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Dynamic Programming Study of a Hybrid Electric Powertrain System for a Transit Bus

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Abstract: Great research efforts are invested in the quest for solutions that will increase the fuel economy of ICE-powered vehicles. The main objective of the study presented in this paper has been to analyze the ultimate fuel economy improvement potential of a transit bus by implementing a hybrid electric powertrain system utilizing an ultracapacitors-based accumulator. A simulation model of the vehicle has been calibrated by analyzing data obtained during an experiment conducted in real-world traffic conditions on a Belgrade transit bus. Apart from serving as the input for the powertrain parameters identification procedures, the acquired data also served as the basis for defining the driving cycle that will be used in numerical simulation studies. A Dynamic Programming optimization procedure has been applied on the hybrid powertrain system model in order to assess the ultimate fuel economy improvement potential. The optimization procedure has been executed for various hybrid powertrain parameters and component sizes, allowing the optimal choice of design decisions, in particular the energy accumulator size. Initial study shows that considerable fuel consumption reduction in excess of 30% can be achieved.

Keywords: Dynamic Programming, Internal Combustion Engines, Simulation, Transit Bus, Fuel Economy.

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, and perhaps the most promising, is powertrain hybridization. Achieving improved fuel economy, lower emissions and a relatively low price without incurring penalties 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 undergoing frequent deceleration and acceleration phases, the best solutions are those that can sustain very high power levels, such as the hydraulic hybrid or the ultracapacitors-based hybrid electric systems.

The main objective of the study presented in this paper is to analyze the ultimate fuel economy improvement potential of a transit bus hybrid powertrain system that uses an ultracapacitors-based energy accumulator. An experiment has been conducted on a transit bus circulating in real traffic and occupancy conditions in Belgrade, Serbia to assess the circumstances encountered in this particular type of transportation and in order to obtain the real driving cycle and the vehicle powertrain parameters necessary for conducting virtual analyses involving hybrid solutions. Data acquired during this experiment has been of crucial importance; effectively allowing us to conduct identification procedures on a set of powertrain parameters in order to calibrate the vehicle model used in the simulation.By successfully transferring the real-world physical conditions into computer code, a practically infinite number of numerical study possibilities has been opened.

In the following section of this paper the methodology is presented, which includes subsections on the experimental setup and the identification procedures used on the acquired data to extract the powertrain parameters and the driving cycle of the transit bus. The methodology section also includes the vehicle model used in this simulation, along with the calibration procedure and its results. Next, the details on the hybrid powertrain system considered in the study are presented. Finally, the Dynamic Programming procedure and the design parameters are laid out.

The results and concluding remarks are presented in their respective sections, following the methodology section.

2. Methodology

The methods employed in this study are presented in the following subsections.

2.1. Experimental setup

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 IK206 vehicle, equipped with a MAN D2066 LUH 11 engine (10.5 dm^3, 6-cylinder, turbocharged diesel engine) and Voith 864.5 automatic transmission, circulating on line 83 of the public transportation system in Belgrade, Serbia.

An autonomous data acquisition system based on National Instrument's CompactRIO hardware platform and LabVIEW software has been designed for this purpose. The powertrain parameters were acquired by accessing the vehicle's J1939 CAN bus by means of a high-speed NI 9853 CAN module. The raw network stream has been logged and afterwards processed according to the SAE J1939 standard [1]. In order to obtain the GPS coordinates of the driving cycle, which are needed for determining the road slope, a Garmin GPS 18x 5 Hz receiver streaming NMEA messages was used. Suspension system pressure sensors have also been installed in order to log the vehicle mass during the experiment.

This experiment has been conducted for the duration of several weeks, during which a vast amount of highly valuable data has been collected. Out of a vast number of recorded driving cycles, one was chosen to serve as the reference cycle for numerical analyses that will be conducted. The driving cycle specification, along with acceleration and vehicle mass distribution can be found in Figures 1 and 2. The recorded driving cycle vehicle speed is shown in Figure 3.

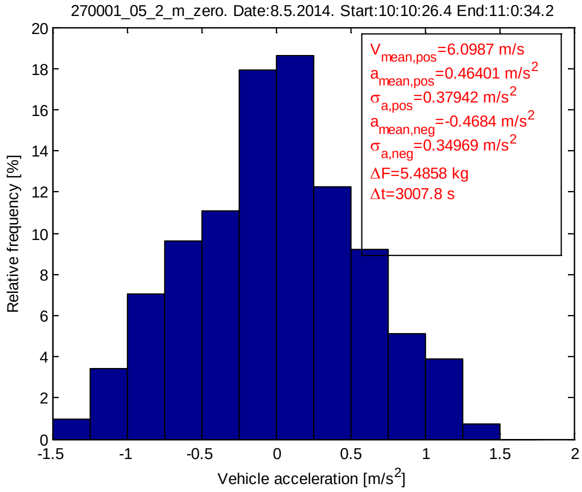

Figure 1. Driving cycle acceleration distribution

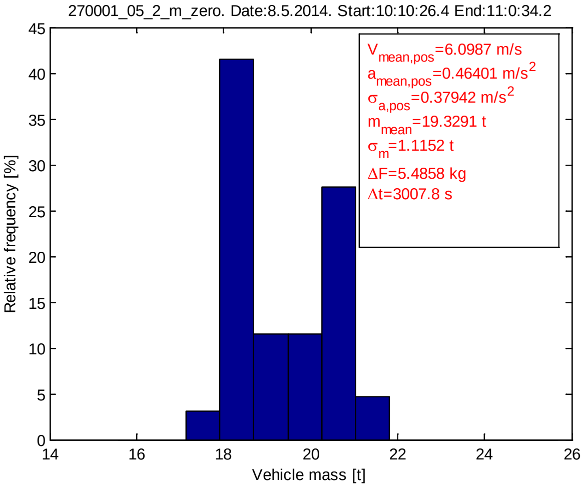

Figure 2. Vehicle mass distribution

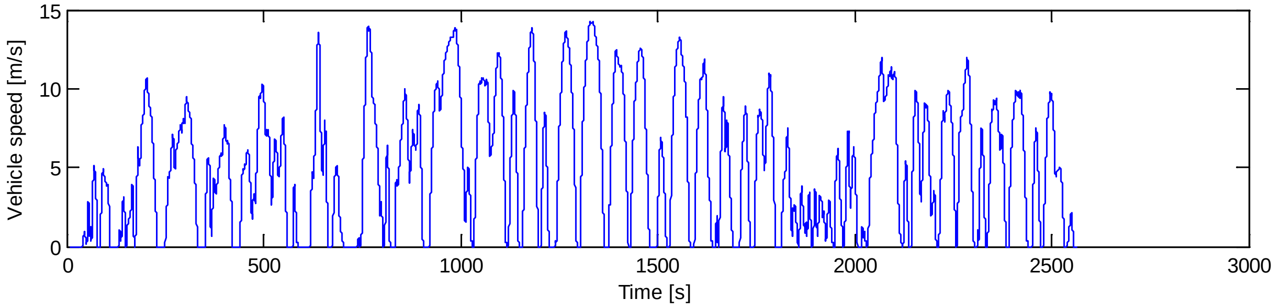

Figure 3. Driving cycle vehicle speed profile

2.2. Powertrain parameters and vehicle cycle identification procedure

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 related 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 4) 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 points 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 could be obtained. In order to form the Brake Specific Fuel Consumption (BSFC) map for the entire operating range of the engine (Figure 5), this set of values is further used as an input to a Kriging interpolation algorithm (DACE for Matlab toolbox) [2].

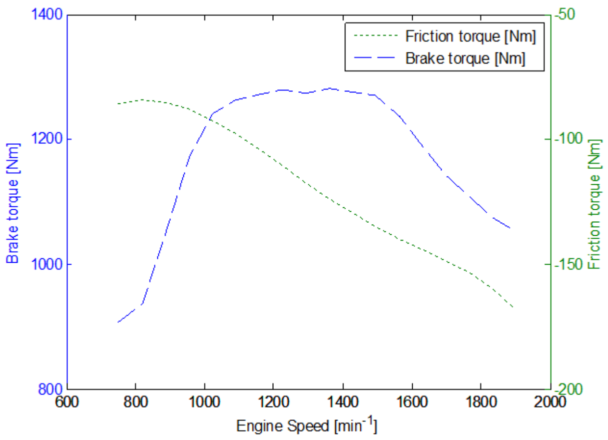

Figure 4 Max. engine brake torque and friction torque

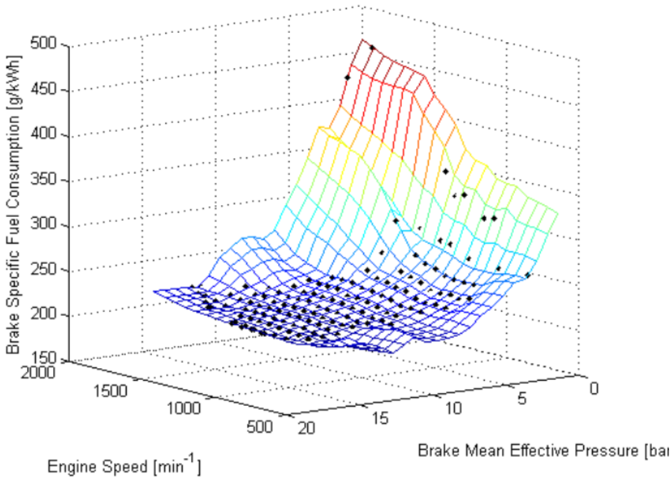

Figure 5 Brake Specific Fuel Consumption (BSFC) map

Another set of identification procedures has been performed to obtain the characteristics of the automatic gearbox torque converter. The dependence of the torque converter torque ratio on the speed ratio, along with the capacity factor have been identified and implemented into the simulation models.

The road slope has been calculated using the Digital Elevation Model (DEM) data files from the Shuttle Radar Topography Mission [3]. 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. 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 6).

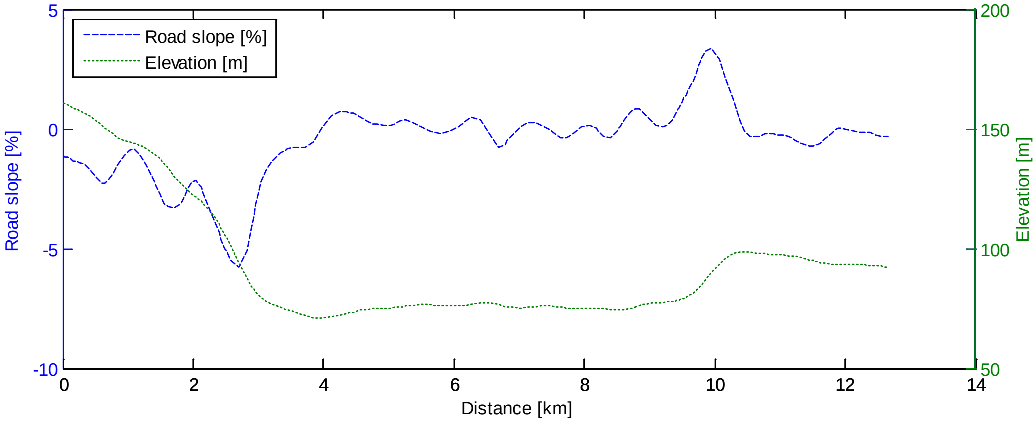

Figure 6 Driving cycle elevation and road slope profiles

2.3.Reference vehicle model and calibration

The total resistive force a transit bus experiences is evaluated using the following equation, taking into account the climbing resistance, the aerodynamic drag and the rolling friction:

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

where$m_{veh}$is the total equivalent vehicle mass (including the wheels inertia) in kg, α is the road slope in %, ρ_{air} is the air density in kg/m^3, c_x is the aerodynamic drag coefficient, S is the vehicle frontal area,$v_{veh}$is the vehicle speed in *m/s*, f is the constant (Coulomb) rolling friction coefficient, k is the rolling friction coefficient proportional to vehicle speed (viscous coefficient) and w to the vehicle speed squared (windage coefficient).

A vehicle model calibration procedure has been performed in the LMS Amesim integrated simulation platform in order to obtain the rolling friction coefficients for the transit bus.An optimization procedure in the Design Exploration module in Amesimhas been used to calibrate the rolling friction parameters so that the sum of the squared difference between the simulated and the acquired mass of fuel consumed along the route was minimized. The recorded and simulated cumulative fuel consumption curves along the driving cycle that was considered in this study are shown in Figure 7. Additional details regarding this procedure can be found in [4].

Table 1. Results of the calibration process

Coefficient	Value
Rolling friction Coulomb coefficient	f=0.01643
Rolling friction viscous coefficient	k=0.0003147 1/(m/s)
Rolling friction windage coefficient	w=1.515 $\cdot 10^{-5}$ 1/(m/s)^2

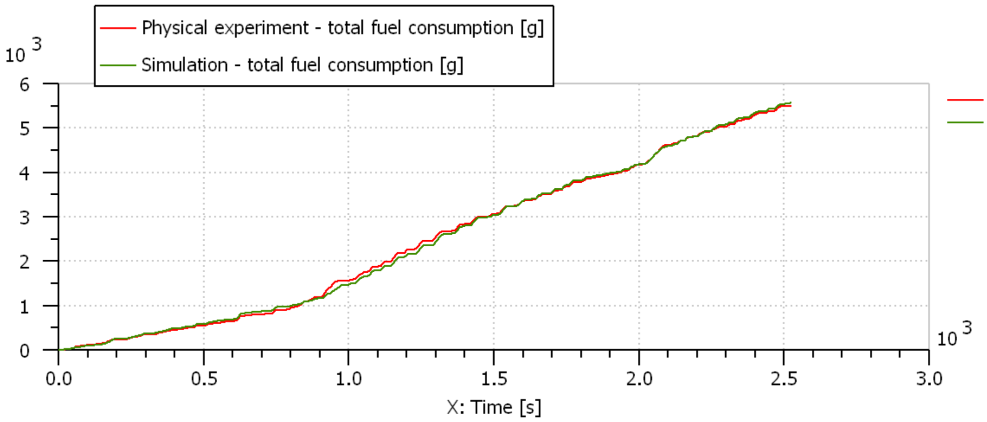

Figure 7 Cumulative fuel consumption matching

2.4. Hybrid powertrain system

Due to the characteristics of the driving cycle, which has a significant number of starting and stopping events, a parallel hybrid powertrain system employing a bank of ultracapacitor modules has been chosen as the configuration for this study.

A 175 kW electric motor/generator is placed between the torque converter and the gearbox through a reduction gear. The reference torque map of the motor/generator is shown in Figure 8.

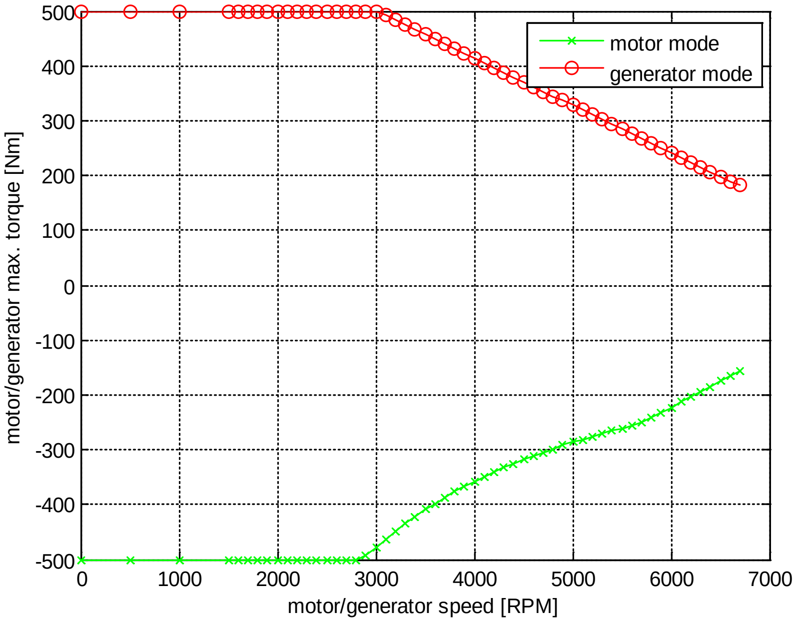

Figure 8Electric motor/generator max. torque

Table 2. Electrical characteristics of ultracapacitor modules

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
5 modules/series	12.6	90	625	1.85
6 modules/series	10.5	108	750	2.22

For accumulating the energy obtained during the regenerative braking phases, a bank of ultracapacitor modules has been chosen. The electrical characteristics of this energy accumulator system is presented in Table 2 for the number of series-connected modules that are considered in this paper.

2.5. Dynamic Programming Model

For the purpose of evaluating the ultimate fuel economy performance of the hybrid configuration described in the preceding subsections, a dynamic programming approach to obtaining the control law that minimizes the amount of fuel consumed has been employed in this study. Dynamic programming relies on the principle of optimality, which states that [5] “An optimal policy has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision.”

By decomposing a control problem into segments or sub-problems, an optimal decision can be discovered at each stage starting from the end and moving toward the initial start time. By defining the desired final system state, a dynamic programming algorithm starts with evaluating the optimal decision at the stage preceding the final stage that will result in the system reaching this final state at minimal cost. This is done by discretizing the state space which results in a time-state space grid with nodes at which the cost is evaluated by sweeping the admissible control values, subject to state constraints. By proceeding backwards, an optimal control decision can be stated for each stage-state combination that will bring the system from the current stage-state point to the desired final state at minimal cost. By ultimately reaching the initial time stage, the cost-to-go matrix, and optimal control matrices are obtained, representing respectively the cost and optimal control decisions for each admissible stage-state combination. Mathematically, this can be stated through a recurrence relation [6]:

$$J^*_{N-K,N}\left(\vec{x}\left(N-K\right)\right)=\min_{u\left(N-K\right)}\left\{\begin{array}{l} g_D\left(\vec{x}\left(N-K\right),\vec{u}\left(N-K\right)\right)+ \\ +J^*_{N-(K-1),N}\left(\vec{a}_D\left(\vec{x}\left(N-K\right),\vec{u}\left(N-K\right)\right)\right)\end{array}\right\} \tag{2}$$

By knowing $J^*_{N-(K-1),N}$, the optimal cost at (K-1) stage, the optimal cost for the K stage $J^*_{N-K,N}$ can be determined, along with its corresponding control.

In this study, the torque ratio between the engine and electric motor during the traction phases, and the torque ratio between the electric generator and the friction brakes during braking phases is the actual control variable. The hybrid powertrain system is described in the Dynamic Programming (DPM) model by a single, discretized state equation representing the state of charge of the ultracapacitors modules.

A generic MATLAB implementation of the dynamic programming algorithm has been used in this study [7]. All the relevant data obtained during the physical experiment and identified afterwards has been transferred into MATLAB to be used by this DPM algorithm. The vehicle resistive forces models, driving cycle data (vehicle speed, acceleration, road slope, vehicle mass and selected gear), electric motor/generator maps, engine BSFC map, transmission characteristics, and ultracapacitors-based energy accumulator models have been implemented into a MATLAB function that is evaluated by the DPM routine.

One of the shortcomings of Dynamic Programming, besides its inability to yield an implementable control algorithm and its slow pace for problems involving several state variables, is its inability to include design parameters in the optimization. For this reason and in order to show the dependencies of different parameters on the fuel consumption of the hybridized transit bus, several design parameters have been included in the analysis, such as the gear ratio between the electric motor (EM) and the gearbox (GB), the electric motor size, the energy accumulator size and the maximum electric current through the ultracapacitor (UC) bank. A summary of values assumed for these design parameters is shown in Table 3. It should be noted that the electric motor size parameter influences the maximum torque values that can be achieved in the motor and generator modes by applying a gain on the values shown in Figure 8. Besides the torque values at which it is defined, the efficiency map of the EM is left unaffected, such as that the efficiency pole is attained at a different (lower) torque than for the reference case (motsize=1.0).

Table 3. Summary of design parameters variations

Design parameter	Name	Values
Gear ratio between the EM and GB [-]	‘reductor’	2.0, 3.0, 4.0
EM size [-]	‘motsize’	0.4, 0.6, 0.8, 1.0
Number of UC modules [-]	‘accusize’	2, 3, 4, 5, 6
Maximum UC current [A]	‘accucurrent’	300, 500, unlimited

3. Results

In the following subsections, the results of the Dynamic Programming optimization are shown for different sets of independent variables (design parameters).

3.1.EM size and Number of UC modules variation (reductor=3.0)

The results of the Dynamic Programming optimization obtained by sweeping the values of EM size and Number of UC modules independent variables for different levels of the Maximum UC current are shown in Figures 9 to 11. It should be noted that the reference fuel consumption is 5.501 kg (recorded during the experiment) and that the results show the relative reduction in the quantity of fuel consumed during the Dynamic Programming runs. The ‘reductor’ parameter has been held constant during this variation, with a value of 3.0.

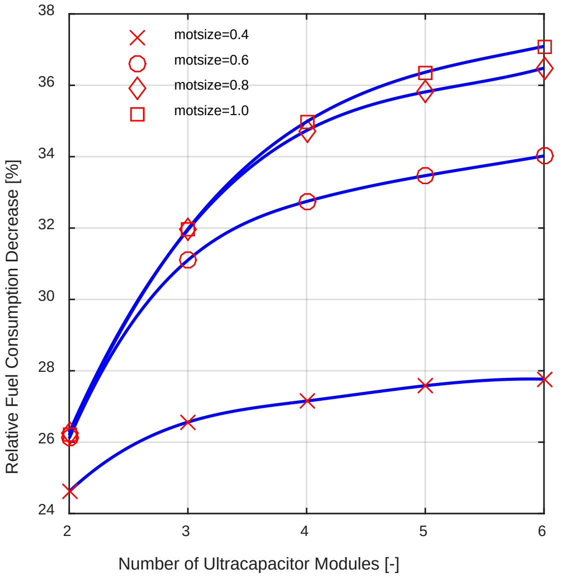

Figure 9‘accusize’ and ‘motsize’ sweep at max UC current of 300 A

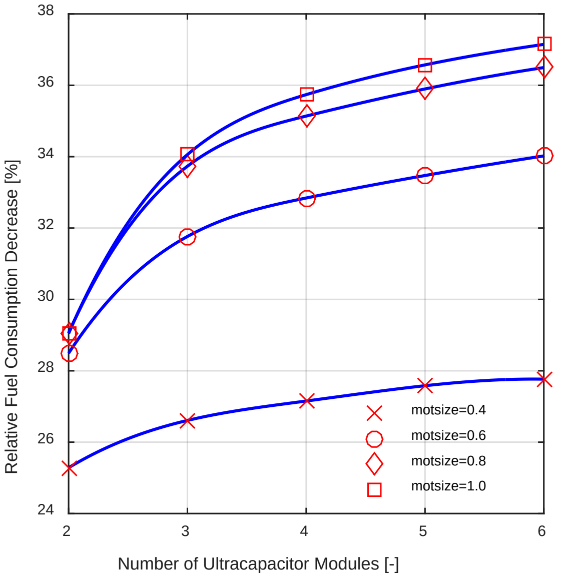

Figure 10‘accusize’ and ‘motsize’ sweep at max UC current of 500 A

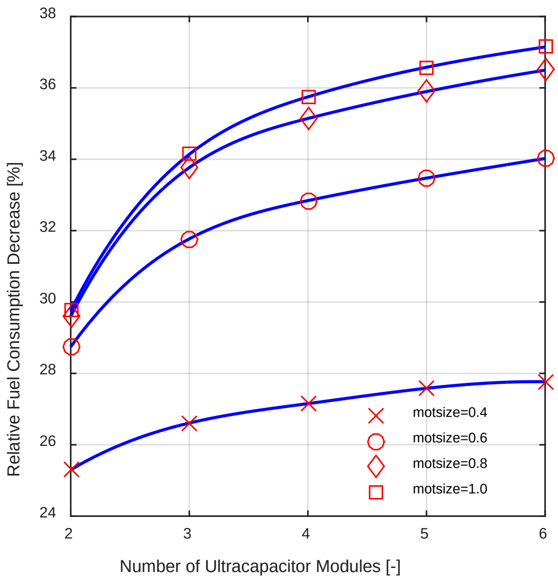

Figure 11 'accusize' and 'motsize' sweep with no limit on UC current

Looking at the results, the first impression is that the potential for the reduction of fuel consumption is significant, with values ranging from more than 24% in the worst case to in excess of 37% in the best design case. As expected, the least amount of fuel saving potential is reserved for the smallest electric motor coupled with the energy accumulator with the least energy storing capacity and for the UC current limit of 300 A.

By increasing the EM size from 'motsize' 0.4 to 0.6, effectively raising the EM power from 70 kW to 105 kW, a significant leap in fuel saving potential can be achieved, with incremental savings exceeding 6% for 6 ultracapacitor modules. With further increases to the EM size, the fuel saving potential follows the law of diminishing returns, with the jump from 0.8 to 1.0 in EM size parameter bringing less than 1% incrementally.

The influence of the energy accumulator size is also significant, with fuel saving potential increments ranging from less than 3% (motsize=0.4, no UC current limit) to in excess of 10% (motsize=1.0, UC current limit of 300 A) by increasing the 'accusize' parameter from 2 to 6. By raising the ultracapacitor module capacity, given the fact that this increase is executed by increasing the number of UC modules connected in series, its voltage at a given State Of Charge (SOC) level is greater. This in turn allows a regenerative braking event at a given power level to be harnessed at a lower UC current, thus dramatically lowering the use of friction brakes during the driving cycle by not exceeding the imposed UC current limits. This is also why the effect of raised UC current limit has little to no incremental effect on the fuel saving potential for the hybrid powertrain configurations with the maximum UC accumulator capacities.

3.2. Gear ratio between the EM and GB and Number of UC modules variation (motsize=1.0)

The results of the Dynamic Programming optimization obtained by sweeping the values of the gear ratio between the EM and the gearbox (GB) and Number of UC modules independent variables for different levels of the Maximum UC current are shown in Figures 12 to 14. The 'motsize' parameter, representing the size of the electric motor/generator, has been held constant during this variation, with a value of 1.0.

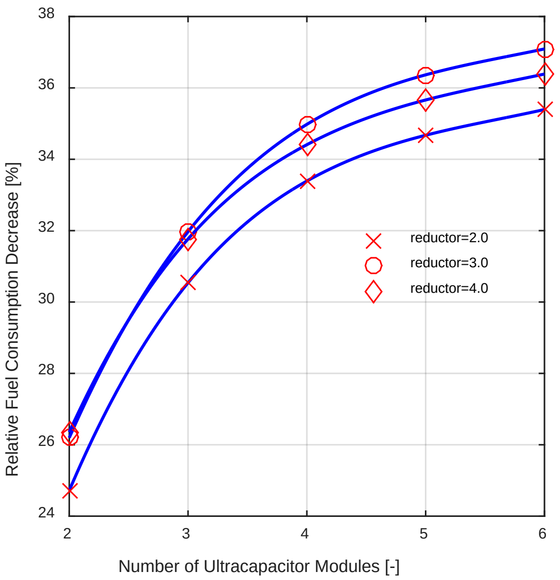

Figure 12 'accusize' and 'reductor' sweep at max UC current of 300 A

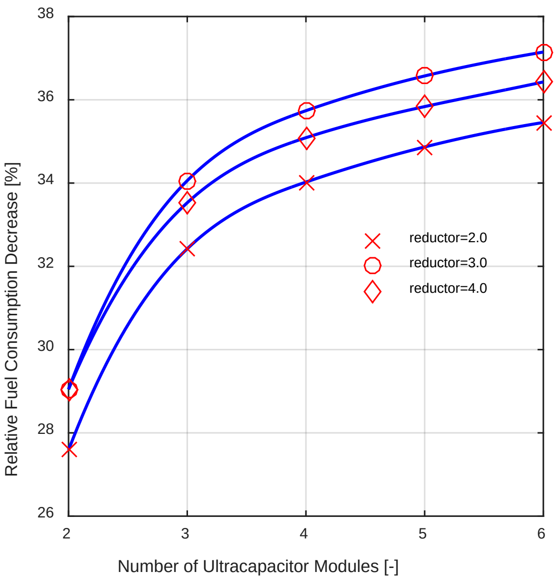

Figure 13'accusize' and 'reductor' sweep at max UC current of 500 A

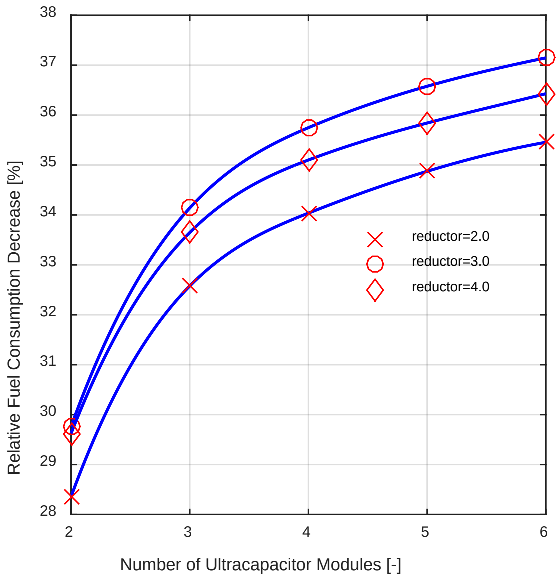

Figure 14 'accusize' and 'reductor' sweep with no limit on UC current

The variation of the 'reductor' parameter allows for a design decision for the gear ratio between the EM and the gearbox to be made with regards to its effect on the fuel saving potentials of a hybrid powertrain-equipped transit bus. If this gear ratio is set too low, the operating points of the EM at a given vehicle speed lie at low rotational speeds, thus limiting the maximum available power. If the gear ratio is set too high, it can shift the operating points in the EM map to the high rotational speed region that is characterized by decreasing efficiency.

Looking at Figures 12 to 14, it can be said that the sensitivity of the optimal gear ratio is practically null, with the influence of design parameters on the optimal gear ratio only visible at the lowest UC accumulator capacity. Out of the values that have been tested, the optimal gear ratio for this hybrid powertrain configuration is 3.0. The only exceptions occur at maximum UC current levels of 300 A and 500 A for the configuration with 2 UC modules, where the optimal gear ratio is 4.0.

4. Concluding remarks

A conventional transit bus powertrain system has been modeled and calibrated according to data obtained during an experiment carried out in real traffic and occupancy conditions on a transit bus circulating in Belgrade, Serbia. A parallel hybrid electric powertrain model, employing an ultracapacitors-based energy accumulator, has subsequently been formed based on the calibrated conventional powertrain system. For evaluating the ultimate fuel economy improvement of this configuration and in order to evaluate the influence of different design parameters on the hybrid powertrain system performance, a Dynamic Programming algorithm has been used. It has been shown that fuel savings up to 37% can be achieved with this system. The influences of electric motor/generator and energy accumulator sizes, along with the EM-GB gear ratio and the maximum allowable UC current on the fuel economy improvement potential have been presented. The results in this study can be used to make final design decisions according to performance, reliability (in particular the UC modules, which depends on the current levels sustained in operation) and cost criteria.

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