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A SIMULATION STUDY OF FUEL ECONOMY IMPROVEMENT POTENTIALS OF A TRANSIT BUS

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ABSTRACT

The AMESim model of motor vehicle driving simulation has been applied on a transit bus to investigate the potentials for fuel economy improvement. With the purpose to calibrate the simulation model and to evaluate the real driving cycle, a data acquisition using vehicle CAN bus has been performed on a transit bus in real driving conditions. This was the basis for constructing a high-fidelity AMESim simulation model of the vehicle for subsequent hybrid systems simulations. It was observed that a great fraction of the total fuel mass was consumed when the bus was stationary. Initial simulation study shows that fuel consumption reduction in excess of 12% could be achieved by implementing a relatively simple start/stop micro-hybrid system. Also, braking energy reaches cca. 60% of the energy released by the engine, representing a potential basis for the application of regenerative braking hybrid system.

KEYWORDS

Simulation, Transit Bus, Start/Stop System, Acquisition, Internal Combustion Engines

INTRODUCTION

Rising fuel prices and increasing awareness of environmental issues place greater emphasis on the quest for solutions that improve vehicle fuel economy and reduce harmful emissions. One of the many possible directions in that regard, but perhaps the most promising, is powertrain hybridization. Hybrid drives usually combine at least two energy converters and two energy storage systems for powering the vehicle. Internal combustion engines, hydraulic or electric motors are most commonly used as energy converters in hybrid systems. Fuel tanks, electrochemical batteries and hydraulic accumulators are examples of energy storage devices. What all hybrid concepts have in common is the advantage of possessing additional energy sources whose optimal operating conditions differ, effectively broadening the efficient operating range of the vehicle.

Achieving improved fuel economy, lower emissions and relatively low price without penalty in performance, safety, reliability, and other vehicle-related aspects represents a great challenge for the automotive industry. For accommodating the hybrid powertrain demands of heavy vehicles, particularly those marked by frequent deceleration and acceleration phases, perhaps the best solution represents the hydraulic hybrid approach. However, even relatively simple systems, like micro-hybrid (or start/stop) can provide a significant reduction of fuel consumption at a fraction of the implementations costs of the fully-fledged hydraulic hybrid systems.

The numerical investigation, whose results will be presented in this paper, relies on model-based design tools. Modeling of vehicle and propulsion systems has been carried out using the LMS Imagine. Lab AMESim 1D multi-physics system simulation environment [1]. This platform provides a graphical programming interface and an extensive set of validated components organized in different libraries to construct and analyze system performance. An experiment has been conducted on a transit bus circulating in real traffic and occupancy conditions to assess the circumstances encountered in this particular type of transportation and in order to obtain the real driving cycle and powertrain parameters necessary for conducting virtual analyses involving hybrid solutions. Data acquired during this endeavor has been of crucial importance; effectively allowing us to calibrate the parameters of the propulsion components in AMESim. Precisely, submodels of components such as the automatic gearbox, torque converter, internal combustion engine, among others, have been set up and calibrated.

By successfully transferring the conditions encountered in the real world into the computer code, a vast array of numerical study possibilities opens up. In this paper, the results of a simulation involving the start/stop system are laid out, along with deceleration energy calculations quantifying the expected energy recovery source for regeneration systems.

DATA ACQUISITION AND PARAMETER IDENTIFICATION

Experimental setup

As mentioned in the introduction section, acquiring the real driving cycle in differing occupancy and traffic conditions, along with drivetrain and powertrain parameters is of crucial importance for predicting achievable fuel economy improvements. The experiment was conducted on an Ikarbus IK218N vehicle, equipped with a MAN D2066 LOH1 engine (10.5 dm^3, 6-cylinder, turbocharged diesel engine) and Voith 864.5 automatic transmission, circulating on line 65 of the public transportation system in Belgrade. The complete driving cycle consists of two runs; from Zvezdara to Novi Belgrade and back from Novi Beograd to the starting point.

As can be seen in Figure 1, the driving cycle of the line 65 is characterized by a relatively long distance (run of approximately 14300 m) and considerably changing elevation profile, thus being perhaps the most desirable in Belgrade to conduct an acquisition on due to vastly changing conditions encountered along the route.

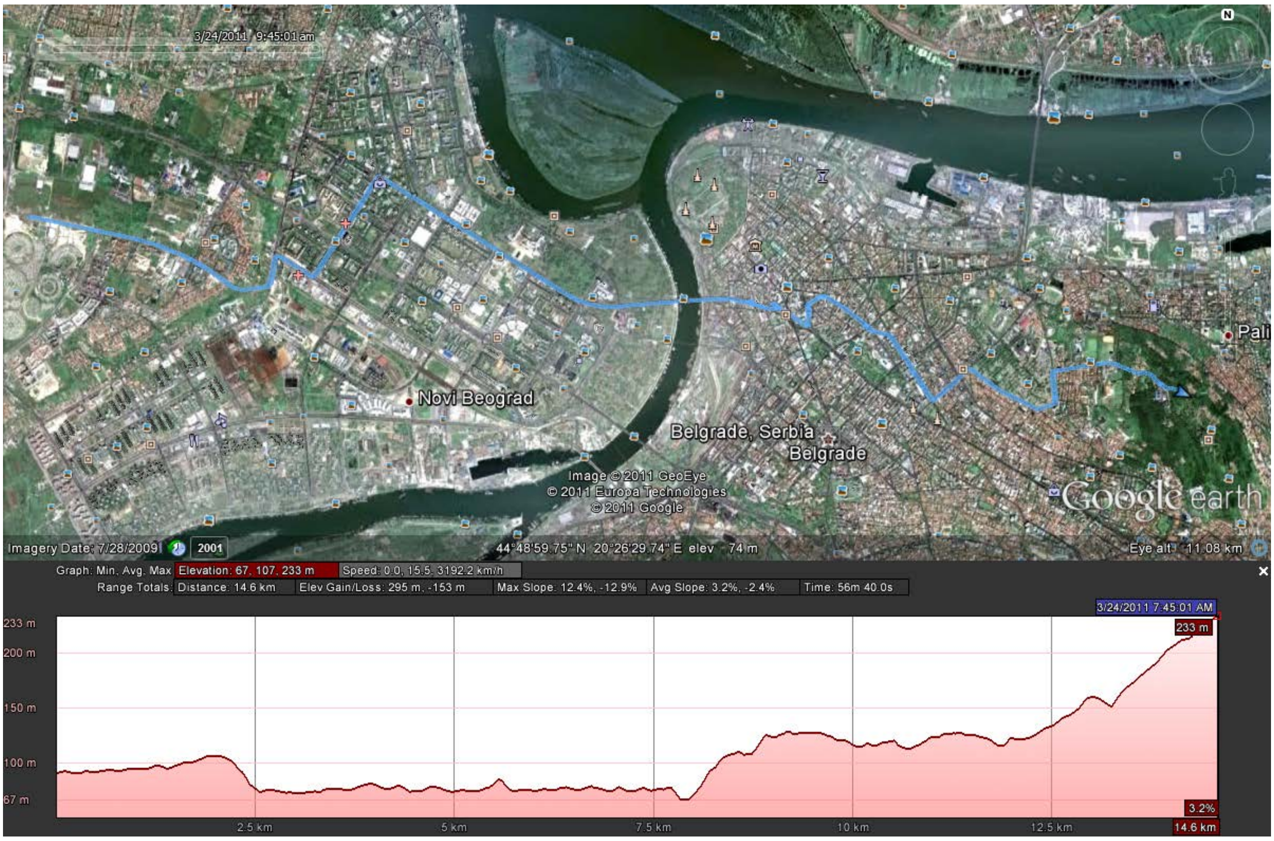

Figure 1 Driving cycle of line 65 and its elevation profile

Figure 2 Experimental setup diagram

Table 1 Driving cycles description

Driving cycle run code #	Departure/arrival location and time	Run duration[min:s]	Mean vehicle speed when moving [m/s]
200	Zvezdara 06:03:15 - NoviBeograd 06:45:56	42:41	7.029
201	NoviBeograd 06:48:21- Zvezdara 07:45:00	56:39	6.012
300	Zvezdara 13:10:35 - NoviBeograd 14:02:20	51:45	6.533
301	NoviBeograd 14:09:23- Zvezdara 15:03:17	53:54	5.966
400	Zvezdara 15:11:09 - NoviBeograd 15:58:29	47:20	6.460
401	NoviBeograd 16:11:49- Zvezdara 17:18:12	66:23	5.294

Three complete driving cycle runs have been recorded using the CompactRIO platform from National Instruments [2]. The powertrain parameters were acquired by accessing the vehicle's J1939 CAN bus by means of a high-speed NI 9853 CAN C module. The raw network stream was being logged and has been processed afterwards according to the SAE J1939 standard [3]. In order to obtain the GPS coordinates of the driving cycle considered, a Garmin GPS 18x 5 Hz receiver, streaming NMEA messages was utilized. These NMEA messages were stored in ASCII format and have been used to determine the road slope along the route. An IP camera, mounted in front of the windshield, has been employed to discern the causes of vehicle braking phases.

Parameter identification

Certain requirements shall be met if one is considering a successful transition from real into the world of virtual simulation. If the scope of the simulation effort encompasses fuel efficiency considerations, perhaps the most important parameters are those relating to engine fuel consumption and torque maps. By analyzing and processing the acquired data channels, specifically those included into Electronic Engine Controller 1 (Parameter Group Name EEC1) and Electronic Engine Controller 3 (PGN EEC3) J1939 messages, maximum/minimum torque limits (Figure 3) and brake specific fuel consumption maps have been arrived at.

A Matlab script has been written to extract data according to a predefined engine operating regime map. By singling out and collecting values of volumetric fuel flow rate associated with certain operating regimes into arrays, and subsequently processing them by eliminating outliers (using a bisquare robust, locally weighted linear regression model), a sound set of fuel flow rate values has been obtained. In order to form the Brake Specific Fuel Consumption (BSFC) map for the entire operating range of the engine (Figure 4), this set of values is further used as an input to a Kriging interpolation algorithm (DACE for Matlab toolbox) [4].

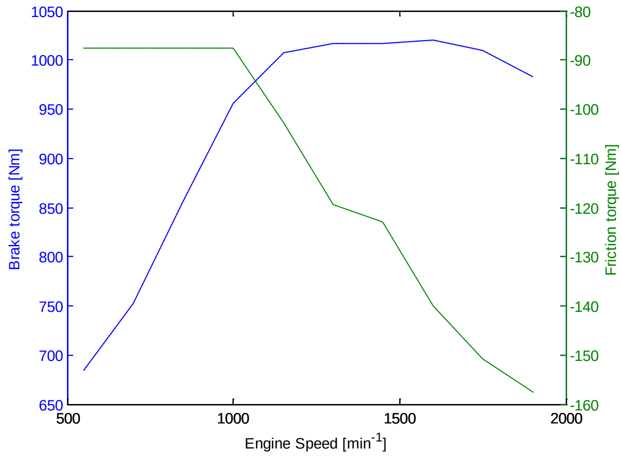

Figure 3 Max. engine brake torque and friction torque

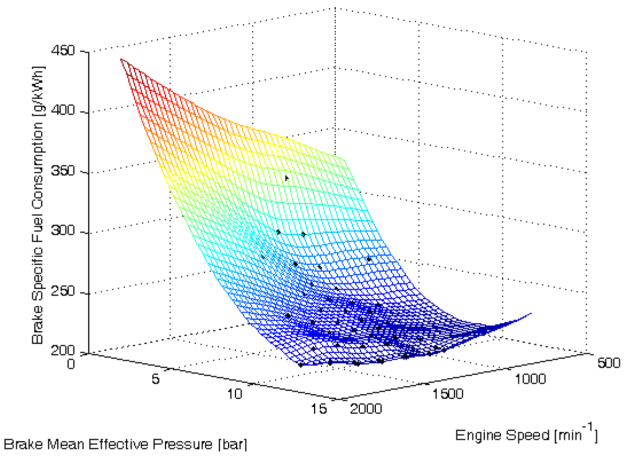

Figure 4 Reconstructed engine BSFC map

Another set of identification procedures has been performed to obtain the characteristics of the automatic gearbox shifting map and torque converter. The torque ratio of the torque converter, defined as the ratio of turbine to impeller torque is dependent on the speed ratio and is shown in figure 5. The capacity factor of the torque converter, defined as

$$K = \sqrt{10\frac{n_{imp}^2}{T_{imp}}}, \qquad (1)$$

where n_{imp} is the impeller rotary speed and T_{imp} is the impeller torque, is shown in Figure 6.

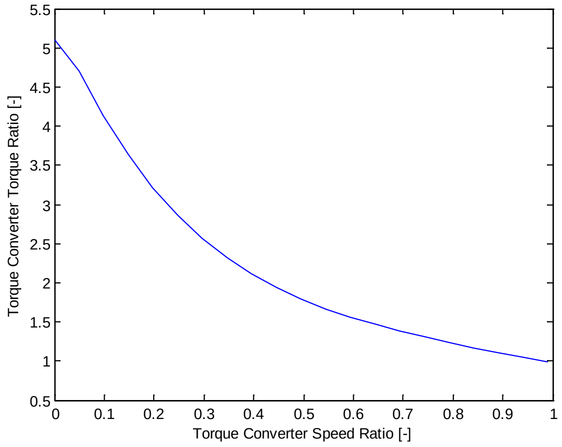

Figure 5 Torque ratio of the torque converter

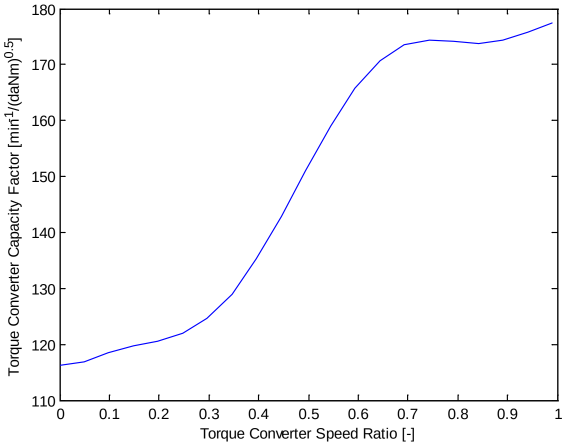

Figure 6 Torque converter capacity factor

Considering the fact that AMESim expects a shifting map table contingent on the engine load and vehicle speed, a least square algorithm has been imposed on the set of data points for each gear shift transition to derive the shifting rule (Figure 7).

The road slope has been calculated using the Digital Elevation Model (DEM) data files obtained during the Shuttle Radar Topography Mission [5]. These represent the most reliable and accurate widely-accessible elevation data files currently available. Due to the great sensitivity of the road slope on the force required to sustain a given vehicle speed, certain provisions regarding the smoothness of the elevation profile along the route had to be taken. For this aim, the GPS coordinates for 200 intervals of the distance from one part of the city to the other were averaged to obtain 200 values of elevation (Figure 8). This elevation data was subsequently smoothed by means of a cubic smoothing spline algorithm and the obtained model was further differentiated to finally obtain the road slope (Figure 8). By interpolating the elevation data by a cubic spline, continuous first and second derivatives are obtained, which is important in the case of road slope calculation.

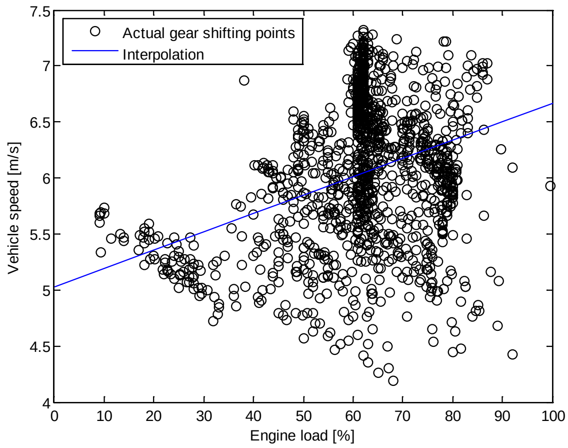

Figure 7 1st to 2nd gear shifting rule determination

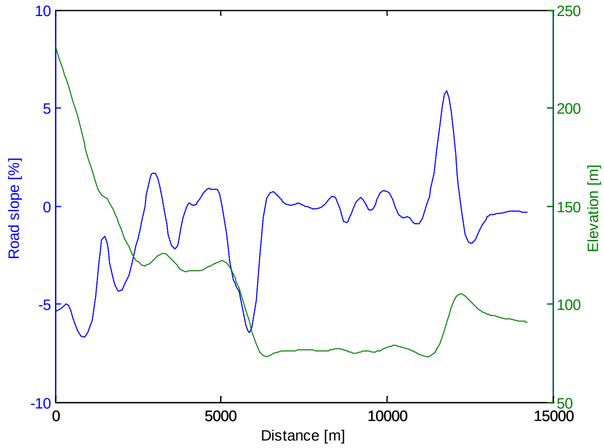

Figure 8 Elevation and road slope

SIMULATION ANALYSIS

In this section of the article, a short overview of the most important submodels and equations being solved in the LMS Imagine. Lab AMESim simulation environment will be given for the case of components in the IFP Drive library. The calibration procedure and results will be shown and finally, the simulation study objectives and design will be presented after which results will be presented, followed by a discussion.

AMESim model

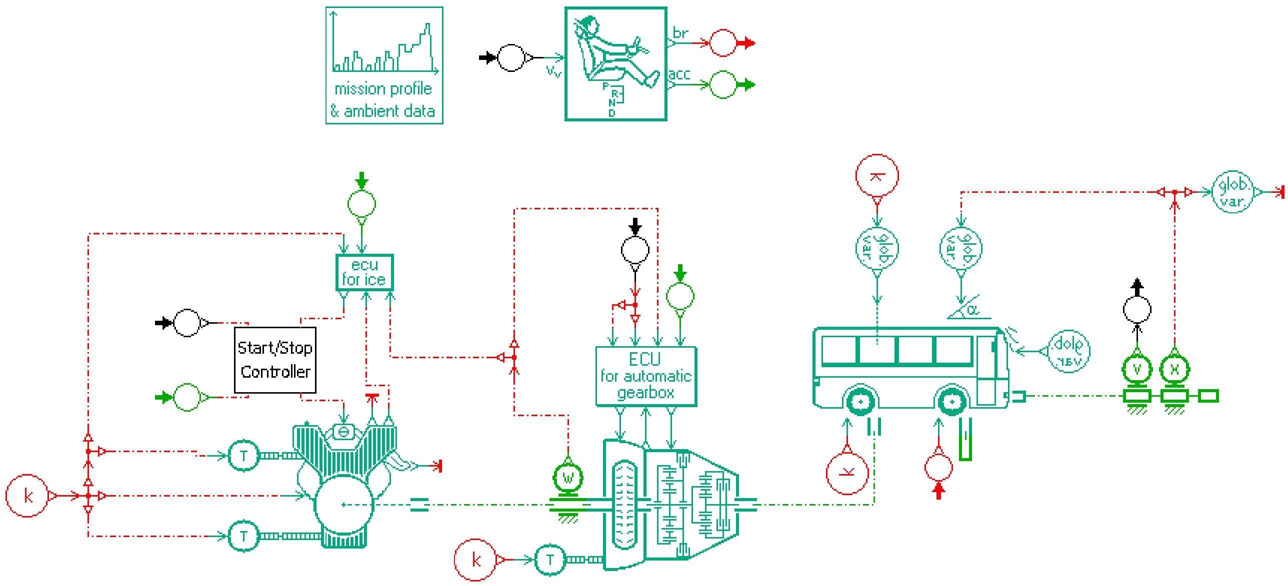

Figure 9 AMESim model of the transit bus

The bus component is responsible for evaluating the acceleration to be integrated by the AMESim solver in order to obtain the actual vehicle velocity [6]:

$$\frac{dv_{veh}}{dt} = \frac{1}{m_{veh}}\left[F_{dr} - \left(F_b + F_{res}\right)\cdot C_{stat}\right], \tag{2}$$

where C_{stat} is the stiction coefficient, which is greater than one only when the vehicle is stationary (1.2 in this study). The driving force F_{dr} is calculated by means of the following equation:

$$F_{dr} = \left(T_2 + T_4\right)/R_w, \tag{3}$$

whereT_2 and T_4 are input torques at ports 2 and 4 (read and front axles) of the bus and R_w is the wheel radius.

In addition to raising the kinetic and potential energy of the vehicle, part of the energy from the propulsion system is used to accelerate rotating parts of the drivetrain. The inertial force of the vehicle wheels is calculated using the following equation [7]:

$$F_w = \frac{\Theta_w}{R_w^2}\cdot\frac{dv_{veh}}{dt}. \tag{4}$$

Considering the case where wheel slip is not accounted for, the contribution of the wheels to the vehicle overall inertia is given by

$$m_w = \frac{\Theta_w}{R_w^2}, \tag{5}$$

where Θ_w is the wheels inertia and equals 120 kgm^2 in this simulation study.

The braking force is similarly obtained:

$$F_b = \left(T_{b,front} + T_{b,rear}\right) / R_w. \tag{6}$$

The resistance force is evaluated using the equation taking into account the climbing resistance, aerodynamic drag and rolling friction:

$$F_{res} = F_{cl} + F_{aero} + F_{roll} = \left(m_{veh} \cdot g \cdot \sin\left[\arctan\left(0.01 \cdot \alpha\right)\right]\right) + \left(\frac{1}{2} \cdot \rho_{air} \cdot c_x \cdot S \cdot v_{veh}^2\right) + \left(m_{veh} \cdot g \cdot f\right) \tag{7}$$

where α is the road slope in %, S is the vehicle frontal area and f is the rolling friction coefficient. Even though AMESim allows defining the influence of vehicle speed on the rolling friction force, it was assumed that a constant friction coefficient was appropriate in this case (because the vehicle speeds do not exceed 15 m/s and the influence of the vehicle speed on the rolling friction becomes significant at greater speeds where resonance phenomena occur [7]).

The propulsion torque is controlled by the driver component, which is a PID controller taking the difference between the actual and desired vehicle speed to form an acceleration command supplied to the engine ECU. After the controller unit reacts and sends an appropriate load signal to the engine, the output torque is multiplied in the gearbox and transferred to the bus. On the other hand, the braking command, also initially formed in the driver component, is sent directly to the front axle of the bus model.

The gear shifting rules, along with values of the torque converter capacity factor and torque ratio have been implemented into the automatic gearbox and ECU for automatic gearbox submodels in AMESim. The lockup clutch command is activated as soon as shifting from the 1^{st} to 2^{nd} gear occurs, as is the case on the vehicle involved in the experiment.

A start/stop controller has been constructed in order to control the transition of the engine combustion mode from 1 (primary working mode) into the null combustion mode, effectively turning off the engine. This so called “supercomponent” takes as input the engine turn-off delay, expressing the time duration between the moment the vehicle becomes stationary and the actual command to turn the internal combustion engine off. Its only variable is the number of times the engine has been turned off during the run. The timer starts when and if the acceleration command and vehicle speed reach both a near-zero value.

In order to accommodate the future needs of evaluating the implications of different bus load scenarios on the overall performance of the vehicle, special mission profile and driver submodels for truck and bus applications have been used in this simulation study. The conventional case involves using the velocity versus time mission profile definition, which can lead to misleading results if the vehicle cannot reach the target speed (with the consequence of differing total displacements between runs). Whereas the submodels for truck and bus applications call for a definition better suited to heavy vehicles: namely the maximum velocity versus displacement profile. In this case, even if the vehicle does not reach the target velocity, the total displacement will always be the same, only the time required to complete a given driving cycle will differ.

Calibration procedure and results

For making sure the conditions are successfully transferred and the dynamic behavior of the most important variables are in agreement with the ones acquired during the physical experiment, and for the sake of conducting final parameters tuning (rolling friction, drag coefficient, etc.), a calibration procedure was set up. This procedure was meant to be conducted on a portion of the driving cycle devoid of significant elevation changes to avoid taking into account data determined with the highest uncertainty, which the road slope values certainly are. The portion in question is situated on Mihailo Pupin Boulevard.

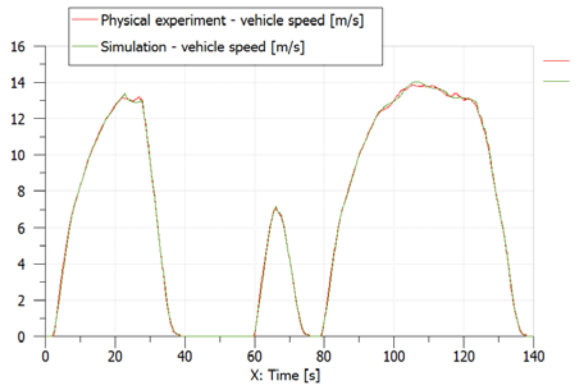

Figure 10 Vehicle speed matching

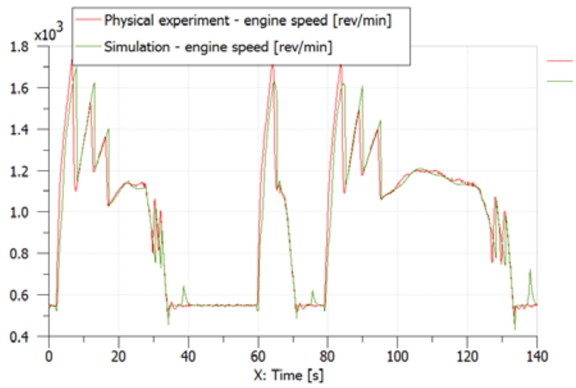

Figure 11 Engine speed matching

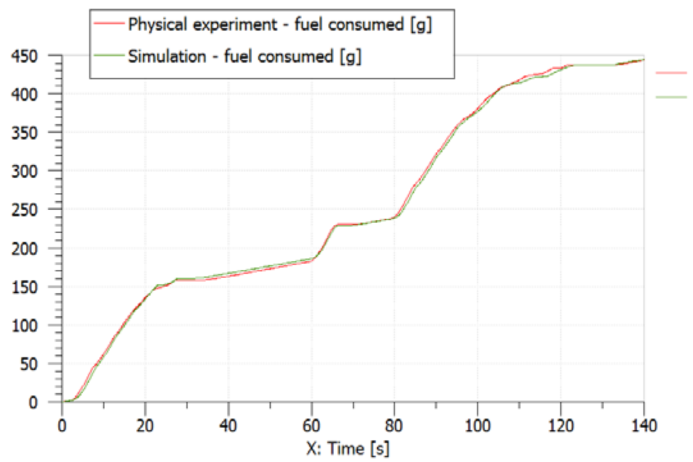

Figure 12 Cumulative fuel consumption matching

Results of the calibration procedure (Figures 10, 11 and 12) show satisfactory matching. Even if some deviations in engine speed and cumulative fuel consumption are discernible, they are sufficiently small for the scope of this article not to require further investigation.

Numerical study design

The major aim of this study is to quantify the fuel economy improvements of a transit bus equipped with a micro hybrid start/stop system. Eventually, most of the accomplishments presented in this article dealing with simulation model setup will be used in subsequent studies regarding the performance and fuel economy improvements brought about by the implementation of full-fledged hydraulic hybrid and electric/supercapacitor hybrid systems. This is why the second objective of the article is to quantify vehicle deceleration energy levels, representing the source on which those regeneration systems function.

By analyzing acquired data, it has been noticed that the idle fuel flow rate mostly fluctuates around values of 2.35 and 4.05 dm^3/h (Figure 13), depending upon the state of the radiator fan, air compressor and alternator loads.

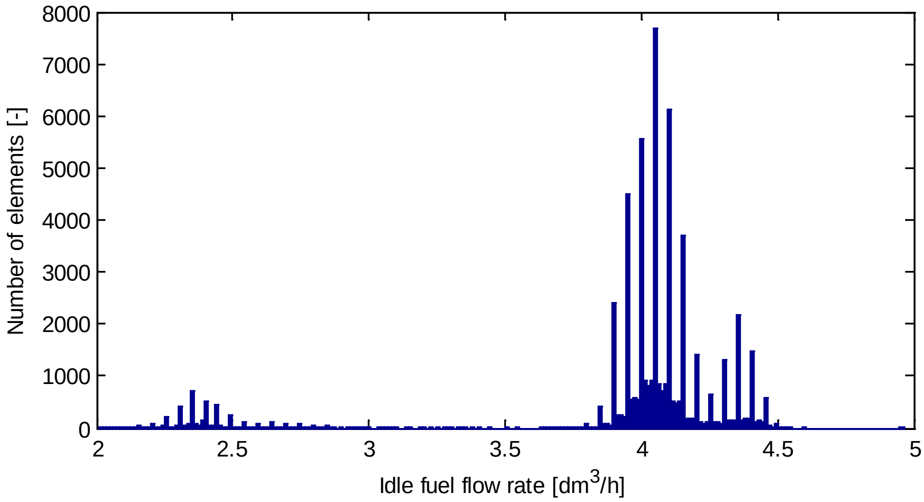

Figure 13 Idle fuel flow rate distribution

The mean value of 3.95 dm^3/h has been used as the reference idle fuel consumption rate in this study. It is important to note that simply discounting fuel consumption at this rate during periods when the vehicle is stationary cannot represent a valid fuel economy improvement measure unless provisions are made for ensuring proper functioning of crucial systems (like alternator, radiator fan, air compressor).In other words, if one is considering the figures that will be put forth in this article, he should keep in mind that an alternative energy accumulator providing power to these systems when the engine is off is assumed.

The baseline data set, to which the simulation results of the bus model with a start/stop controller will be compared, is obtained by running the simulation for 2 values of total vehicle mass and for each of the driving cycles (6 semi-cycles) presented in the introduction section. Then, further simulation runs are initiated by using predetermined values for the engine turn-off delay parameter. By analyzing and comparing these results sets, several conclusions regarding the benefits of a start/stop system can be drawn, particularly the fuel economy savings versus engine switching off frequency can be determined.

Table 2 Parameters for simulation runs

	Reference run	**Start/stop assessment**
Driving cycles	#200, #201, #300, #301, #400, #401	
Total vehicle mass [kg]	20000, 24000	
Engine turn-off delay parameter [s]	∞	1, 7

Additionally, the deceleration energy, engine work and their ratio for several parameters of vehicle mass will be shown, which will prove beneficial in future investigation work that will be dealing with aspects of regenerative braking use.

A couple of assumptions should be kept in mind when analyzing results that will follow:

- Constant vehicle mass is assumed during the entire driving cycle, and
- Only propulsion energy calculations are considered (bus electrical loads, heating, A/C, air compressor not taken into account).

For assessing the influence of the driving cycle and the operating conditions on the deceleration/engine work ratio, the effective engine power, fed into the drivetrain (the impeller of the torque converter, precisely), is taken into account by integrating its value along the driving cycle to obtain the total energy transferred into the vehicle:

$$W_{eng} = \int_{t_0}^{t_f} P_{eng} \cdot dt, \tag{8}$$

where P_{eng} is taken only when positive (engine braking is discounted).

In order to calculate the total vehicle deceleration energy for all driving cycles considered in this study, the braking torque issued by the driver submodel, along with the engine braking torque are summed up, multiplied by the angular speed of the wheel and integrated:

$$W_{br} = \int_{t_0}^{t_f} \left(M_{eng} + M_{br} \right) \cdot \omega_w \cdot dt. \quad (9)$$

Results and discussion

The results dealing with the aspects of the start/stop fuel saving potential are presented in Table 3.

Table 3 Start/stop system performance

	Driving cycle 1 (#200 and #201)		**Driving cycle 2 (#300 and #301)**		**Driving cycle 3 (#400 and #401)**	
Engine turn-off delay [s]	1	7	1	7	1	7
Fuel cons. reduction [g]	1377	924	1791	1300	1673	1165
Fuel cons. reduction [%] (20 t veh. mass)	10.0	6.7	12.6	9.1	12.4	8.6
Fuel cons. reduction [%] (24 t veh. mass)	8.9	5.9	11.1	8.0	11.0	7.7
Engine switching off occurrences [-]	97	76	105	73	102	76

For the same given vehicle velocity along a single run, the absolute fuel consumption reduction brought by activating the engine start/stop controller should be the same. However, small differences (no greater than 5%) occur when changing the total vehicle mass because the attained driving cycle is slightly different. Mean values of absolute and relative fuel reduction for both vehicle mass parameters are presented in Table 3.

The potential benefits of implementing a start/stop system on the fuel savings for the bus circulating on the line 65 of the Belgrade public transportation system range from 8.9 to 12.6% when switching off the engine 1 s after the vehicle becomes stationary and from 5.9 to 9.1% when turning off the engine after 7s. Approximately 70% of the absolute fuel reduction is retained when increasing the engine turn-off delay, which has the beneficial effect of reducing the occurrences of engine restarting phases. The driving cycle 1, being conducted in the morning when traffic congestion was not significant, is characterized by the least fuel reduction potential. On the other hand, the driving cycles 2 and 3, conducted in the afternoon when vehicle stops were increasingly becoming caused by traffic congestion, are characterized by significantly greater potential for improving the fuel economy.

Table 4 Driving cycle 1 energy calculations results

Total vehicle mass	**Fuel consumed**	**Deceleration work**	**Engine work**	**Deceleration/engine work ratio**
[kg]	[kg]	[MJ]	[MJ]	[-]
20000	13.79	111.8	189.6	0.590
24000	15.56	130.4	222.5	0.586

Table 5 Driving cycle 2 energy calculations results

Total vehicle mass	**Fuel consumed**	**Deceleration work**	**Engine work**	**Deceleration/engine work ratio**
[kg]	[kg]	[MJ]	[MJ]	[-]
20000	14.25	112.5	188.7	0.596
24000	16.17	134.3	224.8	0.597

Table 6 Driving cycle 3 energy calculations results

Total vehicle mass	Fuel consumed	Deceleration work	Engine work	Deceleration/engine work ratio
[kg]	[kg]	[MJ]	[MJ]	[-]
20000	13.53	98.7	174.1	0.567
24000	15.22	116.1	205.6	0.565

Tables 4, 5 and 6 present the energy calculations made for simulation runs. Aside from the obvious, intuitive fact that fuel consumption rises with increasing vehicle mass, it is interesting to note the overall deceleration/engine work ratio remains practically the same. The deceleration/engine work ratio is a useful parameter for assessing the proportion of the energy given to the vehicle drivetrain by the internal combustion engine that is available for energy recovery when braking occurs. Indeed, if we were to subtract the value of the deceleration/engine work ratio from 1, we would obtain the ratio of engine effective work that, ultimately, is to be dissipated in the atmosphere during a driving cycle run (through aerodynamic drag, rolling friction, drivetrain losses,…).Bearing in mind that the most influential effect of vehicle mass on resistive forces is on the uphill driving force (climbing), a conservative one, it is logical that the ratio remains practically the same with changing vehicle mass.

On a more important note, the relatively high ratios of approximately 60% indicate that a great potential for significantly reducing fuel consumption lies in the implementation of a full-fledged hybrid solution that will be capable of harnessing the deceleration energy at power levels encountered along the route. A slight decrease in the deceleration/engine work ratio occurred on the third driving cycle, which can be explained by the lower mean vehicle speeds encountered during this run (see Table 1). Even though the aerodynamic drag is reduced, the drivetrain losses, brought by excessive use of the first gear, during which the torque converter is operating, more than offset the gains obtained elsewhere.

CONCLUSION

A simulation analysis was conducted in order to quantify the fuel savings potential of a start/stop micro-hybrid solution implemented on a transit bus. For defining the driving cycles that were used in the simulation and in order to calibrate the parameters of the propulsion system components in AMESim, an acquisition was conducted on a transit bus circulating in real traffic and occupancy conditions. It was shown that fuel consumption improvement in excess of 12% is possible. It should be noted that fuel economy improvements concerned with the start/stop calculations have been made without considerations for energy consumers other than the propulsion system. Further investigation shall be made to assess the precise amount of achievable fuel savings considering the necessary electrical loads of the bus and the needs of the pneumatic compressor during periods when the vehicle is stationary. The maximum benefit would be achieved on lines characterized by a high number of stops and those particularly affected by traffic congestion.

Furthermore, a deceleration-propulsion energy analysis was conducted to assess the ratio of the energy a vehicle possess while driving along a route that is made available to be used by regenerative braking systems forming the basis of full-fledged hydraulic hybrid solutions. It was shown that 60% of energy invested in the vehicle by the propulsion system is available for recovery.

Further work concerning this subject will include using optimization techniques to extract vehicle mass from the acquired data, which will prove beneficial for analyzing the implications of different load scenarios on the fuel consumption. Also, a modeling effort is to be made in AMESim to construct electrical and hydraulic hybrid/regenerative systems in order to predict the portion of the deceleration energy that can be put to use effectively.

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