ASSESSMENT OF REAL DRIVING EMISSIONS OF A BUS OPERATING ON A DEDICATED ROUTE

by

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The reducing of real driving emissions from public transportation which is using intracity lines has become more important in recent years. This is because the petroleum derived fuel combustion products contributes the global warming as well as adversely the air quality. The fuel consumption perspective is another major economical concern for operating companies that should be optimized. In this context a part of Istanbul Metrobus public transportation system of which is using fully a dedicated line is assessed via on board emission and fuel metering devices for two loading conditions. The relevant vehicle and engine operating data is logged during the tests. The logged data is post processed for developing the average emission factors. The results are also analyzed from acceleration and altitude change perspective and alternative scenarios are discussed for cleaner and economic operation. Lastly the in-service conformity parameters are identified and the results are compared with homologation values. It was found that for the same velocity, acceleration affect was found significant and the critical acceleration level is determined as 0.4 m/s². For NO_x, and CO emissions velocities smaller than 20 km/h and 40 km/h was found dominant at positive acceleration zones. Also for fuel consumption and CO_2 emission levels the velocities higher than 30 km/h was found critical for all positive acceleration levels. It was shown that the real driving and emission data can be used efficiently for developing more environmentally friendly engine calibrations and decreasing fuel consumption and emissions.

Key words: *public bus transportation, fuel consumption, real driving emissions, emission factors.*

Introduction

The reduction of regulated emissions and CO_2 and also the fuel consumption of public transportation system becoming an emerging issue in recent years. The road transport using internal combustion engines powered powertrain units contributes the global warming as well as adversely the air quality. Lorries, buses, and coaches produce around a quarter of CO_2 emissions from road transport in the EU and around 5% of the EU's total GHG emissions – a greater share than international aviation or shipping [1]. The EU is planning to decrease emissions from road transportation by 50% to the year 2050. Also the movement to new emission legislation (Euro VI) for heavy duty vehicles presenting a huge reduction in the NO_x emission limit for steady-state testing (2.0-0.4 g/kWh – 80% reduction), and transient testing (2.0-0.46 g/kWh – 77% reduction). The particle matter limit was also significantly reduced for steady-state testing (0.02-0.01 g/kWh – 50% reduction), and transient testing (0.03-0.01 g/kWh – 66% reduction). Also the certification

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cycles are replaced. European steady-state cycle, the European transient cycle, and the European load response cycle are replaced with World harmonized stationary cycle and World harmonized transient cycle. Also, at the latest phase, with the Euro VI adaptation the regulation set out the requirements for checking and demonstrating the conformity of in-service engines and vehicles using portable emission measurement systems [2]. Considering to the public transportation is using especially intracity lines the emissions and the real driving conditions are becoming more important. There are lots valuable researches that can be found in the literature.

Joumard *et al.* [3] investigated the effect of loading on to real driving emissions (RDE) for different vehicle categories in terms of average cycle velocity and vehicle load. They also analyzed the driving conditions and developed representative driving cycles. They revealed according to the average velocity of the cycle the emissions generally evolved according to U-shape curve, the on board load generally resulted as decrease in CO, HC, and particulate matter (PM) emissions an increase in NO_x and CO_2. Vujanović *et al.* [4] worked on the activities applied to increase the energy efficiency of transport companies. The analyses of operating parameters that influence fuel consumption were carried on. The vehicles permissible weight range (2.5-40 tonnes) was used as test range. The measurements were performed under same environmental conditions. The measurement were realized with by means of an on-board computer. Their assessed the specific the increase in fuel consumption is linked with the increase of carried weight so the payload factor. But they revealed the increase is not proportional. Manojlović *et al.* [5] assessed the influence of specific parameters of vehicle operational lifecycle costs. They studied energy costs and estimated vehicle energy consumption, on vehicle choice in the procurement procedure. Pollutants' emissions and total energy consumption were estimated by means of the COPERT IV model for selected scenarios. They showed defined fleet renewal scenarios could significantly decrease the energy consumption. Peng *et al.* [6] investigated fuel consumption and emission characteristics of liquid petroleum gas (LPG) and LPG-hybrid electric vehicle (HEV) city transit busses. They showed that effect of velocity on fuel consumption is non-linear. The average fuel consumption is decreased with the increase of average velocity at first and then increased with the increased average velocity. The minimum fuel consumption is obtained at ~50 km/h. They showed that when the buses is in deceleration mode or closed to constant state the fuel consumption was found stable. The increase of acceleration increased the fuel consumption. They also revealed that average velocity has a non-linear effect on average emission factors. All emission factors showed clear inverse trend with average velocity. Also the exhaust emission factors are clearly steady in deceleration modes and they increased with the increase of acceleration. Zhang *et al.* [7] studied real world emissions of heavy duty diesel trucks. They reported the emission levels in acceleration conditions was significantly higher than of deceleration conditions. They revealed the incomplete combustion of fuel for sudden acceleration demands resulted with greater emission rates. So they proposed this phenomenon can be reduced with changing the driving behavior. They also reported gaseous emission rates increased with increasing vehicle specific power (VSP) values. Gallus *et al.* [8] studied the driving style and altitude effect on RDE with two diesel (Euro V and Euro VI) vehicles. The CO_2 and NO_x emissions showed a strong correlation with driving parameters, CO and HC emissions did not show any distinct separation with different driving styles. The NO_x emissions was found in the same range at the routes with similar cumulated altitude gain for constant driving dynamics. Also, CO_2 and NO_x emissions showed a good correlation with the road grade for all road parts. Yu *et al.* [9] investigated emissions created near bus stops. They revealed emitted pollutants near bus stops is forming the 20% of the total emissions, road intersection segments is assessed as 30%, and 50% was assessed as at links Also the number of passengers affected the stop and idling time so the emissions. Yu *et al.* [10] also investigated passenger load factor. They showed that for emissions (CO_2, NO_x, and HC) and fuel consumption rates, the influence of passenger load is becoming significant when the bus travels over 30 km/h while passenger load had no impact on CO emissions. They also revealed that per-passenger emission and fuel consumption factors showed an inverse correlation with passenger load which meant when the bus is running on low load, the per-passenger emissions and fuel consumption factors may not lower than private cars. A detailed review about road vehicle emission factor development is presented by Franco *et al.* [11]. They presented the importance of RDE testing with PEMS for emissions modelling and emission factor validation There are also numerous valuable research in this area which can be found in [12-22].

In this context, one of the world biggest transportation axle, Istanbuls' most important public transportation line, Metrobus Line, was chosen as the research area for identifying RDE and fuel economy of compression ignition (CI) engine equipped mass public transportation. Metrobus Line is a strategic dedicated transit bus line planned by Istanbul Metropolitan Municipality which crosses the Istanbul city from Asia to Europe. Its length is about 52 kilometers and there is more than 550 busses in 24 hours service, which enables mass transit transport (over ~1 million passenger daily) between two continents. The public bus that run in a part of this dedicated line equipped with measurement and data logging devices (*fuel consumption, emissions controller area network – CAN*) used for research purpose. The investigation was carried out for two different pay load conditions (6.500 kg and 13.000 kg) at the Avcilar (A) – Beylikduzu (B) part of Metrobus Line for A to B (AB) and B to A directions. Then the research data was post processed in order to develop emission factors and critical operating parameters that effect the emissions and fuel consumption. The altitude affect is also analyzed. Then the alternative scenarios are discussed for decreasing the emissions and fuel consumption among this context.

Methodology

Experimental set-up

Table 1. Vehicle and engine properties

Weight (gross)	32 tones
Articulation	Articulated
Length	18 m
Number of cylinders	6
Engine capacity	11.9 liters
Power	2000 rpm-260 kW
Torque	1100 rpm-1600 Nm
Emission level	Euro V

An Euro V public bus which is powered by a diesel engine was used. The properties of the test vehicle is presented in tab. 1. The AVL MOVE system consisting of AVL gas portable emission measurement system (Gas PEMS) for CO, CO_2, NO_x, and O_2 measurements and AVL PM PEMS equipped with micro soot sensor was used for soot monitoring. The measurement devices and their accuracy is given in tab 2. The gaseous emissions and soot is continuously measured. The total gravimetric PM measurement was not made active in order to assess the soot simultaneously, so the soot is accepted as PM. The position of the vehicle in terms of latitude, longitude and altitude was monitored with 2 Hz GPS equipment. The temperature, humidity an atmospheric pressure was also monitored with 1 Hz resolution during the measurements for post processing purposes. Also the relevant CAN data (actual can engine torque, accelerator pedal position, gear,

Table 2. Properties of measurement devices

Measurement system	Device	Method	Accuracy
Fuel consumption	AVL KMA mobile	Rotational type flow meter	±0.1%
Emission	AVL gas PEMS	NO → NDUV[i]	±0.2%
		NO_2 → NDUV[i]	±0.2%
		O_2 → Oxygen sensor	±1%
		CO → NDIR[ii]	±30 ppm
		CO_2 → NDIR	±0.1%
Emission	AVL PM PEMS	Soot → Photoacoustics	~5 μg/m³

[i] NDUV: non-dispersive ultraviolet. [ii] NDIR: non-dispersive infrared

and wheel based vehicle velocity in longitudinal direction) of the vehicle that is needed for further analyses were collected. The system controller equipment by AVL controlled all systems and logged all data synchronized during operation. The system layout is presented in figs. 1(a) and 1(b).

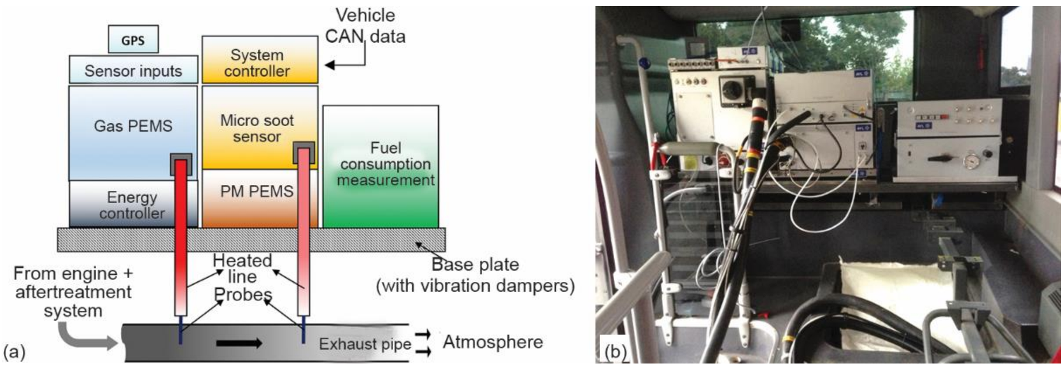

Figure 1. (a) Test system layout, (b) test system set-up

Test route and vehicle load

The test are carried on Istanbul Metrobus Line. The Metrobus line is consisting of 3 main parts. These parts are Sogutlucesme → Zincirlikuyu – 11 km length with 8 stations, Zincirlikuyu → Avcilar – 29 km length with 25 stations and the last part is Avcilar (A) – Beylikduzi (B) – 16 km length with 12 stations. The tests were carried on Avcilar-Beylikduzu route which is called 34B route by Istanbul Public Transportation Company (IETT) that has the maximum altitude change (173 meters) during in its operation. The tests are realized for both A to B (AB) and B to A (BA) direction. The test route is Google Earth presented in fig. 2.

The vehicle is loaded with sand bags for simulating payload (passenger load) during the tests. Two considered load conditions are full load (FL) – 13 tons of sandbag, and half load (HL) – 6.5 tons of sandbag. The FL condition is simulating the heavy operating conditions during morning and night times, and HL simulates the normal daily operation. Test tests were realized with following up and imitating the cruising characteristics of the front bus method with a safe distance which is at normal operation schedule. The bus is operated under similar atmospheric conditions for minimizing the environmental influences (*i. e.* wind, temperature,

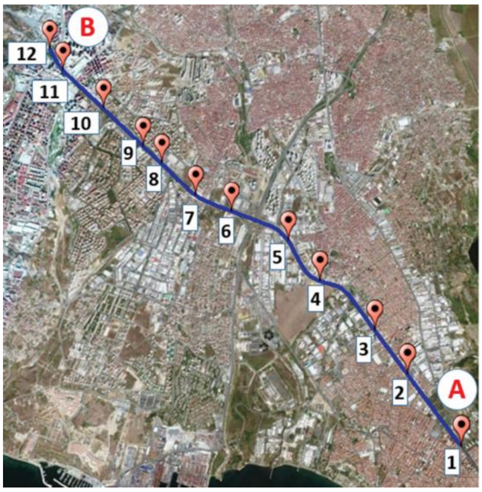

Figure 2. Avcilar-Beylikduzu test route Google Earth image

dry course, *etc.*). For each direction and payload condition 5 test is realized (totally 20) for obtaining the average results. The test are separated as 3 in week 2 weekend days for each condition for obtaining an average that represent total week operation. The total research period is consisting of 4 weeks for the whole research for all conditions.

Results and discussion

The velocity, altitude and the emissions (CO_2, CO, NO_x, and soot) logged during a FL cruise from A to B direction and calculated acceleration from logged velocity is given in fig. 3 as time based series. The characteristic changes of emissions behavior is evident especially at high power and acceleration demand zones which occurs realized especially take-offs from stops. Also the average values for trip statistical characteristics are given in tab. 3.

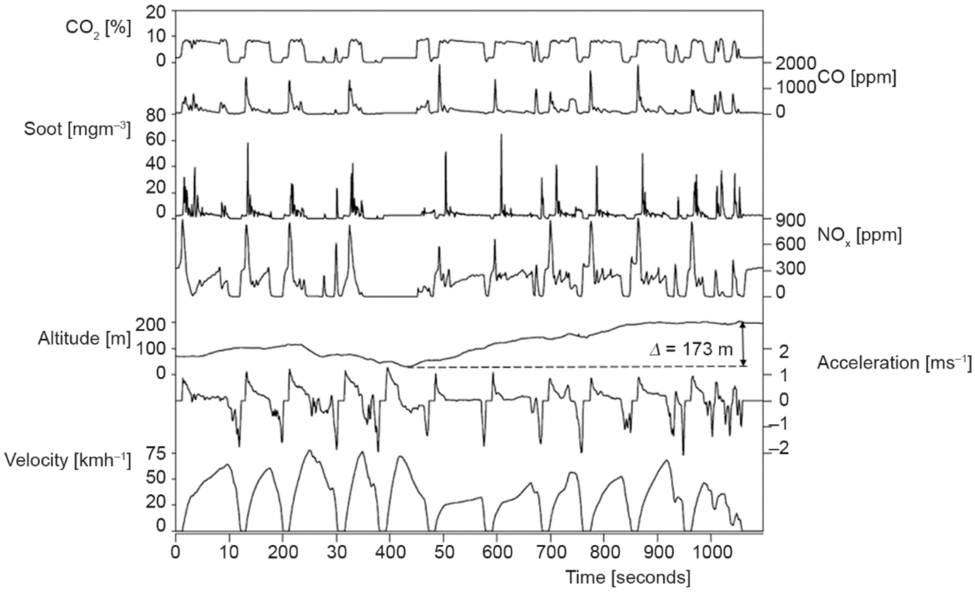

Figure 3. Time based logged data at AB direction with FL condition

Table 3. Vehicle cruise analysis (average values)

Direction	Unit	AB		BA	
		FL	HL	FL	HL
Velocity	[kmh^{-1}]	32.07	30.05	35.22	35.64
Acceleration	[ms^{-2}]	0.51	0.53	0.51	0.50
Deceleration	[ms^{-2}]	-0.29	-0.32	-0.34	-0.38
Acceleration duration	[%]	51.91	53.69	51.39	49.58
Deceleration duration	[%]	29.38	32.80	34.32	38.32
Cruising + stop duration	[%]	18.71	13.51	14.29	12.10
Trip duration	[second]	1098	1193	1021	1059

For analyzing the effect of altitude the fuel rate contour graph is given at fig. 4. As it is seen from the graphics the uphill cruises at AB direction (in red) results as fuel rates over 30 g/s and the altitude change (Δ = 173 m) is one of the main factor in this direction. Opposite to this behavior the BA direction is having a major downhill characteristic. As its seen from the graphic, negative gradient resistance effect because of the negative altitude change and the engines fuel cutoff strategy (in green) realized by engine control unit helped to reduce the total fuel consumption. Also it is analyzed in fig. 5(a) that average fuel factors for AB route is always higher than the BA for all both load conditions.

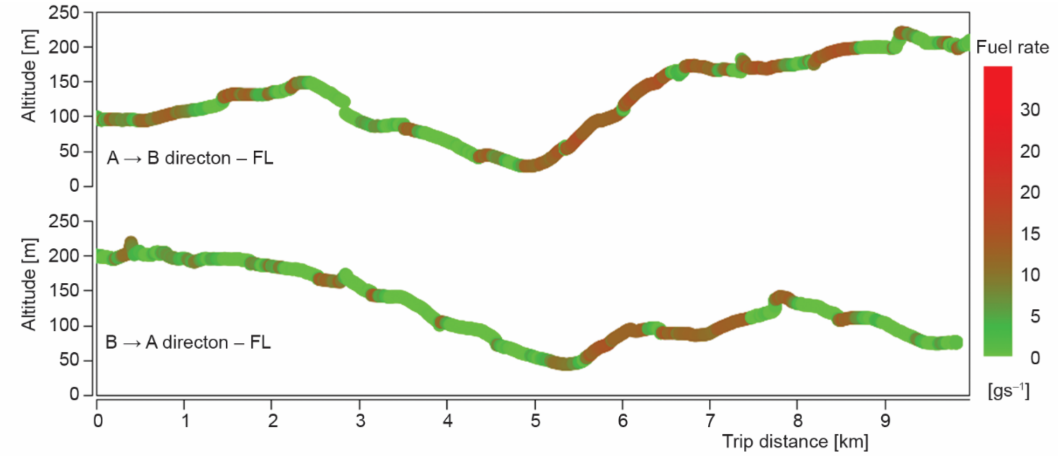

Figure 4. The effect of altitude change on fuel consumption rate at AB and BA directions

Fuel consumption and emission factors development

The fuel consumption and emission results are analyzed to develop both average fuel consumption and emission factors and the identifying the relationship between the factors and the vehicle velocity. As a first stage all five tests results for each condition is averaged. The average results and their maximum and minimum values are given in figs. 5(a)-5(e).

Parallel to fuel consumption values the CO_2 emission factors are presenting a similar behavior. They are higher at AB route which is a result of uphill climbing and high torque de-

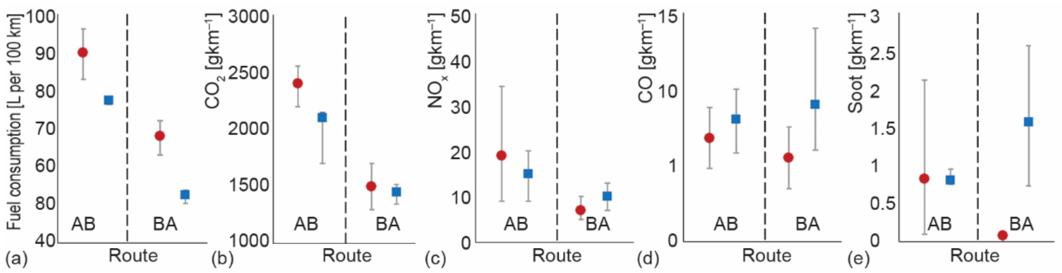

Figure 5. The average fuel and emission factors of whole trips for AB and BA routes at FL (●) and HL (■) conditions

mand. Also, all FL conditions are presenting a higher CO_2 values parallel to high fuel rate demand. For NO_x emission factors the AB direction average values are higher than BA values which can be expressed higher altitude change in AB direction. When an inner comparison was made for NO_x values it is seen that the HL values are higher at BA direction. This can be interpreted with the control strategy of after-treatment system, *i. e.* selective catalytic reduction (SCR) system, and the engine calibration strategy. For CO emissions for FL conditions the AB direction values are generally higher than the BA direction, and BA direction values are higher for HL values. All of the results are changing between 5-10 g/km range. Similar trend was observed for soot emissions, for FL conditions the AB results are higher than BA results. Also the soot emission for FL condition at BA direction is noted as smaller than 0.1 g/km which is very low. For HL condition values for CO and soot emissions a similar trend the BA conditions are higher than of the AB values which was attributed to higher positive acceleration with less load at take-offs , which enhances incomplete combustion during acceleration phases. The fuel consumption and emission factors in [gkm^{-1}] are analyzed by the change of velocity in fig. 6. For analyzing them the data is grouped with 5 km/h increments and averaged in its bin. Also the trend lines are given with the these average data points. As its seen from those graphics the velocity has non-linear effect on fuel and emission factors. It is shown in the graphic the factors are especially higher for the velocities lower than 20 km/h and also an opposite effect is evaluated with the increase of velocity. With the increase of velocity the emission factors decreases significantly. Also the rate of this decrease lowers with the increase of velocity. As the buses are limited to 70 km/h by the municipality, the velocities reached higher than this limit are generally realized downhill section of the routes, that generally low level fueling or fuel cut strategy of the vehicle realized. So the factors at velocities that excesses 70 km/h are found nearly zero.

Fuel consumption and emissions contours regarding to acceleration and velocity

For the same test given in fig. 3 (AB-FL), the contour graphics of fuel consumption, CO_2, CO, NO_x, and soot emissions of whole test is given in figs. 7(a)-(e) regarding to velocity and acceleration. As its seen from the figures the emission values and fuel consumption values in [gs^{-1}] of the vehicle increases with the increase of vehicle velocity and acceleration. On the other hand it is evident that the effect of acceleration is higher than the velocity increase during operation. For fuel consumption and CO_2 emission all positive acceleration events at a velocity higher than 20 km/h plays a critical role. Considering to the NO_x, CO, and soot emissions the +0.4 m/s² acceleration level found as critical. The NO_x emissions are evident at this acceleration level between 20-40 km/h which can be explained by power demand because of acceleration demand from driver at takeoff session. At higher velocity the NO_x level decreases for same

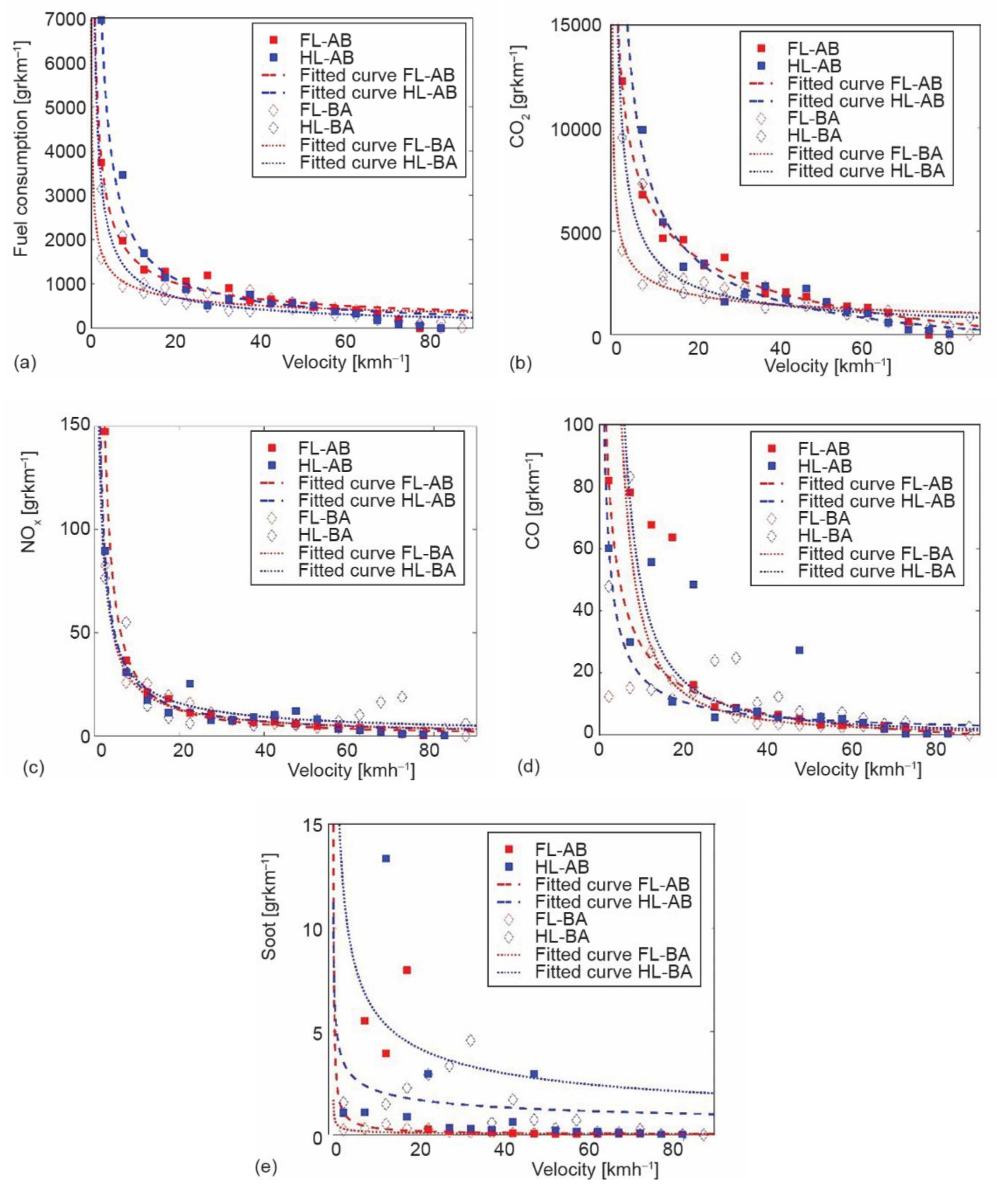

Figure 6. Fuel consumption and emission factors by vehicle speed

acceleration levels which was attributed to SCR strategy. The CO emissions are higher when the velocity is lower from 40 km/h and acceleration level is higher than +0.4 m/s². The soot emission formation is found critical especially at low velocity (v >20 km/h) – high acceleration operating zones (acc >0.4 m/s²) (take-offs).

Emission in-service conformity

All trips are evaluated in order to analyze the in-service conformity factors (CF) of the engines during the operation phase and compare these values with the homologation limits.

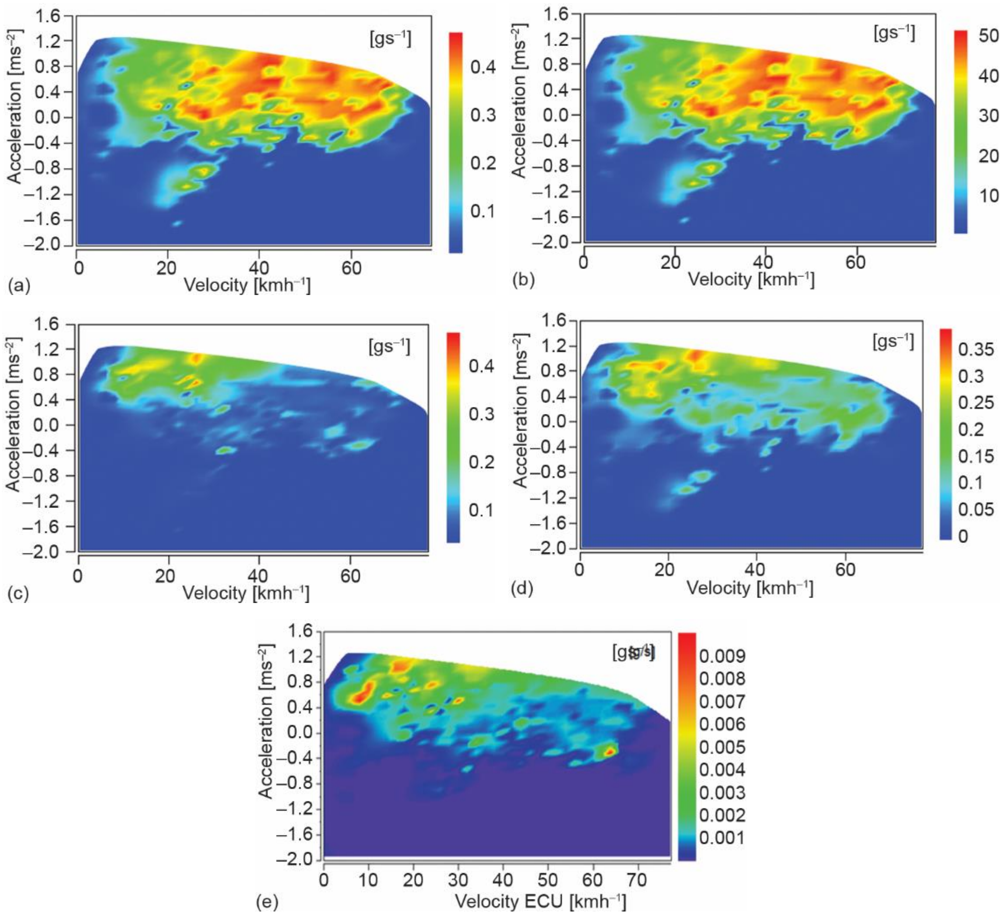

Figure 7. Fuel consumption and emissions by acceleration and velocity change; (a) fuel consumption, (b) CO_2 emission, (c) NO_x emission, (d) CO emission, (e) soot emission

The engine homologation emission level is Euro V so the transient testing limits according to the EU Directive [23] is given in tab. 4 with the average conformity factors calculated. While paper based measurement was not made the soot emissions are accepted as PM emissions. The brake specific emissions of the engine for the whole trips are calculated with the usage of total mass emissions (post processed from the measurements) calculated for each emission component and the engine power calculated from the logged actual engine CAN torque with eq. (1). The calculation are carried with AVL Concerto Pems Postprocessing Tool [24]. As it shown at tab. 4, the factors for NO_x and PM are over 1.5 for AB route at FL conditions, also the NO_x and PM levels are exceeded for AB route at HL conditions. The factors for BA route found in the homologation limits, excepts BA route HL condition. The PM emission levels was found 10 times higher than the limits during the operation.

$$CF = \frac{\text{brake-specific emission of the component } [\text{gkW}^{-1}\text{h}^{-1}]}{\text{limit of the component } [\text{gkW}^{-1}\text{h}^{-1}]} \ [-] \tag{1}$$

Table 4. In-service conformity factors

Component type	Component limit [gkW^{-1}h^{-1}]	Conformity factors [–]			
		AB		BA	
		FL	HL	FL	HL
NO_x	2	1.545	1.245	0.97	1
CO	4	0.54	0.787	0.415	0.76
PM	0.03	2	6.666	1	10

Conclusions

The public transportation bus working in istanbul Metrobus line is equipped with PEMS and mobile fuel consumption measurement devices. The developed graphics are summarized in environmental context:

- For the same velocity, acceleration effect is significant both on fuel consumption and emission values.
- For CO, NO_x, and soot control, the cruise acceleration levels should be controlled considering to the critical positive acceleration level +0.4 m/s² for all velocities.
- The NO_x emissions was found higher especially at low velocity (v <20 km/h) positive acceleration zones, which can be explained by power demand because of acceleration demand from driver at takeoff session. So it can be recommended to limit the acceleration at the take of sessions for decreasing the NO_x emissions by considering the safety concerns.
- The CO emissions was found higher especially below moderate velocities (v <40 km/h) and positive acceleration duration which can be explained the insufficient mixture formation so the increased rich regions in the combustion chamber during this movement. So for decreasing CO emissions especially the sharp accelerations should be avoided below 40 km/h.
- For fuel consumption and CO_2 emission levels, the velocities higher than 30 km/h was found critical for all positive acceleration levels. In this context it is recommended to avoid sharp acceleration changes higher than 30 km/h for cleaner transportation.
- The average emission factors are developed for each direction separately average; for AB direction; CO_2 is ~2400 g/km, NO_x is ~19 g/km, CO is ~7.5 g/km, soot is ~0.9 g/km, at FL conditions while ~2100 g/km, ~17.5 g/km, ~8.5 g/km, and ~0.9 g/km for CO_2, NO_x, and soot emissions, respectively, at HL conditions. For BA direction, CO_2 ~1450 g/km, NO_x is ~8 g/km, CO ~6 g/km, ~soot 0.1 g/km for FL conditions and 1400 g/km, 9 g/km, 9 g/km, 1.6 g/km for CO_2, NO_x, and soot emissions, respectively, at HL conditions. Analyses showed that they are higher for the velocities smaller than 20 km/h.
- This research showed that, it is possible to realize more efficient and mode cleaner public transport and relevant engine control calibration set with analyzing the real driving data. There is a big potential is existing if the acceleration and vehicle velocity is controlled in this context. All of these parameters should be clearly evaluated and the parameters should be optimized in this context with multi objective approach, taking the arrival timing and safety concerns.

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