# Optimal Energy Management Strategy of Plug-in Hybrid Electric Bus in Urban Conditions

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Abstract: In this paper, an energy management strategy (EMS) for a specific multi hybrid plug-in electric bus is designed. This bus is equipped with an internal combustion engine, a hydraulic motor, an electric motor and battery. Considering the physical characteristics of the studied hybrid electric bus (i.e., the system dynamics and the power sources limits), an optimal control technique based on Pontryagin's minimum principle (PMP) is used in order to ensure that the bus achieve a significant improvement in energy efficiency. Furthermore, information of traffic conditions obtained from intelligent transportation systems is used to further optimize the energy management strategy and to accurately control the battery depleting rate. The work proposed in this paper is conducted on a dedicated high-fidelity model of the hybrid bus, that was developed on MATLAB/TruckMaker software. The obtained results verify the effectiveness and validity of the developed energy management strategy.

## 1 INTRODUCTION

A hybrid vehicle uses, by definition, at least two energy sources associated with the mechanical transmission to ensure its propulsion. The advantage of the hybridization of vehicles is to overcome the two main drawbacks of internal combustion engines that are the low energy efficiency and the power irreversibility which makes the engine unable to retrieve the energy incurred during braking. Hybridization will therefore draw on the strengths of different types of engines by combining the excellent efficiency and reversibility of electric motors with the high energy density of fossil fuels which increases the energetic autonomy, limits the vehicle weight and reduces refueling time. The presence of additional power sources in the HEV introduces additional degrees of freedom in controlling the drivetrain, since at each time the driver's power request can be delivered by either one of the on-board energy sources or their combination. The additional degrees of freedom can be leveraged to reduce fuel consumption and pollutant emissions and also to optimize other possible cost such as battery life (Tang et al., 2015). This task is performed by the energy management strategy which is the highest control layer of the drivetrain's control strategy. In commercially available HEV, the energy management has been traditionally performed using heuristic controllers in which rules are designed to manage the on-board energy of the vehicle (Mashadi and Emadi, 2010) (Kamal et al., 2017). Such control strategies are effective in real-time implementation but they require a careful calibration of the parameters (Mi et al., 2011). A significant improvement with respect to such strategies is achieved with model based optimal control methods. These methods can be divided into numerical and analytical approaches. In numerical optimization methods like dynamic programming (Ximing et al., 2015), the global optimum is found numerically under the assumption of full knowledge of the future driving conditions. Unfortunately, the results obtained through dynamic programming cannot be implemented directly due to its high computational demands. To remedy this problem, approximated dynamic programming (Johannesson et al., 2007) and stochastic dynamic programming (Moura et al., 2011) (Johannesson et al., 2007) had been suggested as possible solutions. Analytical optimization methods, on the other hand, use a mathematical problem formulation to find an analytical solution that makes the obtained solution faster than the purely numerical methods. Within this category, Pontryagin's minimum principle based energy management strategy is introduced as an optimal control solution (Teng et al., 2014). This approach can only generate an optimal solution if implemented offline since in this case the

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driving cycle is supposed to be known in advance. For online implementation Equivalent Fuel Consumption Minimization (ECMS) methods that lead to suboptimal solutions have been proposed for HEVs (Volkan et al., 2011). ECMS is based on instantaneous optimization, and is simple enough to be implemented in real-time applications. Model predictive control based methods have been also applied to solve online the energy management problem (Fengjun et al., 2012). One of the main drawbacks of this approach is the high computational power required to calculate the optimal power split at each sampling interval. This paper details the development of energy management strategies to optimize the power distribution in a plug-in hybrid bus actuated by three distinct types of power (internal combustion engine, electric motor and hydraulic motor). Among the energy management strategies discussed above, Pontryagin's minimum principle based optimization turns out to be the most appropriate approach to design an energy management strategy for the considered hybrid bus since it can guarantee, under given conditions, near optimality while keeping the methodology simple. Thus, an adaptation of this optimization approach to a plug-in multi hybrid bus is proposed in this work and the obtained optimization algorithm is implemented in an overall optimization scheme in order to achieve the most efficient way of bus operation. The key contributions are firstly in formulating the optimization problem so as all the sources of power of the studied hybrid bus are considered by the optimization algorithm. Secondly, the general concepts initially presented in literature are improved by taking into account the motors dynamic limits. And finally, an overall optimization scheme based on the use of predicted optimal velocity trajectory of the bus is proposed. In fact, since the route of the bus, roads levels variations and even traffic lights are well known, prediction of optimal velocity trajectory for the trip can be carried out by means of information obtained from intelligent transportation systems (Wu et al., 2014). This available knowledge of the future driving cycle is exploited, in this latter contribution, to make the bus more efficient (even in the presence of exogenous and unpredictable events such as the traffic jam) and to ensure the desired battery depleting level. The paper is structured as follows: section 2 describes the studied hybrid bus architecture and model. Section 3 introduces the proposed energy management strategy. In section 4, several simulations results are presented showing the efficiency of the proposed energy management strategy. Finally, conclusions and some prospects are given in the last section.

# 2 MODELING OF THE HYBRID BUS

The aim of this section is to illustrate the architecture and the mathematical model of the studied system, i.e., BUSINOVA hybrid bus, developed by SAFRA (cf. Figure 1)[1]. This bus is composed of an electric motor, a hydraulic motor, an internal combustion engine and battery as the propulsion drivetrain system of the vehicle. The electric motor is a 103 $kW$ permanent magnet electrical machine from Visedo® developed especially for heavy duty applications. It has six polepairs and its nominal voltage is 500 $V$ (VISEDO, 2014). The internal combustion engine is produced by VM Motori®. It delivers a maximum torque of 340 $N.m$ at 1400 $rpm$ and its maximum produced power is 70 $kW$ (VMMotori, 2015). The hydraulic motor is a Parker® V14 series with a displacement that varies between 22 and 110 $cm^3$ (Parker, 2014).

Figure 1: BUSINOVA hybrid bus.

## 2.1 Hybrid Bus Drivetrain Architecture

The model of the studied hybrid bus is based on a series-parallel power-split hybrid architecture. A simple block diagram of the power flows on the bus is shown in Figure 2.

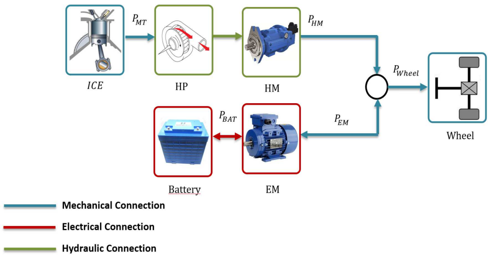

Figure 2: Block diagram of the drivetrain power flows. (ICE: internal combustion engine, HP: hydraulic pomp, HM: Hydraulic motor, EM: electric motor).

The electric and hydraulic motors are both directly connected to the transmission and can ensure simultaneously or independently the traction of the bus. On

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[1] http://www.businova.com

the other hand, the internal combustion engine is coupled to a hydraulic pump for driving the hydraulic motor and therefore allowing the engine load shifting.
The rotational speeds of the hydraulic motor and the electric motor are imposed by the wheels speed in proportion to the reduction ratios of hydraulic and electric motors respectively.
Moreover, the rotational speed $\omega_{HM}$ and the torque $T_{HM}$ of the hydraulic motor are expressed as a function of the rotational speed and the torque of the internal combustion engine as follows.

$$\begin{cases} \omega_{HM}\left(T_{ICE}, D_{HM}\right) = \dfrac{D_{HP}.\eta_{v_{HM}}.\omega_{ICE}}{D_{HM}.\eta_{v_{HP}}} & \text{(1a)} \\[2ex] T_{HM}\left(T_{ICE}, D_{HM}\right) = \dfrac{D_{HM}.\eta_{m_{HM}}.T_{ICE}}{D_{HP}.\eta_{m_{HP}}} & \text{(1b)} \end{cases}$$

where $\omega_{ICE}$, $T_{ICE}$ are respectively rotational speed and torque of the engine, and $D_{HM}$, $D_{HP}$, $\eta_{m_{HM}}$, $\eta_{m_{HP}}$, $\eta_{v_{HM}}$, $\eta_{v_{HP}}$ are respectively the displacements, mechanical efficiency and volumetric efficiency of the hydraulic motor (HM) and the hydraulic pump (HP).

## 2.2 Control Oriented Model

The amount of residual energy of the battery, commonly represented by the estimation of the battery state of charge *SOC* (Tang et al., 2015) or the battery state of energy *SOE* (Mura et al., 2015) is the main dynamic state in optimal control of HEVs. In particular, the state equation connects the variation of the battery's remaining energy to the control variable of the system. In the formulation of the energy management problem of the hybrid bus studied in this paper, the *SOE* instead of the *SOC*, is considered as the dynamic state $x(t)$. There are several advantages of using the estimated *SOE* to represent the battery residual energy. Indeed, the energy loss on the internal resistance, the electrochemical reactions and the decrease of the battery voltage are considered in the *SOE* estimation (Xingtao et al., 2014). Based on the previous assumption of using estimated *SOE* to represent the battery residual energy, the control oriented model can be represented by:

$$\dot{x}(t) = f\left(x(t),\, u(t),\, w(t)\right) \tag{2}$$

where

$$x(t) = SOE(t),\; u(t) = \begin{bmatrix} T_{HM} \\ \omega_{HM} \end{bmatrix},\; w(t) = \begin{bmatrix} T_{wheel} \\ \omega_{wheel} \end{bmatrix} \tag{3}$$

$u(t)$ is the control input and $w(t)$ is an exogenous input.

The above model can be rewritten as follows.

$$\dot{x}(t) = \frac{d\ SOE\,(t)}{dt} = -\frac{P_{BAT}}{E_{max}} = -\frac{P_{EM}}{\eta E_{max}} \tag{4}$$

Depending on whether the battery is in discharging phase ($\dot{SOE} \leq 0$) or in charging phase ($\dot{SOE} \geq 0$), $\eta$ is defined as follows (Tremblay et al., 2007):

$$\eta = \begin{cases} \eta_{BAT} & \text{in discharging phase} \\ 1/\eta_{BAT} & \text{in charging phase} \end{cases} \tag{5}$$

Equation (4) is obtained from the battery internal resistance model (Tremblay et al., 2007). In this equation, $E_{max}$ is the maximum energy that can be stored in the battery, $\eta_{BAT}$ is the efficiency of the battery, $P_{BAT}$ is the power delivred by the battery and $P_{EM}$ is the power consumed by the electric motor to produce torque $T_{EM}$ at speed $\omega_{EM}$.

## 3 ENERGY MANAGEMENT STRATEGY

The following section details the design procedure of the proposed energy management strategy, which aims to decide how to split the driver's demanded power between the different power sources of the hybrid drivetrain. This should allow to optimize the selected criterion without sacrificing the bus drivability. The optimal control problem formulation is firstly presented and then the analytical expression of the proposed solution is described. These power management strategy is based on Pontryagin's minimum principle.

### 3.1 Optimal Control Problem Formulation

Since our primary goal is to minimize the energy consumption of the bus, the energy management problem is formulated as an optimal control problem. The objective is to find, at each sample time, the optimal value of the control input that minimizes a cost function representing the power consumption of the drivetrain. This minimization of the cost function must be done under a certain number of constraints. In fact, the drivetrain components dimensioning imposes minimum and maximum limits on the exchanged powers. These limits form the following constraints:

- The internal combustion engine and electric motor have limited operating ranges. Therefore, provided or absorbed torques must be comprised between minimum and maximum limits.

$$T_{EM}^{min} \leq T_{EM}\ (t) \leq T_{EM}^{max} \tag{6}$$

$$T_{HM}^{min}\left(T_{ICE}^{min}, D_{HM}\right) \leq T_{HM} \leq T_{HM}^{max}\left(T_{ICE}^{max}, D_{HM}\right) \tag{7}$$

The maximum and minimum torque limits of the internal combustion engine and electric motor vary according to the variation of the system's operating point (torque-speed). Look-up tables are therefore used to determine their values at each time.

- The instantaneous power demand of the drivetrain should always be satisfied, which results in,

  $$\rho_1 T_{HM}(T_{ICE}, D_{HM}) + \rho_2 T_{EM}(t) - T_{wheel}(t) = 0 \tag{8}$$

  where $\rho_1$ and $\rho_2$ are the gearbox' reduction ratios of hydraulic and electric motors respectively. The total torque at the wheels is equal to the sum of the torques delivered by each of the motors proportionally to the reduction ratios.

Compared with energy management problem formulation for charge sustaining HEV (Mura et al., 2015), there is no sustainability constraint on the final *SOE* for plug-in HEV allowing the charge depleting operation. Thus, the energy consumed on the entire cycle does not come exclusively from the fuel since most of the available electrical energy is supplied from the grid. This implies that the cost function must take into account all the energy sources used to ensure the traction of the bus. This is why the cost function $J$ to be minimized over the time interval $[t_i,\ t_f]$ is defined based on the total electric and fuel energy consumed by the vehicle as follows.

$$J = \int_{ti}^{tf} P_F\left(u(t)\right) + P_{BAT}\left(u(t)\right) dt \tag{9}$$

where $P_F$ is the instantaneous power of the fuel (engine power input). As in several other papers dealing with this topic (Mura et al., 2015), it is expressed in terms of the fuel flow rate $\dot{m}_f$ and the lower heating value of the fuel ($Q_{LHV} = 43MJ/kg$) using the formulation given in equation (10).

$$P_F\left(\ u(t)\right) = \dot{m}_f\left(u(t)\right)\ Q_{LHV} \tag{10}$$

The control variables ($T_{HM}$ and $\omega_{HM}$) are linked together trough the hydraulic motor dynamics, therefore, there can only be one target control value at a time. In this paper, we have chosen to leave the rotation speed free so that it will be imposed by the wheels speed. The hydraulic motor torque is thus the only remaining control variable that can be used to decide how to split the driver's demanded power.

The optimization problem is then to find the hydraulic torque that should be provided at every sample time in order to minimize the total energy consumed while checking the constraints thus mentioned above (cf. equations (6) to (8)). To these constraints it is added a new constraint (11) which aims to limit the admissible control region in order to take into account the limits of the hydraulic motor dynamics and consequently taking into account the limits of the internal combustion engine dynamics.

$$\frac{dT_{HM}}{dt} - \xi \geq 0 \tag{11}$$

with $\xi$ is the maximum hydraulic torque variation measured over a short period of time.

To introduce constraints in the optimization problem, these are transformed into equality constraints. The constraint (11) can be rewritten as follows (Wang and Wah, 1998).

$$\frac{dT_{HM}}{dt} - \xi - \dot{\varepsilon}^2 = 0 \tag{12}$$

where $\varepsilon$ is a slack variable.

By using equation (8), it is possible to rewrite the constraints (6) and (7) as a single constraint on the control variable as follows.

$$\tilde{T}_{HM}^{min}\left(T_{HM}^{min}, T_{EM}^{max}\right) \leq T_{HM} \leq \tilde{T}_{HM}^{max}\left(T_{HM}^{max}, T_{EM}^{min}\right) \tag{13}$$

with

$$\tilde{T}_{HM}^{min} = \max(\rho_1.T_{HM}^{min}, T_{wheel} - \rho_2.T_{EM}^{max}) \tag{14}$$

$$\tilde{T}_{HM}^{max} = \max(\rho_1.T_{HM}^{max}, T_{wheel} - \rho_2.T_{EM}^{min}) \tag{15}$$

It means that when the torque applied to the wheel is too significant to be only produced by the electric motor, the $\tilde{T}_{HM}^{min}$ limit imposes a minimum torque on the hydraulic motor. Additionally, $\tilde{T}_{HM}^{max}$ limit prevents the electric motor torque set-point to become less than $T_{EM}^{min}$.

Finally, using a $2^{nd}$ order approximation, the constraint (13) is written as the equivalent form given by (16),

$$-T_{HM}^2 + \alpha T_{HM} + \beta = 0 \tag{16}$$

with

$$\alpha = \tilde{T}_{HM}^{max} - \tilde{T}_{HM}^{min} \tag{17}$$

$$\beta = \tilde{T}_{HM}^{max}\ .\ \tilde{T}_{HM}^{min} \tag{18}$$

### 3.2 Energy Management Algorithm

With the optimization problem fully defined, Pontryagin's minimum principle can be used to give numerical solution. According to Pontryagin's minimum principle, minimizing the cost function given in (9) is equivalent to minimizing the Hamiltonian function $H$ of the system at each instant of time.

$$H\left(x(t),\,u(t),\,\lambda(t)\right) = P_F\left(\rho_1 T_{HM}(t),\frac{1}{\rho_1}\omega_{HM}(t)\right) - \left(\frac{\lambda(t)}{\eta E_{max}}-1\right) P_{ME}\left(\rho_2 T_{EM}(t),\,\frac{1}{\rho_2}\omega_{EM}(t)\right) \tag{19}$$

where $\lambda(t)$ is the costate (or the Langrange multiplier).

For the considered energy management problem, an extended Hamiltonian function is defined to account for the constraint (12) and (16). The additional terms are introduced using a new Lagrange multiplyers (i.e., $\gamma(t)$ et $\sigma(t)$ respectively).

$$H\left(x(t),\,u(t),\,\lambda(t),\,\gamma(t),\,\sigma(t)\right) = P_F\left(\rho_1 T_{HM}(t),\frac{1}{\rho_1}\omega_{HM}(t)\right) - \left(\frac{\lambda(t)}{\eta E_{max}}-1\right) P_{ME}\left(\rho_2 T_{EM}(t),\,\frac{1}{\rho_2}\omega_{EM}(t)\right) + \gamma(t)\left(-T_{HM}^2+\alpha T_{HM}+\beta\right) + \sigma(t)\left(\frac{dT_{HM}}{dt}-\xi\right)^2 \tag{20}$$

The optimal control law which minimize the Hamiltonian $H$ must satisfy the following necessary conditions for optimality:

$$\frac{\partial H(t)}{\partial u(t)} = \frac{\partial H(t)}{\partial T_{HM}(t)} = 0 \tag{21}$$

$$-\frac{\partial H(t)}{\partial x(t)} = -\frac{\partial H(t)}{\partial SOE(t)} = \dot{\lambda}^*(t) \tag{22}$$

$$\frac{\partial H(t)}{\partial \lambda(t)} = \dot{x}^*(t) \tag{23}$$

$$\frac{\partial H(t)}{\partial \gamma(t)} = -T_{HM}^2 + \alpha T_{HM} + \beta = 0 \tag{24}$$

$$\frac{\partial H(t)}{\partial \sigma(t)} = \left(\frac{dT_{HM}}{dt}-\xi\right)^2 = \dot{\varepsilon} \tag{25}$$

The costate $\lambda$ is determined by the condition (23).

While taking into account the battery discharge characteristics shown in Figure 4, it is clear that battery voltage is relatively independent on the battery state of energy *SOE* and thus the power consumed by the electric motor $P_{EM}(t)$ is also independent on the battery *SOE* (Kirk, 2012) (Lino and Sciarretta, 2007). Under this assumption, it is straightforward to consider that the costate $\lambda$ is a constant value during the entire driving cycle since the derivative of the Hamiltonian function $H$ in (23) is null in this case.

The condition (21) determines the optimal control trajectory $T_{HM}^*(t)$. If this necessary condition is satisfied, then the optimal hydraulic torque $T_{HM}^*(t)$ must be given by equation (26).

$$T_{HM}^*(t) = \arg\min_{T_{HM}\in U} H\left(SOE(t),T_{HM}(t),\lambda(t)\right) \tag{26}$$

where $U$ is defined as the admissible control set.

After the hydraulic motor torque is obtained, the internal combustion engine torque and speed are calculated according to the desired speed and torque of the hydraulic motor. Thanks to the displacement tuning capability of the hydraulic motor, the internal combustion engine load can be shifted freely to operate this latter close to its maximum efficiency curve. Especially in this case, the speed of the internal combustion engine is not imposed by the wheels speed and it can be set to a nearly constant value where the engine is the most efficient. To reach this goal, the displacement of the hydraulic motor is controlled online by using equation (1a). Thereafter, the engine torque is calculated as a function of the displacement and the optimal torque of the hydraulic motor by using equation (1b).

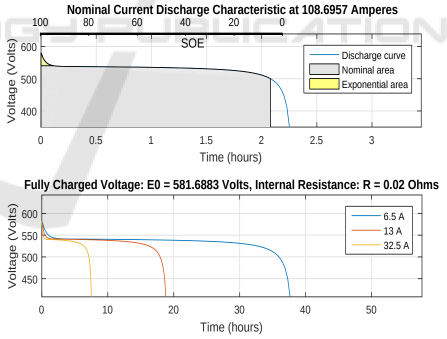


Figure 3: Discharge characteristics of the used battery.

The energy management strategy could have greater potential for power savings if an optimal speed profile is predicted for each trip of the bus based on the actual driving conditions. Indeed, buses run on the same route every day, stop invariably at similar locations and they could even have some dedicated lanes of the road in some cities which facilitates driving conditions prediction compared to other type of vehicles. Therefore, several studies have been conducted to optimize bus speed profiles (Dib et al., 2014). With this approach in mind and to further improve the energy management strategy proposed in this paper, a control scheme that uses the information on the optimal speed profile is proposed in order to configure the energy management algorithm developed previously. Therefore, the optimal speed profile is first determined by using a dedicated speed profile optimization algorithm based on a predictive intelligent control (Gunter et al., 2016). Thereafter, at the beginning of each new trip of the bus, the obtained optimal speed profile is utilized to search iteratively, using a shooting search method (Serrao et al., 2011), the value of the costate $\lambda$ that generates the correct final $SOE_f$ at the end of the daily duty time of the bus. In fact, for a given driving cycle there exists only one value of the costate for which the solution that minimizes the Hamiltonian $H$ at each sample time is also the one that satisfies the terminal condition on the final value of $SOE$. This corresponds to the global optimal solution of the problem. The obtained overall energy management scheme is illustrated in Figure 4. As stated before, the choice of the costate value must be made to ensure, in each trip of the bus, a charge-depleting rate which allows to reach desired final $SOE_f$ at the end of a full day driving period. In this paper, it is considered that the initial value of $SOE$ is 90% and the desired final value of $SOE$ after eight hours of driving is 17%. The working hypothesis behind this assumption is to use the maximum amount of energy that can be consumed from the battery in one day driving.

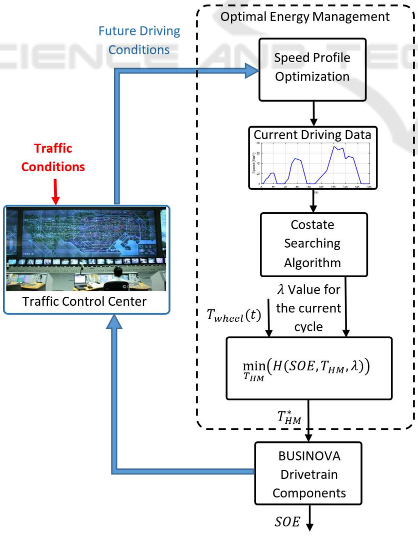


Figure 4: Block diagram of the proposed power management strategy.

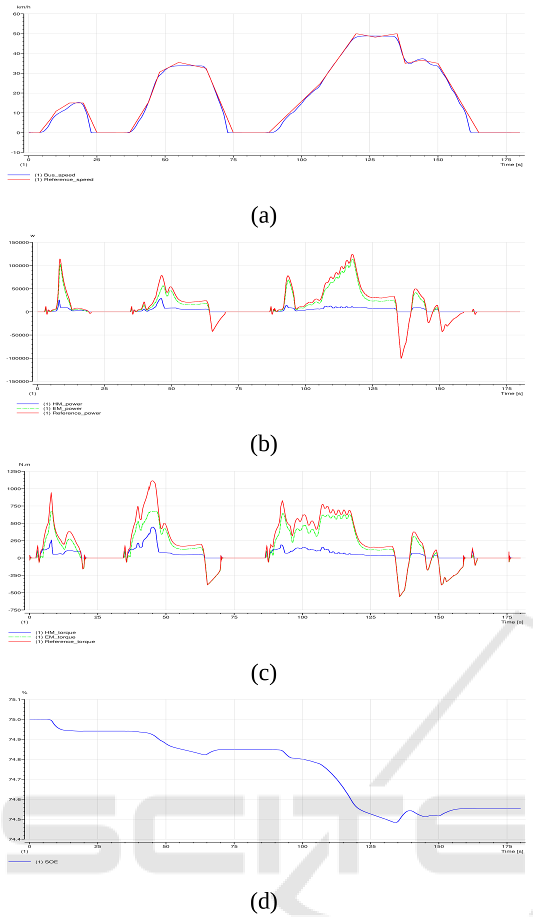
## 4 SIMULATION RESULTS

The implementation of the proposed energy management strategy is carried out using a dedicated high-fidelity model of the hybrid bus, that was developed on Matlab/TruckMaker software (cf. Figure 5), in order to investigate their performance in a test platform which reproduces accurately the real operating behavior of the bus.

Figure 5: TruckMaker test platform.

Figure 6 shows the overall simulation results of the proposed energy management strategy over an optimized driving cycle which represents different usage conditions of the studied hybrid electric bus including urban and extraurban driving environments. The video showing this overall demonstration using TruckMaker is available from this link: https://goo.gl/8mJT3s.

Figure 6(a) gives an outline of the desired speed and the actual bus speed when the designed optimization algorithm is applied to calculate the optimal power split. As one can observe in this figure, the bus speed follows the reference speed curve with only a small tracking error. This observed speed tracking error is due to the important response time of the motors. The contribution of the fuel energy and the electric energy to the total power and torque at the wheels is illustrated in Figure 6(b) and 6(c) respectively. The $SOE$ profile is also illustrated in Figure 6(d). According to Figure 6 (b), it is shown that the distribution of the power demand between the electric motor and the hydraulic motor is correctly assured and the required power at the wheels is totally satisfied over the entire driving cycle. The dynamic limits of the motors defined during the synthesis of the energy management strategy are also respected as can be seen in these figures. Since the driving cycle is known in prior, the proposed energy management strategy finds the optimal power split which operates the engine around its maximum efficiency curve to minimize the power consumption of the drivetrain. The fluctuation range of the power delivered by the engine is directly related to the amount of electric energy available for electric assist and it allows to always satisfy the constraints of the final $SOE$ of the battery. A battery discharge of 0.45% is observed at the end of the driving cycle sim-



(a)

(b)

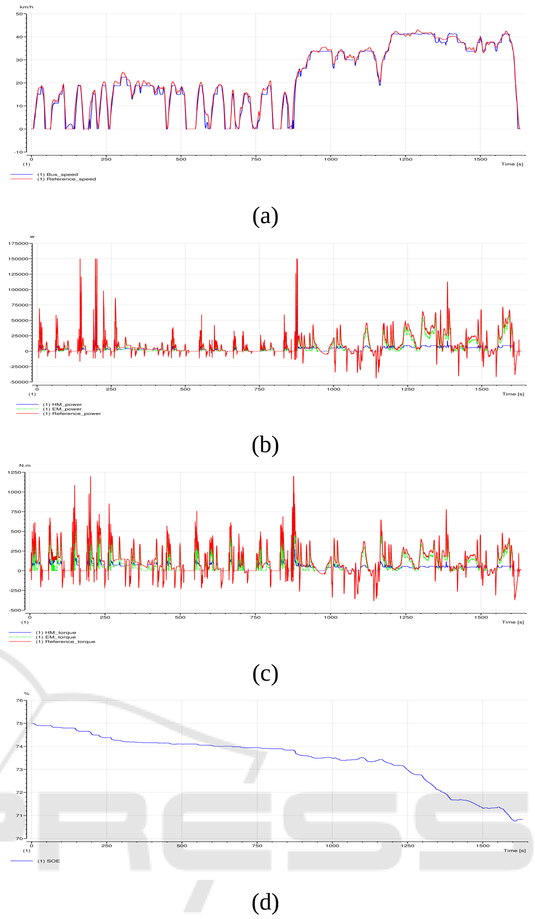
(c)

(d)

Figure 6: Simulation results of the proposed energy management strategy: (a) driving cycle, (b) power distribution profile, (c) torque distribution profile, (d) *SOE* profile.

ulated in this test, which corresponds, by extrapolation, to a discharge from 90% to 17% after 8 hours driving period. Otherwise, the energy management strategy doesn't use the engine to charge the battery, because its efficiency is too low and thus recharging the battery using fuel energy is not cost-effective.

deepen the analysis under more realistic and exhaustive test conditions, the proposed energy management algorithm is evaluated over the FTP-75 (Federal Test Procedure) normalized driving cycle. This cycle includes acceleration and deceleration phases in urban and suburban environments. It thus constitutes an interesting study support for evaluating the performance of the energy management strategy in the different phases of operation of the real hybrid bus. The results obtained from this test are presented in Figure 7.



(a)

(b)

(c)

(d)

Figure 7: Simulation results of the energy management algorithm on the FTP-75 driving cycle: (a) driving cycle, (b) power distribution profile, (c) torque distribution profile, (d) *SOE* profile.

# 5 CONCLUSION

An optimal energy management strategy, based on Pontryagin's minimum principle, is designed in this paper for a a plug-in multi hybrid bus. The proposed approach combines the system's dynamical equations with the control objectives formulated in the form of a cost function and constraints to determine at each instant the optimal value of the control variable which minimizes the power consumption of the hybrid bus. Furthermore, based on the characteristics of the studied urban bus, which runs generally on the same routes, the energy management strategy is further improved by searching the optimal driving cycle for each bus trip while using the available traffic information. The final battery SOE level is also controlled by selecting an appropriate value of the costate at each time the bus starts a new lap. The validation tests results show that the proposed optimization approach can ensure optimal operation for the hybrid bus while having the advantage of being very simple to implement in practice thanks to its high computational efficiency. Nonetheless, to achieve this performance level, good accuracy for estimating road traffic conditions is required. In future works, additional optimization criterion such as: reduction of battery aging and pollutant emissions will be added to the already existing optimal control algorithm. The tradeoff between the different optimization criteria will be investigated in order to achieve the most efficient drivetrain operation.

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