A FUEL CONSUMPTION MODEL FOR PUBLIC TRANSPORTATION WITH 3-D ROAD GEOMETRY APPROACH

by

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Public transportation fuel consumption modeling shows a great importance because of economic and environmental aspects. Considering to the metropolises with millions of inhabitants with circulating thousands of buses that uses intercity lines, its importance is becoming vital in planning both operation of transportation company and city mobility planning. In this context a detailed fuel consumption modelling approach for public transportation buses was used for vehicle fuel consumption assessment during operation. The methodology was developed with IPG TruckMaker + AVL Cruise co-simulation environment following instantaneous speed, load and 3-D road data primarily besides model parameters. The model was validated at one of the most important public transportation axle of the world, Istanbul Metrobus System, at two direction which carries over ~1 million passenger daily in 24 hours operation with petrol engine buses. The comparison simulation/measurements showed that the proposed fuel consumption model is accurate and can predict fuel consumption behavior for public transit buses in a reliable band. In addition, this methodology can be used to investigate various powertrain and operating scenarios near future for more efficient public transportation with high reliability.

Key words*: fuel consumption, modelling, 3-D road geometry, public transportation*

Introduction

Low energy request mobility is essential for a sustainable future and competitive cities where people, businesses and culture can thrive. In this context the International Association for Public Transportation (UITP) developed a vision for energy efficient transportation up until 2025 which reduces the dependency of fossil fuels [1]. Considering to the share of public transportation, the public buses is still account the 50-60% of public transportation which the ~90% of this share is propelled with Diesel engine technology [2-5]. In this context, for lowering the energy consuming in public bus transportation sector, both the governing bodies, manufacturers and also researchers are using vehicle fuel consumption models that can be implemented in traffic simulations which estimates real world operation data. These simulation methodologies were classified into two main categories by Faris *et al.* [6] . These are: (a) Scale of Input Variable-based modelling (SIVM), and (b) Formulation Approach-based Modelling (FAM). One of the main sub-modelling category of the SIVM is Microscopic Modeling (MIM) that estimate

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instantaneous vehicle fuel consumption and emissions. The instant vehicle characteristics and road conditions are needed in this modelling methodology [7].

There are numerous MIM types reported in the literature. These are, comprehensive modal emission model (CMEM) [8] uses second by second speed road grade angle and accessory use as input with general model parameters for estimating emission and vehicle fuel consumption data. It uses in house developed six modules for predicting, engine power, engine speed, engine out emissions and catalyst pass fraction. The model was fundamentally developed on dynamometer data which it limits the capability of the model for represent real driving conditions. The VT-Micro [9, 10] uses instantaneous vehicle fuel consumption and acceleration data and predicts fuel consumption and emissions of the vehicle. The model take the driving patterns in to account. The model showed enhanced prediction capability of vehicle fuel consumption compared with CMEM. The passenger car and heavy duty emissions model (PHEM) [11] which uses emission map look up tables for vehicle emission estimation. It was first developed for heavy duty vehicles and then extended to passenger car segment. It uses road speed and load as input data and predicts CO, CO_2, HC, and NO_x. VERSIT+ [12] which fundamentally developed for light duty vehicles emission estimation CO_2, NO_x and particulate matter less than 10 μm in diameter (PM_{10}) in traffic stream. The main inputs are instantaneous velocity and acceleration with model parameters. It has set of statistical models for vehicle categories constructed with multiple regression analysis. Different from most of the models it takes into account real world driving conditions. Multi-Scale Motor Vehicle & Equipment Emission System (MOVES) [13] developed by Unites States Environmental Protection Agency (EPA). The inputs of the program is instantaneous vehicle speed and acceleration and the output is the emission rates. A relational database for storing underlying data and calculation of aggregate energy and emission inventories. Microscopic emission and fuel consumption (MEF) [14] model which was primarily calibrated by multivariate least-squares method for two types of light-duty vehicle using on-board data collected in Beijing, China, by a portable emission measurement system (PEMS). The inputs are acceleration and speed while the outputs are emission and fuel consumption rates.

All of these modelling techniques uses the instantaneous vehicle data as an input. They mainly focus on the powertrain system of the vehicles. Different from these technics, this paper deals with a co-simulation environment which handles the problem as a fast complete vehicle and 3-D road modelling for fuel consumption prediction. The IPG TruckMaker [15] software is used as fundamental simulation environment for fast and detailed vehicle and 3-D road modelling and AVL Cruise [16] is used as principal detailed powertrain modelling simulation which integrated into the IPG TruckMaker environment like a sub model. This co-simulation environment enables us to test the developed speed scenarios for an efficient public transportation with considering to the complete vehicle perspective besides analyzing the logged big statistical vehicle data from a city or public transportation company.

In this context, one of the world biggest transportation axle, Istanbuls' most important public transportation line – Metrobus Line – was chosen as the development environment for this co-simulation methodology. Metrobus Line is a strategic dedicated transit bus line planned by Istanbul Metropolitan Municipality which crosses the İstanbul city from Asian to European. Its length is about 52 kilometers and there is more than 550 buses in 24 hours service, which enables mass transit transport (over ~1 million passenger daily) between two continents. In public transportation, the fuel cost is the most important part of the operating cost, which is ~125 million euro for İstanbul Municipality. A detailed drive train, vehicle and 3-D road model was created by using co-simulation methodology. The real public bus was equipped with fuel consumption and physical measurement devices for real driving data collecting. The developed model is validated for fuel consumption with the collected data for three loading condition.

Description of methodology

The used methodology is consisting of two consecutive steps. The first one is experimental step, which is consisting of data collection from real operation. The second phase is the modelling step, which the fuel consumption of the public bus is predicted and validated with the experimental data.

Experimental step

Measurement system

A diesel fueled public bus was used for measurements. The vehicle properties are given at tab. 1. The AVL KMA Mobile (which is connected directly to vehicles fuel system) was used for fuel consumption measurements. The measurement uncertainty of the device is ±0.1% . The device is using a servo controlled positive displacement meter – PLU (Pierburg Luftfahrtgeraete Union) measuring principle [17] for measurement and the created pressure difference on the fuel line of the vehicle is zero ($\Delta P = 0$). So the default operating conditions of the engine is not effected from the measurement system. The position of the vehicle in terms of latitude, longitude and altitude was monitored at 2 Hz GPS equipment. The temperature, humidity and atmospheric pressure were also monitored at 1 Hz resolution during the measurements. Also the relevant controller area network (CAN) data (actual torque, engine speed, gear, and wheel based vehicle speed) of the vehicle needed for further analyses were collected with Goblin System CAN diagnostic tool [18] during the measurements with 1 Hz resolution. All system was controlled by AVL system controller equipment. All measurement system is assembled on a base plate with vibration dampers for disabling the vibrations arouse from vehicle for a better measurement sensitivity. The measurement system configuration was given in fig. 1.

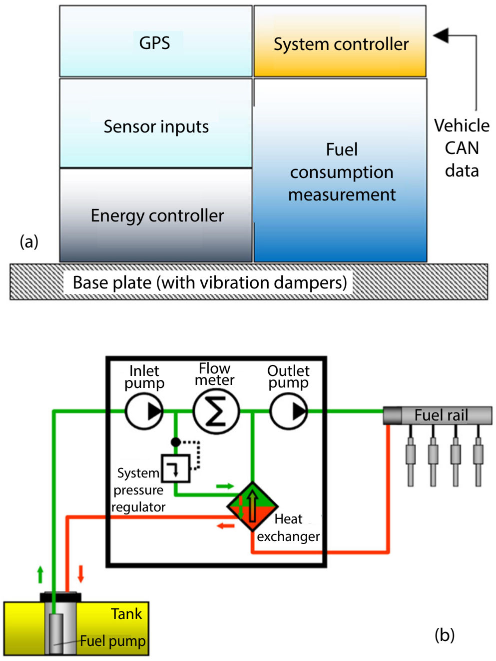

Figure 1. (a) Test system configuration, (b) fuel consumption measurement principle [13]

Table 1. Vehicle and engine properties

Gross vehicle weight	32 tones
Type	Articulated
Vehicle length	18 m
Number of cylinders	6
Engine capacity	11.9 l
Power	260 kW at 2000 rpm
Torque	1600 Nm at 1100 rpm
Compression ratio	17.75:1
Min. brake specific fuel consumption at full load – 1400 rpm	185 g/kWh
Emission certification level	Euro 5

Test route and vehicle load

The tests were carried on Metrobus line of Istanbul. Metrobus line, which crosses the city axle, is consisting of 52 km special dedicated route. It is working 7 days 24 hours with different shuttle frequencies. The route is divided into three main part. These parts and their properties are given at tab. 2. The test route is consisting only the second and the longest part of (Avcılar – A ⟶ Zincirlikuyu – Z) the Metrobus line. The buses are using same stations on both directions. The routes' map derived from Google map with stations is given at Figure 2. As the Part 2 is using the core city center route, the number of passengers in Part 2 (A ⟶ Z , Z ⟶ A) is higher than other parts. Also the number of shuttles is higher than other parts because of this reason. Additional to these factors Part 2 is the longest part and the core part of the Metrobus line with 29 km length. So the Part 2 is chosen for this research which has a major effect on fuel consumption and mentioned characteristics of the Metrobus line.

Table 2. Metrobus line properties

Directions	Length, [km]	Number of stations
Sogutlucesme-Zincirlikuyu	11	8
Zincirlikuyu-Avcılar	29	26
Avcılar- Beylikduzu	9	12

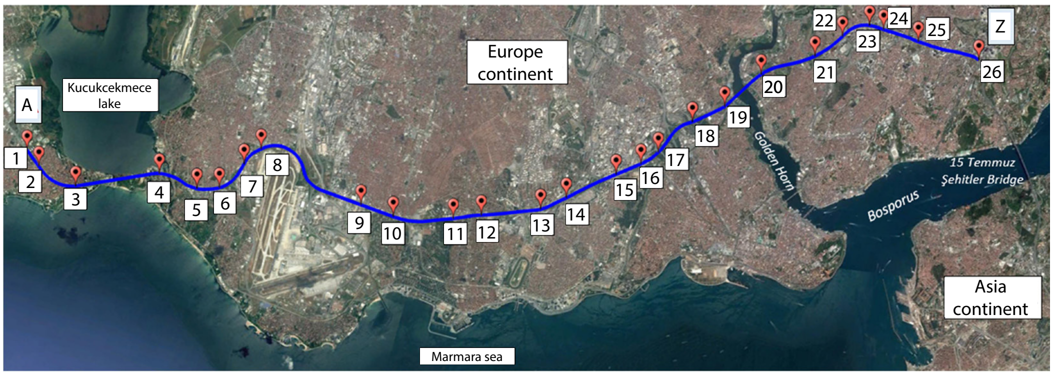

Figure 2. Metrobus AZ line – Part 2- with stations

As it is known from the literature the energy efficiency and the fuel consumption is directly affected by the weight of the vehicle. Vujanovic *et al.* [19] quantified the load factor on fuel consumption and confirmed that the specific fuel consumption increases with cargo weight related to load factor increase, but they found that the relation is not proportional. Joumard *et al.* [20] showed the on-board load increased the CO_2 emissions and the fuel consumption. In this perspective for simulating the effect of load the vehicle is loaded with sandbags for the simulation of passenger weights. The measurement of real trip with real passengers was not considered in this because of safety issues. Three measurement events were considered regarding to the operating conditions of transportation system for validation purposes:

- no load condition (NL). Only the measurement system and test team was loaded. This condition simulates the night time operation with few passengers,
- half load condition (HL) with 6500 kg of sandbag additional to NL condition. This condition simulates the daily operation of the transportation system, and
- full load condition (FL) with 13.000 kg of sand bag additional to HL condition. This condition simulates the heavy passenger loading conditions early in the morning and evening period.

For both load conditions including NL the public bus is tested for both AZ and ZA directions via following up the front bus and imitating its cruising characteristics. All tests were realized under similar dry weather and temperature conditions, for avoiding the influence of wind and other atmospheric conditions.

Modelling methodology

In this phase, two different environments IPG TruckMaker and AVL Cruise are used as co-simulation. The TruckMaker environment needs a detailed set of vehicle data that helps to simulate a more realistic cruises. The primary inputs of simulation for TruckMaker system are: vehicle body properties, mass variation, axle properties such as, spring compress-force look up table, damper velocity-force look up table, buffer compress-force look up table, kinematic properties, stabilizer properties, steering characteristic values, tire properties, brake properties, pedal actuation forces, brake pressure distribution, aerodynamic properties, road geometry (x, y, z or Google Earth data, track width, *etc.*) data for creating 3-D road. Also the same properties are needed for trailer side for articulated buses as it was used in this research paper.

The driver model used in the research work is the standard IPG driver that is existing in the environment [21]. It enables to control the actions of a cruise like a human driver. These actions include fundamentally the steering (steering wheel angle or the steering wheel torque), braking (force on brake pedal position) and throttle position. The gearbox and also the clutch can also be controlled by the driver model, but it is disabled and embedded in to powertrain simulation environment. The reason for this is that the test vehicle is using an automatic gearbox system. For validation purposes the driver model followed the course and the target speed on a given track from the real measurement. On the other hand it is known from the literature the aggressiveness of the driver has an significant influence on fuel consumption. Ma *et al.* [22] and Vagg *et al.* [23] studied the effect of acceleration and driving styles which they concluded the acceleration has significant effect on acceleration. In this context the maximum longitudinal acceleration and deceleration and also the maximum lateral acceleration can be identified in the model. Moreover, it is possible to identify the positive and negative acceleration dependent to velocity. This properties gives the ability to simulate the driver aggressiveness on fuel consumption combined with vehicle properties after model validation.

In addition, a detailed 1-D-powertrain model (maps, auxiliary data, efficiencies, *etc.*) is built in AVL Cruise simulation tool. Although CRUISE is able to simulate the whole vehicle, the focus is on the simulation of the powertrain. The primary inputs of simulation for AVL Cruise system are: vehicle component friction properties, coast down times, real frictions, drags, rolling radius of tires, engine component properties like full load curve, 3-D fuel consumption maps, auxiliary management strategies, gearbox program, torque converter properties, brake pedal map [16, 24]. Different from the other modelling techniques, this co-simulation environment makes possible to simulate the complicated public bus dynamics with advanced powertrain properties on a 3-D road, which enhance the results reliability. The velocity demand comes from IPG environment and all powertrain related simulation is realized at AVL Cruise at each step. The traction and vehicle dynamic properties are run in IPG TruckMaker environment the same time. The fuel consumption is calculated in AVL Cruise fundamentally. The IPG TruckMaker environment enables to simulate all road related data at this time. The stops, road grade, road surface properties and their effects on fuel consumption can be simulated. The methodology flow chart and modelled road are given in fig. 3.

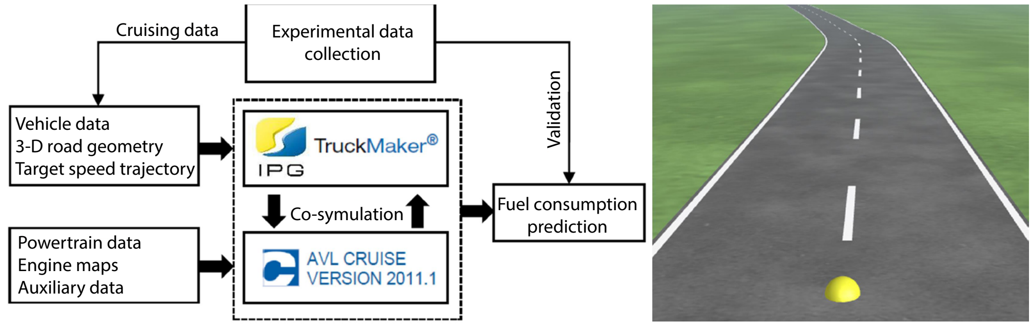

Figure 3. (a) Methodology flow chart, (b) modelled 3-D road

Results and discussion

A random FL condition vehicle speed and altitude data, used for validation purposes at the proceeding section is given at fig. 4. As it is seen from the figure, the top speed of the vehicle is limited with 70 km/h by the operating authority regardless to the topographic and load (number of passenger) conditions.

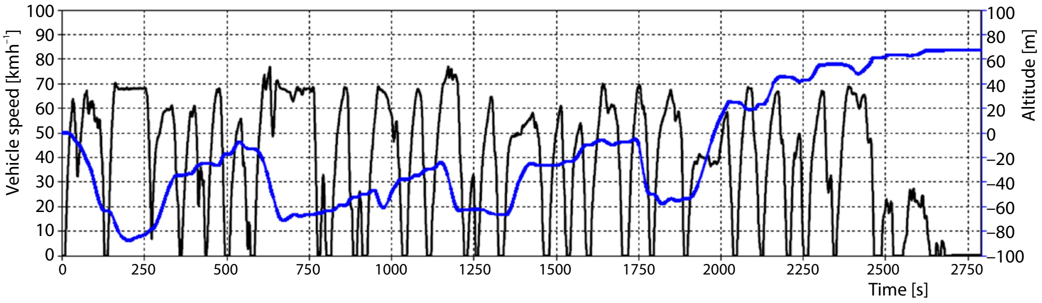

Figure 4. An example whole real logged vehicle speed with altitude in AZ direction

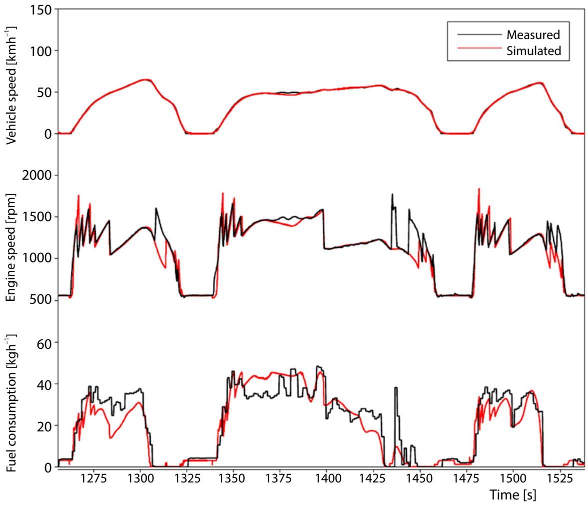

Figure 5. An example of simulated vehicle speed, engine speed and fuel consumption (*for color image see journal web site*)

In order to verify the effectiveness of the simulation method, the simulation results are compared with the measurement results shown below. The simulated fuel consumption history, engine and vehicle speed for the given speed trajectory in fig. 4 and the comparison with the real values between four station is given in fig. 5. As it is seen on the figure, the simulation results are matching with the measurement values. There are some mismatch points in engine speed simulation which can be explained of engine dynamic behavior uncertainty. It is no possible to simulate all acceleration and deceleration events accurately with high accuracy in this type of methodology. In addition, same small inaccuracies are found in fuel consumption history, which is aroused from detailed engine control algorithm definition. The developed methodology is using 1-D look up table based fuel consumption data for simulation issues so detailed fuel consumption control algorithm is not embedded into simulation environment.

The 26 station full cruise fuel consumption and simulated and measured (target) data regarding to the engine torque is given as scatter plot with trend lines are given in fig. 6 for NL, HL an FL conditions for AZ direction. In addition, the cumulative fuel consumption changing history of simulated and measured values for AZ direction is given in fig. 7. As it is shown in figs. 6 and 7 the proposed model can provide accurate and reliable torque-fuel consumption values compared to the testing data. Also the cumulative fuel consumption data is matching with the measurements which can be interpreted as satisfying.

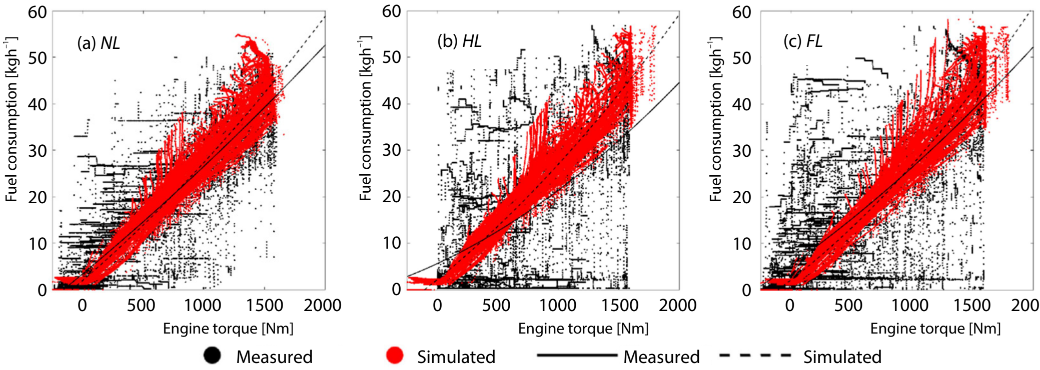

Figure 6. Scatter plots for engine torque, fuel consumption values and fitted trend lines (*for color image see journal web site*)

The measured and simulated characteristic values like speed, acceleration, deceleration and total fuel consumption, acceleration percentage, deceleration percentage and fuel factors consumption are given in tab. 4. Comparing the average speeds, the difference of measured and simulated is in 1-3 % range, which is found the speed simulation characteristic of used approach is quite reliable. In addition, the average accelerations and average decelerations are given in tab. 4. The average simulated values are matching with the measured values. The total fuel consumption values, which is important for the effectiveness of the simulation outputs, are

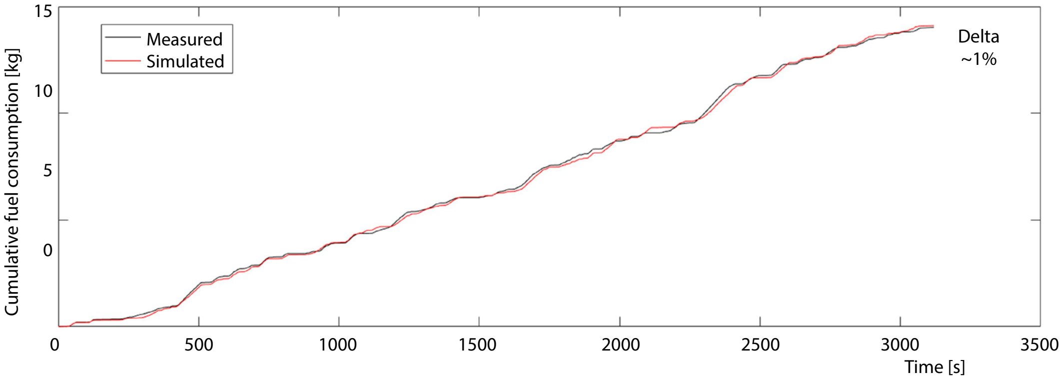

Figure 7. Comparison of cumulative fuel mass consumption of measured and simulated fuel consumptions at AZ direction for full load trip (*for color image see journal web site*)

Table 4. Comparison of measured and simulated values

Magnitude	Unit	AZ					
		NL-M*	*NL-S**	*HL-M**	*HL-S**	*FL-M**	*FL-S**
Av. speed^{i}	kmh^{-1}	37.29	37.14	37.76	36.07	35.22	34.47
Av. acceleration^{i}	ms^{-2}	0.38	0.35	0.30	0.28	0.30	0.24
Av. deceleration^{i}	ms^{-2}	–0.51	-0.39	–0.46	–0.36	–0.39	–0.27
Tot. fuel cons. vol.^{ii}	Litre	15.50	14.64	16.92	16.10	17.31	17.23
Fuel factor	g km^{-1}	443.22	420.17	472.85	453.08	500.56	487.90
Z1 fuel cons.^{iii}	kg	9.54	9.28	9.15	9.43	9.87	9.11
Z2 fuel cons.^{iii}	kg	1.78	1.51	1.36	1.26	1.27	1.26
Z3 fuel cons.^{iii}	kg	0.35	0.45	0.66	0.61	0.76	1.23
Z4 fuel cons.^{iii}	kg	0.73	0.46	2.63	1.20	1.00	1.35
		ZA					
		NL-M*	*NL- S*	*HL-M*	*HL-S**	*FL-M*	*FL-S*
Av. speed^{i}	kmh^{-1}	40.48	40.40	37.66	37.46	32.82	32.15
Av. acceleration^{i}	ms^{-2}	0.37	0.36	0.32	0.31	0.30	0.27
Av. deceleration^{i}	ms^{-2}	–0.42	-0.37	–0.48	–0.37	–0.34	–0.29
Tot. fuel cons. vol.^{ii}	Litre	13.56	13.09	16.25	15.76	18.17	17.34
Fuel factor	gkm^{-1}	386.82	374.12	453.49	442.03	506.17	485.76
Z1 fuel cons.^{iii}	kg	7.90	7.6	8.21	8.9	8.50	7.87
Z2 fuel cons.^{iii}	kg	1.75	1.86	1.97	2.08	1.80	1.65
Z3 fuel cons.^{iii}	kg	0.71	0.69	0.80	0.72	0.64	1.08
Z4 fuel cons.^{iii}	kg	0.71	0.51	1.74	0.68	0.73	1.03

i – Av.: Average
ii – Tot. fuel cons. vol.: Total Fuel Consumption Volume
iii – Z1: Zone 1, Z2: Zone 2, Z3: Zone 3, Z4: Zone 4
* – M: Measured, – S: Simulated, NL-No Load, HL-Half Load, FL-Full Load

evaluated at tab. 4. The difference between total fuel consumption for both load conditions and directions is changing between 2-5% which means that the simulation output characterizes the real cruise with a good prediction capacity. Also the fuel factors are evaluated at tab. 4. When the measured and simulated values are compared the difference was found between 3-7%. The difference is slightly higher than other physical values, which is arouse from the difference of speed between measured and simulated values are resulting slightly different distance values.

For further analyses the on-road experiments are analyzed in terms of percent engine load, acceleration and the whole trip is divided in to four load dependent acceleration (LDA) zones. Then the fuel consumption is compared with the simulated values for each zone. The operating points with higher than 50% engine load is accepted as high engine load (HEL). The HEL points with acceleration named as *Zone 1* and also the HEL points with deceleration is names as *Zone 2*. Harmonious with this categorizing given above the engine loads lower than 50% accepted as low engine load (LEL). The LEL points with acceleration is named as *Zone 3* and LEL points with deceleration is named as *Zone 4.*

The measured fuel consumption map in these zones as given in fig. 8 for AZ direction. The analyses of these measurements shows that 76.74%, 66.74%, and 72.55% of total consumed fuel is consumed in *Zone 1*, 14.36%, 9.85%, and 16.86%, of total consumed fuel is consumed in *Zone 2*, 2.89%, 4.38%, and 4.62% of total consumed fuel is consumed in Zone 3, 6.01%, 19.04%, and 5.97% of total consumed fuel is consumed in Zone 4 for NL, HL, and FL trips at AZ direction, respectively. The measured and simulated values comparison for these LDA zones are given in tab. 4. The obtained small difference values of LDA zones fuel consumption values is interpreted as the models capacity for the public bus type of transportation is reliable.

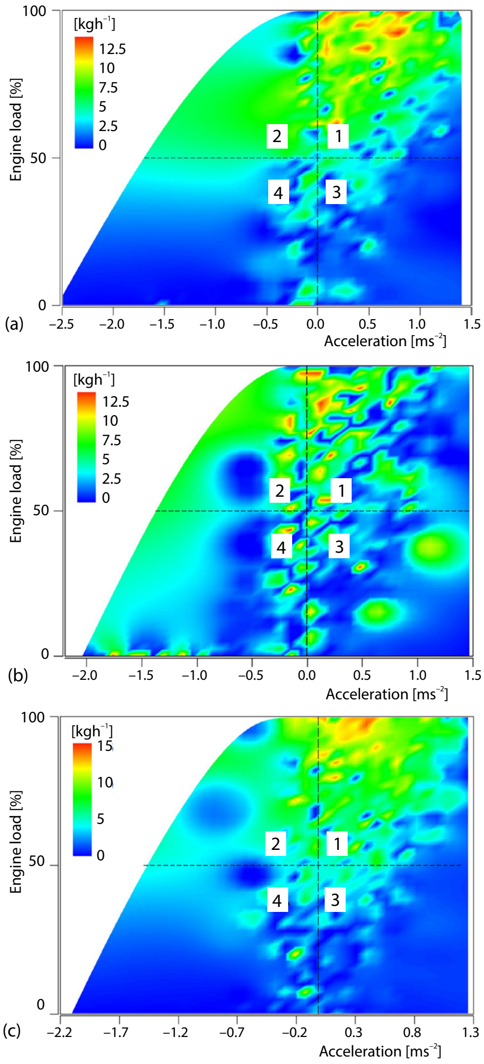

Figure 8. Load dependent acceleration zones

Conclusion

In this paper, we presented a research for developing a fuel consumption modelling approach, which is using 3-D road geometry for public bus transportation. Using of 3-D road geometry, vehicle dynamics and powertrain co-simulation technic at the same time resulted with high fuel economy assessment capacity for a public transportation system. The fundamental vehicle and powertrain properties are used as inputs for fuel economy prediction in the developed environment. Both instantaneous, average and aggregate validation were performed to verify the prediction accuracy of the model. Considering to the instantaneous validation, the model showed good performance when compared with the measurement results. In addition, the average results are found quite reliable with the measurement results, where the difference lies in ~1-5% band average. The cumulative results difference is found matching with the measurement results. The result showed that, the model can be used to investigate the alternative energy efficiency scenarios for alternative driving characteristics for a public transportation system.

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