FUEL ECONOMY COMPARATIVE ANALYSIS OF CONVENTIONAL AND ULTRACAPACITORS-BASED, PARALLEL HYBRID ELECTRIC POWERTRAINS FOR A TRANSIT BUS

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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. 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 electric 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. This platform provides a graphical programming interface and an extensive set of validated components organized in different libraries for modeling and analyzing 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 experiment 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 real-world physical conditions into computer code, a vast array of numerical study possibilities has been opened. In this paper, the results of a simulation involving the use of an ultracapacitors-based hybrid electric powertrain system are laid out. Also, considerations regarding the optimal control of such a hybrid solution are presented, with an emphasis on optimal control theory and in particular the Dynamic

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Programming principle. This principle has been applied on a simplified powertrain model in Mathworks MATLAB software in order to derive an optimal control trajectory and to assess the ultimate fuel economy improvement potential for the vehicle and the driving cycle in question. A Dynamic Programming model of a hybrid powertrain can be used to great effect for determining the optimal component size (such as the energy accumulator capacity, for example) because an optimal control is obtained for every single component parameter that can be changed. Design decisions regarding the optimal gear ratio between the electric motor/generator and the gearbox and the number of ultracapacitors modules have been made using this Dynamic Programming (DPM) model.

DATA ACQUISITION

In the following paragraphs, the experiment conducted on a transit bus circulating in real traffic and occupancy conditions is described. Furthermore, the results of a data analysis on data obtained during this experiment, which are subsequently used as input for the simulation models, are presented in this section of the article.

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 dm3, 6-cylinder, turbocharged diesel engine) and Voith 864.5 automatic transmission, circulating on line 83 of the public transportation system in Belgrade.

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 [9]. 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, only one was chosen that will serve as the reference cycle for which numerical analyses will be conducted. Information about the chosen driving cycle, 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.

POWERTRAIN PARAMETERS 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 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.

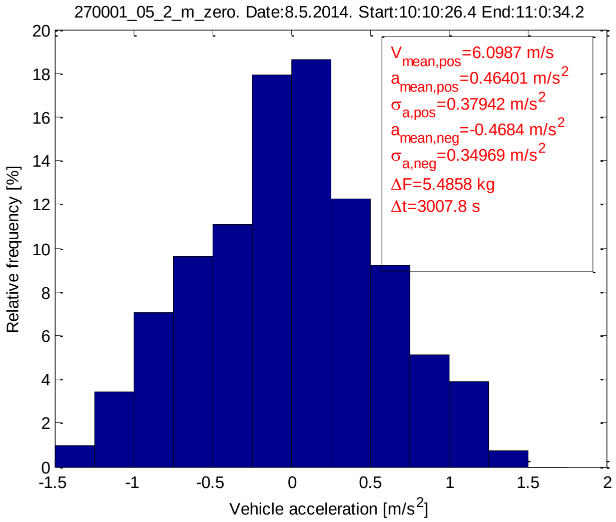

Figure 1 Driving cycle acceleration distribution

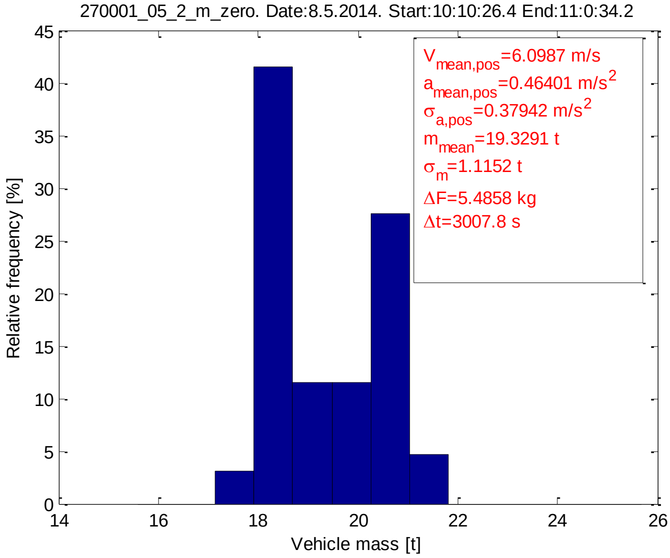

Figure 2 Vehicle mass distribution

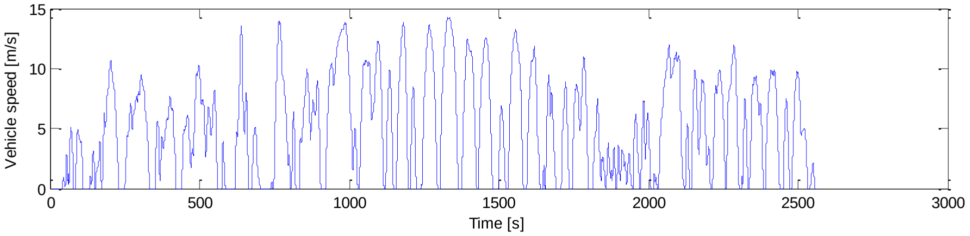

Figure 3 Driving cycle vehicle speed

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) [5].

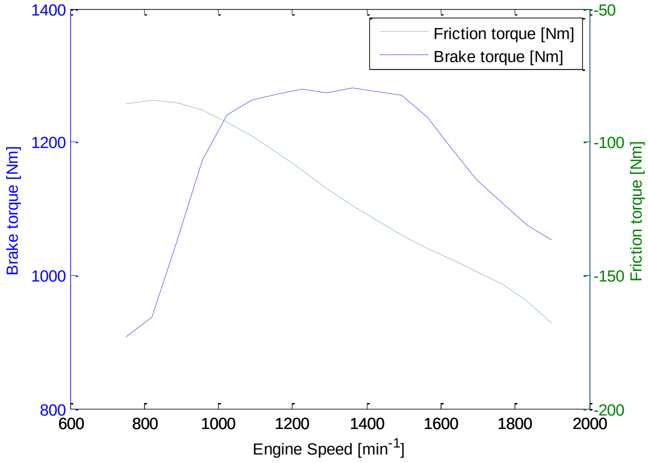

Figure 4 Max. engine brake torque and friction torque

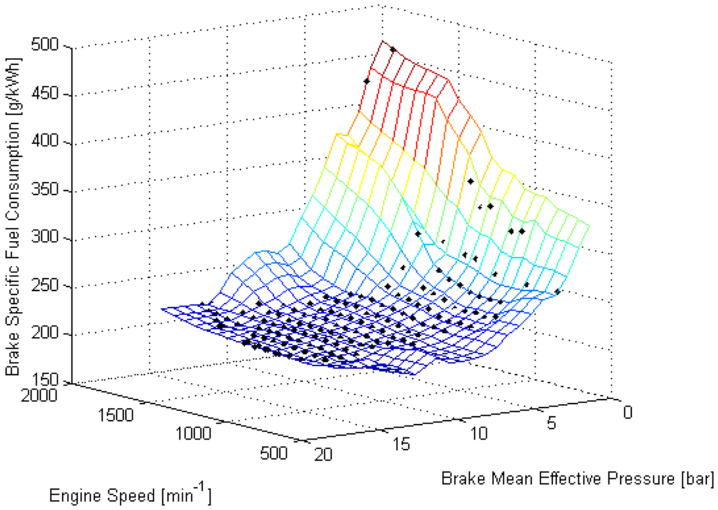

Figure 5 Brake Specific Fuel Consumption (BSFC) map

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 [8]. 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).

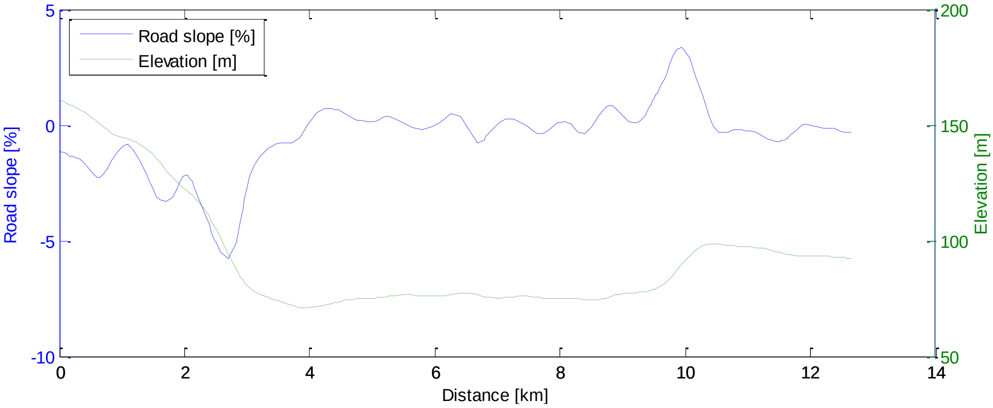

Figure 6 Driving cycle elevation and road slope profiles

SIMULATION ANALYSES

This section of the article deals with the simulation analyses that are set up according to parameters and driving cycle details presented in the preceding paragraphs. First, an overview of the most important submodels and corresponding equations that are used in the LMS Imagine.Lab AMESim simulation environment will be given. Results of a calibration procedure of the simulation model will also be presented before moving to a discussion of the results of a comparative analysis of hybrid and conventional powertrains using a simple, implementable control law. At the end of this part, a Dynamic Programming model of the transit bus hybrid powertrain will be presented, along with results showing the ultimate potential of the hybrid solution considered in this study.

CONVENTIONAL TRANSIT BUS POWERTRAIN MODEL

A simulation model of a conventional transit bus powertrain system has been set up in AMESim, which was used to compare the results of the hybrid powertrain system to.

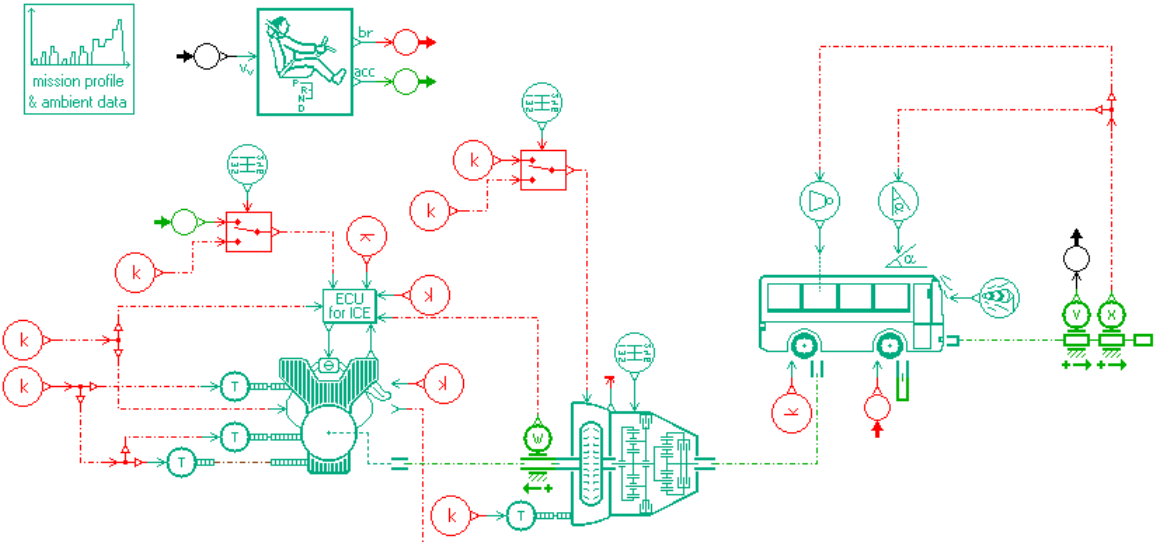

Figure 7 AMESim model of a conventional transit bus powertrain system

The bus component is responsible for evaluating the acceleration to be integrated by the AMESim solver in order to obtain the actual vehicle velocity [1]:

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

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:

$$F_{dr} = \left(T_2 + T_4\right)/R_w \tag{2}$$

where T_2 and T_4 are input torques at ports 2 and 4 (rear 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 [3]:

$$F_w = \frac{\Theta_w}{R_w^2}\cdot\frac{dv_{veh}}{dt} \tag{3}$$

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

$$m_w = \frac{\Theta_w}{R_w^2} \tag{4}$$

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

The braking force is similarly obtained:

$$F_b = \left(T_{b,front} + T_{b,rear}\right)/R_w \tag{5}$$

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

$$F_{res} = F_{cl} + F_{aero} + F_{roll} = \left(m_{veh} \cdot g \cdot \sin\left[\arctan\left(0.01 \cdot \alpha\right)\right]\right) + \\ + \left(\frac{1}{2} \cdot \rho_{air} \cdot c_x \cdot S \cdot v_{veh}^2\right) + m_{veh} \cdot g \cdot \left(f + k \cdot v + w \cdot v^2\right) \tag{6}$$

where α is the road slope in %, S is the vehicle frontal area, f is the constant (Coulomb) rolling friction coefficient, k is the rolling friction coefficient proportional to vehicle speed (viscous coefficient) and w to vehicle speed squared (windage).

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.

Gear shifting occurrences have been transferred from collected data into the simulation model. It should be noted that the lockup clutch in the torque converter engages in all gears except the first.

MODEL CALIBRATION

For making sure the conditions are successfully transferred and the dynamic behavior of the most important variables are in agreement with the ones that were acquired during the physical experiment, a calibration procedure was set up. An optimization procedure in the Design Exploration module in AMESim was 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. A genetic algorithm was used to that effect because it converges to the global minimum. The population size was 100, reproduction ratio being 60%. The number of generation was 20 with mutation probability of 10% and an amplitude of 0.6. The resulting rolling friction parameters are presented in Table 1.

Table 1 Results of the calibration process

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

The recorded and simulated cumulative fuel consumption curves are shown in Figure 8. A satisfactory matching has been achieved, even though a slight deviation appears at about the 950 s mark. It should be noted that the calibration procedure has been performed for a limited range of time from 0 to 2525 s because the remaining part of the driving cycle includes only stationary vehicle state with engine turned off.

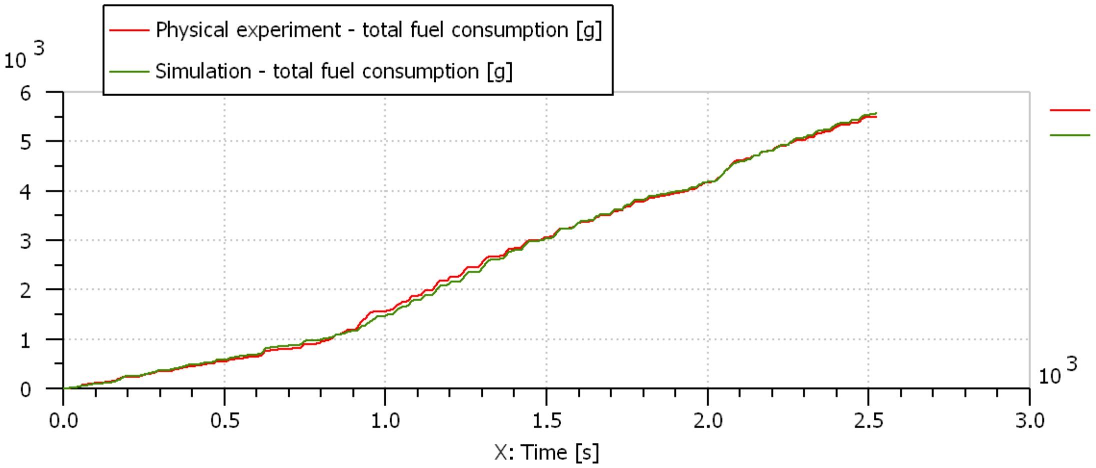

Figure 8 Cumulative fuel consumption matching

HYBRID TRANSIT BUS POWERTRAIN MODE

lA parallel hybrid transit bus powertrain system has also been modeled in AMESim. It includes a 175 kW electric motor/generator (max. torque 500 Nm up to 3000 RPM, max. power at 4400 RPM) placed between the torque converter and the gearbox through a 3.5 reduction gear. Several ultracapacitor (UC) configurations are used as energy accumulators in this hybrid electric system. They are based on the Maxwell 125 V transportation module [6] (BMOD0063 P125, see Table 2). The energy accumulator is coupled to the electric machine by means of an electric power converter module that adjusts the variable ultracapacitors voltage to a given motor/generator voltage (set to a constant value of 650 V in this study, with constant conversion efficiency in both directions of 90%).

Table 2 Electrical characteristics of 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 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 9. The motor is contributing to the overall vehicle traction until the State of Charge (SOC) of the ultracapacitor module falls below 50%.

During braking phases, the generator is used to decelerate the vehicle and recuperate as much energy as possible, unless the recuperation isn't possible. If the deceleration achieved by the generator is not enough, friction brakes are applied.

The results of the numerical analysis are given in Table 3. Fuel consumption has been decreased by 16.8% (when using 4 ultracapacitor modules) compared to the conventional vehicle. It can be seen that no significant fuel consumption reduction can be achieved by increasing the number of ultracapacitor modules. Indeed, by doubling the effective energy storage capacity, only an additional 0.68% of fuel can be saved.

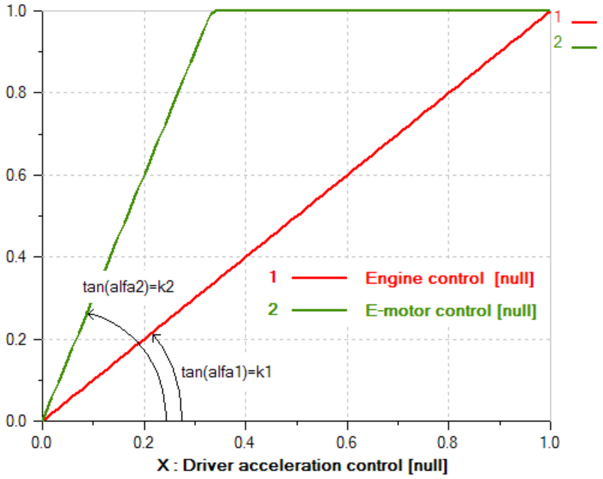

Figure 9 Traction control law [1]

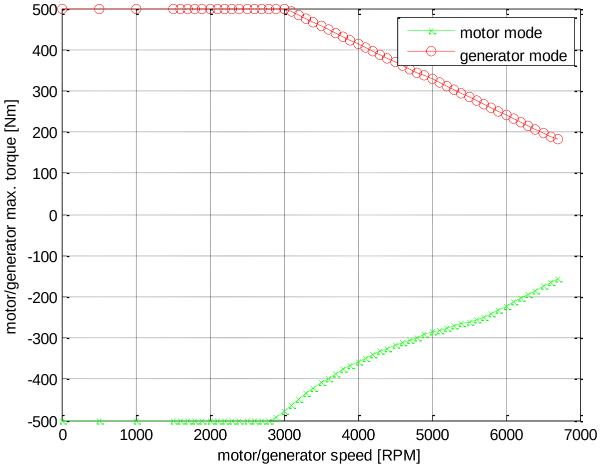

Figure 10 Motor/generator max. torque

Table 3 Fuel consumption for the conventional and hybrid transit bus powertrains

	Reference run (conventional powertrain)	Hybrid electric configuration (number of ultracapacitor modules)		
		2	3	4
Absolute mass of fuel consumed [g]	5501.457	4613.17	4590.026	4575.358

Fuel consumption decrease [%]	-	16.15	16.57	16.83

The reasons for such insignificant fuel economy improvements with increasing energy capacities can be seen by taking a look at Figure 11, depicting the energy accumulator state of charge (SOC) during the simulation. The SOC of the accumulator with the least amount of energy capacity (with 2 ultracapacitors) reaches 100% only in 4 occurrences. The accumulators with 3 and 4 UC modules never reach 100% SOC. It can be said that the increased energy storage capacity is not being efficiently used.

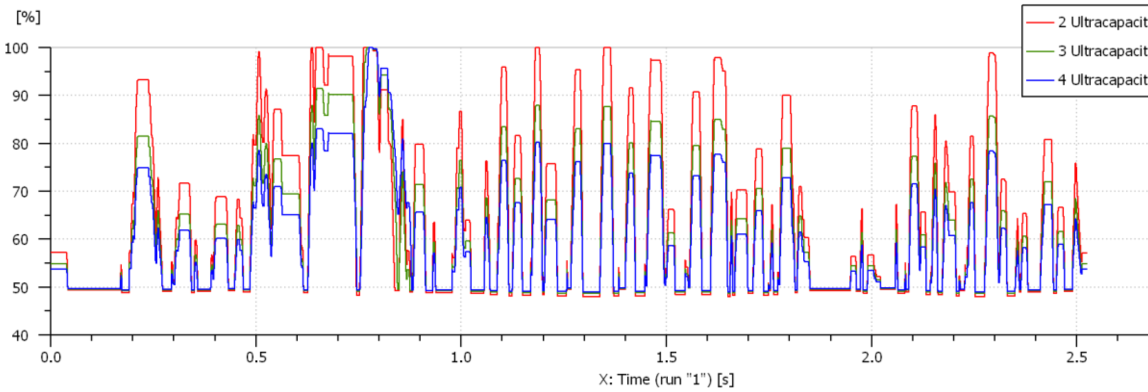

Figure 11 Cumulative fuel consumption matching

By looking solely at the fuel consumption figures of the conventional and hybrid powertrain systems, one would not be justified in choosing a configuration with more than 2 UC modules. However, considering the difficulties associated with performing efficient, high-ratio voltage amplification, 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. Also, peak and mean current levels at the interface between the UC modules and the electric power converter module are decreased by increasing the number of ultracapacitors, thus favorably impacting their lifespan.

DYNAMIC PROGRAMMING MODEL OF THE HYBRID TRANSIT BUS POWERTRAIN

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 [2] “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 [4]:

$$J^*_{N-K,N}\left(\vec{x}(N-K)\right)=\min_{u(N-K)}\left\{\begin{array}{l} g_D\left(\vec{x}(N-K),\vec{u}(N-K)\right)+ \\ +J^*_{N-(K-1),N}\left(\vec{a}_D\left(\vec{x}(N-K),\vec{u}(N-K)\right)\right)\end{array}\right\} \qquad (7)$$

By knowing , the optimal cost at (K-1) stage, the optimal cost for the K stage 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.

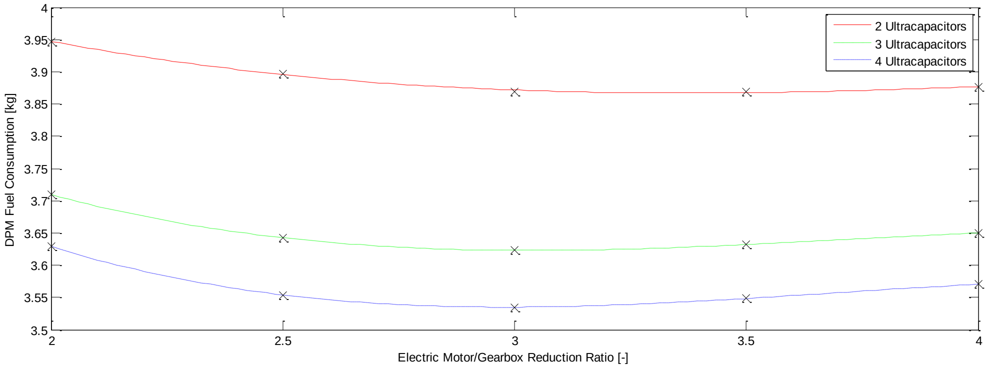

Figure 12 DPM fuel consumption results – accumulator capacity, reduction ratio parameters sweep

Table 4 Fuel consumption comparison between the conventional and DPM hybrid transit bus models (3 UC)

	Reference run (conventional powertrain)	DPM Hybrid electric configuration (reduction ratio) for 3 UC modules				
		2	2.5	3	3.5	4

Absolute mass of fuel consumed [g]	5501.457	3709.7	3642.7	3622.9	3632.2	3650.2
Fuel consumption decrease [%]	-	32.6	33.8	34.1	34.0	33.7

The final state has been fixed to the accumulator SOC of 0.65. The admissible state values range from 0.5 to 1.0 and are discretized evenly into 101 total values. The admissible control values range from 0 to 1 and are discretized also evenly into 101 total values. The simulation time step has been set to a relatively low 0.2 s in order to preserve the shape and smoothness of the vehicle acceleration data that has a high influence on the total vehicle resistive force and to obtain more accurate fuel consumption results.

The results of the DPM simulation are shown in Figure 12 for a range of reduction gear ratio values and 3 values of total accumulator energy capacities (equal to 2, 3 and 4 UC modules, with electrical characteristics as shown in Table 2). It can be seen that the absolute amounts of fuel consumed are significantly lower than in the case of a simple control used in the AMESim simulation, and up to 34% of fuel can be saved using three UC modules. As can be seen in Figure 13, the range of SOC variation in DPM simulation is greater than in the corresponding simulation case that uses a far simpler control algorithm. The optimal reduction gear ratio has been found to be approximately 3, with the slopes of the DPM fuel consumption-gear ratio curves increasing with additional UC modules around this value.

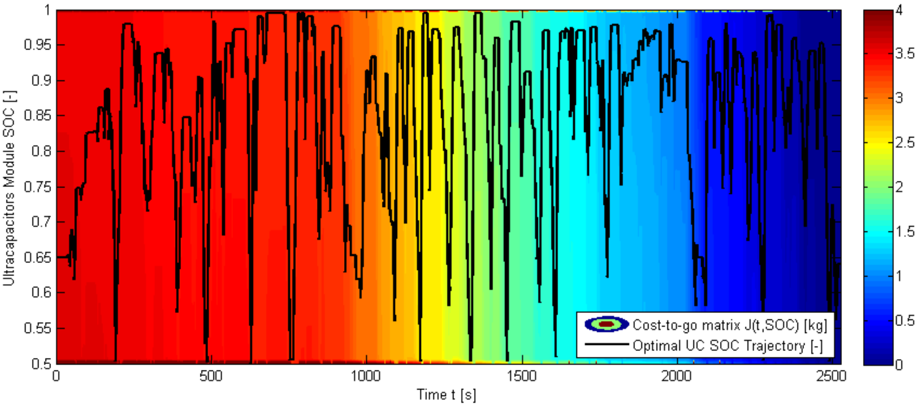

Figure 13 Cost-to-go matrix visualization with optimal SOC trajectory (reduction ratio=3, number of UC modules=3)

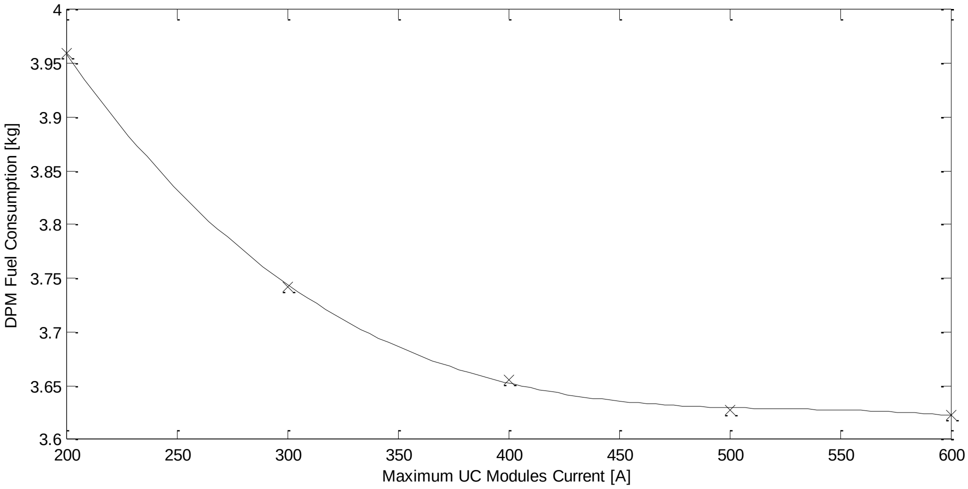

Figure 14 DPM fuel consumption results – maximum allowable UC current sweep

The DPM simulation can also be used to obtain the optimal values of parameters that have a pronounced effect on components lifespan, such as the maximum allowable ultracapacitor current. The results of such a calculation is shown in Figure 14, for the gear ratio value of 3 and 3 UC modules. By increasing the allowable absolute current levels, the fuel consumption is decreased but a compromise must be made with regard to acceptable UC lifespan.

CONCLUSION

A transit bus powertrain system has been modeled and calibrated in the AMESim simulation software environment based on data collected during a data acquisition experiment conducted on a vehicle circulating in real traffic and occupancy conditions. This calibrated model has subsequently been used to form a hybrid powertrain simulation model in AMESim with a simple, implementable control law for determining the fuel economy improvements of an ultracapacitors-based parallel hybrid electric solution. It was shown that moderate fuel reduction of approximately 16% could be achieved using a very simple control algorithm. For determining the ultimate fuel economy improvements achievable using this hybrid solution, a Dynamic Programming approach to solving the optimal control problem has been used. Using this approach, it has been determined that a fuel consumption decrease of 36% percent is the ultimate achievable goal. This approach can render making certain design decisions with regard to their effect on the fuel economy and lifespan relatively easy, such as in the case of determining the achievable fuel economy improvement with different absolute maximum values of UC currents. This data can be used to make a sound choice in the allowable current levels based on the optimal compromise between the lifespan of a component and fuel savings.

It should also be noted that a DPM algorithm is not implementable, meaning that it cannot be used on a real vehicle, due to reasons that have to do with its contingency on conditions that will be experienced in the future. That is why this approach can only be used for determining the ultimate achievable performance of a set criterion and as a reference which certain sub-optimal, implementable control laws can be compared to. Further work into this matter will include a research into the implementable control algorithms best suited for the case presented in this article..

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