Optimization of Fuel Consumption of a Bus used in City Line with Regulation of Driving Characteristics

Muammer Ozkan, Orkun Ozener, Irfan Yavasliol

***Abstract*—**The fuel cost of the motor vehicle operating on its common route is an important part of the operating cost. Therefore, the importance of the fuel saving is increasing day by day. One of the parameters which improve fuel saving is the regulation of driving characteristics. The number and duration of stop is increased by the heavy traffic load. It is possible to improve the fuel saving with regulation of traffic flow and driving characteristics. The researches show that the regulation of the traffic flow decreases fuel consumption, but it is not enough to improve fuel saving without the regulation of driving characteristics. This study analyses the fuel consumption of two trips of city bus operating on its common route and determines the effect of traffic density and driving characteristics on fuel consumption. Finally it offers some suggestions about regulation of driving characteristics to improve the fuel saving. Fuel saving is determined according to the results obtained from simulation program. When experimental and simulation results are compared, it has been found that the fuel saving was reached up the to 40 percent ratios.

***Keywords*—**Fuel Consumption, Fuel Economy, Driving Characteristics, Optimization

I. Introduction

FOR a vehicle powered with an internal combustion engine, the amount of fuel consumed per unit road and per unit vehicle weight and the emission emitted are two important criteria in terms of fuel economy and environment. Decrease of fuel amount consumed per unit road and unit mass will indirectly decrease the amount of emission resulting from combustion. [1]

Specific fuel consumption, brake power and operation time of the engine will determine the amount of fuel consumed. Instantaneous braking power depends on the physical properties of the vehicle, topographic characteristics of the line, environmental conditions, performance characteristics of the engine and on the driving characteristics [2]-[3]. The term ‘driving characteristic’ covers acceleration, deceleration, and variation of speed, maximum driving speed and gear step preferences of the driver.

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The fuel consumption of a vehicle in urban and suburban traffic is determined by the complex interaction of many factors. These include the detailed control inputs the individual driver makes to his vehicle, how his vehicle interacts neighboring vehicles and with a complex traffic control system. As a consequence of these factors, vehicles operating in urban traffic undergo frequent changes in speed. Fuel consumption is affected by the manner in which individual and collective human behavior interacts with a large complex system, as well as by the physical characteristics of the vehicle. Driving characteristics are crucial for fuel consumption especially while driving in the city [4]. In this study, it is aimed to decrease the fuel consumption of a bus operating through the city line by the regulation of driving characteristic.

Fuel cost has a significant share within the operating expenses of establishments that perform public transportation. The bus used in the study has been selected among a bus fleet belonging to Istanbul Metropolitan Municipality, Directorate General of İ.E.T.T. Directorate General of İ.E.T.T, which provides public transportation services in Istanbul controls a fleet composed of nearly 2609 buses. There are 2676 (bus) stops in 525 lines. Number of daily trips is approximately 28.500. Daily number of passengers is approximately 3.200.000. Daily fuel consumption is approximately 266.500 liters. The line where measures between Eminönü and Üçşehitler are conducted has a length of 6.300 meters and there are 10 bus stops. The distances between stops are respectively 1090, 810, 570, 790, 656, 588, 330, 356, 170, 550 meters [5,6]. In the measurements, Corrysy-Datron measurement devices were used, which belong to Mercedes-Benz Türk A.Ş. bus factory R&D department.

The study is composed of three parts. In the first part, cumulative fuel consumption, road, speed, acceleration, deceleration values and gear steps of a bus working on intracity line were recorded with 1-second intervals. The passengers on the bus are counted in each stop and recorded accordingly.

All Measurements are performed at warmed-up engine condition. The bus was droved by different drivers at reel traffic conditions. In the second part, the measured data are analyzed and the impact of driving characteristic on the fuel consumption has been determined. In the third part, software, which calculates fuel consumption, was written. Measurement results and software outputs are compared and the validation of the model was made. Later on, studies were conducted on the decrease of fuel consumption by the regulation of driving characteristic via utilizing the software.

II. Calculation Of Fuel Consumption

To keep a vehicle moving, the engine has to develop sufficient power to overcome the opposing road resistance power, and to pull away from a standstill or to accelerate a reserve of power in addition to that absorbed by the road resistance must be available when required.

The road resistance opposing the motion of the vehicle is made up of four components as follows;

Rolling resistance, R_R

Aerodynamic drag, R_{Aero}

Climbing resistance, R_C

Acceleration resistance, R_{Acc} [7]

$$B_e = \frac{b_e . P_e . \int dt}{\int v . dt} \quad (1)$$

$$P_e = R_\Sigma . v \quad (2)$$

$$R_\Sigma = R_R + R_{Aero} + R_C + R_{Acc} \quad (3)$$

$$R_R = f.m.g.\cos\alpha \quad (4)$$

$$R_{Aero} = \frac{1}{2} . \rho_A . C_D . A . v_R^2 \quad (5)$$

$$R_C = m.g.\sin\alpha \quad (6)$$

$$R_{Acc} = \varphi . m . \frac{dv}{dt} \quad (7)$$

[8,9]

TABLE I
UNITS

Symbol	Quantity	Unit
A	frontal area	m^2
Be	fuel consumption	g/m
CD	drag coefficient	-
Pe	road resistance power	kW
R_{Acc}	acceleration resistance	N
R_{Aero}	aerodynamic drag	N
RC	climbing resistance	N
RR	rolling resistance	N
RΣ	total road resistance	N
be	mean specific fuel consumption	g/kWh
dt	time interval	s
dv/dt	acceleration	m/s^2
f	coefficient of rolling resistance	-
g	gravitational acceleration	m/s^2
m	mass	kg
v	speed	m/s
v_R	relative wind speed	m/s
α	angle of ascent	°
η_m	mechanical efficiency	-
ρ_A	air density	kg/m^3
φ	mass factor	-

According to the Equations, fuel consumption increases by the first power of acceleration and third power of driving speed. For the fuel consumption to be decreased, acceleration and maximum driving speed should be as low as possible.

During the accelerating movement, acceleration resistance emerges on top of the resistances formed during constant speed driving.

Rolling resistance coefficient (f), mass of the vehicle (m), angle of ascent (α), specific mass of the air (ρA), and frontal area (A) are the variables that are out of control and command of the driver while driving. Vehicle speed (v), acceleration (dv/dt) and deceleration (-dv/dt) are controlled by drivers. The preference of gear level has a notable impact on the fuel consumption. The selection of gear level depends on the driving characteristics. Because, the gear level used affects engine speed and therefore specific fuel consumption. According to the above-specified equalization, with the acceleration and increase of the speed which are under the control of the driver, fuel consumption increases [10]-[11].

III. Characteristics Sections Of The Vehicle Movement

It is possible to travel over a specific distances with different speed-time trajectories. Acceleration, deceleration and constant speed values selected will determine the fuel consumption. Speed-time trajectory composed of acceleration, constant speed and deceleration sections are named regular trajectory (RT). In the Fig. 1, the travelling over the same distance with different speed-time trajectories has been exemplified.

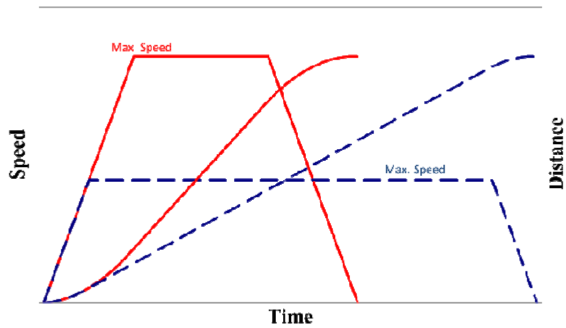

Fig. 1 Two different example for Regular Time – Speed and Time-Distance trajectory

Driving style can have a significant bearing on fuel consumption, but it is often unclear how one should controlled the vehicle to get the best possible fuel economy [12]. Likewise, theoretically, limitless number of Regular Time-Speed trajectory (RT) may be acquired with different acceleration, constant speed and deceleration values. The variation of speed-time trajectory will cause different amounts of fuel consumption in the same distance. The determination of the option providing the least fuel consumption among the limitless option will require optimization. In reality, this operation covers certain acceptances. Though the options are endless, it is only possible to realize some of them. Motor and power train characteristics include the most significant restrictions. For that reason, engine performance and driveline system characteristics should also be taken into consideration in the optimization [13].

In case the distance being travelled over ceaselessly is long, then the impact of acceleration and deceleration on the fuel consumption will be less. However, in intracity trips when the vehicle stops frequently, acceleration and deceleration has a significant impact on the fuel consumption. The increase of acceleration will increase acceleration resistance and therefore fuel consumption will increase. As to deceleration, it increases the fuel consumption with turning kinetic energy of the vehicle into thermal energy without using it for travelling over.

A good driver, in terms of obtaining the best possible fuel economy, is sensible, steady and drives at modest speed [2].

IV. Measurement Results And Analyses

A. Measurement Results

In order to better understand the general characteristics of trips, as an example, time-speed and distance-speed trajectories belonging to 19:25 trip was given in Fig. 2 and 3. Time-speed and distance-speed trajectories of other 11 trips are similar to the trajectories of 19:25 trip. From the graphics, we see and understand that the bus does not travel with a stable speed between the stops and that the bus firstly accelerates and then decelerates between the stops. The movement of the bus between stops may be separated into two parts as acceleration and deceleration. After acceleration period, there is a deceleration process within a similar period. Speed-time trajectory of the bus between stops is quite different from the regular trajectory created by deceleration, constant speed and deceleration sections.

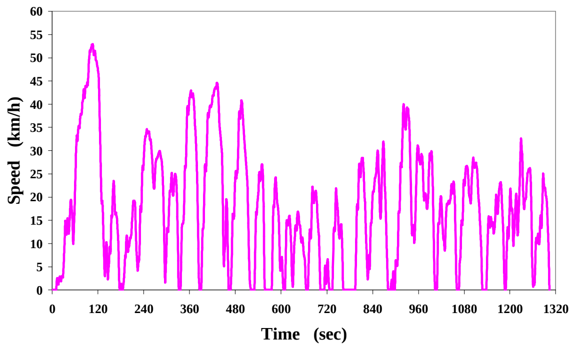

Fig. 2 Time - Speed trajectory of 19:25 trip

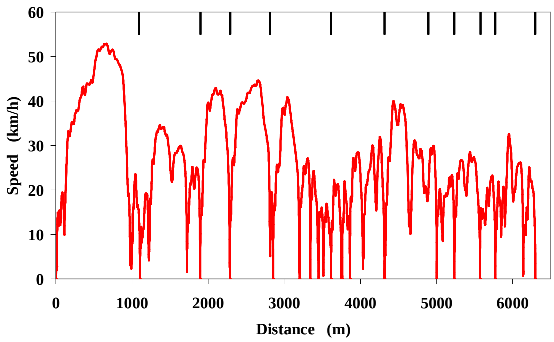

Fig. 3 Time - Distance trajectory of 19:25 trip

In order to facilitate the interpretation of results in terms of driving characteristics, a calculation has been made in terms of fuel amount consumed per unit road and unit mass. Fuel consumption and time measurement results have been given in Fig. 4 and Fig. 5 respectively according to Departure time. Fuel consumption which measured has been named MFC.

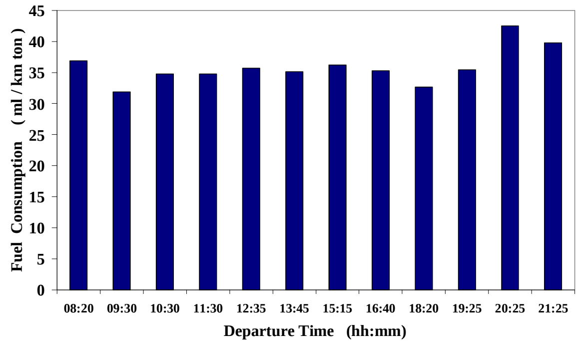

Fig. 4 Fuel consumption variation according to departure time

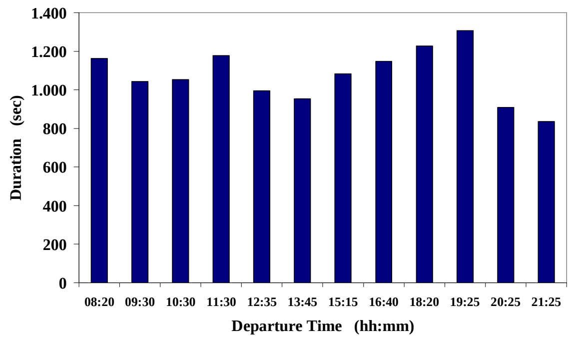

Fig. 5 Time variation according to departure time

In most of the times, fuel consumption is associated with traffic density in direct proportion. The decrease of trip duration indicates that average speed has increased and therefore the traffic density has decreased. Yet, the decrease of traffic density does not always indicate that the fuel consumption has decreased. As in trips, the departure times of which are 20:25 and 21:25. As to 19:25 trips, while the trip duration has increased due to the traffic density, fuel consumption has realized under 20:25 and 21:25 trips.

B. Analysis of Measurement Results

In order to analyze the results, characteristic sections must be determined.

Characteristic sections having an impact on the fuel consumption have been provided *below.*

Stops (In the stops and due to the traffic)

Acceleration

Constant speed

Deceleration [1]

In acceleration, constant speed and deceleration sections, different road resistance groups have an impact on the bus. Rolling resistance, aerodynamic resistance, climbing resistance and acceleration resistance, acceleration period are

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resistances that the engine has to overcome. In travelling at the constant speed, the resistances that the engine has to overcome are rolling resistance, aerodynamic resistance and climbing resistances. And in deceleration period, while rolling resistance, aerodynamic resistance and climbing resistance try to stop the vehicle, negative acceleration resulting from deceleration creates a push impact driving the vehicle to move in the reverse direction to other resistances. In the deceleration period, incase total resistances are positive, the engine must overcome the resistances.

1. Analysis of fuel consumption

Measurement results indicate that approximately 73-89% of the fuel consumed in trips with different traffic conditions and passenger numbers is consumed at the acceleration part (Fig. 6). The amount of fuel consumed depends on the maximum speed and the time elapsing to reach that speed. .

Dense traffic conditions will limit maximum speed. On the contrary, open traffic conditions will allow drivers to drive the vehicles with a full speed and generally drivers use this possibility. Measurement results indicate that there is a deceleration process similar to the deceleration time after the trip with a high speed. In general, in this process when breaking system is put into service, kinetic energy of the vehicle is turned into thermal energy with braking system or engine brake. As the kinetic energy, which is obtained with the conversion of chemical energy of the fuel and which enables the movement of the vehicle, is turned into thermal energy via the braking operation, this will cause the increase of fuel consumption. Measurement results have indicated that the fuel consumed in deceleration processed in trips with high speeds is more than the fuel consumed in constant speed processes.

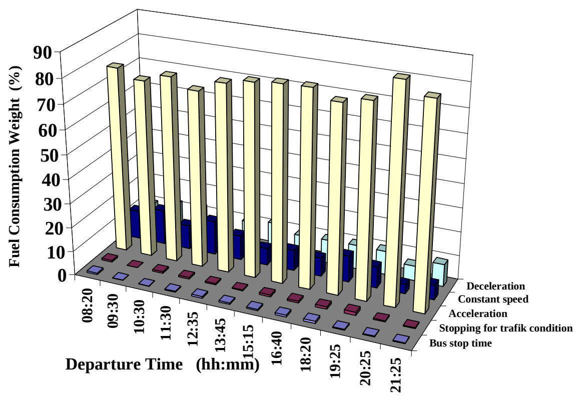

Fig. 6 Distribution of fuel consumed to the acceleration, constant speed, deceleration and stopping period

2. Analysis of Fuel Consumption

Although trips are made with different traffic density and passenger number, the periods of acceleration and deceleration have similar values (Fig. 7). 83-94% of the total distance is travelled over in acceleration and deceleration periods. From the Fig. we understand and see that traffic and load conditions have an important impact on the acceleration and deceleration characteristic.

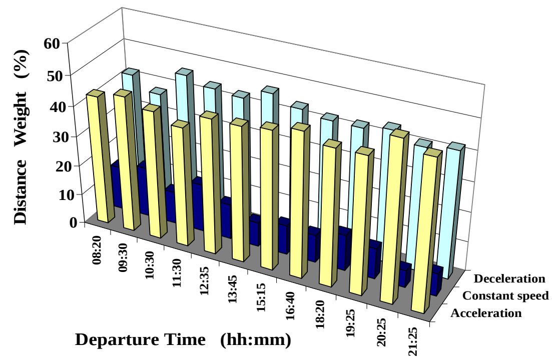

Fig. 7 Distribution of distance

V. Mathematic Model And Validation Of Mathematic Model

A. Mathematic Model

In the second part of the study, a computer program (software) has been prepared for the calculation of fuel consumption where engine map, technical characteristics of the vehicle and the distance travelled over according to time, speed, acceleration, gear step, fuel consumption and passenger number values constitute an input. By the utilization of data recorded with 1-second time interval, instantaneous engine breaking power and engine speed have been calculated. The mathematical model of the engine map has been formed in the software sub-model. In the modeling of the engine map, spline functions have been used. Engine model calculates the instantaneous value of specific fuel consumption under instantaneous braking power and engine speed condition. As to instantaneous fuel consumption is calculated with the multiplication of engine braking power, engine specific fuel consumption and operation time (1 second). These operations are repeated throughout the trip and total amount of fuel consumption has been calculated. Fuel consumption simulation calculation which is made by using real trip/travelling conditions has been named MODE 0.

B. Validation of Mathematic model

Measured fuel consumptions of the trips and software MODE 0 outputs have been compared, and a fault graphic has been prepared and software has been validated.

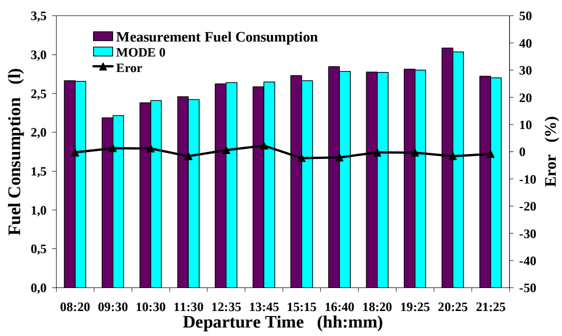

Fig. 8 Measured fuel consumption according to departure time, Mode 0 results and fault variation

The differences between measured and calculated fuel consumptions result from the assumption that weights of all passengers are equal to one another and instantaneous resistance variations that are not anticipated. Relative error is ±2.2 (Fig. 8).

VI. Results Of Mathematic Model

In this part, the amount of fuel to be consumed in case the bus travels over the distance between the bus stops in conformity with regular trajectory resulting from acceleration, constant speed and deceleration processes has been calculated by the employment of a software. In the calculations, measurement values have been used for the number of passengers and stop times. Acceleration and deceleration trajectories have been created with average data obtained from measurement results for each gear step/level. Gear transitions are made by considering real usage conditions. Two different modes have been used for constant speed values. In the first mode (MODE 1), a constant speed value has been selected in a way that the trip times calculated and real trip times will be the same. In the second mode (MODE 2), constant speed value has been sought, by which optimum fuel consumption is enabled. In MODE 2, different from the MODE 1, it has been changed in a specific interval and constant speed value providing the least fuel consumption has been sought. Fig. 9 indicates real and regular trajectory variation for MODE 1. Although speed-distance trajectories are different, travelling time and average speed are the same for both of the trajectories.

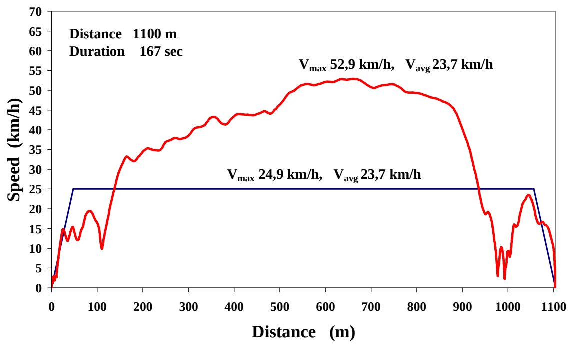

Fig. 9 Sample trajectories for Real and MODE 1 simulation

In the calculations, a similar arrangement has been made by taking total trip time as the basis. The purpose of MODE 1 is to enable regulated trajectories to be in conformity with real trip times. In the calculations made in both of the modes, real values of the number of passengers and distances between bus stops have been taken. Because, in order to decrease fuel consumption, variation of passenger number and the distance travelled over is in contradiction to the service purpose of the bus.

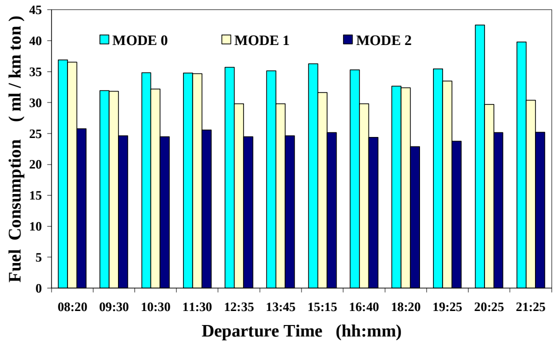

Fig. 10 Fuel consumption variation according to departure time for MODE 0, MODE 1 and MODE 2

The results demonstrate that it is possible to decrease fuel consumption by regulating speed-time trajectory (Fig. 10).

The results calculated indicate that the rate of fuel consumed in the motion at constant speed in accordance with MODE 1 and MODE 2 speed-time trajectory (Fig. 12 and 13). This is a result of avoiding acceleration and deceleration course which causes the increase of fuel consumption. Along with that, we see that fuel economy is better in MODE 2, where movement is less at the constant speed.

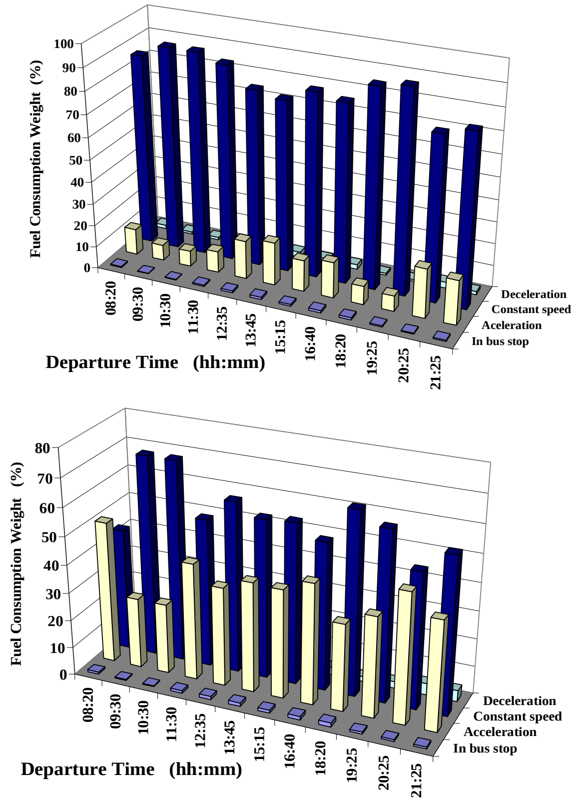

Fig. 11 Distribution of fuel consumed to characteristic processes for MODE 1 and MODE 2

Traveling the distance between the bus stops in accordance with speed-time trajectory arising from acceleration, constant speed and deceleration processed will improve fuel economy up to 30% for MODE 1 and up to 41 % for MODE 2 (Fig. 11). For MODE 1, we have observed that fuel economy improvement potential is quite less in certain trips. The reason of this is that the maximum and average speeds of the mentioned trips are very low. Low travelling speeds decreases road resistance power ($P_e.\eta_m$). The engine is operated under the conditions when specific fuel consumption (b_e) is high. Also, the decrease of the speed increase operation time (t). The regulation of ideal speed-time trajectory of trips in such characteristics will decrease travelling speeds more and more and therefore the fuel consumption will remain at low levels. However, in order to achieve maximum fuel economy, it is necessary to change speed limits used in MODE 1. MODE 2, where speed limits are changed so as to achieve optimum fuel consumption, demonstrates that fuel economy may be improved at a rate of approximately 22-41% (Fig. 12). These values have been obtained at the 32-36 km/h constant speed interval. In case the bus travels faster or slower, the fuel economy decreases. In case the bus drives faster, the increase of acceleration process will increase fuel consumption and in case the bus drives slower, it will be approached to low-speed MODE 1 travelling conditions.

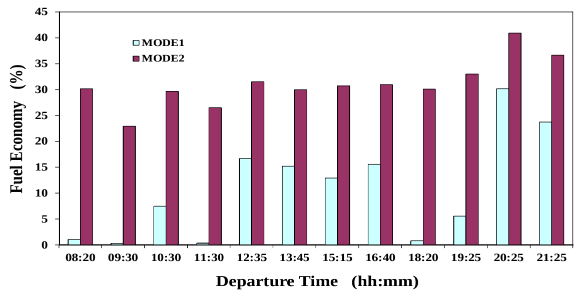

Fig. 12 Variation of fuel economy depending on the departure time in MODE 1 and MODE 2

Better results have been attained in MODE 2 in comparison to MODE 1. As speed values of some trips are low, there is not a potential to improve fuel consumption of such trips with MODE 1 conditions.

VII. Conclusion

The results indicate that the impact of driving characteristics is more obvious in traffic conditions with less density. However, it is not a realistic approach to expect drivers to conform to driving conditions to improve fuel economy. For that reason, it will be useful to equip the vehicles with auxiliary equipments that establish speed and acceleration control in terms of improving fuel economy. Nowadays, the information such as gradient and cornering data could be transferred into the vehicle management system (VMS) via GPS and also the ongoing traffic condition data could be transferred in to the VMS via GPRS. It is possible to establish a system that informs the driver about driving conditions for a fuel efficient drive or that bans the driving conditions except the fuel efficient drive via processing previously mentioned data with the engine specifications. The use of proper speed-time trajectory to be chosen depending on simultaneous traffic information will significantly decrease the fuel consumption.

The results obtained in the study demonstrate that a fuel economy by average 11% may be achieved in Mode 1 and by 31% in MODE 2, which aim to complete the trips within the same period. Aside from fuel cost, there will be a significant decrease in CO_2 and other emissions and PM released by busses.

CO_2, CO, HC, NO_2, SO_2 and PM constitute an important part of Diesel motor exhaust emissions. As combustion in diesel engines realizes in the condition of high access air coefficient, HC, CO emission resulting from the emission is at an insignificant level. In consequence of advancements in the diesel fuel technology, sulphur amount within the fuel has been decreased down to 10 ppm level and SO_2 amount given off from the exhaust has significantly decreased. For diesel engines, NO_x, CO_2 and PM are emissions that are primarily taken into consideration. [14]-[15]

Although environmental effects of NO_x emission via post-combustion emission decreasing systems, this increases the operating costs of the systems. For CO_2, the case is quite different. It is because the only known method to decrease CO_2 emission is consuming less fuel. As a result of combustion of one kg carbon, approximately 3,67 kg CO_2 is released into the atmosphere. Approximately 86% of diesel fuel is composed of carbon [16]- [17].

In Istanbul, where the study was conducted, approximately 266.500 liters of diesel fuel is consumed on a daily basis with the intracity public transportations by bus. According to results obtained from the calculations, with the regulation of driving characteristic, there is a potential to improve fuel economy by 10-41%. With the effects to arise in the implementation of simulation results to real conditions, even in the improvement of fuel consumption by 10%, significant economic and environmental benefits will be achieved. The improvement of fuel economy by 10% will decrease the amount of fuel consumed in a day by 26.650 liters and decrease CO_2 amount released into the atmosphere by 60 tons. Annual decrease amount in CO_2 emission will be approximately 21.900 tons.

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APPENDIX

Technical specifications of the city bus use in study

Vehicle mass : 10300 ±%5 (kg)

Passenger : 97+1 (person)

Engine : RABA-MAN D 2156 HM6UT

Engine brake power : 162 (kW) / 2100 (rpm)

Engine brake torque : 819 (Nm) / 1600 (rpm)

Gear box : C sepel ZF S6-9OU-049

Wheels/ Tire size : 8.00-20" / 11.00R-20 STC

Muammer Özkan He was born at 1967 at İstanbul. He took his B.Sc.Degree at 1988, M.Sc. at degree 1997 and the PhD Degree at 1997 from Yıldız Technical University İstanbul. He is working as Assoc. Prof. at Mechanical Engineering Department/Automotive Subdivision where he began to work as a research assistant at 1990. He worked at the projects like vehicle development for military, commercial diesel engine and bus developing. He conducted some research projects about fuel consumption and diesel engine emissions. Some publications are Muammer ÖZKAN, "A Comparative study of effect of Biodiesel and diesel fuel on CI engine's performance, emissions and its cycle by cycle variations", Energy and Fuels, Volume 21, Issue 6, pages 3627-3636, 2007, ii- Muammer ÖZKAN, Orhan DENİZ, Tarkan SANDALCI, "Experimental Study of the effect of top-ring clearance volume on unburned hydrocarbon Concentration", International Journal of Environment and Pollution, Vol 18, No.2, 2002, page 197-201, iii- Muammer ÖZKAN, Tarkan SANDALCI, Derya Burcu ÖZKAN "Comparison of EGR ratios determined by four different methods for electronic re-circulation gate control", International Journal of Environment and Pollution ,Vol. 23, No:2, 2005.

Orkun Özener was born at İstanbul - 29.06.1980. He took his bachelor degree from Mechanical Engineering Department- Automotive Subdivision at 2004 from Yıldız Technical University(YTÜ)-İstanbul and he took his master degree from Mechanical Engineering Department Automotive Subdivision from YTÜ at 2007. During his master research he worked on determining the flame speed of alternative internal combustion engines fuels. His PhD is ongoing at YTÜ Automotive Subdivision by the year 2011 and he is working on optimizing the multiphase injection strategies at common rail equipped injection diesel engines. Now he is working at Yıldız Technical University Mechanical Engineering Department Automotive Subdivision at İstanbul as a Research Assistant since 2005. He made publications and researches about the fuelling the compression ignition(CI) engine with biodiesel, its effects on engine performance and lubrication characteristics. He also made researches about gasoline fumigation at diesel engines and application of artificial neural networks for identifying the engine performance values at CI engines. Some publications are ; i- "Comparison of Fuel Consumption and Emissions of An Urban Bus Fuelled with Diesel and Biodiesel."pg.49-67. Özkan Muammer, Özener Orkun ,Özoğuz Berk, Yüksek Levent . 3rd International Symposium on Environment ,Athens ,22-25 May 2008 . ii- "Modeling the Effects on Fuel Costs When Farmers Produce Their own biodiesel Fuel." pg.67-77 Özkan Muammer, Özoğuz Berk, Özener Orkun. 3rd International Symposium on Environment,Athens,22-25 May 2008. iii- "The Effect and Comparison of Biodiesel-Diesel Fuel on Crank Case Oil ,Diesel Engine Performance and Emissions." Pg.173-179 . Levent Yüksek, Hakan Kaleli, Orkun Özener, Berk Ozoguz . Serbiatrib'09 International Conference, 2009 Belgrade/Serbia. His research areas; combustion, internal combustion engines, pollutant emissions, bio fuels , artificial neural networks, multiple injection in diesel engines.

Irfan Yavaşlıol got his BS degree on mechanical engineering from Yıldız Technical University in 1970 and MS degree from Yıldız Technical University in 1972. He participated Research activities at Cranfield Institute of Technology in 1976 and Institute for Internal Combustion Engines of Vienna Technical University in 1981. He was the Dean of Mechanical Engineering Faculty between 1992 and 1997. He worked as a project supervisor on various projects with TOFAŞ which produces Fiat Auto products in Turkey. Currently he is the Professor of Yıldız Technical University and the Head of Automotive Studies Subdivision and I.C Engines Laboratory