Isı Bilimi ve Tekniği Dergisi, 34, 2, 143-154, 2014
J. of Thermal Science and Technology

ISSN 1300-3615

COMPARISON OF OPERATING CHARACTERISTICS OF CONVENTIONAL, DIESEL-ELECTRIC AND HYBRID-ELECTRIC CITY BUSSES UNDER REAL WORLD URBAN DRIVING CONDITIONS

Şeref SOYLU
Sakarya University Faculty of Engineering , 54187 Sakarya

(Geliş Tarihi: 15.08.2013, Kabul Tarihi: 17.01.2014)

Abstract: Basic operating characteristics of Conventional, Diesel-Electric (DE) and Hybrid-Electric (HE) city busses were compared under real world urban driving conditions. To perform the comparison, real-time operating data of the buses were collected on Campus-Return route of Sakarya Municipality. It was observed that although traction powers versus bus speeds indicated similarities for all the buses, engine powers versus bus speeds did not indicate the same similarities. The main difference was that while the engine powers of the conventional and DE buses increased steeply to their maximum with the increasing bus speed, the engine power of the HE bus increased gradually to its maximum. Traction, braking and engine energy traces of the buses indicated similar trends, also. While the traction and braking energy traces were quite similar, the engine energy traces were significantly different although the buses were driven on the same route. The engine energies per km travel for the HE, conventional and DE buses were 1.30, 1.55 and 2.08 kW-h/km, respectively. Compared to the engine energy of the HE bus, that of the conventional and DE buses are 20% and 60% higher, respectively. In addition, the engine energies were 1.29, 1.48 and 1.84 times higher than their respective traction energies for the HE, conventional and DE buses, respectively. The main reason for the lower energy consumption of the HE bus is that while the HE bus takes advantages of downhill and frequent stop-and-go driving conditions by recovering the braking energy, the conventional and DE buses waste their braking energies.
Keywords: City busses, Hybrid electric, Diesel electric, Real world operation, Urban driving, Regenerative braking

KONVANSİYONEL, DİZEL-ELEKTRİK VE HİBRİT ELEKTRİK BELEDİYE OTOBÜSLERİNİN ÇALIŞMA KARAKTERİSTİKLERİNİN GERÇEK DÜNYA SÜRÜŞ ŞARTLARI ALTINDA KARŞILAŞTIRILMASI

Özet: Konvansiyonel, Dizel-Elektrik ve Hibrit Elektrik şehir otobüslerinin temel operasyon karakteristikleri gerçek dünya şehir içi sürüş şartlarında karşılaştırıldı. Bu karşılaştırma için otobüslerin gerçek zamanlı dataları Sakarya Büyükşehir Belediyesi'nin Kampüs-Dönüş rotasında toplandı. Bütün otobüslerin çekiş gücü-otobüs hızı karakteristiklerinin benzer olduğu halde motor gücü- otobüs hızı karakteristiklerinin farklı olduğu görüldü. Temel farklılık, Konvansiyonel ve Dizel-Elektrik otobüslerin motor güçlerinin artan hız ile aniden maksimuma ulaştığı halde Hibrit-Elektrik otobüsün gücü tedrici olarak yükselmesiydi. Otobüslerin çekiş, frenleme, ve motor enerjileri de benzer bir yönelim göstermekteydi. Otobüsler aynı rota üzerinde kullanıldığı halde çekiş ve frenleme enerjileri benzerlik gösterirken motor enerjileri oldukça farklı kalmaktaydı. Konvansiyonel, Dizel-Elektrik ve Hibrit-Elektrik otobüslerin motor enerjileri her km seyehat için sırası ile 1.30, 1.55 ve 2.08 kW-h/km oldu. Hibrit-Elektrik otobüsün motor enerjisi ile kıyaslandığında Konvansiyonel ve Dizel-Elektrik otobüsün enerjileri %20 ve %60 daha fazla olmuştur. Ek olarak, Konvansiyonel, Dizel-Elektrik ve Hibrit Elektrik otobüslerin motor enerjilerinin kendi çekiş enerjilerinden sırası ile 1.29, 1.48 ve 1.84 kat daha fazla olduğu görülmüştür. Hibrit-Elektrik otobüsün eneji tüketiminin daha az olmasının en önemli sebebi Konvansiyonel ve Dizel Elektrik otobüsün bayır aşağı ve sık sık dur kalk yapan sürüşlerdeki frenleme enerjisini ısıya dönüştürerek kayıbettiği halde Hibrit-Elektrik otobüsün bu frenleme enerjisini geri kazanabilmesidir.
Anahtar Kelimeler : Belediye otobüsü, Hibrit elektrik, Diesel elektrik, Gerçek Dünya şartları, Şehiriçi sürüş, Rejeneratif frenleme.

INTRODUCTION

City buses are the most economic transport vehicles for public transportation. However, energy needs of the busses are generally provided with the combustion of diesel fuel, which releases both the local emissions such as particulate matter (PM), nitrogen oxides (NOx), carbon monoxide (CO), hydrocarbons (HC) and the global emission carbon dioxide (CO_2) in densely populated urban areas as combustion products. Adverse health effects of the local emissions have been known for many decades and in order to prevent these effects many strict legislations, which have reduced the emission limits more than 90% over the last decades, have been implemented (DieselNet, 2013).

The exhaust gas after-treatment systems have been remedy for the dramatic reduction of the local emissions. But, there is no any feasible after-treatment system to reduce the CO2 emissions from the vehicles yet. Nowadays, both the European Commissions (EC) and Department of Energy of the United States (USDOE) are taking actions to drastically reduce CO_2 emissions with the goal of keeping climate change below 2 ^{0}C. It is suggested by the EC that in order to reach the goal, transport sector needs to reduce their GHG emissions at least 60% by 2050 with respect to that of 1990 (White Paper, 2011).

Similarly, USDOE is taking actions with its Vehicle Technology Program (VTP) with partnership of the industry leaders, the national laboratories, and universities (Davis, PB., 2012; VTP, 2013). The main goals of the VTP are to enable the US to significantly reduce fossil fuel consumption, GHGs, and the local emissions. The GHG emission level of 2005 is expected to be reduced by over 40% in 2030 and by over 80% in 2050. In order to reach the goals, improving the energy efficiency of vehicle powertrains by hybridizing them is chosen to be one of the most promising and cost effective approaches. Singh et al., 2011 reported that when coupled with hybrid electric powertrains more than 30% fuel economy can be expected from commercial vehicles.

The fuel economy and emissions of city buses operating under urban driving conditions are strongly dependent on their operating conditions (Erlandsson et al., 2008; Cocker et al., 2004; Johnson et al., 2009; Durbin et al., 2007; Zhihua et al., 2011). If operated at cruising conditions on a flat route without auxiliaries, the buses would be needed enough energy only for the frictional and aerodynamic losses, but the real world operations of the buses are far from such idealized conditions. Depending on traffic and road conditions which may involve many short micro-trips with accelerations, decelerations and various road grades, the braking energy losses and the auxiliaries can increase energy consumption dramatically and deteriorate the fuel economy.

Electrical hybridization of city buses, on the other hand, can be remedy for the excessive fuel consumption of under urban driving conditions. When compared to conventional buses, hybrid buses can easily save fuel and minimize emissions because of two main reasons. First hybrid city buses, which have generally series hybrid configuration, do not have mechanical links from their engines to the wheels. Therefore, their engine can always operate in the optimum region of the fuel consumption map. Second the kinetic energy, which is normally wasted with conventional buses during the braking periods, can be recovered and stored in the form of electricity during the braking with the hybrid buses. Therefore, hybrid buses have very high potential to minimize both fuel consumptions and the emissions.

Computer modeling and simulation tools are highly effective and economic solutions to examine effects of the design alternatives and energy management strategies on the hybrid vehicles before a prototype construction begins (Butler et al., 1999; Schaltz, 2011; Ganley, 2012). Barrero et al., 2009 simulated and compared several power flow management strategies for hybrid city buses by using a quasi-static 'backwards/forward looking' simulation program. The simulation results indicated that energy savings can be achieved in a range from 32.6 % when using the kinetic strategy with 0.3 kW-h of energy storage system to 40% when using the ICE on-off strategy and an energy storage system of 0.65 kW-h.

Xiong et al., 2009 developed an energy management strategy for a series-parallel hybrid city bus by using a forward-facing simulation program based on the software Matlab/Simulink. The simulation results indicated that the engine operation can be kept in a high-efficiency region and the fuel economy can be improved theoretically by 30.3% to that of the conventional bus under transit bus driving cycle. Ahn et al., 2009 simulated regenerative braking system of a hybrid electric vehicle at various driving conditions by using Matlab/Simulink. It was observed that hybrid electric vehicles with regenerative braking can improve the fuel economy in a range from 20 to 50%.

All these modeling works indicated that hybridization of the vehicles provides various degrees of benefits in terms of fuel economy and the emissions. In order to quantify and compare the benefits under real world urban driving conditions, a research project entitled "Measurement and Modeling of Hybrid City Bus Emissions under Real World Operating Conditions" was introduced by Sakarya University with the support of Turkish Ministry of Science Technology and Industry, and TEMSA R&D which is R&D department of a local bus manufacturer.

In the first phase of the project, real–time data for the basic operating characteristics of a 12 m conventional city bus was collected under real world urban driving conditions. Then, in the second phase, the similar data for DE and HE versions of the bus were collected and analyzed. Initial tests and reports of the project indicated that fuel economy of the buses are strongly dependent on the characteristics of the bus routes and driving conditions (Soylu et al., 2010; Bal et al., 2010; Semercioğlu et al., 2010) In the present work these dependencies were further clarified by examining and comparing the basic operating characteristics, which include traction, braking, engine, Ultra-capacitor (Ucap) recovery and feedback powers and energies, of the buses under real world urban driving conditions.

EXPERIMENTAL SETUP

Test vehicles were TEMSA brand city buses. The length and loaded weight of the buses were 12 m and 15 tons, respectively. The conventional bus was powered with a 6.7 liter Euro 4 CUMMINS diesel engine. The hybrid city bus, which was manufactured based on the conventional bus, has a SIEMENS ELFA hybrid drivetrain system. The hybrid bus was powered with a 6.7 liter Euro 5 CUMMINS diesel engine. Both the Euro IV and V engines have the same power and torque characteristics. Figures 1a and 1b indicate the schematics of the conventional and HE drivetrains. Basic specifications of the ELFA drive train components and the engines are given in Table 1. The HE bus can also operate in DE bus mode. The only difference between the HE and the DE modes is that the Ucap of the bus is not functional in the DE mode.

As can be seen from the schematics, the HE drivetrain (Series Hybrid) does not have a mechanical link from the engine to the wheels. Instead, the ICE drives the generator that feeds the M/G (Motor/Generator). Therefore, the engine can operate in the most efficient regions of its fuel consumption map. Additionally the Ucap, which can be charged by the regenerative braking or the generator, feeds the M/Gs especially during the accelerations of the bus.

The tests were carried out on the Campus-Return route of Sakarya Municipality, and data for the vehicle speed and location, the engine operation, the exhaust emissions and environmental conditions were sampled second by second by using SEMTECH DS from Sensor Inc. Semtech DS is a portable emission measurement system (PEMS) that is capable of monitoring real time gaseous emissions and environmental data such as ambient pressure, temperature and humidity. It also has a vehicle interface module (SAE-J1708) to collect engine and vehicle operation data.

Examinations of the city bus operating characteristics

Speed and altitude profiles of city buses on urban routes are very specific because of the traffic, frequency of bus stops and road grades. Note that the road grade is percent change in route altitude per unit horizontal distance, and it is calculated by using the altitude data. Even if the same bus is consecutively tested on the same route with the same driver, every test may have different speed profile under real world driving conditions. This is actually nature of the real world driving. Figure 2 indicates speed and altitude profiles along with acceleration histograms for Campus-Return route.

As can be seen from the profiles, the buses have highly frequent stop-and-go events with dramatic altitude changes on this route. It should be noted here that the altitude is divided by 5 for better presentation of the figure. The speed profiles involve many micro-trips, which are the trips between two complete stops, with changing speeds and time durations. The micro-trips generally have an acceleration range from -2 to 2 m/s^2 on this route. The similarities of the speed profiles can be easily compared with their basic characteristics as given in Table 2. As can be seen from the table, although the buses were driven over the same route, the measurement results are slightly different from each other. If the dates of the tests are checked, it can be seen that there is more than a year between the tests. During that period the route was slightly modified due to construction works. For this reason the travel distances are slightly different although the starting and the ending points are the same. By comparing the number of micro-trips and the maximum and mean speeds, it can be said that the conventional and HE bus speed profiles have a higher degree of similarity. Since the DE bus speed profile has much less number of micro-trips, its maximum and mean speeds are higher than the others.

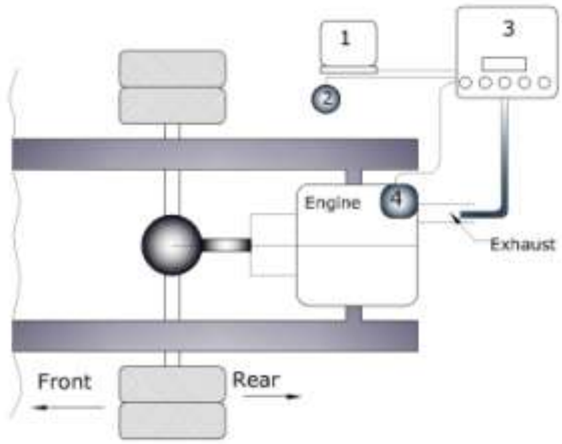

Figure 1a. Schematics of the conventional drivetrain and its instrumentation (1. Computer, 2. GPS, 3. SMTECH DS, 4. Engine).

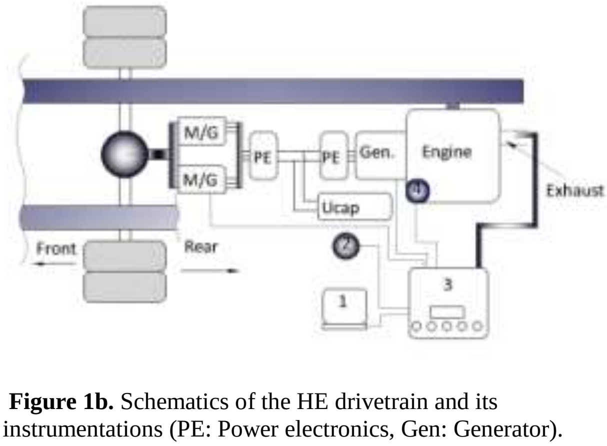

Figure 1b. Schematics of the HE drivetrain and its instrumentations (PE: Power electronics, Gen: Generator).

Table 1. Specifications of ELFA drivetrain components.

	Generator	M/G	Ucap	Engine (ISB6.7)
Rated Power	145 kW @ 4000 rpm	85 kW	233 kW	184 kW @2325 rpm
Rated Torque	368 Nm @ 220 A	220 Nm	-	1020 Nm @1200 rpm
Rated Voltage	700 V	650 V DC	720 V DC	-
Maximum Speed	5,000 rpm	10,000 rpm	-	-
Weight	120 kg	120 kg	180 kg	-
Capacity (Farad/kW-	-	-	10.4/0.74	-

Table 2. Basic driving characteristics of the busses on the Campus-Return route.

	Conventional	DE	HE
Travel distance, km	11.08	11.64	9.78
Travel time, seconds	2086	2172	2214
# of microtrips	40	32	38
Vmax*, km/h	35.80	41.70	32.43
Vmean*, km/h	21.10	25.20	19.60
Test Date	11.06.2009	06.05.2010	19.09.2011

*Vmax and Vmean are calculated based on the micro-trip speed. They don't involve boarding time durations at the bus stops

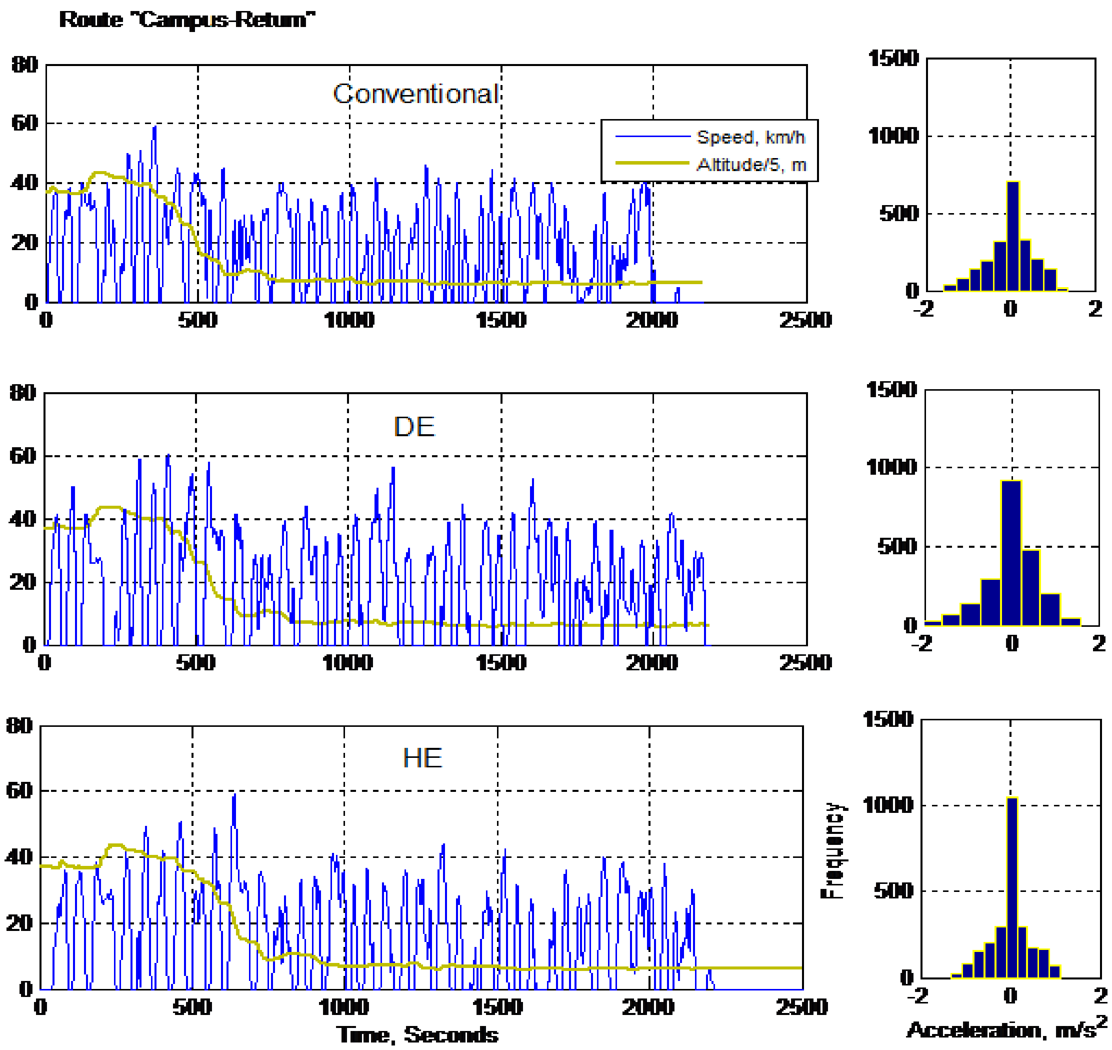

Figure 2. Speed, altitude and acceleration profiles of the busses on the Campus-Return route.

Modeling of the City Bus Traction Power

If operated at a constant speed over a flat road, a bus engine would run at its most efficient operating condition and provide traction force for rolling and aerodynamic resistances as follows:

$$F_{roll} = m.g.C_{roll} \quad (1)$$

$$F_{aero} = (1/2).\rho.C_d.A_f.v^2 \quad (2)$$

where, F_{roll} is the force to overcome the rolling resistance, m is the mass of the bus, g is the acceleration of gravity, C_{roll} is the coefficient for the rolling resistance, F_{aero} is the force to overcome the aerodynamic resistance, ρ is the density for the air, C_d is the drag coefficient, A_f is the frontal area of the bus and v is the speed.

But, as was shown in the speed and altitude profiles in Figure 2, typical city bus operation under urban driving conditions involves frequent changes in the speed, which is a measure of kinetic energy (KE), and the altitude, which is a measure of potential energy (PE). At these conditions, the bus engine must provide enough traction force for increasing the KE and PE, also.

$$F_{ke} = m.a\ (1+\varepsilon) \quad (3)$$

$$F_{pe} = m.g.\sin\theta \quad (4)$$

where, F_{ke} is the force to increase the KE, a is the bus acceleration, ε is the factor for the rotational components of the bus powertrain, F_{pe} is the force to increase the PE and θ is the angle for road inclination.

Finally, the traction force and power for the bus can be written as follows:

$$F_{traction} = F_{roll} + F_{aero} + F_{ke} + F_{pe} \quad (5)$$

$$P_{traction} = v.F_{traction} \quad (6)$$

The coefficients for the rolling and aerodynamic drag were initially chosen from Jimenez-Palacios, 1999 and MOVES2010, 2010, but they were slightly modified later for fine tuning of the model with experimental data from the tests. In order to tune the rolling and drag coefficients, the traction and engine powers were compared at various speeds. During the comparison the third power dependency of aerodynamic resistance to vehicle speed is especially observed. The rolling resistance linearly increases with speed.

After determining the final values of the coefficients as given below, traction and braking powers for the conventional, DE and HE busses were computed.

ε=0.1, C_{roll}=0.007, C_d=0.72

It is well known from the first law of thermodynamics that energy cannot be destroyed but converted to other forms of energy. In this sense, energy used to increase kinetic and potential energies of the bus can be recoverable with some efficiency during deceleration and downhill driving of the bus. It is actually the most important advantage of hybrid city buses as they can recover the braking energy and store it with their regenerative braking system. If the braking energy was recovered with 100% efficiency and converted to mechanical energy, the bus would be needed energy to overcome rolling and aerodynamic resistance, only. Such an operation of a bus would be highly fuel efficient.

Effects of speed and altitude profiles on the traction and engine powers

Figure 3 indicates scatter plots for the traction power, engine power and engine torque that correspond to the speed and altitude profiles of the buses as given in Figure 2. As can be seen from the figure, exception for the DE bus, the traction power scatter plots are quite similar for the buses. The scatter plot of the DE bus is slightly different from that of the conventional and HE bus especially at higher speeds. As was given in Table 2, the micro-trips of the DE bus have little higher maximum and mean speeds than that of the conventional and HE buses, and this difference is directly reflected in the traction power scatter plot. However, by examining the gradual increases of the traction powers with the speed, it can be said that these buses have similar traction power characteristics especially during the take-off periods of the buses.

On the other hand, the engine power and torque scatters are significantly different for the HE bus from that of the others. As can be seen from the figure, the power and torque of the HE bus engine increase gradually to the maximum with the speed but, that of the conventional and DE buses increase steeply to the maximum. The engine powers for both the conventional and DE buses rise up to their maximums before their speeds reach to 20 km/h, but the HE bus engine power is about 100 kW (2/3 of the maximum) at the same speed. This means that the HE bus engine is loaded smoothly which is very advantageous for the emissions and fuel economy. This is actually one of the important advantages of the HE bus. Since the secondary power source of the HE bus, which is the Ucap for this case, provides assistance to the engine, the engine is loaded gradually although the traction power characteristics remain the same as that of the other buses. This advantage of the HE bus can better be explained with Figures 4 and 5. The engine, generator and M/G power scatter plots are compared for the DE and HE buses in Figure 4. The M/G power scatters are actually quite similar to the traction power scatters in general. The only difference is that the traction power is the power at the wheels and there are frictional losses from the M/G to the wheels. To this end, the powers are correspondingly higher for the M/G powers for both

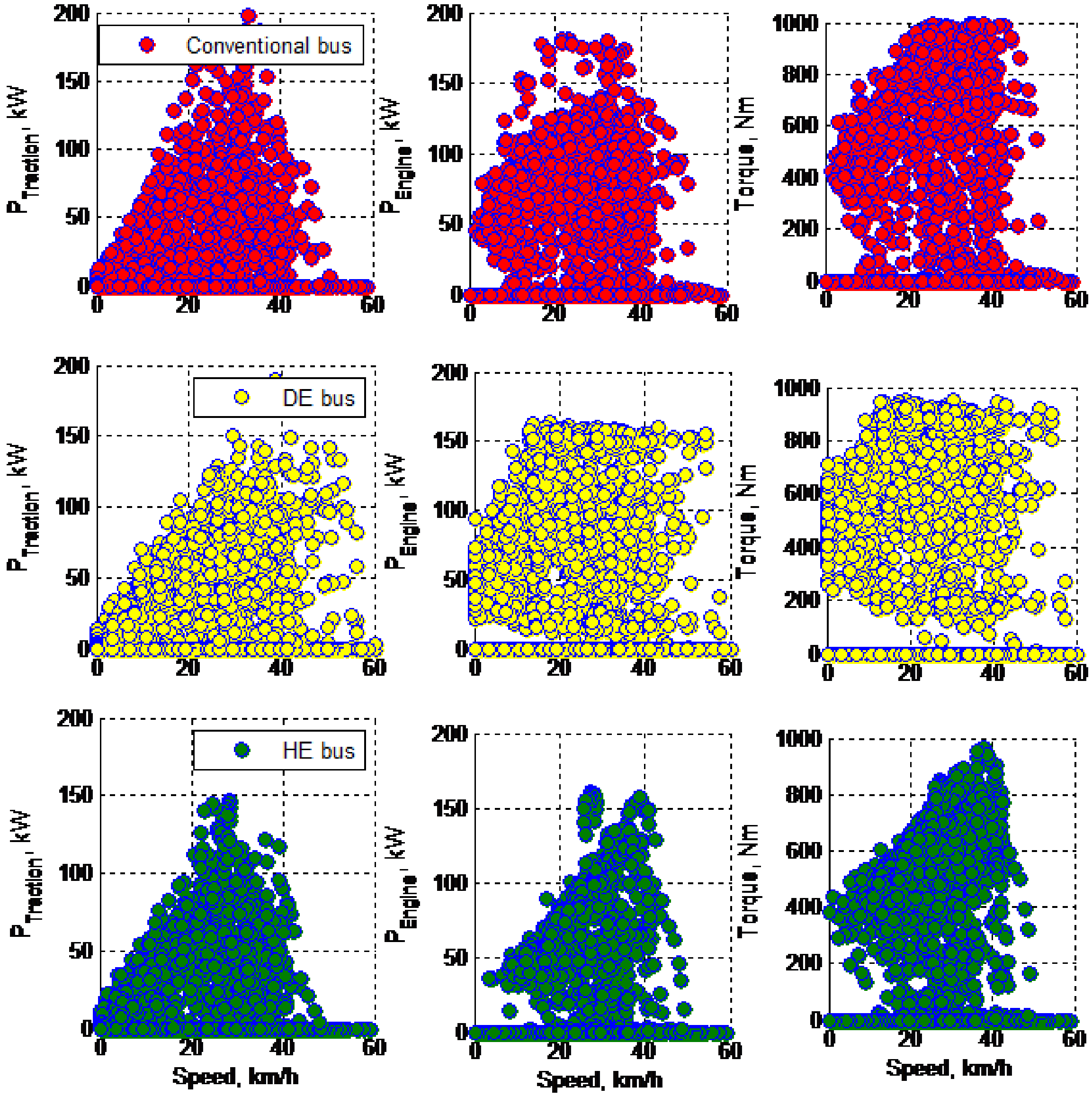

Figure 3. Traction power, engine power, and engine torque scatter plots for the conventional, DE, and HE busses.

the DE and HE bus. Similarly, the generator power scatter is also very similar to the M/G power scatter for the DE bus. The difference is that there are of course energy losses in power electronics components from the generator to the M/G. Therefore, the DE bus generator powers are correspondingly higher than the M/G powers. But, if the M/G power scatter of the HE bus is compared with its generator power scatters, the significant difference can be seen clearly. The generator power is almost zero until the bus speed reaches to about 10 km/h and then the power increases gradually to its maximum. A similar trend can also be seen from the engine power scatter of the HE bus, but the powers are little higher than that of the generator due to the generator efficiency and the auxiliary loads of the engine. The difference between the generator and M/G power scatters of the HE bus can better be explained with Figure 5. In this figure, the M/G, generator, Ucap recovery, and Ucap feedback powers scatter plots are presented. The recovery power is the power for the regenerative braking that charges the Ucap, and the feedback power is the Ucap discharge power that feeds the M/G. As mentioned earlier, the regenerative braking is the main advantage of the HE bus and it recovers the braking energy normally wasted by the conventional and DE buses. Once the Ucap is charged, it can assist the generator with the feedback power. Actually, the feedback power is the difference between the M/G and the generator powers. The feedback power is especially used during the take off period of the bus to assist the engine so that the engine can be loaded smoothly. As a result, improved fuel economy and the emissions for the HE bus are provided.

Effects of the speed and altitude profiles on cumulative energies of the characteristics

Figure 6 indicates the effects of the speed and altitude profiles of the buses on their cumulative traction, braking and engine energy traces. As can be seen from the figure, the braking energy traces have similar trends and they are highly sensitive to the decreasing altitude for all the buses. This sensitivity is especially pronounced in the period from 200 to 700 seconds for all the buses. During this period (downhill driving period), the braking is so powerful that absolute value of the braking energy increases steeply to keep the bus speed at the limited levels. Then the braking energy increases gradually to the maximum as a result of the frequent stop-and-go driving conditions. As can be seen from Table 3, the traction and braking energies are not changing significantly for the buses. They have standard deviations of 0.93 and 1.67 kW-h, respectively. However, the engine energy traces for the buses are highly different with a standard deviation of 5.77 kW-h. The HE bus energy is significantly less than that of the others. This means that the recovery of the braking energy provides important advantages for the HE bus.

Comparison of the energies for the same route can provide valuable information regarding the advantages of the different bus technologies but, as was given in Table 2, the driving distances and the maximum and mean speeds are little different for each bus due to the real world testing. It is well known that the traction, braking and engine energies are strongly dependent on the travel distance and the bus speed. For this reason, these dependencies must be neutralized for a better comparison.

In order to neutralize the effects the distance, the energies of the characteristics were calculated in terms of energy per km driving distance as given in Table 4. As can be seen from the table although the traction and braking energies per km driving are not changing significantly for the conventional, DE and HE buses, the engine energies are changing significantly with a standard deviation of 0.40 kW-h/km. The engine

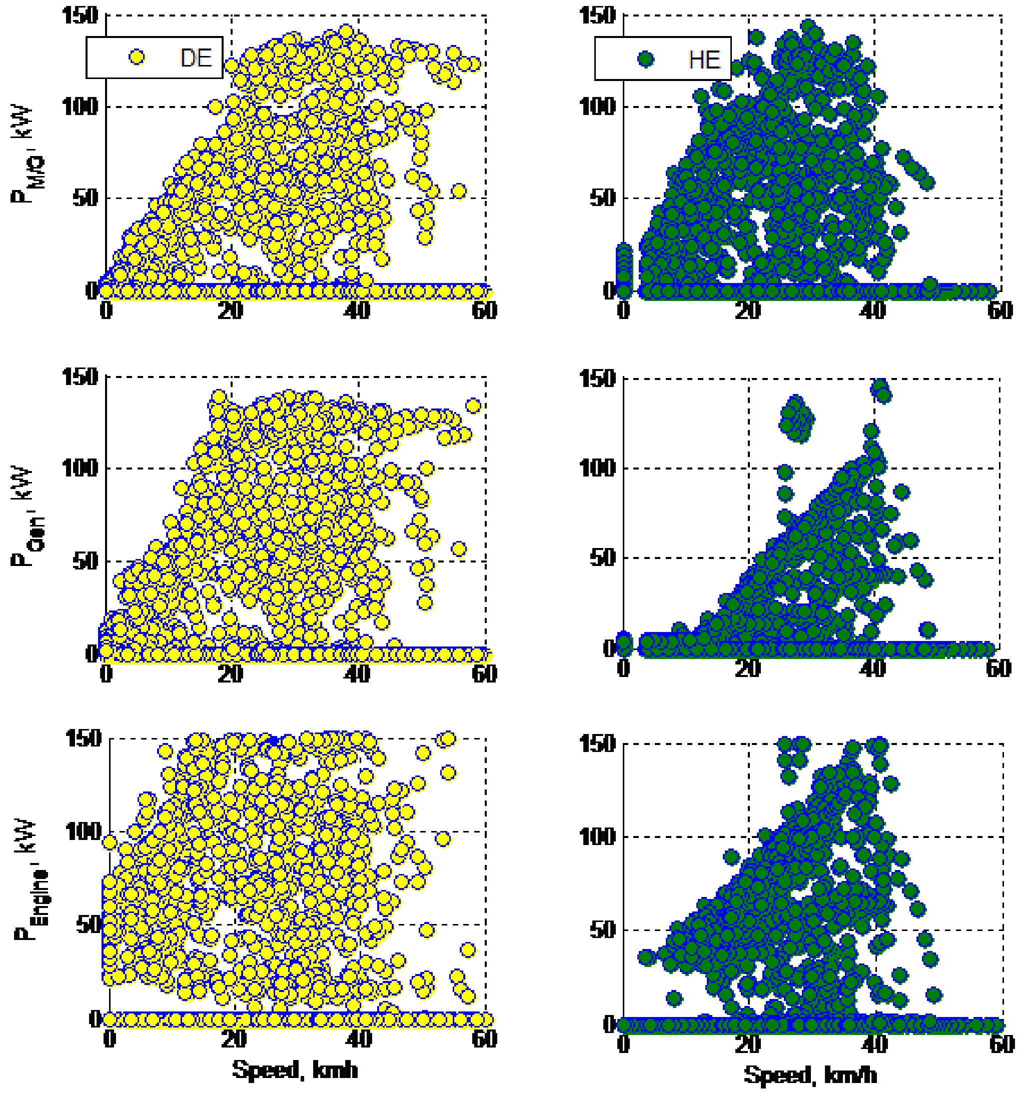

Figure 4. M/G, Gen and engine powers scatter plots for the DE and HE busses.

energy per km driving for the HE bus is 1.30 kW-h/km which is 0.25 and 0.78 kW-h/km less than that of the conventional and DE buses, respectively. Then to neutralize the effects of the speeds, the engine and braking energies, as given in Table 4, were divided by their respective traction energies. Table 5 indicates the results which are highly accurate comparison parameters. As can be seen from the table, the engine energies are 1.48, 1.84 and 1.29 times higher than their respective traction energies for the conventional, DE and HE bus, respectively. Because of the auxiliary loads and drivetrain losses, it is normal to expect energy losses from the engine to the wheels. But, it seems that the losses of the DE bus are very high when compared to that of the conventional bus. The DE bus drivetrain losses are 0.36 kWh higher than that of the conventional bus for every kWh of the traction energy. The losses are mainly caused by real world performance of the generator, M/G and power electronics components together with the auxiliary loads for cooling the electrical drivetrain components. It is well known from the literature that the combination of the motor/generator and its power electronics have approximately 80% efficiency while operating under frequent stop-and-go operating conditions (Baisden et al., 2004; Grbovic et al., 2012; Miller, JM., 2003; Mi et al., 2008; O'Keefe et al., 2002;

Williamson et al., 2006; Williamson et al., 2007). It seems that in the HE bus case, these losses were compensated, and even further improvements were provided with the regenerative braking.

Figure 7 indicates the effects of the speed and altitude profiles on the M/G and Ucap characteristics. This figure further clarifies the effects of the speed and altitude profiles on the recovery and feedback energies for the Campus-Return route. As can be seen from the figure the M/G braking energy trace is quite similar to that of the braking energy as given in Figure 6. The final values of the braking and M/G braking energies are -13.02 and -9.54 kW-h, respectively. It seems that

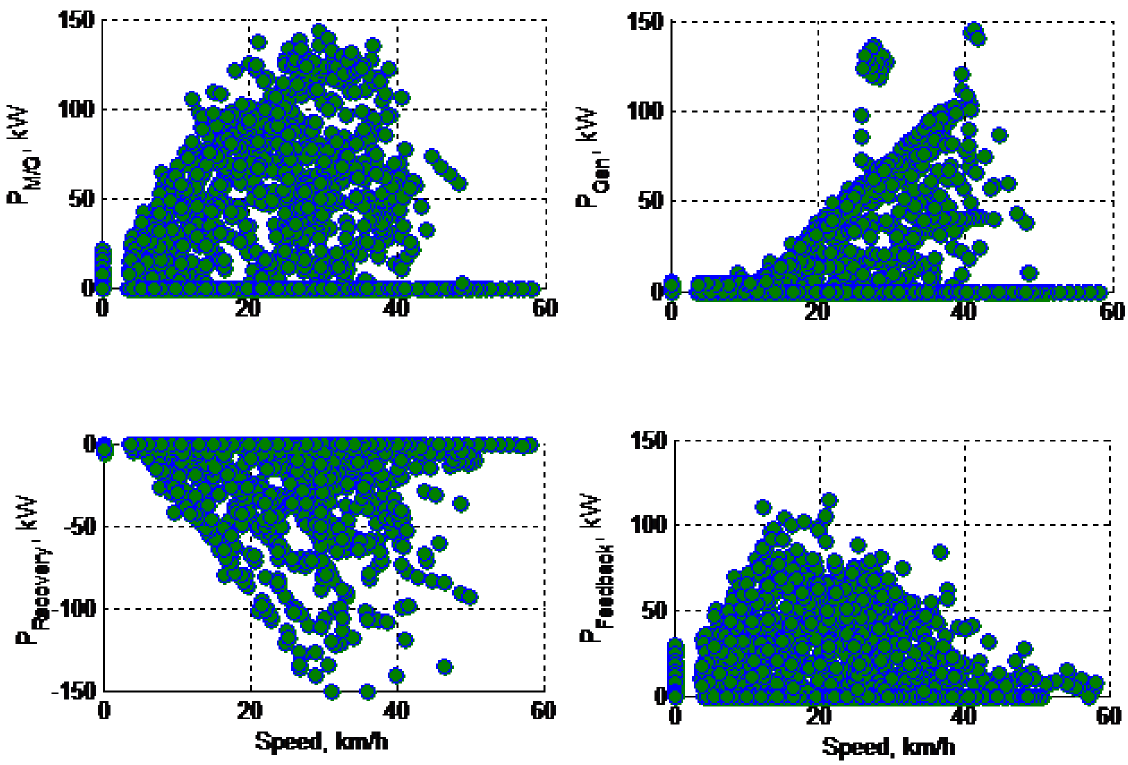

Figure 5. M/G, generator, recovery and feedback powers scatter plots for the HE bus.

Table 3. Cumulative energies of the busses for the Campus-Return route.

Energy kW-h	**Conventional bus**	**Diesel Electric bus**	**Hybrid Electric bus**	**Standard Deviation**
Traction energy	11.62	13.16	9.83	1.67
Braking energy	-14.88	-13.97	-13.02	0.93
Engine energy	17.17	24.17	12.72	5.77

Table 4. Cumulative energies per km travel of the busses for the Campus-Return route.

Energy kW-h/km	**Conventional bus**	**Diesel Electric bus**	**Hybrid Electric bus**	**Standard deviation**
Traction energy	1.05	1.13	1.01	0.06
Braking energy	-1.34	-1.20	-1.33	0.08
Engine energy	1.55	2.08	1.30	0.40

Table 5. The engine and braking energies per kW-h of the traction energy.

Energy ratio (kW-h/km)/(kW-h/km)	**Conventional bus**	**Diesel Electric bus**	**Hybrid Electric bus**
Engine energy/Traction energy	1.48	1.84	1.29
Braking energy/Traction energy	-1.28	-1.06	-1.32

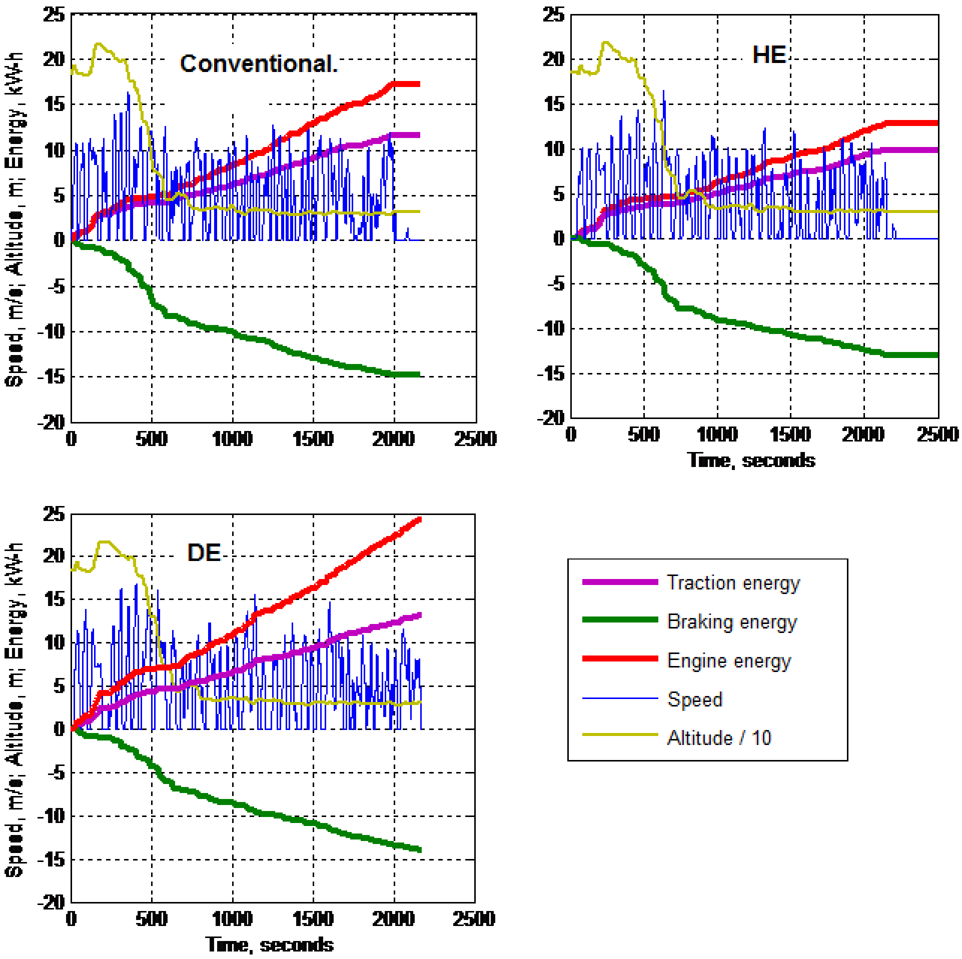

Figure 6. The speed – altitude profiles and corresponding cumulative energy traces for the busses.

the M/G provides 73% of the HE bus braking energy. The difference between the M/G and HE bus braking energies are accounted for the mechanical braking and the frictional losses from the M/G to the wheels. It would be ideal to provide all braking needs of the HE bus with the M/G and recover all of the braking energy but, it requires very high capacity Ucap which may not be feasible because of the weight and cost considerations. As can be seen in the period from 500 to 1000 seconds of Figure 7, the altitude decreases steeply which provides a great opportunity for energy recovery. However, the Ucap recovery trace cannot follow the M/G braking trace closely in this period. The reason for this can better be explained by examining the SOC line in the same time period. As can be seen from the figure, at the time of 500 second the SOC level is around 20%, and in the following 250 seconds the SOC reaches to its maximum and it cannot recover anymore of the M/G braking energy. The rest of the M/G braking energy is wasted as heat by an

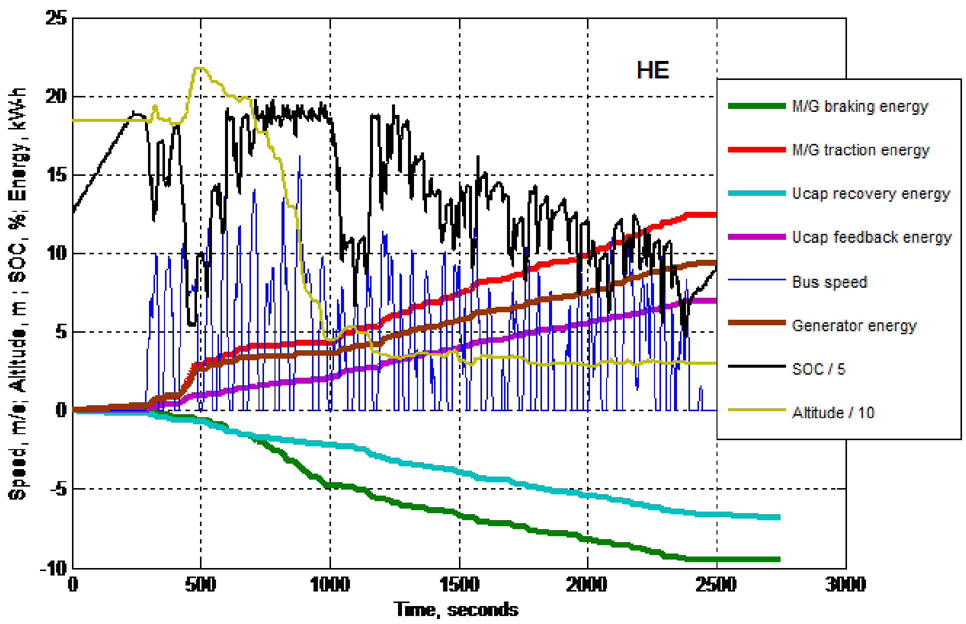

Figure 7. The speed – altitude profiles and corresponding M/G and Ucap cumulative energy traces of the HE bus.

electrical resistance installed on the bus. After completing the downhill driving the Ucap is starting to recover the M/G braking energy again. It seems that the optimization of the Ucap capacity is highly important for fuel economy of HE buses. The main advantage of the HE bus can also be seen clearly by comparing the M/G traction and generator energies in Figure 7. As can be seen from the figure, the M/G traction energy is significantly higher than the generator energy. As given in Table 6, the final values of the M/G traction, generator and feedback energies are 12.42, 9.65 and 6.94 kW-h, respectively. The generator energy provides 78% of the M/G energy and the rest of the energy comes from the Ucap feedback energy which is recovered from the braking energy.

Table 6. Cumulative energies for basic operating characteristics of the HE bus.

HE bus characteristics	Cumulative energies, kW-h
Generator	9.65
M/G traction	12.42
M/G brake	-9.54
Ucap recovery	-6.83
Ucap feedback	6.94

CONCLUSIONS

Because of the frequent stop-and-go operations, the maximum and mean speeds of the city buses are quite low on the Campus-Return route. The maximum speeds of the micro-trips are ranged from 32.43 to 41.70 km/h and the mean speeds are ranged from 19.60 to 21.10 km/h for the conventional, DE and HE buses. The accelerations are also ranged from -2 to 2 m/s^2.

The traction power scatter plots indicate that the buses have quite similar traction power characteristics. However, the engine power scatter plot of the HE bus is significantly different from that of the conventional and DE buses.

The engine energies per km travel for the HE, conventional and DE buses were 1.30, 1.55 and 2.08 kW-h/km, respectively. Compared to the engine energy of the HE, that of the conventional and DE buses are 20% and 60% higher for the Campus-Return route, respectively.

The engine energies are 1.48, 1.84 and 1.29 times higher than their respective traction energies on the Campus-Return route for the conventional, DE and HE bus, respectively.

The M/G traction, generator and feedback energies of the HE bus on the Campus-Return route are 12.42, 9.65 and 6.94 kW-h, respectively. The generator provides 78% of the M/G energy and the rest of the energy comes from the Ucap feedback energy which is recovered from the braking energy.

The rate of energy recovery with the regenerative braking system is strongly dependent on the speed and altitude profile of the bus route as well as the Ucap size and energy management system.

Because of the limited number measurements and test vehicles, these conclusions cannot be generalized. Depending on the bus route and energy management strategy, hybrid city busses can achieve different energy efficiencies. However, these results provide significant contributions for understanding the importance and advantages of hybrid electric city busses.

ACKNOWLEDGEMENT

Ministry of Science, Technology and Industry for their financial support, TEMSA R&D for their technical and financial support, Ali Fuat Iskender for the technical assistance, Necdet Ayaz for the driving assistance and Muammer Soylu for Autocad drawings of the schematics are acknowledged.

REFERENCES

Ahn JK, Jung KH, Kim DH, Jin HB, Kim HS, Hwang SH. Analysis of a Regenerative Braking System for Hybrid Electric Vehicles Using an Electro-mechanical Brake, Int. J. Automot. Technol. 2009; 10: 229−234.

Baisden, A.C.; Emadi, A. (2004) ADVISOR-Based Model of a Battery and an Ultra-Capacitor Energy Source for Hybrid Electric Vehicles, IEEE Transactions on Vehicular Technology, VOL. 53, NO. 1, January 2004.

Bal A, Semercioglu H, Soylu S, Ay EF. Sehir otobüslerinin gerçek dünya koşullarinda motor calişma şartlarinin ve NOx emisyonlarinin incelenmesi, Otekon 2010 5. Otomotiv Teknolojileri Kongresi, 7-8 Haziran 2010, Bursa,Turkey.

Barrero R, Coosemans T, Van Mierlo J. Hybrid buses: defining the power flow management strategy and energy storage system needs, World Electric Vehicle Journal 2009; 3: 2032-6653.

Butler KL, Ehsani M, Kamath P. A Matlab-Based Modeling and Simulation Package for Electric and Hybrid Electric Vehicle Design, IEEE Trans. Veh. Technol. 1999; 48: 1770-1778.

Cocker DR, Shah SD, Johnson K, Miller JW, Norbeck JM. Development and Application of a Mobile Laboratory for Measuring Emissions from Diesel Engines. 1. Regulated Gaseous Emissions, Environ. Sci. Technol. 2004; 38: 2182-2189.

Davis PB. Overview of the U.S. DOE Vehicle Technologies Program, Office of the Vehicle Technologies Program Energy Efficiency and Renewable Energy U.S. Department of Energy, DOE-ACE-2011AR, USA, 2012.

DieselNet. Internet resources, Emissions Standards: Heavy-Duty Vehicles, www.dieselnet.com/links/regulations_hd.html (2013, accessed 10 February 2013).

Durbin TD, Johnson K, Cocker DR, Miller JW. Evaluation and Comparison of Portable Emissions Measurement Systems and Federal Reference Methods for Emissions from a Back-Up Generator and a Diesel Truck Operated on a Chassis Dynamometer. Environ. Sci. Technol. 2007; 41: 6199-6204.

Erlandsson L, Almen J, Johansson H. Measurement of emissions from heavy duty vehicles meeting Euro IV/V emission levels by using on-board measurement in real life operation. In: 16th International Symposium “Transport and Air Pollution”, 2008, Graz.

Ganley JC. Design and testing of a series hybrid vehicle with an ultracapacitor energy buffer, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering 2012; 226: 869-880.

Grbovic, P.J.; Delarue, P.; Le Moigne, P. (2012) Selection and Design of Ultra-Capacitor Modules for Power Conversion Applications: From Theory to Practice, 2012 IEEE 7th International Power Electronics and Motion Control Conference - ECCE Asia June 2-5, 2012, Harbin, China

Jimenez-Palacios JL. Understanding and Quantifying Motor Vehicle Emissions with Vehicle Specific Power and TILDAS Remote Sensing. Ph. D. Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA, 1999.

Johnson KC, Durbin TD, Cocker DR, Miller WJ, Bishnu JK, Maldonado H, Moynahan N, Ensfield C, Laroo CA. On-road comparison of a portable emission measurement system with a mobile reference laboratory for a heavy-duty diesel vehicle. Atmos. Environ. 2009; 43: 2877–2883.

Mi, C. (2008) Topology, design, analysis and thermal management of power electronics for hybrid electric vehicle applications, Int. J. Electric and Hybrid Vehicles, Vol. 1, No. 3, 2008.

Miller J.M. (2003) Power Electronics in Hybrid Electric Vehicle Applications, Applied Power Electronics Conference and Exposition, 2003. APEC '03. Eighteenth Annual IEEE.

MOVES2010. Highway Vehicle Population and Activity Data. Assessment and Standards Division, Office of Transportation and Air Quality, US Environmental Protection Agency, USA 2010.

O’Keefe MP and Vertin K. An Analysis of Hybrid Electric Propulsion Systems for Transit Buses, Milestone Completion Report, NREL/MP-540-32858, October 2002, USA.

Singh G. FY Progress Report for Advanced Combustion Engine Research and Developments, Energy Efficiency and Renewable Energy Vehicle Technologies Program, DOE-ACE-2011AR, USA, 2011.

Schaltz E. (2011) Electrical Vehicle Design and Modeling. In: Soylu S (ed), Electric Vehicles – Modelling and Simulations, Intech Open Access Publisher, ISBN 978-953-307-477-1, pp 1-25.

Semercioglu H, Soylu S, Bal A. Examination of real world operating conditions and emissions of a hybrid city bus, ICAT'10 International Conference on Energy and Automotive Technologies, November 5, 2010, Istanbul.

Soylu S, Bal A, Semercioglu H, Ay EF. (2010) Examination of an Urban City Bus Operating Conditions and Emissions: Soylu S (ed), Urban Traffic and Electric Vehicles, SCIYO Open Access to Knowledge, D.O.O. RIJEKA 2010, ISBN 978-953-307-100-8, pp. 1-12.

White Paper 2011, Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system, EC staff working paper, SEC(2011) 358 final, Brussels, 28 March 2011.

Williamson, S.S.; Lukic, S.M., Emadi, A. (2006) Comprehensive Drive Train Efficiency Analysis of Hybrid Electric and Fuel Cell Vehicles Based on Motor-Controller Efficiency Modeling, IEEE Transactions on Power Electronics, Vol. 21, No. 3, May 2006.

Williamson, S.S.; Emadi, A. ; Rajashekara, K. (2007) Comprehensive Efficiency Modeling of Electric Traction Motor Drives for Hybrid Electric Vehicle Propulsion Applications, IEEE Transactions on Vehicular Technology, Vol. 56, No. 4, july 2007.

Xiong W, Zhang Y, Yin C. Optimal energy management for a series–parallel hybrid electric bus, Energy Convers. Manage. 2009; 50: 1730–1738.

VTP 2010, Multi Year Program Plan, 2011-2015, US Department of Energy, Energy Efficiency and Renewable Energy, Vehicle Technologies Program, December 2010.

Zhihua L, Ge Y, Johnson KC, Shah AN, Tan J, Wang C, Yu L. Real-world operation conditions and on-road emissions of Beijing diesel buses measured by using portable emission measurement system and electric low-pressure impactor, Sci. Total Environ. 2011;409: 1476–1480.