.g.f_r + \frac{1}{2}\rho_a C_D A_f V^2 + M.g.\sin\alpha\right) \quad (1)$$

V=Vehicle speed in m/s

η_{te}=Efficiency of transmission system

M=Vehicle mass in kg

f_r = Tire rolling resistance efficiency

ρ_a = Air density = 1.202 kg/m^3

C_D = Drag coefficient

A_f= Vehicle frontal area

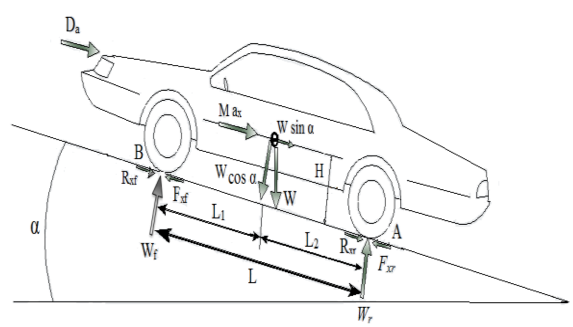

Figure 1: Forces acting on a vehicle

2.2 Battery design

For hybrid and electric city buses, energy storage is one of the most important components in terms of overall energy efficiency, bus lifecycle, and costs. The most common types of batteries found in hybrid electric vehicles are the Nickel-Metal Hydride (Ni-MH) and the Lithium-Ion (Li-Ion). These types of batteries have high power to weight ratio, high capacity,

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fast charging, and long lifecycle, which makes them suitable for automotive applications. Both types are recyclable and the Ni-MH contains no toxic materials. An advantage of the Ni-MH is that it requires simple circuitry whereas the Li-Ion has the need for protection circuits to prevent over-charge and over-discharge. During recent years, lithium-based batteries have proven to be a suitable choice for hybrid and electric passenger vehicles. They offer sufficient power and energy capacity, they are relatively safe, and their calendar and cycle life is long enough at least for hybrid vehicles. The required technical performance of the battery is based on the needed power and energy in a typical driving cycle of a city bus. The power and energy capacity of the battery was evaluated then in relation to the performance of the individual bus application [10]. The battery pack is an important part of the hybrid system as it is the power source for the electric motor and stores the electrical energy recovered from the kinetic energy during regenerative braking. Micro hybrids, mild hybrids, and full hybrids operate at 12-42V, 60-200V, and >200V respectively where >60V is considered as high voltage. The battery pack capacity is sized according to the manufacturer specifications depending on what the degree the vehicle will be operated in electric mode. non-plug-in hybrids use the engine as the main propulsion source and the electric motor as supplementary. In order to keep the vehicle as light as possible, these have relatively small battery packs. The operating range of a battery in terms of the state of charge (SOC) is from 25% to 95%. This gives a usable capacity of 70%. As the battery degrades over time, the capacity reduces to about 80% at the end of its life. To have sufficient usable capacity at the end of life, the battery pack should be oversized. As an example, in order to have at least 5kWh of available energy at the end of life, the initial capacity should be about 9kWh [15]. In some of the driving cycle, acceleration pattern and frequent deceleration lead to poor battery SOC, then, Battery capacity must be determined to avoid this problem. The battery capacity depends on the bus control strategy. In this article selected control strategy is the on-off thermostat and (2) is used for computing the battery capacity.

$$E_{cap} = \frac{\Delta E_{max}}{SOC_{top} - SOC_{bott}} \quad (2)$$

Battery SOC is assumed between 0.5 and 0.6. The energy level in on-off control strategy changes about 0.2. So from the equation 2 battery capacity can be equal to 2 kWh.

2.3 Gear ratios calculation

The function of the transmission system is to optimize the use of the engine by converting the output to meet the driver demand in terms of torque and speed. In the series hybrid, there is no need for a transmission system as the engine only connects to a motor-generator unit. It may be necessary to use a single gear to have the output of the engine match the optimal operating speed of the generator. To obtain gear ratios, (3) is used.

$$i_g = \frac{\pi n_{m,max} r}{30 V_{max}} \quad (3)$$

r = tire radius = 0.46 m

$n_{m,max}$ = maximum engine speed = 2200rpm

V= maximum vehicle speed = 22.2 m/s

So i_g obtain to be 4.775.

3. Driving cycles

Driving cycles are as vehicle speed versus time curves that are used to illustrate driving patterns. A Driving cycle represents traffic phenomena, driving styles, vehicle dynamics, and conditions of a city. In this article, the ECE_EUDC_LOW cycle from reference [3] and the Tehran compound driving cycle from reference [10] is used for simulation. Table 1 presents the

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characteristics of each cycle. Also, Figures 2 and 3 show the driving cycle parameter in curves.

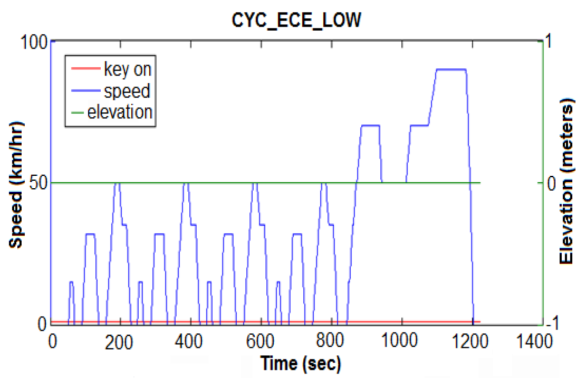

Figure 2:ECE_EUDC_LOW driving cycle [14]

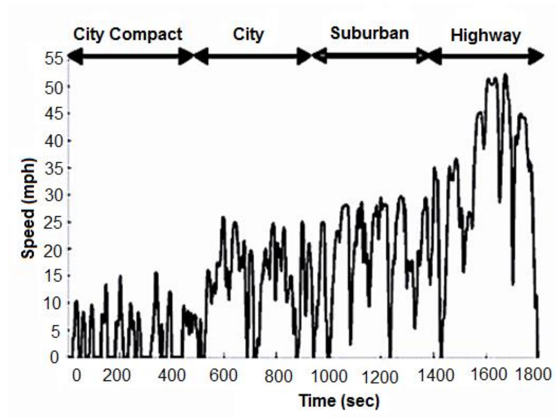

Figure 3: Tehran compound driving cycle [16]

Table 1: ECE_EUDC_LOW driving cycle characteristics [14]

Parameters	ECE_EUDC_LOW Cycle Specification	Tehran compound driving cycle Specification
Time (sec)	1224	1797
Distance (km)	10.59	13.42
Max. speed (km/h)	90	83.94
Avg. speed (km/h)	31.11	26.88
Max. acceleration (m/s)	21.06	21.7
Avg. deceleration (m/s)	20.8 -	22.71

4. Simulation

4.1 Diesel bus simulation

Diesel bus simulation requires structural data including vehicle mass, aerodynamic profile, vehicle geometries, tire and engine specifications. The structural data of a simulated vehicle is presented in table 2. So from equation (1) and data of table 2, the power of the generator calculated 152 kW. In order to achieve engine accessibility, the same engine (OM-355) was used in this simulation. Figure 4 shows the overall structure of the diesel bus in GT drive software. Creating an appropriate structure for vehicle and precise definition of specification including the gear ratios and driving cycle is important in this simulation. Tables' information defined in the software library and called through the simulation blocks.

Table 2: Parameters of the vehicle [14]

Parameters	Specification
Veh.net mass	9800kg
Veh.total.mass with passengers	18000kg
Rolling resistance coefficient	0.01
Aerodynamic drag coefficient	0.8
Front area	5.9m^2
CG height	1.3m
Wheelbase	6.55m
Wheel radius	0.46 m
Engine cylinder capacity	11580 cm3
Engine idle speed	1200rpm
Fuel density	850 kg/m3
Fuel energy high heat value	43 MJ/kg

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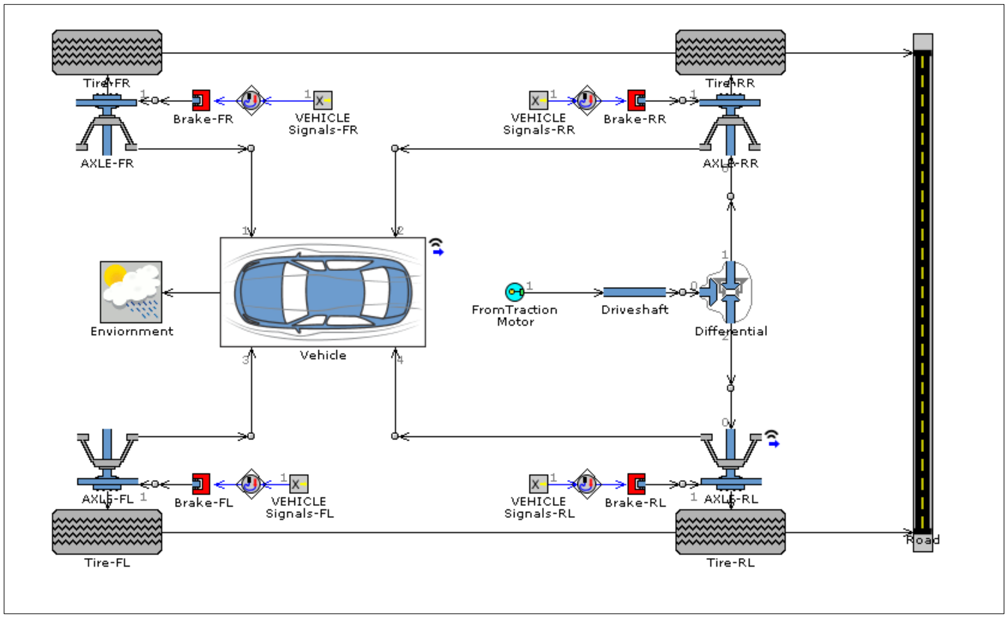

Figure 4: Vehicle block model for diesel bus simulation in GT-Drive

4.2 Series hybrid electric motor selection

The aim of a hybrid-drive system is to run the ICE either at the best possible efficiency or at minimum emissions or a combination of both while maintaining the desired vehicle performance. This goal can partly be reached already at the design phase, by a proper choice of ICE type and size, electrical machines type and size, battery type and size and charging strategy.

A Series hybrid bus was simulated in GT-drive software. The most important characteristic that must be determined in the simulation is Electric motor power, the diesel engine power, the generator power, and Batteries power and capacity. The electric motor power calculated by using the body specification (table 2) and equation 1 as the amount 190 kW then accordingly model AC187 electric motor with a 600 Nm maximum torque was selected.

5. Results verification

Figure 5 shows OM-355 diesel engine experimental torque and power in comparison to simulation results. Experimental data of maximum brake torque is 812 Nm in 1400rpm and maximum power is 164 kW in 2200 rpm. It is seen in figure 5 that maximum torque occurs at medium engine speed. Before 1400 rpm, engine torque increases. But after 1400rpm, engine torque is reduced due to the low volumetric efficiency but power increases with increasing engine speed. Power is the product of torque and speed. So despite the drop in torque at high engine speed, power increases at high engine speed.

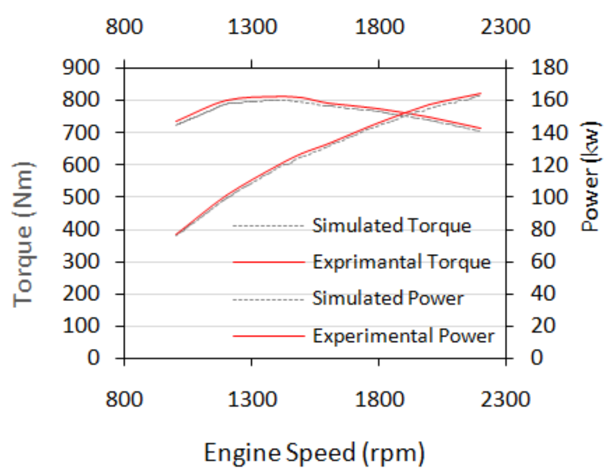

Figure 5: Simulation results of engine torque versus speed in various engine loads

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In order to assess the scientific software results verification, the simulation results in GT-drive were compared with reference [14] results. Reference [14] simulated a series hybrid electric-diesel bus in Advisor software and has compared the fuel consumption. Figure 6 compares the fuel consumption of the diesel bus in ECE_EUDC_LOW driving cycle in GT drive and advisor software. That simulation results show that fuel consumption for base vehicle in ECE_EUDC_LOW drive cycle is 64.4L per 100 km while in GT drive simulation, the fuel consumption for this cycle obtained 43.53L per 100 km.

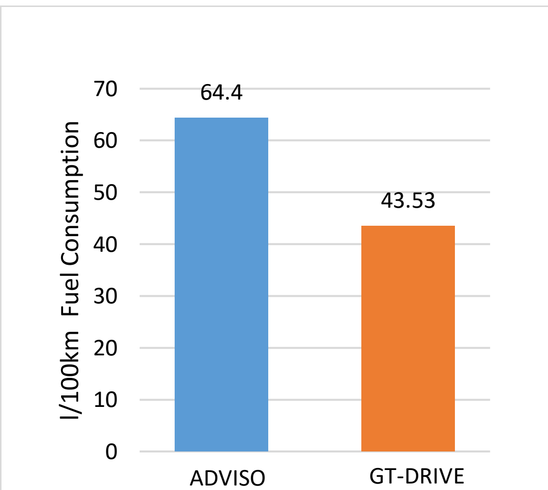

Figure 6: GT-DRIVE and ADVISOR Fuel Consumption Results Comparison in ECE_EUDC_LOW Cycle

For further verification of the results, a diesel bus in Tehran driving cycle simulated and the fuel consumption has calculated. Figure 7 compares the fuel consumption of the diesel bus in Tehran driving cycle in GT drive calculation and actual amount. In this driving cycle, fuel consumption was 53.26L per 100 km. The actual fuel consumption of the vehicle in Tehran driving cycle has presented 59.48L per 100 km in reference [14]. The simulation result in comparison to actual one is slightly different due to the different shifting pattern. We can conclusion from these results that GT-Drive results are better than advisor for driving cycle calculation because its difference is little in comparison to actual amount.

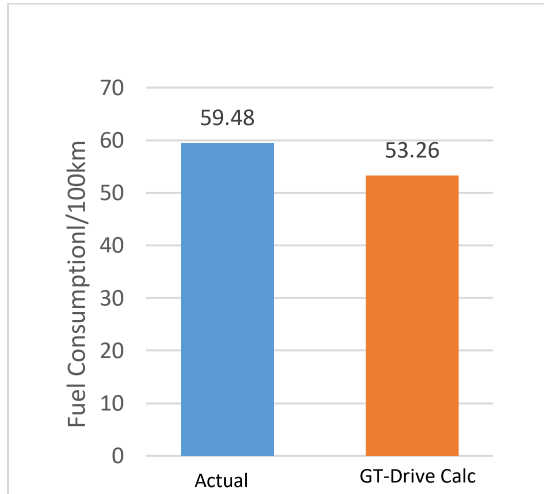

Figure 7: GT-DRIVE and Actual Fuel Consumption Results Comparison in Tehran driving Cycle

6. Series hybrid electric-diesel bus simulation

6.1 ECE_EUDC_LOW driving cycle

In this part, we present the simulation results for the Series hybrid electric-diesel bus designed with the procedure, presented in part 2 of the article. Figure 8 shows the series hybrid electric-diesel bus performance in ECE_EUDC_LOW urban–highway driving cycle. During this driving cycle, the battery charge level is more than 0.4, where the speed is declining, power train requires less power from the battery so electric power consumption has a sudden drop.

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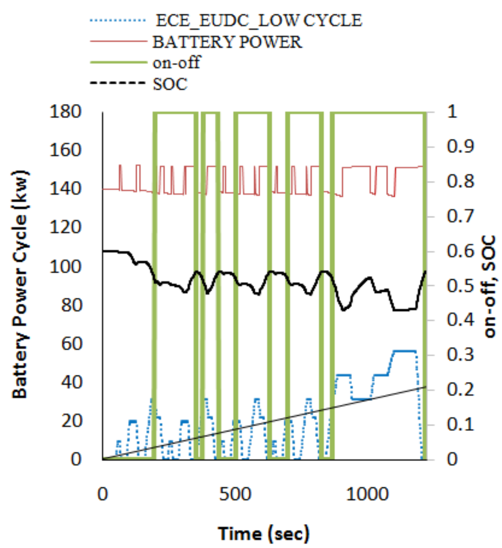

Figure 8: Full hybrid electric-diesel bus performance in ECE_EUDC_LOW Cycle

Fuel consumption of base diesel engine and series hybrid electric-diesel bus was compared in table 3 for the ECE_EUDC_LOW driving cycle. In this cycle, the fuel consumption of the diesel bus is 43.53L per 100km and for the series, a hybrid electric-diesel bus is 30.41L per100 km. The reduction percentage in fuel consumption for this urban–highway driving cycle is 30%.

Table 3: Series hybrid electric-diesel and base diesel engine bus fuel consumption in ECE_EUDC_LOW driving cycle

Type	Fuel consumption(Lit/100 km)
Simulated base diesel engine bus	43.53
Series hybrid bus	30.41

6.2 Tehran driving cycle

Figure 9 shows the series hybrid electric-diesel bus performance in the Tehran compound driving cycle. The adaptation of the cycle simulated with the real Tehran driving cycle is shown in figure 9. This cycle includes four parts: compact city, city, suburban, and highway.

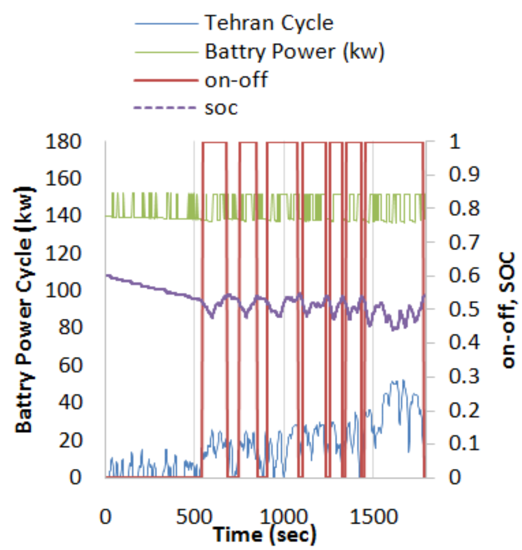

Figure 9: Full hybrid bus performance in Tehran Compound Cycle

Fuel consumption of a diesel and series hybrid electric-diesel bus was compared in table 4 for Tehran driving cycle. In this cycle, the fuel consumption of the diesel bus is 53.26L per 100km and for the series; a hybrid electric-diesel bus is 32.46L per100 km. The reduction percentage in fuel consumption for this urban–highway driving cycle is 39%.

Table 4: Series hybrid bus and diesel bus fuel consumption in Tehran driving cycle

Type	Fuel consumption(Lit/100 km)
Simulated base diesel engine bus	53.26
Series full hybrid bus	32.46

7. Conclusion

In this article, a bus with a series hybrid electric-diesel power train and diesel one was simulated in ECE_EUDC_LOW and Tehran driving cycle and the following results are obtained. In base diesel engine bus simulation, engine torque and power results are very close to experimental data. The numerical results of GT-drive software are more accurate in comparison with the numerical results of advisor software. In the ECE_EUDC_LOW Urban–Highway driving cycle, the fuel consumption of the base diesel engine bus is 43.53L per 100 km and for the series, a hybrid electric-diesel bus is 30.41L

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per 100 km. In the ECE_EUDC_LOW driving cycle, the series hybrid electric-diesel bus fuel consumption is 30% lower than the base diesel engine bus.

In the Tehran compound driving cycle, the fuel consumption of the base diesel engine bus is 53.26L per100 km and the hybrid electric-diesel bus is 32.46L per 100km. In the Tehran driving cycle fuel consumption of the series, a hybrid electric-diesel bus is 39% less than a base diesel engine bus.

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