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

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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 İstanbul 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 NOx CO emissions velocities smaller than 20 km/h and 40 km/h was found dominant at positive acceleration zones. Also for fuel consumption and CO2 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.

1. Introduction

The reduction of regulated emissions and carbon dioxide (CO₂) and also the fuel consumption of public transportation system becoming an emerging issue in recent years. The road transport using internal combustion engines (ICE) powered powertrain units contributes the global warming as well as adversely the air quality. Lorries, buses and coaches produce around a quarter of CO₂ emissions from road transport in the European Union (EU) and around 5% of the EU’s total greenhouse gas 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 nitrogen oxides (NOₓ) emission
limit for steady-state testing (2.0 g/kWh to 0.4 g/kWh- 80% reduction), and transient testing (2.0 g/kWh to 0.46 g/kWh -77% reduction). The particle mass (PM) limit was also significantly reduced for steady-state testing (0.02 g/kWh to 0.01 g/kWh - 50% reduction), and transient testing (0.03 g/kWh to 0.01 g/kWh- 66% reduction). Also the certification cycles are replaced. European Steady-State Cycle (ESC), the European Transient Cycle (ETC), and the European Load Response Cycle (ELR) are replaced with World Harmonized Stationary Cycle (WHSC) and World Harmonized Transient Cycle (WHTC). 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 (PEMS) [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 carbon monoxide (CO), hydro-carbons (HC) and particulate emissions (PM) an increase in NO\textsubscript{X} and CO\textsubscript{2}. Vujanovic 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 t to 40 t) 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. Manojlovic 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 nonlinear. 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 nonlinear 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 5 and Euro 6) vehicles. The CO\textsubscript{2} and NO\textsubscript{X} emissions showed a strong correlation with driving parameters, CO and HC emissions did not showed any distinct separation with different driving styles. The NO\textsubscript{X} emissions was found in the same range at the routes with similar cumulated altitude gain for constant driving dynamics. Also CO\textsubscript{2} and NO\textsubscript{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\textsubscript{2}, NO\textsubscript{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 references [12-22].

In this context, one of the world biggest transportation axle, İstanbul’s’ 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 İstanbul Metropolitan Municipality which crosses the İstanbul city from Asia to Europe. Its length is about 52 kilometres and there is more than 550 busses in 24h 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 Avcılar (A)- Beylikdüzü(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 affect 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.

2. Methodology

2.1. Experimental Set Up

A Euro 5 public bus which is powered by a diesel engine was used. The properties of the test vehicle is presented at Table 1. AVL MOVE system consisting of AVL Gas Portable Emission Measurement System (Gas PEMS) for CO, CO\textsubscript{2}, NO\textsubscript{X},O\textsubscript{2} measurements and AVL Particulate Matter (PM) PEMS equipped with Micro Soot sensor was used for soot monitoring. The measurement devices and their accuracy is given at Table 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 2Hz 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 Controller Area Network (CAN) data (Actual CAN Engine
Torque, accelerator pedal position, gear, 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 at Figure 1 a-b.

| 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-260kW@ |
| Torque         | 1100rpm-1600Nm@ |
| Emission Level | Euro 5 |

| Table 2. Properties of Measurement Devices |
| Measurement System | Device | Method | Accuracy |
| Fuel Consumption   | AVL KMA Mobile | Rotational type flow meter | ±0.1% |
| Emission           | AVL PEMS | NO → NDUV i | ± 0.2% |
|                    | AVL PEMS | NO2 → NDUV ii | ± 0.2% |
|                    |         | O2 → Oxygen Sensor | ± 1% |
|                    | AVL PEMS | CO → NDIR iii | ± 30ppm |
|                    | AVL PEMS | CO2 → NDIR | ± 0.1% |
|                    | AVL PEMS | Soot → Photoacoustics | ~ 5 µg/m³ |

iNDUV     : Non Dispersive Ultraviolet
iiNDIR    : Non Dispersive Infrared

2.2. Test Route and Vehicle Load

The test are carried on İstanbul Metrobus Line. The Metrobus line is consisting of 3 main parts.
These parts are Söğütlüçeşme→Zincirlikuyu- 11 km length with 8 stations, Zincirlikuyu→Avcılıar –
29 km length with 25 stations and the last part is Avcılıar (A) – Beylükdüzü (B) -16 km length with 12
stations. The tests were carried on Avcılıar - Beylükdüzü route which is called 34B route by İstanbul
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 at Figure 2.
The vehicle is loaded with sand bags for simulating payload (passenger load) during the tests. Two considered load conditions are; i- Full Load (FL) - 13 tons of sandbag. ii- 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 (ie. wind, temperature, 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 week for the whole research for all conditions.

3. Results and Discussion

The velocity, altitude and the emissions (CO₂, CO, NOₓ, soot) logged during a FL cruise from A to B direction and calculated acceleration from logged velocity is given in Figure 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 Table 3.

![Figure 3 – Time based logged data at AB direction with FL condition.](image)

<table>
<thead>
<tr>
<th>Direction</th>
<th>Unit</th>
<th>FL</th>
<th>HL</th>
<th>FL</th>
<th>HL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>km/h</td>
<td>32.07</td>
<td>30.05</td>
<td>35.22</td>
<td>35.64</td>
</tr>
<tr>
<td>Acceleration</td>
<td>m/s²</td>
<td>0.51</td>
<td>0.53</td>
<td>0.51</td>
<td>0.50</td>
</tr>
<tr>
<td>Deceleration</td>
<td>m/s²</td>
<td>-0.29</td>
<td>-0.32</td>
<td>-0.34</td>
<td>-0.38</td>
</tr>
<tr>
<td>Acceleration Duration</td>
<td>%</td>
<td>51.91</td>
<td>53.69</td>
<td>51.39</td>
<td>49.58</td>
</tr>
<tr>
<td>Deceleration Duration</td>
<td>%</td>
<td>29.38</td>
<td>32.80</td>
<td>34.32</td>
<td>38.32</td>
</tr>
<tr>
<td>Cruising + Stop Duration</td>
<td>%</td>
<td>18.71</td>
<td>13.51</td>
<td>14.29</td>
<td>12.10</td>
</tr>
<tr>
<td>Trip Duration</td>
<td>second</td>
<td>1098</td>
<td>1193</td>
<td>1021</td>
<td>1059</td>
</tr>
</tbody>
</table>

Table 3. Vehicle Cruise analysis. (Average Values)
For analyzing the effect of altitude the fuel rate contour graph is given at Figure 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=173m) 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 at Figure 5a 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.

### 3.1. 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 Figure 5 a-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 demand. 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 aftertreatmentsystem (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 gr/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 gr/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 g/km are analyzed by the change of velocity at Figure 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 nonlinear 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 down hill section of the routes, that generally low level fuelling or fuel cut strategy of the vehicle realized. So the factors at velocities that excesses 70 km/h are found nearly zero.
Figure 6 – Fuel Consumption and emission factors by vehicle velocity

3.2. Fuel Consumption And Emissions Contours Regarding To Acceleration And Velocity

For the same test given in Figure 3 (AB-FL), the contour graphics of fuel consumption, CO₂, CO, NOₓ, soot emissions of whole test is given in Figure 7 a-e regarding to velocity and acceleration. As its seen from the figures the emission values and fuel consumption values in g/s 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
CO₂ emission all positive acceleration events at a velocity higher than 20 km/h plays a critical role. Considering to the NOₓ, CO and soot emissions the +0.4 m/s² acceleration level found as critical. The NOₓ 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 NOₓ level decreases for same 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).

![Graphs showing fuel consumption, CO₂ emission, NOₓ emission, CO emission, and soot emission](image)

**Figure 7– Fuel Consumption and emissions by acceleration and velocity change**

### 3.3. 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. The engine homologation emission level is Euro 5 so the transient testing limits according to the EU Directive [23] is given Table 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 Equation 1. The calculation are carried with AVL Concerto Pems Postprocessing Tool [24]. As it shown at Table 4, the factors for NO\textsubscript{X} and PM are over 1.5 for AB route at FL conditions, also the NO\textsubscript{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.

\[
CF = \frac{\text{brake-specific emission of the component, g/kWh}}{\text{limit of the component, g/kWh}} \quad [-] \tag{1}
\]

<table>
<thead>
<tr>
<th>Component Type</th>
<th>Component Limit [g/kWh]</th>
<th>Conformity Factors [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AB FL</td>
<td>HL FL</td>
</tr>
<tr>
<td>NO\textsubscript{X}</td>
<td>1.545</td>
<td>1.245</td>
</tr>
<tr>
<td>CO</td>
<td>0.54</td>
<td>0.787</td>
</tr>
<tr>
<td>PM</td>
<td>2</td>
<td>6.666</td>
</tr>
</tbody>
</table>

**Conclusion**

The public transportation bus working in İstanbul Metrobus line is equipped with PEMS and Mobile Fuel Consumption measurement devices. The developed graphics are summarized in environmental context;

i) For the same velocity, acceleration effect is significant both on fuel consumption and emission values.

ii) For CO, NO\textsubscript{X} and soot control, the cruise acceleration levels should be controlled considering to the critical positive acceleration level + 0.4 m/s\(^2\) for all velocities.

iii) The NO\textsubscript{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\textsubscript{X} emissions by considering the safety concerns.

iv) 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.

v) For fuel consumption and CO\textsubscript{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.

vi) The average emission factors are developed for each direction separately average; for AB direction; CO\textsubscript{2} is ~ 2400 g/km, NO\textsubscript{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\textsubscript{2}, NO\textsubscript{X} and soot emissions respectively at HL conditions. For BA direction, CO\textsubscript{2} ~1450 g/km, NO\textsubscript{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 CO₂, NOₓ and soot emissions respectively at HL conditions. Analyses showed that they are higher for the velocities smaller than 20 km/h.

vii) 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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References


