A Model Based approach for the analysis and simulation of an Hybrid Bus in a Urban Context

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Abstract: In recent years, environmental protection has become a goal shared by policymakers, governments, private companies and citizens. The large number of policies, such as the plan 20-20-20, and companies seeking to reduce emissions and energy consumption confirm this growing interest. Energy management becomes really important in hybrid electric vehicles to reduce pollutant emissions and minimize fuel consumption. Hybrid technology applied to urban transport increases in recent years due to the introduction of urban legislation, which include restricted traffic zones in the city center or restrictions on vehicle engine emissions. In this paper a numerical model, realized in *Matlab Simulink*, is presented. The model takes into account all the elements necessary to reproduce the behavior of a Hybrid Bus. The objective is to implement a control strategy to partialize the energy sources so as guarantee propulsion and operation of vehicle's auxiliary systems. We realized the control using *if-then* rules, considering the dynamic of every single component of the vehicle.

Keywords: model based simulation, hybrid vehicles, public transportation, battery model, power management

1 Introduction

The development of policies, aimed at promoting more clean forms of mobility in urban areas, is opening the road to unconventional transport systems, such as electrical and hybrid vehicles. If purely electric transport provides benefits in terms of emissions and pollutants, it still has some limitations that make it ineffective in these policies. For this reason hybrid vehicles are a viable alternative to conventional transport. Buses for urban transport are particularly suited to introduce hybrid vehicles, as they are used to make predetermined paths, at moderate speed, with frequent stops and starts. Another advantage is that buses have higher volumes at their disposal, compared to a classic passenger car. In fact, from a technological and practical point of view, a strong limitation to the development of hybrid and electric vehicles is represented by the large dimensions of the storage devices and the energy storage able to meet the operational energy requirements [Lajunen, 2014],[Geng et al., 2013],[Yu et al., 2016], On the one hand they have the same autonomy of thermal solutions, on the other they offer the advantage of being able to go in purely electric mode for short paths, where it is required by mobility policies. As a consequence of the exploitation of an existing architecture, the purpose of the work is not related to the design of a new vehicle architecture, but to the management of the vehicle: the aim is to develop an efficient way of exploiting the power available from both the motor and the engine. In the analysis of an hybrid urban bus, fulfilling *Euro VI* standards, is considered and the performance evaluation is based on an approximation of the *European Transient Cycle (ETC)* and the *Braunschweig City Driving Cycle*[Barlow et al., 2009].

The problem is addressed by means of an approach that can be defined as static. The focus will be on the optimization of the battery considered as a tool for the power supply of the system and for the propulsion of the vehicle in purely electric mode, for short distance journey. We therefore face an energy management problem: a strategy to define the best way to exploit the power produced by the combustion engine and by the electric motor during the normal vehicle operations is proposed. The problem is formalized in an analytical way, for understanding and highlighting the relationships between the different components of the system, but solved using an heuristic approach that leads to the definition of control laws based on "*if-then*" statements and Boolean logic.

2 Hybrid Electric Vehicle: an overview from battery point of view

For the aim of this paper an hybrid series architecture has been considered: the main features are described in figure 5, where the energy balance in the key nodes is pointed out.[Silvas et al., 2017],[Panday and Bansal, 2014], [Shen et al., 2011]. In this kind of vehicle the Internal Combustion Engine (ICE) is directly coupled with the electric generator: in such a way decoupling the mechanical axle of the ICE from the traction wheels can increase the global efficiency of the vehicle. If needed, it is possible to provide electric mode traction for short journeys. The key point becomes the energy storage system, that must be sized to achieve all the power requested by every single component installed on board. The interface between ICE, electric motor and energy storage system is provided by a power electronic unit on which energy management strategies can be implemented. In a hybrid vehicle, the battery energy capacity must be kept at a certain level, to ensure the power required to accelerate and, at the same time, accept energy from regenerative braking. This is one of the key points, since the thermal part of the hybrid vehicle is designed and controlled to work at steady state condition that is selected in order to minimize emissions. Any acceleration, or pure electric traction, is governed by the battery. At the same time, the battery may not be too charged, because in that case it would be difficult to take advantage of the contribution of regenerative braking.
Another feature is the ability to use the vehicle in pure electric mode: when the battery is fully charged the internal combustion engine could be turned off or put in standby; as soon as battery capacity falls below a predefined level the ICE is switched on and should provide the pulling power and, if possible, also the battery energy. This specific behavior is governed by the control strategy implemented in the energy management system, which

receives information from the vehicle and battery management system.
In this work a lithium polymer battery is considered, where the lithium-salt electrolyte is in an organic solvent [Veneri et al., 2012]. For the battery a dynamic model is considered, as shown in figure 2, where the open circuit voltages (V_s), the resistances (R), and capacitors (C), were modeled as functions of State Of Charge (SOC) of the battery and of number of cycles (n) ([Gruosso and Ramacciotti, 2014],[Bolzoni et al., 2015],[Gruosso, 2015]), as shown by the following equations:

$$R_j = f_1(SOC, n) \tag{1}$$
$$C_j = f_2(SOC, n) \tag{2}$$
$$V_{sj} = f_3(SOC, n) \tag{3}$$

The main parameters and functions related to the battery are based on the previous works of [Veneri et al., 2012] [Veneri et al., 2016] .

The energy management is , at this point, carried out through a logic implemented on the Vehicle Management Unit (VMU), which is responsible for the elaboration of the state information coming from the batteries by the Battery Management System (BMS). This logic defines the behavior of every single component as the ICE, electric motor, the battery pack and coordinates them in order to obtain the required performances. The basic functions of the VMU can be summarized as:

- exchange information between driver and vehicle;
- determine drive performance;
- monitor and control the power flow for optimizing the energy consumption and availability.

The purpose of this work is to define, through model-based design, techniques for the correct functioning of the VMU. These logics implemented through high-level software, will then be encoded with automatic code generation tools to be deployed in the control unit of the buses[Reeves et al., 2016].

3 Power management control: objective function

As stated before the series hybrid is a system where ICE and battery both supply the propulsion. These two sources are different and need to be merged in order to manage in a correct way the amount of required energy, obtaining the maximum efficiency. In this paper the energy optimization is considered as an open loop problem, in which the input signal (power request), that has to follow a desired trajectory (defined by vehicle speed), is known. The problem can be formalized by means of control variables that define the operation mode and thus the correct mix of the two supply systems. The implementation of the algorithm starts from the the characteristics of the vehicle and of the main components (the battery, electrical motors , etc.), in order to define the the energy balance equation written as:

$$P_t(t) = \alpha(t)P_{batt}(t) + \beta(t)P_{ICE}(t) - P_{aux}(t) \tag{4}$$

where P_{aux} is the power requested by auxiliary systems, P_{batt} and P_{ICE} are the available power from battery and internal combustion engine and P_t is the traction power. The previous relation can be simplified as follows:

$$P_{req}(t) = \alpha(t)P_{batt}(t) + \beta(t)P_{ICE}(t) \tag{5}$$

bringing together P_T and P_{aux}, and defining the requested power P_{req}

In this paper, whose aim is to present the general methodology, the auxiliary power is not considered even if in general it is not negligible, especially in the case of urban transport where the air conditioning plays a non-secondary role on consumption. The battery power and the internal combustion engine power will be detailed in the following.
The energy in the battery can be considered as the state variable that describes the behavior of the system: knowing battery capacity and maximum input and output power it is possible to estimate if it is able to provide or receive power. This determines the value of parameter α, that is positive when generate and negative during charging. It is worth noting the battery capacity depends on the number of charging cycles, as show in figure 5: this is an important effect that has to be taken into account, especially if micro charging cycles are considered. The ICE power source can operate at its maximum efficiency, reducing emissions and fuel consumption. In this paper a range in which the ICE works always at his maximum efficiency is considered: this effect is described by parameter β that govern the ICE behavior defining when it has to provide power, or has to be switched off. The previous problem can be resolved by means of optimization procedure [Schouten et al., 2003], but in order to evaluate the performance of the vehicle an *"if-then"* rule has been considered. Defining all the energy flows in the vehicle a strategy to manage energy sources obtaining maximum efficiency is devised. This allows to better identify the different modalities implementable on a hybrid vehicle. The last term of the equation is the requested power that is defined by simulation on the two different driving cycles. The key idea of the control strategy that internal combustion engine is used to the minimum fuel consumption and pollutant emission. In the following the procedure will be described.

4 Modeling and Simulation

In this section a quasi static model of the hybrid bus which aims to analyze the energy flow management, focusing the attention on the variation of requested and available power during a normal operating cycle of a urban bus [Hofman and van Leeuwen, 2009] and [Yu et al., 2016], is described. The aim of the paper is modelling the vehicle in order to study new control algorithm. At this stage the control in an open loop control, and more work has to be done in order to cope with actual vehicle strategy. The model can be used as framework for future works. In the quasi static simulation the input variables are the speed, the acceleration of the vehicle, and the angle that describes the slope of the road. With this information it is possible to calculate the force for traction as the force required by the driving wheels of a vehicle to perform a given path. In this first phase, the vehicle is described by its basic parameters and the simulation is performed for a reduced time interval. Once obtained the force we proceed with the formulation of an energy balance equation of the required power and the losses of the entire system and proceed to the simulation for longer time intervals. The complete model is presented in figure 4.

4.1 Driving Cycle

The first block of the model is the *Driving Cycle*, which describes the speed of the vehicle in a specific road condition during a fixed period of time. The considered driving cycles are the European standards defined for an urban bus:

- Braunschweig City Driving Cycle;

- European Transient Cycle (ETC).

The *Braunschweig City Driving Cycle* was developed at the Technical University of Braunschweig. It is a transient driving schedule simulating urban bus driving with frequent stops. This cycle has been frequently used in various research projects, for example in [Barlow et al., 2009], as well as for some equipment certification programs. With the introduction of ETC cycle, the importance of the Braunschweig cycle has decreased. The *European Transient Cycle* has been introduced in 2000 and developed by the former FIGE Institute, Aachen, Germany, based on real road cycle measurements of heavy duty vehicles. Compared to Braunschweig City Driving Cycle it consists of three different parts(The duration of the entire cycle is 1800s. The duration of each part is 600s):

- part one represents city driving with a maximum speed of 50 km/h, frequent starts, stops, and idling;
- part two is rural driving starting with a steep acceleration segment. The average speed is about 72 km/h;
- part three is motorway driving with average speed of about 88 km/h.

4.2 Vehicle

The vehicle block, receiving speed and acceleration from the driving cycle, produces wheel angular speed, angular acceleration and torque, considering the longitudinal dynamics of the urban bus. We assumes that the energy produced by ICE, is temporarily stored in the vehicle and that the resistant forces to absorb energy from such reserve. This approach is useful when will have to distinguish between the different effects taking place within the system. Generally, energy in the vehicle is stored in two different form: kinetic and potential energy. On the other hand, the quantity of mechanical energy requested by a vehicle that has to follow a path, depends on:

- aerodynamic resistance loss;
- rolling resistance loss;
- breaking energy loss.

Starting from these considerations the equation that describes the dynamic behavior of the vehicle becomes:

$$m_v \frac{d}{dt} v(t) = F_t(t) - (F_a(t) + F_r(t) + F_g(t) + F_d(t)) \tag{6}$$

where F_a is the aerodynamic resistance, F_r is the rolling resistance, F_g is the resistance due to the gravity force, F_d is the sum of disturbances and forces not considered in the previous elements. The traction force, F_t, is the force produced by the propulsion system and does not consider the force used to accelerate rotational elements and resistive losses of the cinematic chain. In this paper only aerodynamic forces, rolling resistance forces and inertial forces has been considered:

$$F_t(t) = F_a(t) + F_r(t) + F_{in}(t) \tag{7}$$

The aerodynamic resistance can be evaluated considering the bus as a prismatic body with a frontal area A_f as follows:

$$F_a(v) = \frac{1}{2}\rho_a A_f c_d(v, ...)v^2 \tag{8}$$

where v is vehicle speed, ρ_a is air density and $c_d(v,...)$ is a parameter determined experimentally that describes the aerodynamic resistance. Rolling resistance is typically modeled by the equation:

$$F_r(v, p, ...) = c_r(v, p, ...)m_v g \tag{9}$$

where v, p are vehicle speed and pressure between tires and road respectively, m_v is vehicle mass, g gravity acceleration and $c_r(v,p,...)$ is the rolling resistance coefficient that is experimentally evaluated.
The last term of the equation is the inertial force of the vehicle and of all the rolling elements that generate forces. In this pages we consider only vehicle inertia and wheel inertia.

$$F_{in} = (m_v a) + (m_w a \frac{\rho_w^2}{r_w}) \tag{10}$$

where m_w, r_w, ρ_w, are: mass, inertia and radius of gyration of the wheel. The simulink model of vehicle is represented in figure 7.

4.3 Transmission

In motor vehicles transmission adapts the output of the internal combustion engine to the wheels. In particular receives a certain angular speed ω_1 and torque T_1 from a source and output a different angular speed ω_2 and torque T_2 to the user, as follows

$$\omega_1 = \gamma\omega_2 \tag{11}$$

$$T_2 = \gamma T_1 \tag{12}$$

where γ defines the gear ratio.
To simplify the model and the simulation we consider the transmission as an ideal transformer can be seen as an interface between a source and a load, with a perfect coupling and zero power losses.

4.4 Propulsion systems

For the two propulsion systems simplified models that consider losses and that are able to determine requested and available power have been implemented. The primary power source is composed by the internal combustion engine, the transmission and the electric generator.
On the other hand, the electric motor it is the element that must provide always the traction power because it is directly connected to the traction wheels. The power of the electric motor is exactly the product of wheel angular speed and traction torque.
The battery has been considered as a system that can receive energy from regenerative breaking and give energy to the whole system, considering traction and auxiliary system. Knowing battery capacity the simulation determines how it changes during normal operating conditions of the urban bus. The battery system control checks battery characteristics, as state of charge and health state, and defines strategies considering requested and available power.

4.5 Power management Strategy

The power management Strategy in this case is a deterministic structure, based on a state machine. It is ruled by simple condition transitions that shift the operation points of the vehicle components, and it is based on five states starting from the initial state, Engine Start-Up. After that, if the battery SOC is above the lower boundary and the driver requires both low speed and torque, the state is shifted to Electric Mode. Translating to Engine Mode, it is necessary that the SOC be above the minimum limit with moderate speed and torque or if the SOC is bellow the minimum with high speed and torque requirement. The Hybrid Mode is called when the SOC is above the minimum limit with high speed and torque or if the SOC is bellow the minimum with low or moderate speed and torque requirement. Finally, the Regenerative Braking Mode is activate only when the torque demand is negative. More states can be implemented, of course, as in, the transitions are conditioned by hard accelerations/decelerations, sensing the throttle and brake pedals position. But the idea of this paper is to focus on the model of vehicle and not on the Power management strategy, so the simplest if-then rule is used for the simulations, as shown in table 1.

Here, 45 km/h has been considered the boundary between low and medium speed, while 75 km/h between medium and high speeds. The lower limit of the battery SOC SOC_{min} has been set to 40. The driver's power demand P_{dem} is obtained by imposing the driving cycle speed requirement in the previous model, and the maximum engine power allowed at the current speed $P_{ice}^{max}(\omega_{ice})$ is obtained from torque-speed relationships. It is quite forward to understand the algorithm logic. At low speed, the electric motor is used, mostly because the ICE is inefficient at this region, but it happens only if the SOC is above the lower limit, in order not to deplete the battery. Above the low-medium speed threshold, the engine kicks in and provides all the needed power. At sudden accelerations, e.g. during over-takes, that happens mostly at high speeds, the electric motor supplies the gap between the power demand and the maximum engine power at its operation speed. Charging occurs when the SOC level falls under the lower limit or during regenerative braking, i.e. negative power variation demand. When charging at low/medium speed, using the ICE to charge the battery can be inefficient, but at high speed it is not - that is why the Charging state is subdivide in two. Charging with the engine on happens at high speed and the ICE efficiency does decrease considerable to run the generator. At low/medium speed, the generator tries to compensate the electrical energy consumption of the electric motor. The generator spins thanks to the planetary gear train speed relationship and provides, in this case, current flowing into the battery, while the electric motor drains battery current. The algorithm is clearly limited, once it does not cover all the conditions possibilities, such as sudden accelerations at medium speeds assisted by the electric motor - with the outline proposed, the ICE needs to supply the gap, probably falling into a highly inefficient region.

5 Simulation results

The first step is the definition of the power requested by the vehicle. We have considered two different driving cycles, *Braunschweig City Driving Cycle* and *European Transient Cycle*. Power request profiles are shown in figure 8 and 9. The main difference between figures 8 and 9 is that the first one presents more peak power due to more accelerations and stops. In figure 9 power increases as a function of the path in which bus is operating. In *Braunschweig City Driving Cycle* we consider the possibility to work the most of time in electric mode. The first hypothesy we make is that battery pack could be used until its state of charge is greater than 20%. Considering the possibility to charge the battery on board, and that it could receive constant power from the ICE, we simulate the system to study the real limitations of the battery. To show a complete charge and discharge cycle we duplicate the driving cycle. Figure 10 shows the behaviour of battery state of charge the same driving cycle when the number of charge and discharge cycles grows. There are represented seven different curves after the 1st, the 501st, the 1001st, the 1501st, the 2001st, the 2501st and the 5001st charge and discharge cycle.

Another interesting point is the decreasing of relative battery capacity when the number of charge discharge cycles grows. This produces a right shift of battery state of charge and thus a reduction of electric mode of the urban bus. The performance reduction after 5001 cycles is around 15%, this is a technological interesting result considering typical performances of batteries.

Starting from this simulation we propose another scenario in which battery pack is subjected to micro-cycles, from 100% to 80% of its SOC. This is a new technical solution that can provide a longer battery life although we do not have precise experimental and technical information. In this case it is possible to provide fast battery charge without reducing battery life, because we are not discharging completely the battery pack. In this simulation we consider normal *Braunschweig City Driving Cycle*.

In figure 12 we can see that until relative battery capacity is in the order of 95% of initial capacity, battery can complete the driving cycle with four charge and discharge cycles, but when capacity decreases to 80% it needs around six cycles. The results obtained in this simulation can provide interesting considerations on the use of battery for traction in a vehicle where it is not installed to provide this feature. The simulation on this driving cycle can not determine if it is more useful to work exclusively in electric mode or continue working hybrid. In this particular situation, however, it is possible to accepts a certain driving period in zero emission modality.

Considering the same strategy, a simulation for the *European Transient Cycle* has been also performed. This driving cycle is composed by three different parts, the interesting solution is to provide traction power by the battery in urban driving conditions. Even in this case the simulation has been realized considering two different kinds of recharge: a fast one and a normal one. Figure 14 shows that battery characteristics allow pure electric mode for urban driving, and considering fast charge modality, the battery can be completely recharged by the internal combustion engine in suburban driving(600-1200 s). Thus battery becomes useful to assist internal combustion engine and supply power peak in motorway driving, to mantain ICE always its maximum efficiency range.

The other simulation is realized considering normal charge, so providing less constant power from ICE to charge the battery(figure 15).

Urban driving is still realized in pure electric mode, although battery is not completely recharged in suburban driving, and in motorway driving, where power request is higher and the internal combustion engine does not succed in providing traction and recharge power.

6 Conclusion

In this paper we propose a model of the energy management of a series hybrid urban bus and simulation results considering different driving cycle and conditions. We can conclude that it is possible to provide some periods of pure electric traction even if the battery is not

Table 1 Finite State Machine algorithm developed

State	**Transition condition**	**Output Signals**
Stopped	Initial State, vehicle stopped	Electric Motor: OFF Generator: OFF $P_{ice} = 0$ ICE: OFF
Electric	$SOC > SOC_{min}$ and $v < 45$ km/h	Electric Motor: ON Generator: OFF $P_{ice} = 0$ ICE: OFF
ICE	$SOC > SOC_{min}$ and $v \geq 45$ km/h or $v \geq 75$ km/h	Electric Motor: OFF Generator: OFF $P_{ice} = P_{dem}$ ICE: ON
Hybrid-Assist	$SOC > SOC_{min}$ and $v \geq 75$ km/h and $P_{ice}^{max}(\omega_{ice}) < P_{dem}$	Electric Motor: ON Generator: OFF $P_{ice} = P_{ice}^{max}(\omega_{ice})$ ICE: ON
Charging	$SOC < SOC_{min}$ and if $v < 75$ km/h or if $v \geq 75$km/h	Generator: ON and Electric Motor:ON ICE: OFF $P_{ice} = 0$ or Electric Motor: OFF ICE: ON $P_{ice} = P_{dem}$
Braking	$P_{dem} < 0$	Electric Motor: ON Generator: ON $P_{ice} = 0$ ICE: OFF

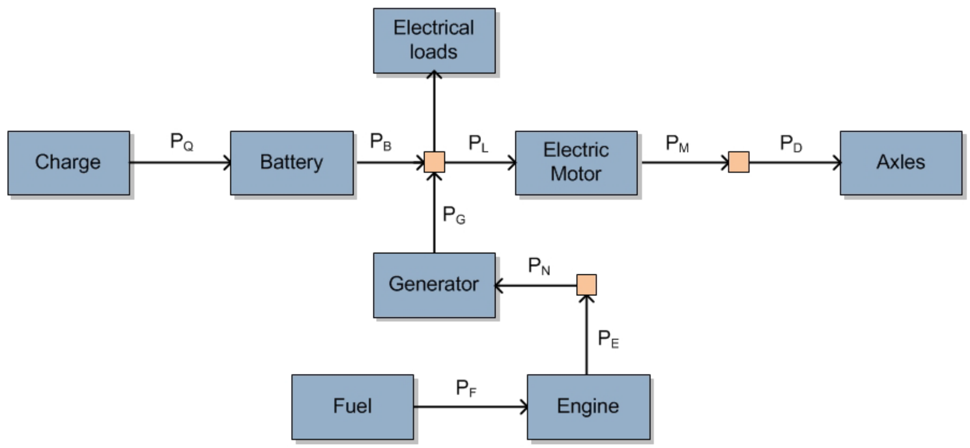

Figure 1 Functional architecture of the hybrid series bus

specifically designed for traction and propulsion. This study clarifies that using the battery can reduce its life, because the number of charge and discharge cycles increases. However, today's battery technology is evolving and achieves up to 5000 thousands cycle reducing their relative capacity to the 80%.
The control strategies we implemented in this study are composed by *if-then-else*. Another important aspect of this study is that we have considered in a different way every single energy flow related to traction and propulsion and auxiliary systems. In a more specific analysis we explicite real energy request of every single component it is possible to better partialize the energy produced by the two power sources.

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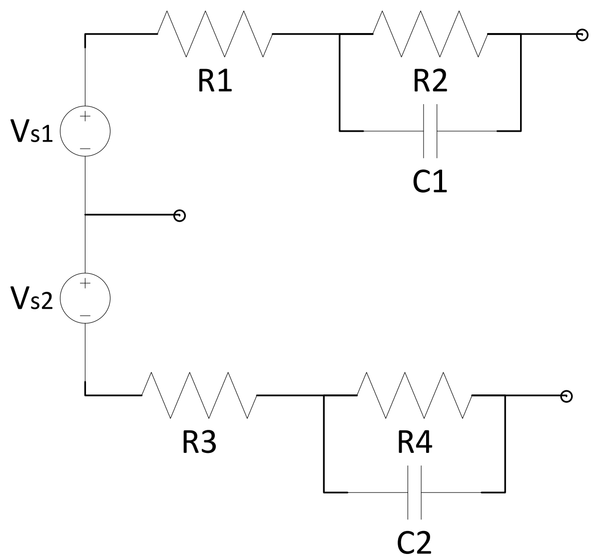

Figure 2 Schematic of the battery model: two cell are connected together to take into account different battery behaviors

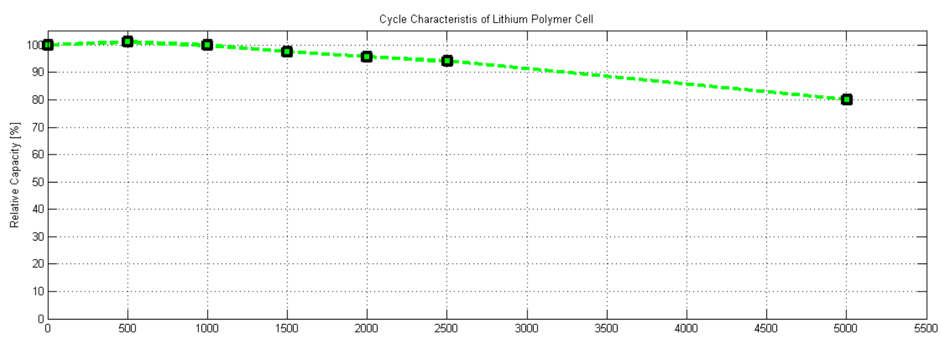

Figure 3 Cycle characteristics of a lithium polymer cell

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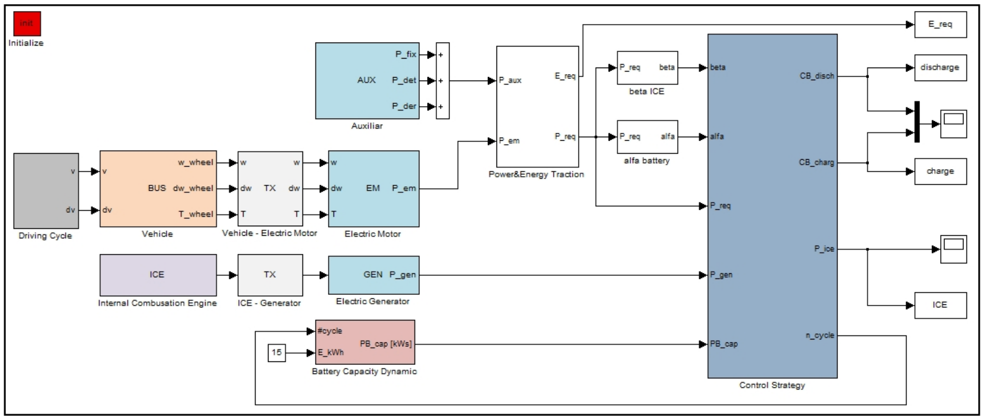

Figure 4 Matlab Simulink series hybrid bus model

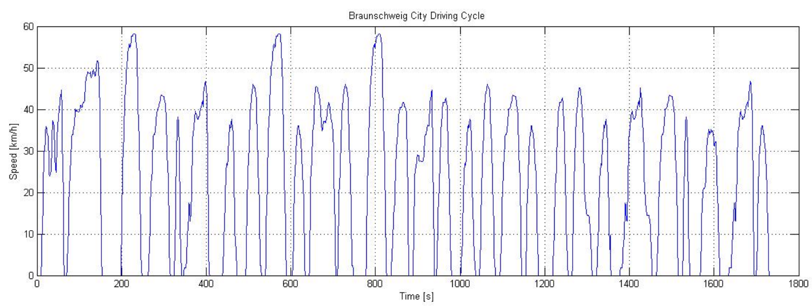

Figure 5 Braunschweig City Driving Cycle

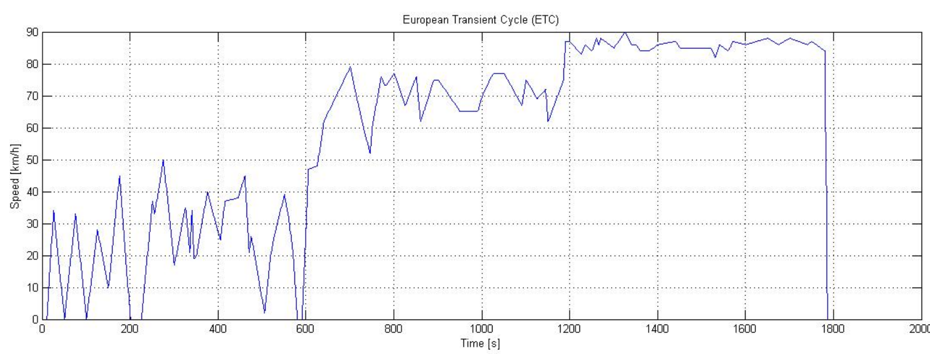

Figure 6 Modified European Transient Cycle

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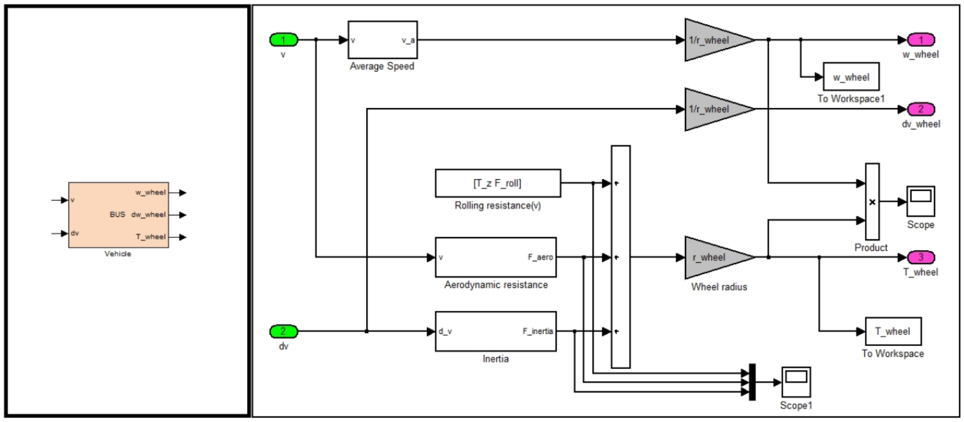

Figure 7 Simulink Vehicle model

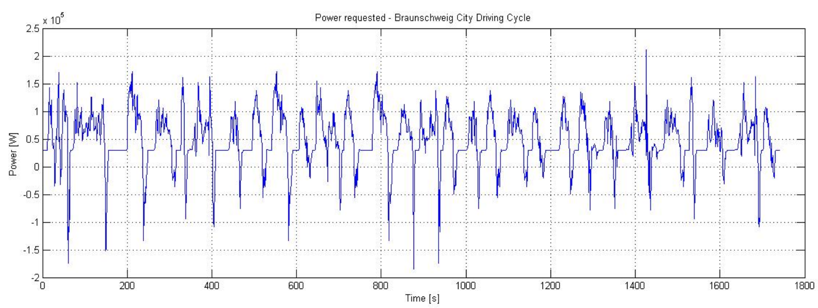

Figure 8 Requested power Braunschweig City Driving Cycle

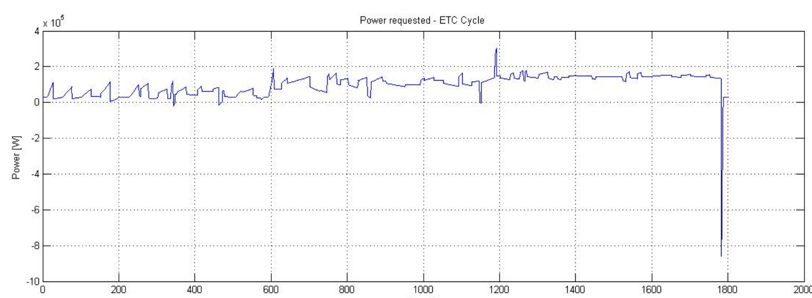

Figure 9 Requested power European Transient Cycle

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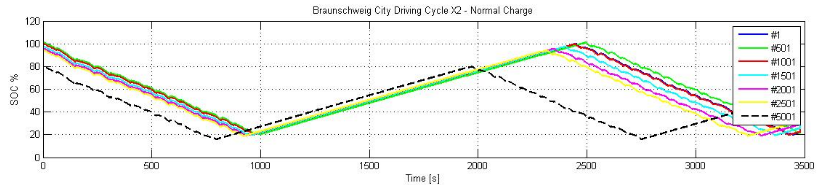

Figure 10 Battery charge and discharge cycle during Braunschweig City Driving Cycle: 100%-80% SOC

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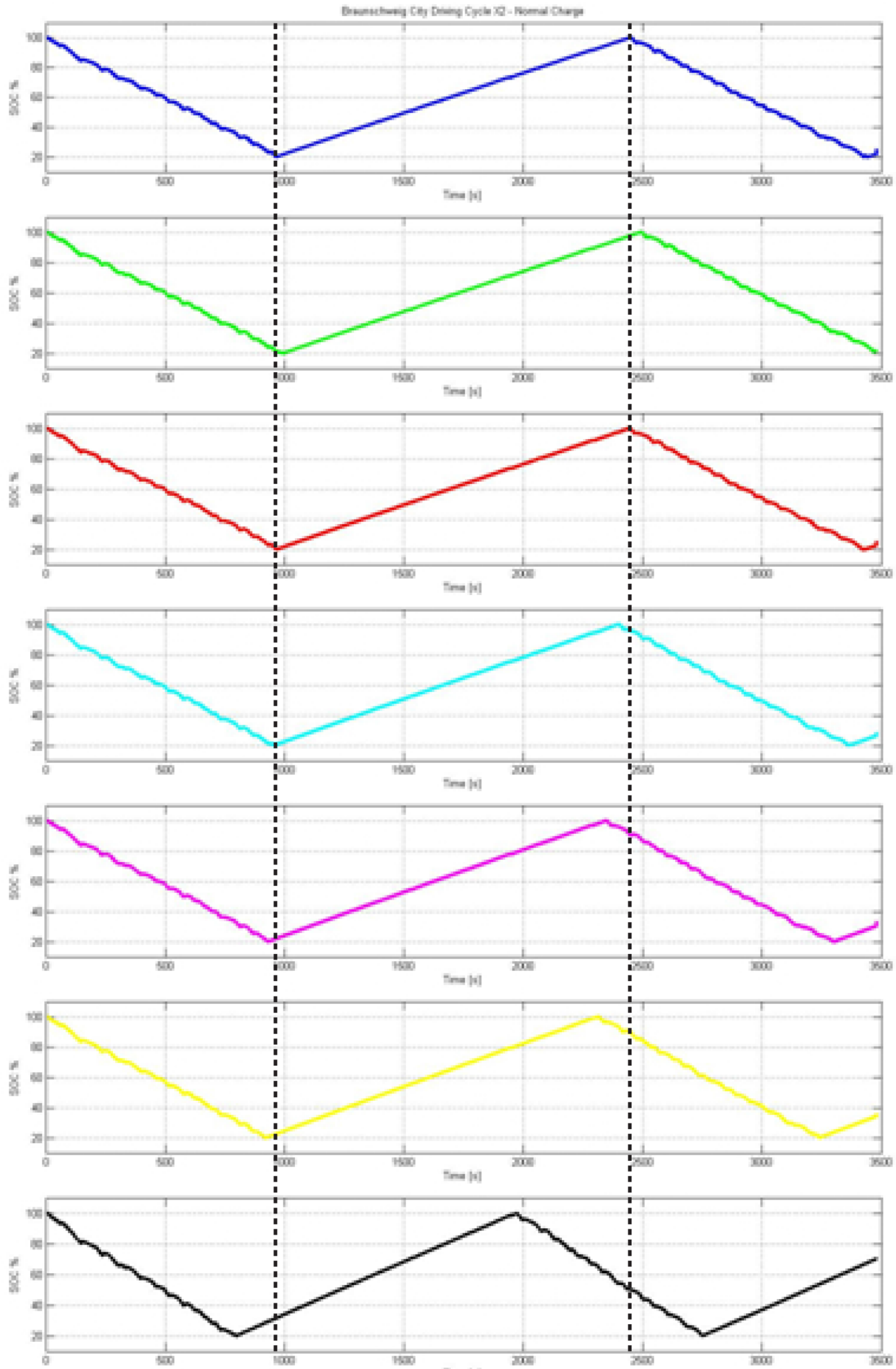

Figure 11 Battery charge and discharge cycle during Braunschweig City Driving Cycle: 100%-80% SOC

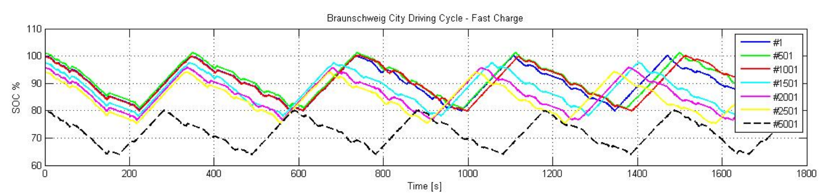

Figure 12 Battery charge and discharge cycle during a Braunschweig City Driving Cycle: 100%-80% SOC

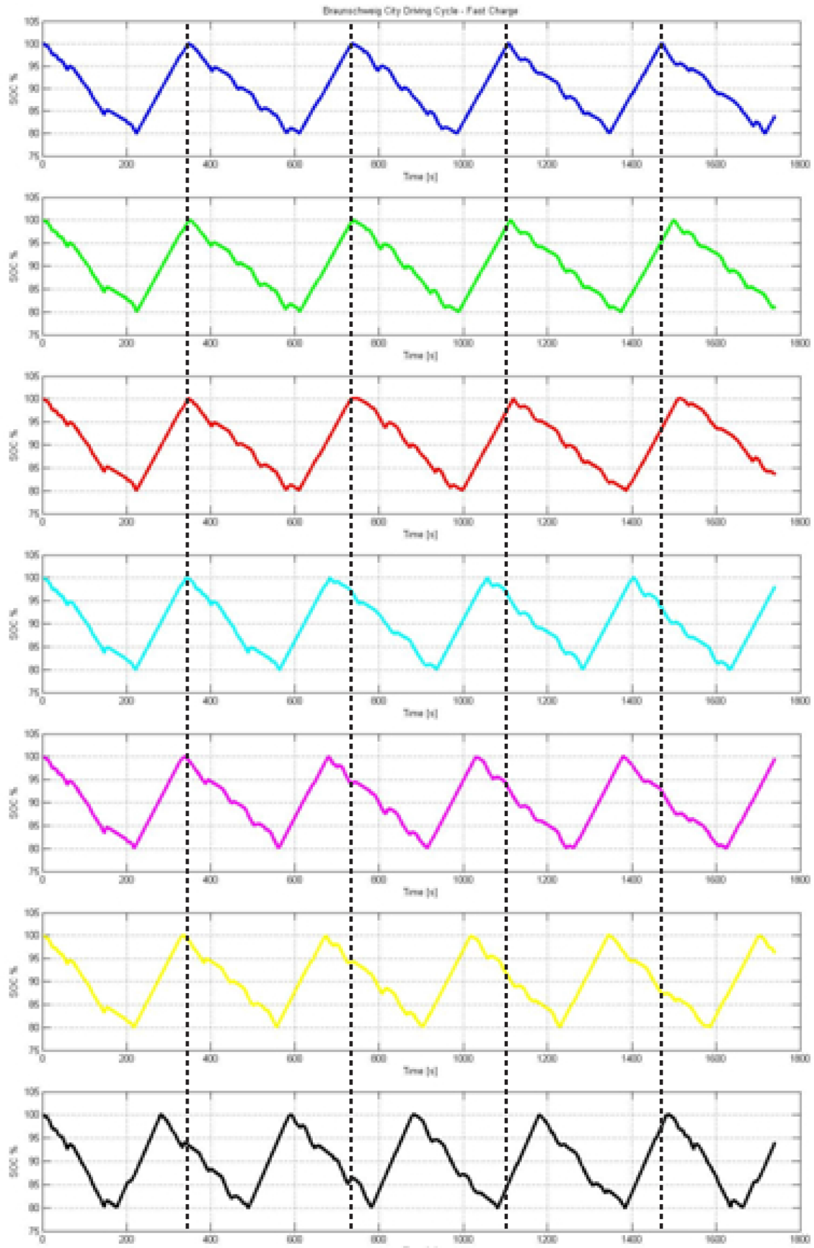

Figure 13 Battery charge and discharge cycle during a Braunschweig City Driving Cycle: 100%-80% SOC

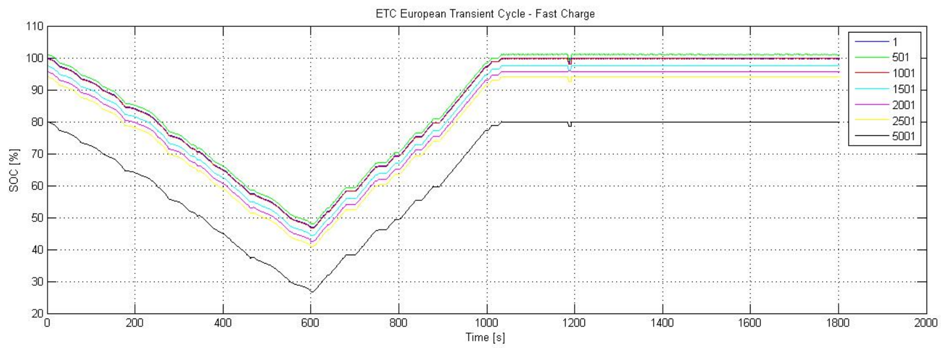

Figure 14 Battery charge and discharge cycle during an ETC, fast charge

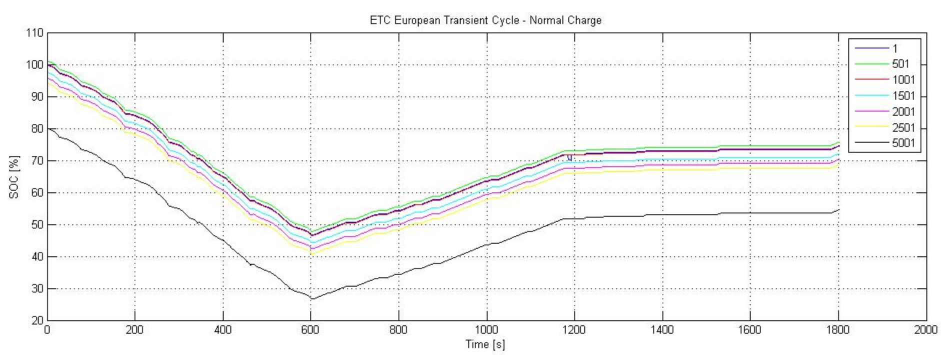

Figure 15 Battery charge and discharge cycle during an ETC, normal charge