SIMULATION STUDY OF A TRANSIT BUS EQUIPPED WITH AN ULTRACAPACITOR-BASED HYBRID SYSTEM

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Summary: *Due to the significant share of Internal Combustion Engines (ICE) in global energy demand, primarily through the transportation sector, great efforts are invested in research for solutions that will increase the fuel economy of ICE-powered vehicles. Several directions, most prominently that of Hydraulic Hybrid Technology, are considered for achieving pronounced powertrain efficiency breakthroughs on heavy vehicles in the near and mid-term. However, even simpler hybrid solutions, such as those employing an ultracapacitor-based energy accumulator, may provide significant fuel economy improvements at diminished implementation costs. In this paper, considerations regarding the use of such a system are laid out. A data acquisition on a transit bus circulating on Belgrade's transportation system has been performed in order to evaluate the real driving cycle and obtain the powertrain parameters necessary for calibrating a high-fidelity AMESim model of the vehicle. Initial study shows that considerable fuel consumption reduction in excess of 15% could be achieved by implementing a regenerative hybrid system employing an ultracapacitor-based accumulator.*
Keywords: *Simulation, Transit Bus, Ultracapacitors, Acquisition, Internal Combustion Engines*

1. 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. For accommodating the hybrid powertrain demands of heavy vehicles, particularly those marked by frequent deceleration and acceleration phases, the best solutions are those employing energy

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accumulators capable of very high power flows, such as in hydraulic hybrid (hydro-pneumatic accumulators) and ultracapacitor-based electric hybrid systems.

A numerical investigation, relying on model-based design tools, has been carried out to determine the fuel economy improvement that could be achieved by implementing an ultracapacitor-based hybrid electric system on a transit bus. Modeling of vehicle and propulsion systems has been performed using the LMS Imagine. Lab AMESim 1D multi-physics system simulation environment [1].

2. SIMULATION MODEL

In order to conduct the numerical analysis, a calibrated simulation model of the vehicle and its propulsion system was needed. The processes that were undertaken to satisfy this prerequisite are briefly explained in the following sections.

2.1 Data acquisition

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.

The experiment was conducted on an Ikarbus IK218N vehicle, equipped with a MAN D2066 LOH1 engine (10.5 dm3, 6-cylinder, turbocharged diesel engine) and Voith 864.5 automatic transmission, circulating on line 65 of the public transportation system in Belgrade. The driving cycle of the line 65 is characterized by a relatively long distance (run of approximately 14300 m) and considerably changing elevation profile.

Three complete driving cycle runs have been recorded using the CompactRIO platform from National Instruments [2]. Powertrain variables were acquired by accessing the vehicle’s J1939 CAN bus through a high-speed NI 9853 CAN C module. For obtaining the GPS coordinates of the driving cycle (that are necessary for determining the road slope), a Garmin GPS 18x 5 Hz receiver, streaming NMEA messages was utilized. Only one complete driving cycle is considered in this study and its characteristics are presented in Table 1.

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 - Novi Beograd 06:45:56	42:41	7.029
201	Novi Beograd 06:48:21 - Zvezdara 07:45:00	56:39	6.012

2.2 Parameters identification and simulation model calibration

Data acquired during the physical experiment has been of crucial importance in performing calibration of 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. Additional information regarding this procedure can be found in [3].

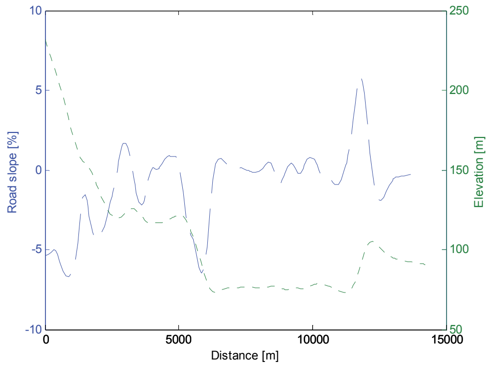

Fig. 1 *Road slope and elevation profile of run #200*

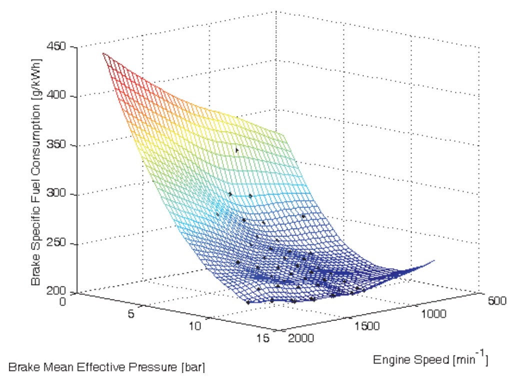

Fig. 2 *Reconstructed engine BSFC map from acquired data*

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 conducted on a portion of the driving cycle devoid of significant elevation changes to avoid taking into account data determined with the highest uncertainty. The portion in question is situated on Mihailo Pupin Boulevard.

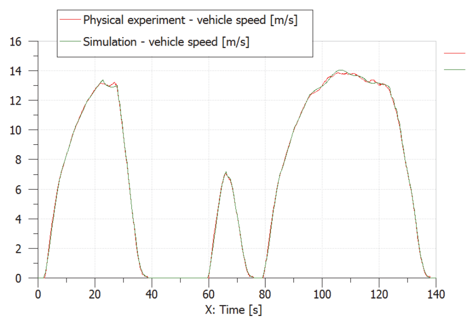

Fig. 3 *Velocity profile of the portion of the driving cycle used for calibration*

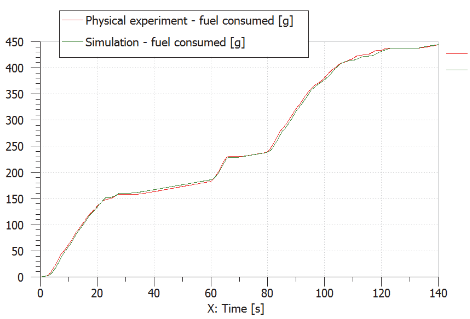

Fig. 4 *Cumulative fuel consumption matching*

2.3 Hybrid electric system configuration

Several ultracapacitor configurations, all based upon the Maxwell 125 V transportation module [4] (BMOD0063 P125, see Table 2), serve as deceleration energy accumulators in this simulation study. The energy accumulator is coupled with the electric motor/generator by means of an electric power converter module responsible for adjusting the variable voltage of the accumulator to a given motor/generator voltage (set to a constant value of 650 V in this study with constant conversion efficiency of 0.9). A 175 kW motor/generator (max. torque 500 Nm up to

3000 RPM, max. power @ 4400 RPM) is connected in between the torque converter and the gearbox through a 3.5:1 reduction gear.

Table 2 *Electrical characteristics of several ultracapacitor modules configurations*

Ultracapacitor configuration	Capacitance [F]	ESR [mΩ]	Rated voltage [V]	Stored energy (50%-100% SOC) [MJ]
1 module	63	18	125	0.37
2 modules/series	31.5	36	250	0.74
3 modules/series	21	54	375	1.11
4 modules/series	15.75	72	500	1.48

A simple, implementable, sub-optimal control law is used for controlling the engine and motor loads during traction phases. Indeed, for every given driver acceleration output (a PID controller forming its output by using the error between the desired and actual vehicle speed), the signal that is sent to the motor is first multiplied by three while the signal sent to the internal combustion engine is sent as is. This has the effect of achieving a variable load splitting ratio, as seen in Figure 6. The motor is contributing to the overall vehicle traction until the State of Charge (SOC) of the ultracapacitor module falls below 50%.

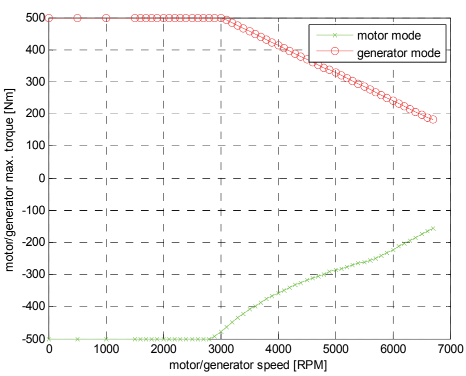

Fig. 5 *Motor/generator max. torque*

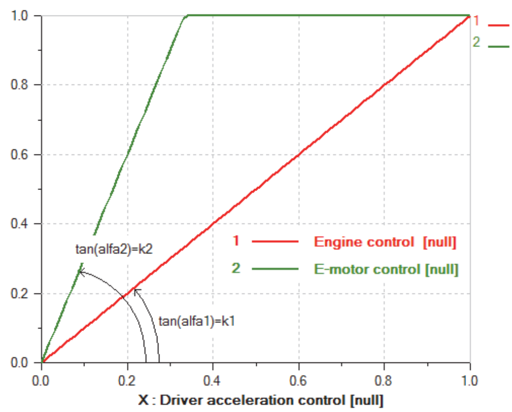

Fig. 6 *Traction control law [5]*

During braking phases, the generator is used to decelerate the vehicle and recuperate as much energy as possible, unless the recuperation isn't possible (due to the accumulator SOC reaching 100% or because the engine speed is below 500 RPM). If the deceleration achieved by the generator is not enough, friction brakes are applied.

3. NUMERICAL ANALYSIS

3.1 Experimental design

The main objective of this study is to quantify the improvement in fuel economy that could be achieved by implementing an ultracapacitors-based, parallel hybrid electric system on a transit bus. A constant vehicle mass of 23000 kg is assumed during the entire driving cycle. It should also be noted that only propulsion energy calculations are considered in this study (bus electrical loads, heating, A/C, air compressor are not taken into account).

Table 3 *Simulation runs parameters*

Parameter	Reference run	Hybrid electric configuration
Driving cycles	#200, #201	
Vehicle mass [kg]	23000	
Number of ultracapacitor modules/configuration	-	2/series, 3/series, 4/series

3.2 Results and discussion

The results of the numerical analysis are given in Tables 4 and 5. Fuel consumption has been decreased by 16.9% (when using 4 ultracapacitor modules) compared to the conventional vehicle. The total vehicle deceleration work ratio between runs #200 and #201 is over 1.55, primarily due to the difference in road slopes between the two directions. This is why the absolute reduction in fuel consumption for run #201 does not significantly change by adding ultracapacitor modules (effectively raising the amount of energy that could be stored in them).

However, considering the difficulties associated with performing efficient voltage amplification at high ratios, the most desirable ultracapacitor configurations are those characterized by a high number of modules connected in series. In these cases, even when the SOC falls to the low limit of 50%, the voltage multiplication is small enough to ensure an efficient power conversion (efficiency assumed constant and equal to 0.9 in this study for all three ultracapacitor modules configurations).

Table 4 *Fuel consumption results*

	Reference run	Hybrid electric configuration (number of ultracapacitor modules)		
		2	3	4
Run # 200 fuel consumption [g]	6217	4921	4773	4733
Run # 201 fuel consumption [g]	9038	7981	7949	7938
Complete driving cycle fuel consumption [g]	15255	12902	12722	12671
Fuel consumption decrease [%]	-	15.4	16.6	16.9

Table 5 *Vehicle deceleration energy by friction brakes comparison*

	Reference run	Hybrid electric configuration (number of ultracapacitor modules)		
		2	3	4
Complete driving cycle friction brakes work [MJ]	120.56	61.56	57.14	55.84
Friction brakes work decrease [%]	-	49	52.6	53.7

By increasing the number of modules, electric current levels at the accumulator output are diminished and the ultracapacitors' life is prolonged. Indeed, considering the driving cycle run #200, the mean absolute accumulator current is 152 A for 2 modules, 117 A for 3 and 92 A for 4 modules connected in series.

Calculations regarding the friction brakes deceleration work are given in Table 5. It is interesting to note that even when the reduction in energy dissipated directly into the atmosphere reaches and surpasses 50%, the fuel consumption decreases by “only” a figure of less than 20%. This could be explained by a number of reasons: gearbox, motor/generator and power converter module efficiencies of less than 100% and a very simple control algorithm that is not effective at shifting the engine operating points into regions of higher efficiencies, among others.

4. CONCLUSIONS AND FURTHER WORK

A simulation model of a transit bus has been designed and calibrated in AMESim in order to conduct numerical analyses involving hybrid propulsion systems. A relatively simple parallel hybrid electric system using ultracapacitor modules as energy accumulator has been implemented into the model of the conventional vehicle. Initial study shows that fuel consumption decrease in excess of 15% is achievable.

Further investigations shall consider the implementation of a better control algorithm that will maximize regenerative braking energy utilization by optimizing the motor and engine traction loads.

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