EXAMINATION OF REAL WORLD OPERATING CONDITIONS AND EMISSIONS OF A HYBRID CITY BUS

Hülya SEMERCİOĞLU, Ayda BAL, Şeref SOYLU*

Sakarya University
Faculty of Engineering
Department of Environmental Engineering
54187 Esentepe/Sakarya

ABSTRACT

Hybrid city busses are known to be advantageous for urban transport because of their regenerative braking systems that are very effective fuel savers at a bus route where stops, decelerations and accelerations are frequent. In this study, real world operating conditions and emissions of a hybrid city bus were investigated over a bus route that is commonly used by municipality busses in Sakarya. The aim of the investigation was to search potentials of the hybrid system for minimization of the fuel consumption and the emissions. It was observed that fuel saving potential of the hybrid system is strongly dependent on speed profile of a bus route and optimization of the hybrid system. Fuel saving potential of the hybrid city bus is determined to be as high as 30% on the "university route". But minimization of the emissions involves serious challenges, because average exhaust gas temperature and flow rate are lower with the hybrid system than that of a compareble conventional bus. Hence, NOx reduction efficiency of the SCR system was adversely affected from the low exhaust gas temperature.

Key Words: hybrid bus, regenerative braking, air pollution, real world emission, emissions measurement, engine operation conditions

INTRODUCTION

Since transport needs of our society is met mainly by motor vehicles, increasing demand for urban transport in parallel to economic and social development brings several problems in urban agglomerations. First of all motor vehicles require mainly fossil fuels that are finite, the second is that burning fossil fuels produces carbon dioxide which is major global pollutant. And the third is that combustion and after-treatment technology for conventional motor vehicles are not currently mature enough to eliminate the local emissions to zero levels. It is well known from the literature that the local emissions are very harmful for human health especially in urban agglomerations (WHO 2003, 2005a, 2005b). City busses on the other hand have important advantages for minimization of traffic congestion, fuel consumptions and urban air pollution as they can meet travel demand of as high as a hundred of passengers in a single bus. But, in order to be preferred as a main transport vehicle for urban agglomerations, city busses should still provide a comfortable travel with less fuel consumption and emissions with their environmentally friendly technology.

*Contact person: ssoylu@sakarya.edu.tr

Typical city busses operate where urban population is very dense and release local emissions such as particulate matter (PM), nitrogen oxides (NOx), carbon monoxide (CO), and hydrocarbon (HC) to the streets where the population live (Soylu, 2007, Soylu et al.,2008). In the streets, concentrations of the released emissions are generally high enough to damage human health and there is no enough time for the emissions to be diluted in the air to a harmless concentration before they are inhaled by human receptors. It is well known from the literature that exposure to even relatively low concentrations of vehicle emissions exacerbates or provokes the following: cardiovascular diseases, respiratory diseases, coughing, asthma, infant mortality, morbidity, neuroxicological damage and cancer and many more (WHO 2003, 2005a, 2005b). For this reason, it is crucial for authorities to employ environmentally friendly city busses for public transportation.

The local emissions from city busses depend strongly on engine combustion technology, exhaust after-treatment system, fuel quality, vehicle aging, and bus operating conditions (Cocker et al., 2004, Lents et al., 2007, EC 2009). Especially the bus operating conditions may have significant effects on the emissions.

Depending on city traffic and road conditions which involves many short trips with frequent accelerations, decelerations, low rush hour speeds and various road grades, vehicle emission factors may be changed with an order of magnitude.
Urban transport operating conditions and especially the city bus operating conditions are quite specific for a particular city and, hence, the well known certification test cycles cannot represent accurately these conditions all over the world. Even in the most developed countries quantity of vehicle emissions to be released in the urban streets has not been reduced in parallel with their stringent emission legislations (Pekar, 2010, Cocker et al., 2004, Lents et al.,2007). For this reason EURO VI regulation for heavy duty vehicles requires application of portable emissions measurement systems (PEMS) for verifying the real world in-use and off-cycle emissions (Cocker et al., 2009). PEMS are remedy for the real world emission measurement as they can be installed quickly to a vehicle and measure in-use emissions. Determination of fuel consumption, emissions and engine operation conditions in the real world conditions provides an important opportunity for vehicle manufacturers to optimize their vehicles under real world conditions.
Due to the difficulties in meeting stringent emission limit with conventional busses under urban driving conditions, bus manufacturers focus also on hybrid city busses as one of the promising alternatives to the conventional technologies. When compared to the conventional busses, hybrid busses can easily save fuel and minimize emissions because of their regenerative braking system. Storing the vehicle's kinetic energy as electricity during the braking and using it during the acceleration provides very good potential to minimize the fuel consumption and hence the emissions.
Frey et al. (2009) compared emissions performance of fuel cell, hybrid, CNG and ethanol vehicles for their emissions performance. And it was concluded that under real world driving conditions, hybrid vehicles are capable of reducing the NOx emissions up to 50%.
Mierlo et al. (2006) examined performance of electrical, hybrid and fuel cell vehicles. It was concluded that when compared to the conventional vehicles, electrical and hybrid vehicles provided up to 50 % and 40 % energy saving, respectively. It was also emphasized that heavy-duty hybrid vehicles can provide up to 30 % savings in energy and emissions.
In a study completed in China, the fuel economy of 12 m conventional and hybrid buses are compared on China transit bus driving cycle. According to this study, the hybrid bus provides at a rate of 30.3 % reduction in energy consumption. It's emphasized as conventional bus consumes 42 liter diesel fuel and the hybrid bus consumes 28.05 liter diesel fuel for 100 km driving (Xiong et al., 2009).
Gao et al. (2008) studied to determine emission impacts that occurred by replacement of conventional vehicles by hybrid electric vehicles in a taxi fleet in New York. It was observed that by increasing hybrid vehicle rate in the taxi fleet to the 9.35%, CO_2, CO, HC, and NOx emissions are reduced at a rate of 2.29%, 1.45%, 1.12% and 1.70%, respectively.
Wall et al. (2008) studied to reduce emission impacts of a city bus fleet. Three different measures were implemented in Winchester city. These implemented measures included introduction of 13 new Euro III buses, re-powering 10 older buses from Euro I to Euro III standard buses and the demonstration of two different diesel/electric hybrid buses during two week-long trials in 2003 and 2004 along the specific routes. Re-powering of 10 older buses form Euro I to Euro III standard provided reduction at a rate of 47%, 64%, 50% and 56% in NOx, PM_{10}, CO and HC emissions, respectively. Also, it was envisaged that four new hybrid electric buses would be purchased. However, this was not possible due to financial and contractual reasons. However, two different hybrid buses were demonstrated on the specific routes for a week in 2003 and 2004 and passenger satisfaction survey was done. Generally, younger people (under 34 years old) participated to survey. According to survey, hybrid vehicles are both more quiet and comfortable than conventional vehicles.
Another study in Belgium was achieved about cost and benefits of PM emission reduction strategies between the years 2000 and 2010. It's determined that a rate of 44% reduction in PM emission was possible by assembling a particulate filter to Euro II vehicles. It was shown that the average CO_2 reduction for replacement of a diesel car by a diesel/hybrid car was approximately 0.93 ton and PM emission reduction was about 0.62 kg/vehicle (Schrooten et al., 2006).
Samaras et al. (2008) studied emissions and fuel economy benefits of the hybrid vehicles on real world simulation driving cycles. Measurements were done by using Honda CIVIC IMA mild hybrid and Toyota Prius II full hybrid on New European Driving Cycle (NEDC) and real world simulation driving cycles (ARTEMIS). As Prius II provided at a

rate of 60% fuel saving, fuel saving rate of Honda CIVIC IMA was 40%.
CTTransit carried out a demonstration project to evaluate emissions and fuel economy performance of hybrid diesel electric transit buses. Hybrid buses were considered to be the next generation of transit vehicles for future fleet replacement that are cost effective and reliable when compared to conventional buses. The project was financially supported by Connecticut Department of Transportation and the project partners were CTTransit, Allison Transmission, Horiba Instruments, Inc., New Flyer Bus Industries, University of Connecticut, ConnDOT Bureau of Public Transportation. In their third quarter report it was concluded that hybrids demonstrated good reliability and low maintenance costs. They observed that the hybrid busses provided 10% better fuel economy than their peer test diesel busses and 35% better than the fleet average (Warren.,2004).
In fact, the electric vehicles are optimum solutions for urban transport as they release no emissions during their operation in the urban area, but, in these days potential use of the electrical vehicles are very limited due to their high cost and limited range and lifetime of their battery pack. Hybrid vehicles on the other hand have properties of both electrical and conventional vehicles and are important alternatives for the transition to electrical vehicles.
Urban traffic in Sakarya, which is a medium size city of Turkey, is dominated by passenger cars with 52 % and light duty vehicles with 39 %. City busses are accounted for only 6% of the traffic. Although vehicle ownership rate is almost one third of developed European cities, traffic congestion is still one of the biggest problems bothering the citizens. City busses can be remedy for the congestion but they are not commonly preferred by the citizens as main transport vehicle. However, most of the city busses in Sakarya are pre-euro level in terms of engine technology and emissions. In order to indicate advantages of modern hybrid city busses, a research project was introduced by Sakarya University with support of Turkish Ministry of Industry and TEMSA R&D. In order to quantify the impacts of hybridization, a two-phase test programme was prepared to measure real world in-use emissions and fuel consumptions of both conventional and hybrid city busses on a specific bus route in Sakarya city center. In the present work, the results from the test programme that involves examination of engine operating conditions and NOx emissions of the Temsa Avenue hybrid city bus are presented.

METHODOLOGY

In this work all the tests were carried out on "university route" of Sakarya Municipality city busses and Figure 1 indicates satellite image of the route. The route includes a round trip between Sakarya University and the city center which represents typical Sakarya urban driving. It is 22 km long and the altitude ranged from 30 m to 220 m. The travel time is approximately 60 minutes. During the test the vehicle was driven on the route and data such as vehicle speed, location, engine operation characteristics, exhaust flow-rate, exhaust emissions and environmental conditions were sampled second by second.
The test measurements were made by using a SEMTECH DS from SENSORS inc. Figure 2 indicates this system that includes a flame ionization detector (FID) for total HC measurement, a non-dispersive infrared (NDIR) sensor for CO and CO2 measurement, a non-dispersive ultra violet (NDUV) sensor for NO and NO2 measurement. The NDUV measurement is different from standard chemiluminescence measurement that is used for the reference method. Exhaust mass flow-rate was measured by using SEMTECH EFM which operates based on Pitot tube technology. The PEMS equipped with global positioning system (GPS), ambient temperature and humidity sensors. Before the test, the PEMS was warmed up according to user manual and then zero, span and audit calibrations were completed to ensure high accuracy. The bus was stopped at every bus station around 10 seconds to simulate the real world conditions. Over the test the ambient temperature varied from 25 to 30 °C and the relative humidity varied from 30 to 45 % which are typical values for summer time.

Figure 1. Satellite image of the university route

Figure 2: image of PEMS

The test vehicle was TEMSA AVENUE HYBRID bus, which is a 12 m long city bus. The bus is full and series hybrid and the hybrid system generator is powered with a 6.7 liter CUMMINS ISB6.7 EURO 5 engine which produces 250 HP at 2500 rpm. The engine was certified to 2 g/kWh NOx standard.

RESULTS

Figure 3 indicates the schematic of the hybrid drive train of the bus, which is series hybrid configuration. In this configuration, there is no mechanical connection between the engine and the wheels. Instead, internal combustion engine drives a generator that feeds the electric motor. The ultracapacitor which is charged during regenerative braking can also power the electric motor especially during the first acceleration after a bus stop.

Thanks to regenerative braking, significant amount of fuel and emissions savings can be achieved.

The state of the hybrid drive train operating parameters which are ultracapacitor state of charge (SOC), hybrid system power (P_SYS), ultracapacitor driving power (P_ES_fst), bus speed (V), generator power (P_GEN), engine power (P_ENG) and CO2 emission (CO2) are given for a period of time in Fıgure 4. As can be seen from the figure while bus speed is starting to accelerate at 30th second, the P_SYS is immediately increasing to a maximum and then gradually going down depending on level of the SOC. Until the bus speed reaches to 30 km/h at 38th second, the internal combustion engine of the bus is idling and it has no contribution for this acceleration at all. For about 8 seconds the bus is driven by the energy of the ultracapacitor that is charged previously during regenerative braking. Actually this is where fuel saving is coming from. After 38th second, P_ENG is starting to feed the generator. As can be seen from the figure P_GEN is just an opposite of P_ENG but the absolute magnitude is little less because of frictional power loss of the internal combustion engine. Once the P_ENG starts to rise depending on the demand from the bus driver, the generator starts to contribute to the hybrid system power and the level of P_SYS increases again. Fuel saving potential of the hybrid system can easily be estimated either by integrating ultracapacitor driving power.

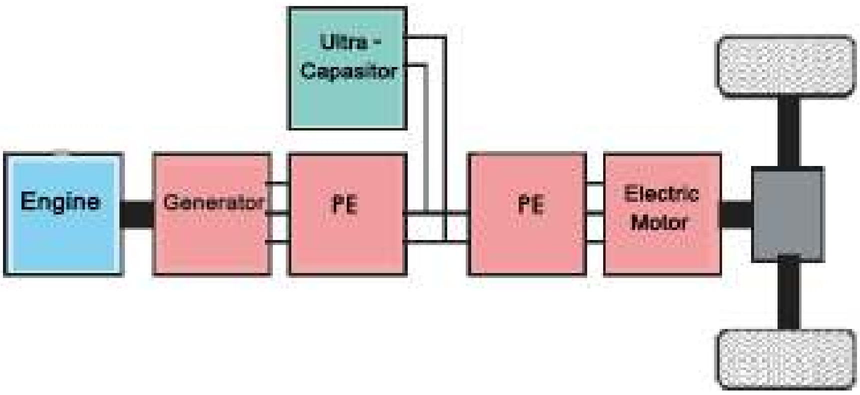

Figure 3: Schematic of the hybrid drive train (PE is power electronics)

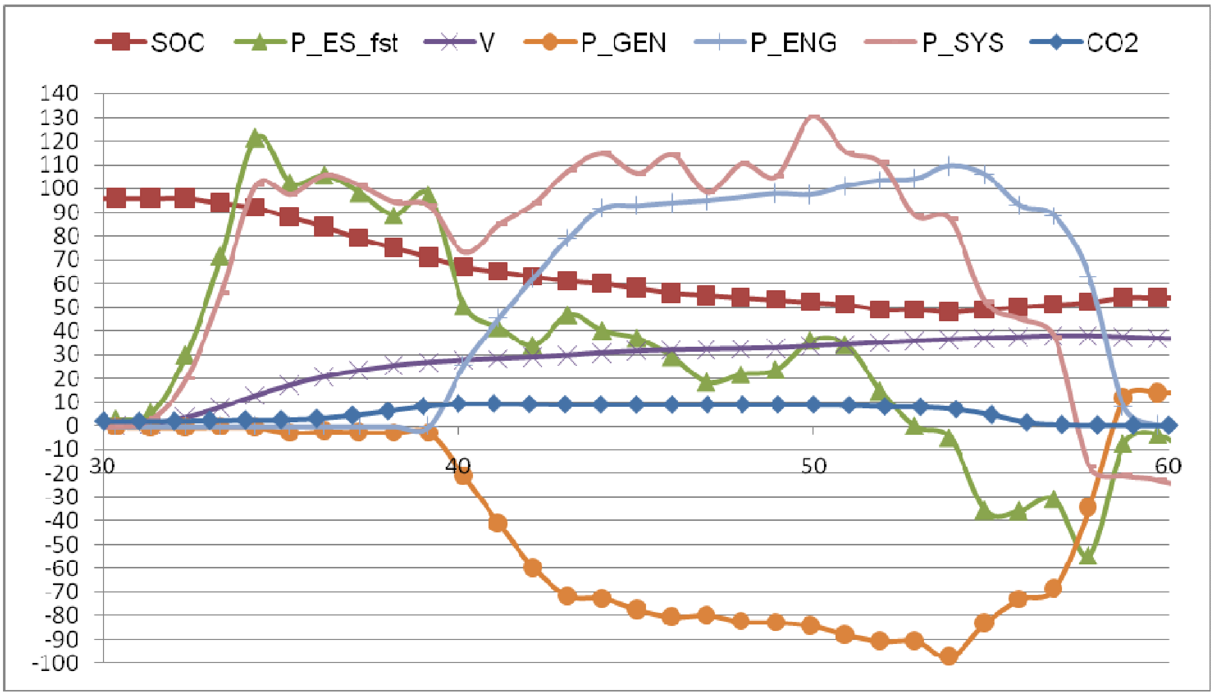

Figure 4: Operating characteristics of the city bus hybrid drive train

(P_ES_fst) or from the decrease of the SOC during the period where the ultracapacitor is feeding the electric motor. Since the capacity of the ultracapacitor is known, amount of energy that feeds to electric motor can easily be calculated from the percent variation of the SOC. And then fuel equivalent of this energy can be calculated by using the following formula:

Fuel saving = n_stops * delta SOC * Capacity / Q_LHV * η (1)

Where, n_stops is number of the stops on the bus route, delta_SOC is the change in charging level of the ultracapacitor during the acceleration, capacity is the ultracapacitor capacity, Q_LHV is the lower heating value of the fuel, and the η is brake thermal efficiency of internal combustion engine.
In this formula the capacity and Q_LHV are constants and the η is strongly dependent on engine speed and load. The n_stops is totally dependent on the speed profile of the bus route but the delta_SOC is dependent on both speed profile of the bus route and the optimization strategy of the hybrid system. Therefore, increasing the Fuel saving potential of a hybrid city bus is strongly dependent on a route the bus is driven and optimization strategy of the delta_SOC.
However, it should be considered that depending on the bus operating condition, the generator can feed the ultracapacitor as well. In this case the Fuel saving should be modified accordingly. While the bus was driven on the university route from Sakarya University campus to city center, the bus fuel consumption was measured to be 3.56 liter. During this trip the fuel saving was calculated to be 1.78 liter. If this fuel had not been saved, total fuel consumption would have been 5.33 liter. As a result of this calculation, the hybrid system provided 30% fuel saving on this trip.
Figure 5 indicates the speed profile for the university route which is a real world city bus speed profile. Highly transient behavior of the route can be seen clearly from the figure. The trip duration is 1922 seconds in total. The bus speed reaches to as high as 50 km/h but there are many stops with corresponding decelerations and accelerations because of road traffic and bus stops. It is well known from literature that vehicle speed profile has a strong impact on operating characteristics of the vehicle engine. Figure 6 indicates engine speed-load frequency map which is the response of bus engine to the speed profile given in Figure 5. As shown in the figure, the map is divided into four zones to examine the map in detail. The first zone is low load-speed zone which the speed varies from 600 to 1000 rpm and the load varies from 0 to 50%. The engine operated in this zone about 720 seconds which most of it corresponds to idling time. The second zone is low load-high speed zone and the engine operated in this zone about 505 seconds. The third zone is high speed-load zone and the engine operated in this zone about 676 seconds. The fourth zone is high load-low speed zone and the engine operated in this zone about 21 seconds.

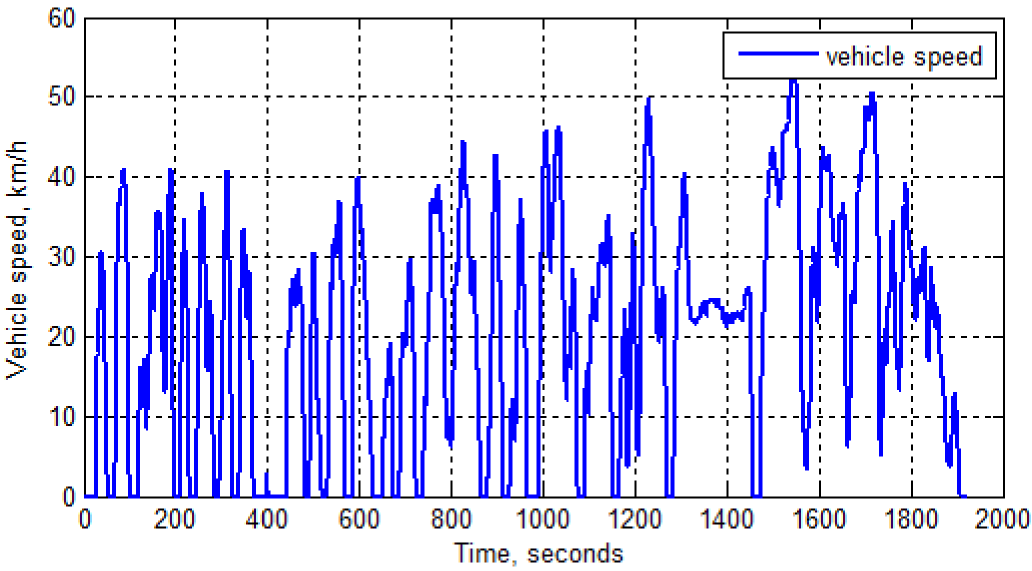

Figure 5. City bus speed profile on the university route

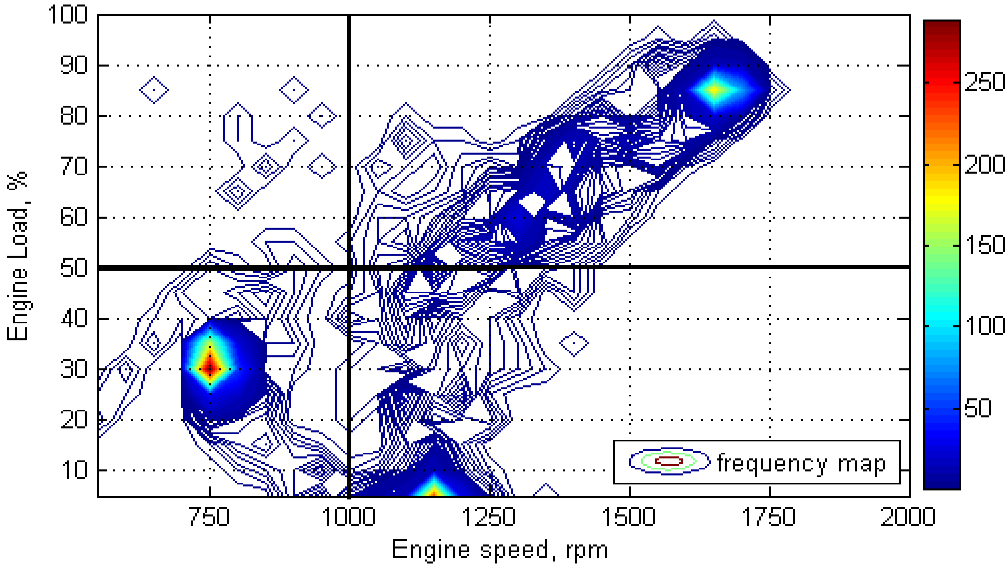

Figure 6. Engine speed-load frequency map for the university route

Since the minimization of fuel consumption and emissions strongly depends on where the engine operates, the operating time in each zone can be considered as a measure of importance of the zone. From this figure it is clear that the bus engine operates most of the trip time at idling conditions. Although the fuel consumption is lower in the first zone than the other zones, the emissions may not have the same trends.

Another concern with the engine speed-load map is that it does not correlate very well with that of the engine certification test cycles. Figures 7 and 8 indicate engine speed-load map for European Stationary Cycle (ESC) and European Transient Cycle (ETC) that are current regulatory test cycles for heavy duty engines. As can be seen from the figures, in these cycles the engine operates mostly at speeds over 1200 rpm.

From these maps it is easy to see that the real world city bus driving conditions are significantly different from that of ESC and ETC test cycles although city bus engines are still certified according to ESC and ETC test cycles. It is therefore questionable if the certification cycle emissions limits ever be realized in the real world driving conditions. A certification test cycle should be able represent real world operating conditions of an engine, however there are different types of use of these engines, such as highway trucks and busses, delivery trucks, and city busses. Engines of these different vehicle classes certainly operate with different frequencies on the engine load-speed map although they all are certified with the same test cycle.

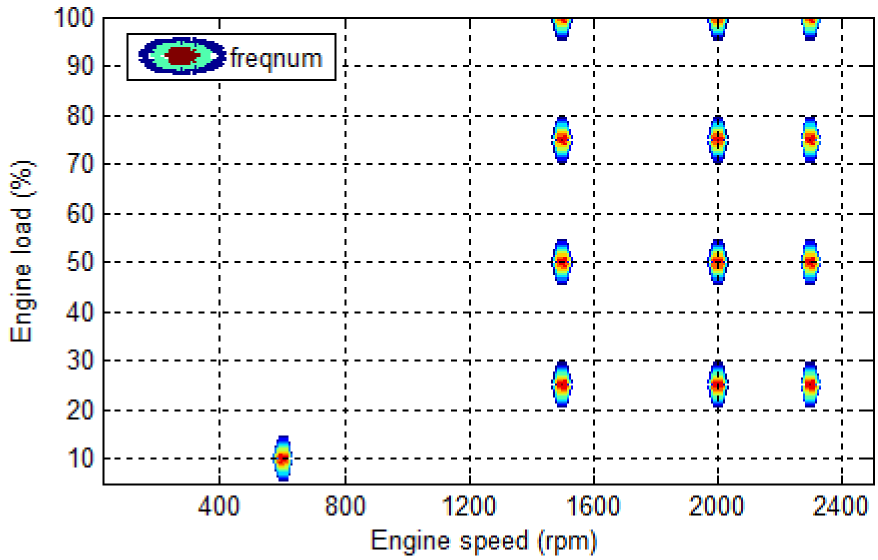

Figure 7. Engine load-speed map for the ESC

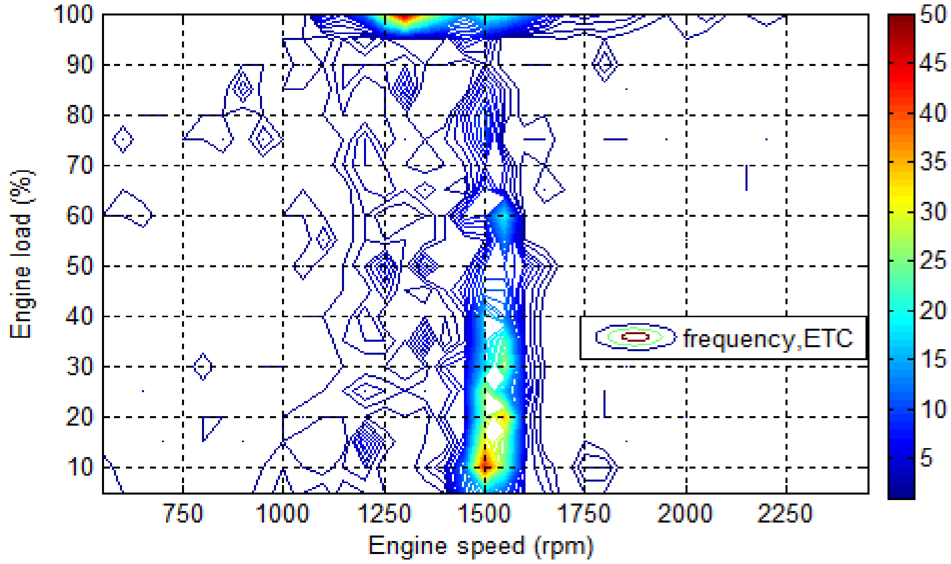

Figure 8. Engine speed-load frequency map for the ETC

Therefore, off-cycle operation of these engines and corresponding emissions can be significantly higher than that of the certification test cycle. In order to minimize these off-cycle emissions, EPA introduced Not To Exceed (NTE) regulations but there is almost no way to completely control engine emissions when considering sophistications at engines and their after-treatment systems.

Engine speed and load are important parameters effecting in-cylinder temperature and NOx emissions formation. Figure 9 indicates variation of exhaust gas temperature with engine speed and load for the university route. As expected the temperature is getting higher with speed and load although there are a few exceptions. While reducing the NOx emissions with Selective Catalytic Reduction (SCR) system, the urea solution in ad-blue tank is injected to hot exhaust gases, Amonium (NH_3) is formed from the injected urea by means of hydrolysis. Then NOx emissions are minimized in the catalyst after its chemical reaction with the NH_3 to form nitrogen and water. Reduction reactions of NO_x emissions are as follows:

$$NO + NO_2 + 2\ NH_3\ 2N_2 + 3H_2O \quad (1)$$
$$4\ NO + O_2 + 4\ NH_3\ 4N_2 + 6H_2O \quad (2)$$
$$2\ NO + O_2 + 4\ NH_3\ 3N_2 + 6H_2O \quad (3)$$

It is well known from the literature that, in order to reduce NOx emissions efficiently, the temperature of SCR system should be over the light-off temperature which is approximately 250 degree C.

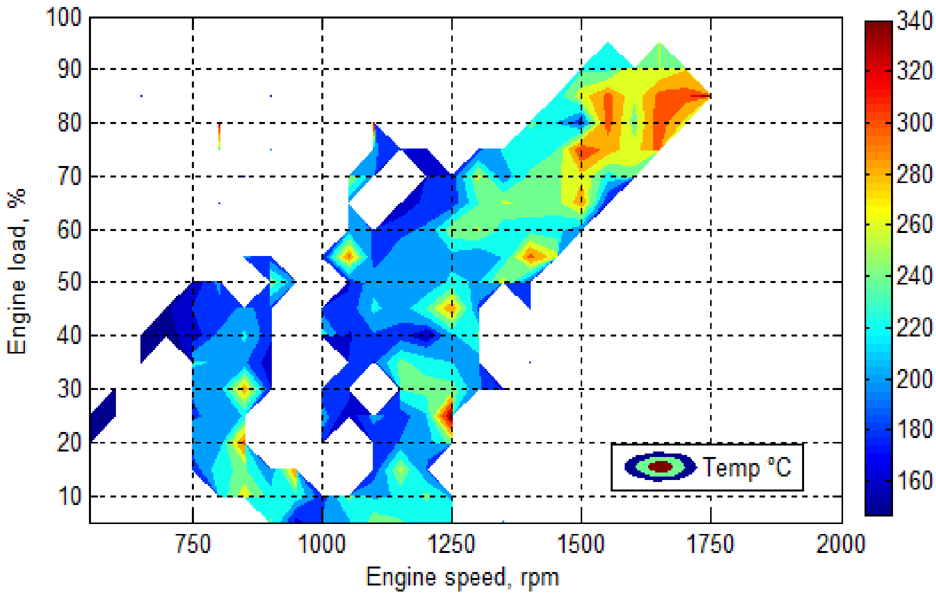

Figure 9: Temperature map for the university route

Therefore, the reduction of NOx with SCR system is highly dependent on engine operating conditions and, hence, city bus driving conditions. Figure 10 indicates variation of NOx emissions with engine speed and load. As can be seen from the figure, NOx emissions are generally higher in the third zone as expected and in this zone they are reduced efficiently only at speed and load conditions where the exhaust temperatures are well above the light-off temperature. As can be seen from Figure 9, the exhaust temperature remains below the light-off temperature over most of the speed-load map. The reason for this low temperature can be low mean loading of the engine on the university route. Because, while certifying this engine as EURO V, it was considered to be an engine for a conventional vehicles and tested over the relevant certification cycles. However under hybrid working conditions mean engine power is lower than that of a conventional engine conditions because of the regenerative braking and hence power assistance of ultracapacitor. As a result, hybrid bus mean exhaust temperature remains low and hence the NOx emissions are not reduced to the certification level but to the level of 4.7 gr/kWh on the unversity route.

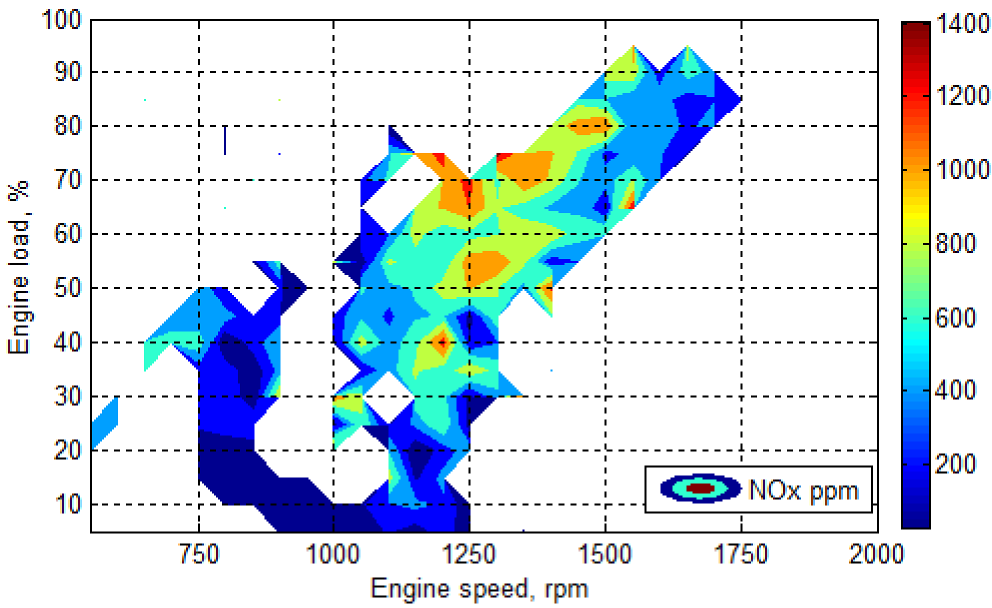

Figure 10: NO_x emission map for City Centre-SAU Campus route

CONCLUSIONS

Hybrid city bus is a very efficient fuel saver due to its regenerative braking but the fuel saving potential is strongly dependent on the speed profile of the bus route and hybrid system optimization strategy. While driving on the university route, fuel saving up to 30% is achieved.

Since the hybrid city bus mean exhaust temperature remains lower than the light-off temperature on the unversity route, the NOx emissions are not reduced to the certification level but to the level of 4.7 gr/kWh, only.

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REFERANCES

Christopher H. Frey, Haibo Zhai and Nagui M. Rouphail, Regional On-Road Vehicle Running Emissions Modeling and Evaluation for Conventional and Alternative Vehicle Technologies, Environmental Science & Technology 43, 8449–8455, 2009.

David R .Cocker, Sandip D . Shah, Kent Johnson, J . Wayne Miller, Joseph M. Norbeck. Development and Application of a Mobile Laboratory for Measuring Emissions from Diesel Engines, 1. Regulated Gaseous Emissions. Environmental Science &Technology 2004- 38, 2182-2189.

David R. Cocker, K.C. Johnson ,T.D. Durbin, W.J. Miller , D.K. Bishnu , H. Maldonado, N. Moynahan, C. Ensfield, C.A. Laroo. On-road comparison of a portable emission measurement system with a mobile reference laboratory for a heavy-duty diesel vehicle. Atmospheric Environment 43 (2009) 2877–2883.

Georgios Fontaras, Panayotis Pistikopoulos, Zissis Samaras, Experimental evaluation of hybrid vehicle fuel economy and pollutant emissions over real-world simulation driving cycles, Atmospheric Environment 42 (2008) 4023-4035.

Graham Wall, Tim Felstead, Andy Rcihards, Mike Mcdonald, Cleaner vehicle buses in Winchester, Transport Policy, 15 (2008) 55-68.

H. Oliver Gao, Vincent Kitirattragarn, Taxi owners' buyiing preferences of hybrid- electric vehicles and their implications for emissions in New York City, Transportation Researc Part A 42 (2008) 1064-1073.

James Lents, Alper Unal, Nizamettin Mangir, Mauricio Osses, Sebastian Tolvett, Onder Yunusoglu. A study of the emissions from diesel vehicles operating in Istanbul, Turkey January 2007.

J. Van Mierlo, G. Maggetto, Ph. Lataire , Which energy source for road transport in the future? A comprarison of battery, hybrid and fuel celll vehicles, Energy Conversion and Management 47 (2006) 2748-2760.

Liesbeth Schrooten, Ina De Vlieger, Filip Lefebre, Rudi Torfs, Costs and benefits of an enhanced reduction policy of particulate matter exhaust emissions form road traffic in Flanders, Atmospheric Environment 40 (2006) 904-912.

M Koebl, M. Elsener, and M. Kleeman (2000). Urea-SCR: a promising technique to reduce NO*x* emissions from automotive diesel engines, *Catalysis Today* 59 (2000) 335–345.

Regulation (EC) No 595/2009 of the European Parliament and of the Council *18 June 20097.*

Seref Soylu., Estimation of Turkish Road Transport Emissions, Energy Policy, Volume 35, İssue 8, Pages 4088-4094, 2007.

Seref Soylu, Mahnaz Gumrukcuoglu, Ayda Bal, Gurkan Senturk, Burcu Aydınlar , Examination of urban transport characteristics and its emissions - Adapazarı case study, (Poster no: 064) ETTAP-09 17th Transport and Air Pollution Symposium - 3rd Environment and Transport Symposium - June 2-4, 2009.

Stephen W. Warren, CTTRANSIT Demonstration and Evaluation of Hybrid Diesel Electric Transit Buses, third quarter report, January, February & March 2004 Report No. CT-170-1884-3-04-5, CT, USA.

Weiwei Xiong, Yong Zhang, Chengliang Yin, Optimal energy management for a series-parallel hybrid electric bus, Energy Conversion and Management 50 (2009) 1730-1738.

WHO, 2003. Health aspects of air pollution with particulate matter, ozone, and nitrogen dioxide. Report on a WHO Working Group, Germany, 2003. www.who.int/en.

WHO, 2005a. Air quality guidelines for Europe; second edition Copenhagen. WHO Regional Office for Europe, WHO Regional Publications. European series; No 91. www.euro.who.int/air/activities/20050223_4.

WHO, 2005b. Health effects of transport-related air pollution. WHO Regional Office for Europe Scherfigsvej 8, DK-2100 Copenhagen , Denmark.

Zachary Pekar, Quantitative health risk assesment for particulate matter, EPA-452/R-10-005 June 2010