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A Simulation Environment for Assessing Power Management Strategies in Hybrid Motorcycles

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ABSTRACT: *Reduction of the environmental impact of transportation systems is a world wide priority. Hybrid propulsion vehicles have proved to have a strong potential to this regard. Differently from cars, and even if they are considered the ideal solution for urban mobility, motorbikes and mopeds have not seen a wide application of hybrid propulsion yet, mostly due to the more strict constraints on available space and driving feeling. In this paper, we consider the problem of providing a commercial 125cc motorbike with a hybrid propulsion system, by adding an electric engine to its standard internal combustion engine. The aim for the prototype is to use the electrical machine (directly keyed on the drive shaft) to obtain a torque boost during accelerations, while reducing the emissions. Two different control algorithms are proposed, based on a standard heuristic and on torque-split optimal-control strategies, respectively. A SIMULINK virtual environment has been realized starting from a commercial tool, VI-BikeRealTime, to test the algorithms. The hybrid engine has been implemented in the tool from scratch, as well as a simple battery model, derived directly from data-sheet characteristics by using polynomial interpolation. The simulation system is completed by a virtual rider and a tool for build test circuits. Results of the simulations on a realistic track are included.*

KEYWORDS: *Hybrid motorcycles, Virtual rider, Dynamic Simulation, Optimal Control, Battery Model, Energy Management.*

1 INTRODUCTION

Transportation systems and efficient energy utilization are two of the most relevant research topics on a world-wide scale, for their economical and environmental impact. In the European context (European Union, 2011), *fossil fuels*, despite their high levels of pollution, are still extensively used for energy production and transportation. To assure sustainability and more confidence on energy supply, the European Union has studied a careful energetic policy for the next ten years, whose aim is to reduce *greenhouse gas levels* and *energy consumption* by 20% and increase the share of renewables by 20%, all these three targets by 2020.

However, the analysis of current trends show that the second target will not be reached. One of the main causes of such phenomenon is associated with the intense use of energy for transportation. Consequently, there is an increasing level of attention on the development of hybrid vehicles, that can help in addressing both the reduction of greenhouse gas levels and the increase of energy efficiency of transportation systems, hence capturing the interest of international research and vehicles manufacturers.

While many models of hybrid cars have been developed and put on the market in the last few years, hybrid scooters and motorcycles have not seen a large scale production yet, despite their promising peculiarities in terms of fuel economy and environmental impact, and mobility capability. One of the main obstacles to their spreading is the limited autonomy of batteries, an even greater problem for two-wheeled vehicles given the limited available space. The presence of the electric engine and the battery pack makes the problem particularly challenging with motorcycles, since it may affect the rider's driving feeling with respect to an equivalent model provided with an internal combustion engine only. In this sense, an appropriate design of the *Power Management System* is crucial to deal with the requirements of acceptable autonomy of the electric engine and preservation of satisfactory driving feelings.

To this respect, it is important to have a means of evaluating the dynamic behaviour of the motorcycle when it undergoes the hybridization step. It's easy to understand that the presence of an electric machine on the motorcycle can highly modify the vehicle behaviour, e.g. due to the increase in weight and the effects of the additional torque provided by the elec-

tric engine. In this context, a *virtual environment* capable of accurately describing the vehicle dynamics is a key feature for testing different engine and power systems management algorithms and their impact on the vehicle manoeuvrability. Moreover, one of the crucial design steps, namely the sizing of the batteries, is usually carried out with static simulations. A standard telemetry is processed off-line, boost and charge steps are identified and *point-wise* energy consumption/recovery values are calculated. Reliability for this kind of analysis is not assured, since the effects of the boost phase on the vehicle stability and performance is not investigated. A *dynamical simulation* environment can therefore be effective also in this design stage.

In this paper we report on the activities of a research project aimed at studying the electrification of a commercial 125cc motorcycle. Starting from an existing software tool for simulation, VI-BikeRealTime (VI-Grade, VI-BikeRealTime documentation, n.d.), a flexible SIMULINK environment has been developed. An easily customizable model for the accumulators has been derived, together with a map-based model for the electric engine. The main focus of this paper is the development of the controller of the Power Management System. Two strategies are proposed, a simpler one based on the evaluation of RPM derivative to select the boost/charge phase for the electric machine, and a more sophisticated *optimal control* strategy studied to obtain the best performance (in terms of available torque) while keeping the battery pack around its optimal operating point. Since the considered vehicle is a sports vehicle, the target is the utilization of the electric engine as a *torque-boost supplier*. Simulations have been carried out using different configuration for the virtual rider tested on different tracks, elaborated with a dedicated tool (VI-Road), to evaluate the performance of the control strategies among different driving conditions. The results show that satisfying performance can be obtained, in terms of both available torque utilization and battery management.

The paper is organized as follows. In Section 2 the prototype is described, in Section 3 the proposed battery model is shown together with the method for deriving it. In Section 4 the proposed control strategies are reported. In Section 5 the implemented virtual environment is described, and the simulation results are shown in Section 6.

2 MOTORBIKE PROTOTYPE

Several configurations for coupling internal combustion and electric engines are available in the literature, which can be grouped in three main architectures, namely, *series* hybrid, *parallel* hybrid and *series-parallel* hybrid, details can be found in Chan

2007, Chan et al. 2010, Ehsani et al. 2007, Emadi et al. 2005. The chosen configuration for the considered prototype is the parallel one, i.e. the two engines can run separately or together. The electric machine replaces the alternator and is keyed on the drive shaft, resulting in the constraint that both engines run at the same rounds per minute.

In the present study, the prototype is considered to be composed of three parts, the motorcycle, the electric engine, and the batteries.

2.1 Motorbike

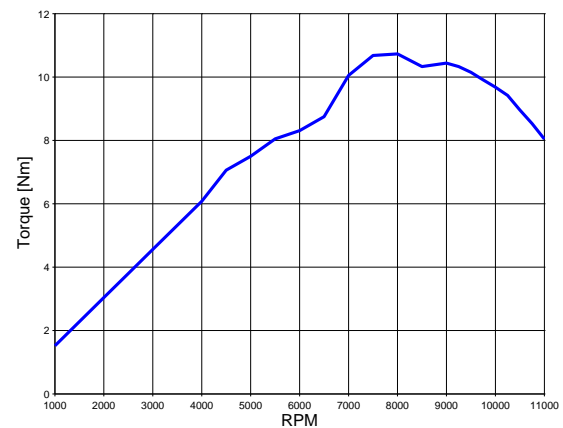
The vehicle we consider is the 125cc motorcycle *Aprilia RS4 125* (Figure 1). It is a commercial sports

Figure 1: Aprilia RS4 125



motorcycle with a small, single-cylinder, four-stroke engine that is described in terms of its torque characteristic curve, given in Figure 2 from *full-gas* measurement at the engine test stand.

Figure 2: Torque characteristic of the endothermic engine

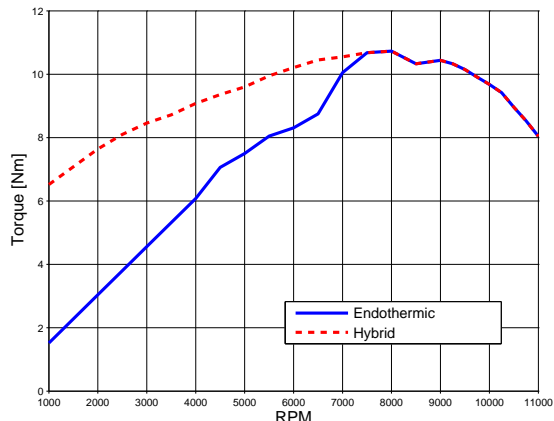


2.2 Electric motor

The chosen architecture for the electric motor is the *Surface Permanent Magnet Synchronous Motor*, which can assure a high torque density with reduced weight and space required. The electrical machine has its rotor keyed to the drive shaft of the internal combustion engine, and is capable to supply torque

such that the overall engine torque profile for the hybrid vehicle is the one shown in Figure 3. Note that

Figure 3: Torque characteristic of the hybrid engine.

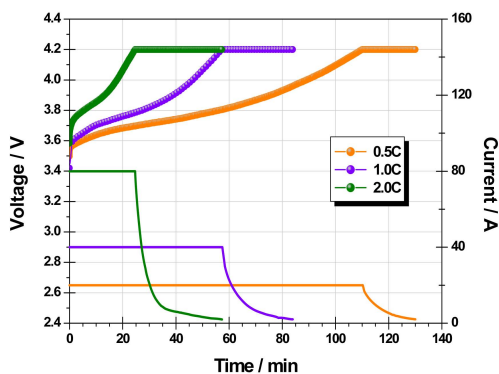


the highest torque requested from the electric motor is approximately 5 [Nm]. The electrical machine acts as a motor when a boost is required, and as a generator when the current driving conditions allow to charge the accumulators.

2.3 Batteries

The battery pack has been designed considering *Lithium-Polymer* cells, which have the advantages of not being flammable and to have a flexible structure that can assure a smarter usage of the available space. A preliminary analysis performed on the basis of static simulations suggests the use of a four cell battery pack; in Figure 4 and 5 the data-sheet characteristics charge and discharge curves for a single cell are shown.

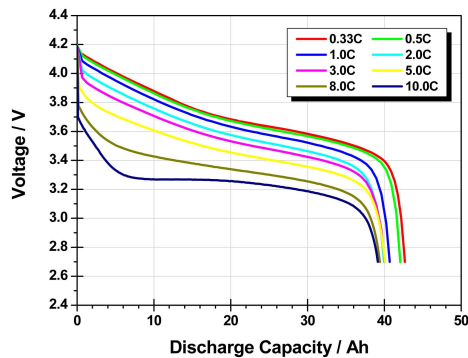
Figure 4: Charge curve.



3 BATTERY MODEL

Deriving a model for a battery is a challenging issue, since its behaviour depends on a wide variety of internal and external variables, e.g. internal temperature, ageing (number of charge and discharge cycles), op-

Figure 5: Discharge curve.



erational conditions, and many more. Variations in these quantities result in modified internal resistance, capacity reduction and, more in general, accumulator damage. In the hybrid vehicles context, having a careful model for batteries is crucial, not only in the design stage but also for control purposes, in order to estimate meaningful informations on the battery state (as State Of Charge or temperature) from easily measurable quantities (as voltage or current).

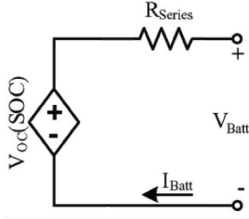
The most common models for batteries are

- *electrochemical* models, which exploit the physical laws that regulate the electrochemical phenomena inside the battery (Debert et al., 2008; Smith, 2010; Smith et al., 2010; Speltino et al., 2009). Such models are very precise, but complex and the knowledge of a great number of parameters as well as availability of sophisticated analysis tools are needed for their implementation. Moreover, they have heavy computational burden and make real-time simulation quite difficult;
- *electric* models, which exploit the *equivalent circuit* and its law to represent the electrical behaviour of the battery (Chen and Rincon-Mora, 2006). Despite being quite an empirical approach, it allows a simple modeling of the accumulators dynamics that can be improved if needed.

The model of the accumulators is a key feature for our simulation purpose. Having (near) real-time constraint (required from the control point of view) and no availability of the real battery pack for measuring the parameters, a simple electric circuit as been adopted (Figure 6), considering the battery as a *real voltage source* controlled by *SOC* (State Of Charge, i.e. the normalized quantity of available energy), hence the supplied voltage is a function $V_{batt}(SOC)$; the same holds for the current $I_{batt}(SOC)$.

The proposed modeling method is inspired by

Figure 6: Equivalent electric circuit for the battery.



Yurkovich et al. 2008 and relies on information directly available from the battery pack data-sheet. Point-wise charge and discharge maps are derived from the characteristic curves in Figures 4 – 5, and applying *polynomial fitting*, analytical representations for $V_{batt}(SOC)$, $I_{batt}(SOC)$ are calculated. Note that

1. characteristic curves are *not* directly given as function of SOC , hence preliminary calculations have to be done to obtain the functions of interest;
2. the model assumes negligible temperature variations (which can be included if information from the data-sheet are available (Dougal, 2002)) and charge losses due to chemical reactions. For the purpose of preliminary control design and simulation, and without a better characterization of the accumulators, these hypotheses are acceptable.

Once V_{batt} and I_{batt} are available, the *power* (and energy) supplied by the accumulators are easily computable.

3.1 Charge functions

In Figure 4, charge voltage and current are given as functions of time, $v_{batt}^C(t)$ and $i_{batt}^C(t)$, for different charging strategies. To obtain these values as function of SOC , the *charge power* function $P_{batt}^C(t)$ is calculated as

$$P_{batt}^C(t) = v_{batt}^C(t) \cdot i_{batt}^C(t) \quad (1)$$

and then integrated to obtain the available energy

$$E_{batt}^C(t) = \int_0^t (P_{batt}^C(t) - V_0 \cdot i_{batt}^C(t)) dt, \quad (2)$$

where V_0 is the *cut-off* voltage value (i.e. the voltage lower bound to avoid damages, given in the data-sheet). By normalizing $E_{batt}^C(t)$ with respect to its maximum value, $SOC(t)$ is computed. Finally, having described each quantity as a function of time, it's easy to obtain $V_{batt}^C(SOC)$ and $I_{batt}^C(SOC)$.

Note from Figure 4 that the charge characteristic is divided in two phases. At first, $I_{batt}^C(SOC)$ is con-

stant and equal to I_{kC}^1 while $V_{batt}^C(SOC)$ increases. When the voltage reaches its maximum value V_{max} , the current has a decreasing transient and becomes null when $SOC = 100\%$. Hence, $V_{batt}^C(SOC)$ and $I_{batt}^C(SOC)$ are

$$V_{batt}^C(SOC) = \begin{cases} f_{V_{batt}^C}(SOC) & \text{if } SOC < SOC_{lim} \\ V_{max} & \text{if } SOC \geq SOC_{lim} \end{cases} \quad (3)$$

$$I_{batt}^C(SOC) = \begin{cases} I_{kC} & \text{if } SOC < SOC_{lim} \\ f_{I_{batt}^C}(SOC) & \text{if } SOC \geq SOC_{lim} \end{cases} \quad (4)$$

where $f_{V_{batt}^C}(SOC)$, $f_{I_{batt}^C}(SOC)$ are polynomial functions of appropriate degree obtained by fitting the transient data,

$$f_{V_{batt}^C}(SOC) = \sum_{k=0}^n v_k \cdot SOC^k,$$

$$f_{I_{batt}^C}(SOC) = \sum_{k=0}^m i_k \cdot SOC^k.$$

3.2 Discharge functions

The discharge law is easily obtained from the characteristic curve (Figure 5): provided that constant current I_{kC} is applied to the load, the voltage is given as a function of the *discharge capacity*, hence by polynomial fitting we obtain the function

$$f_{V_{batt}^D}(SOD) = \sum_{k=0}^n v_k \cdot SOD^k,$$

where SOD is the State Of Discharge, related to SOC as $SOD = 1 - SOC$. Hence, we obtain

$$V_{batt}^D(SOC) = f_{V_{batt}^D}(1 - SOC) \quad (5)$$

$$I_{batt}^D(SOC) = I_{kC}. \quad (6)$$

4 CONTROL STRATEGIES

The control system for the hybrid motorcycle has to assure the best use of the electrical machine in terms of *supplied torque boost*, while avoiding an excessive consumption of the battery in order to prevent damages and possible safety issues. The electric motor works as a generator during charge steps and as an engine during boost: the controller operates in both phases, in particular two different approaches are proposed for boost management, a heuristic one and one based on optimal-control paradigm.

¹ kC means that the constant applied charge current is k times the nominal capacity in [Ah].

4.1 Charge control

As said in Section 3.1, when the battery voltage is less than V_{\max} , the current supplied by the generator is constant, and can be set as a multiple of the nominal capacity. To each value of I_{kC} corresponds a lower bound on $\text{RPM}(t)$, $\overline{\text{RPM}}_{kC}$, below which the generator cannot supply enough power to provide the requested current. Since charging batteries is a slower but safer task than discharging, this operation mode must be activated whenever it's possible, i.e. when the motorcycle is at constant or decreasing speed and $\text{RPM}(t) \geq \overline{\text{RPM}}_{kC}$: hence, the key point of the charging strategy is to decide whether the present vehicle set-up allows the motor to operate as a generator.

Defined the motorcycle speed as $v(t)$, the gear signal as $g(t)$ and the energy level as $E(t)$, four conditions must hold:

1. $\dot{v}(t) \leq \delta v_0$, where $\delta v_0 > 0$ is a threshold below which the speed can be considered constant or decreasing;
2. $\text{RPM}(t) \geq \overline{\text{RPM}}_{kC}$;
3. $\dot{g}(t) \leq 0$, to avoid problems on negative $\dot{v}(t)$ values due to gear-shift and not to real speed variations;
4. $E(t) \leq E_{\max}$: the motor acts as generator only if accumulators are not full-charged.

Note that the third condition has to be temporized, since the variations on $g(t)$ are clearly faster than the correspondent variations on $v(t)$.

4.1.1 Charge mode switching

The chosen cells allow charge currents up to 2C. The higher is the charging mode, one the one hand, the faster is energy accumulation, on the other hand, the higher is $\overline{\text{RPM}}_{kC}$. Depending on the driving context (route, driver's behaviour, traffic), the $\overline{\text{RPM}}_{2C}$ constraint might be too high to allow a satisfactory recharge. The control algorithm then operates an automatic switch of charging modes between 1C and 2C, based on recent driving conditions, to exploit at best the generator capabilities.

Once a time observation window has been set, the time intervals with $\text{RPM}(t) > \overline{\text{RPM}}_{2C}$ and $\overline{\text{RPM}}_{1C} < \text{RPM}(t) < \overline{\text{RPM}}_{2C}$ are computed and compared, and the corresponding charging mode is then applied. An hysteresis-based strategy on the difference between the two time values is applied to avoid chattering of the switching action.

4.2 Boost control

The first element of the boost control strategy is the activation algorithm, i.e. the set of conditions that allow the electrical machine to act as an engine, providing torque contribution. They are very similar to those presented in the last section for the charge algorithm, in particular

1. $\dot{v}(t) > \delta v_0$: boost is applied during accelerations;
2. $\overline{\text{RPM}}_L < \text{RPM}(t) < \overline{\text{RPM}}_H$: the boost acts within a RPM range specified at design stage;
3. $\dot{g}(t) < 0$;
4. $E(t) > E_{\min}$: boost is applied only if energy is available in the accumulators.

The boost stage is more critical than the charge stage, from the point of view of both vehicle stability and battery management. Two algorithms have been designed to manage the boost phase.

4.2.1 Adaptive boost

This strategy acts on the torque supplied by the electrical machine when behaving as an engine. The reference torque map is a *full-boost* map (i.e. includes the maximum torque values that the motor can provide for each RPM value). If the conditions for applying boost hold, the electric motor is controlled to provide a torque *scaled* by a reduction factor proportional to the current *SOC*. The control variable for this strategy is the *SOC* itself. If $\text{SOC} \geq \overline{\text{SOC}}_U$, full-boost is applied, if $\text{SOC} \leq \overline{\text{SOC}}_L$ boost is allowed. For intermediate values of *SOC*, a scaling factor is applied as previously described.

Note that with this algorithm a chattering behaviour can arise for *SOC* values around both the thresholds, with continuous switching between different operative modes. An hysteresis on the threshold values has been applied to prevent this situation.

4.2.2 Adaptive torque splitter

This approach is an optimal control algorithm based on the idea of *torque split*. Given the total torque request $\tau_r(t)$ for a given value of $\text{RPM}(t)$, the optimal *splitting* between the torque that can be provided by the electric motor, $\tau_{em}(t)$, and the internal combustion engine, $\tau_{ice}(t)$, is computed, thus obtaining the best trade-off between battery consumption and fuel economy. This approach has been chosen because of the technical features of the prototype, that is, having the constraint that the two engines run at the same RPM value, it is convenient to regulate the torque

provided by each engine. The constraints for the system are

$$\begin{cases} SOC_{\min} \leq SOC(t) \leq SOC_{\max} \\ \tau_r(t) = \tau_{em}(t) + \tau_{ice}(t) \\ \tau_{em}^{\min}(\text{RPM}t) \leq \tau_{em}(t) \leq \tau_{em}^{\max}(\text{RPM}(t)) \\ \tau_{ice}^{\min}(\text{RPM}t) \leq \tau_{ice}(t) \leq \tau_{ice}^{\max}(\text{RPM}(t)) \end{cases} \quad (7)$$

where the bounds on $SOC(t)$ are given to prevent battery damage (and usually $SOC_{\max} = 1$), and the bounds on $\tau_{em}(t)$ and $\tau_{ice}(t)$ reflect the minimum and maximum torque supplied by the two engines at a fixed RPM value (depending on the absorbed current and the throttle opening, respectively).

The chosen cost function is quite simple, being a weighted sum of $\tau_{em}(t)$ and $\tau_{ice}(t)$,

$$J(\tau_{em}(t), \tau_{ice}(t)) = w_{em}(SOC(t), SOC_{\text{ref}}) \cdot \tau_{em}(t) + w_{ice}(SOC(t), SOC_{\text{ref}}) \cdot \tau_{ice}(t). \quad (8)$$

The weights are function of the current $SOC(t)$ and a reference value, SOC_{ref} , below which the use of the electric motor has to be penalized. The *adaptive* aspect of the control algorithm proposed involves the *dynamic adaptation* of w_{em} and w_{ice} depending on the state of the batteries, and of SOC_{ref} depending on the recent driving conditions: the first are regulated to keep $SOC(t)$ around its optimal operating point SOC_{ref} , the latter varies according to the recent trend of batteries utilization (i.e. if boost has not been much provided SOC_{ref} is lowered and vice versa). Note that a *smoothing constraint* on the derivative $\dot{SOC}(t)$ has been introduced to avoid sudden variations on τ_{ice} request, which can lead to bad driving feelings and issues on driver's safety.

$J(\tau_{em}(t), \tau_{ice}(t))$ can be rewritten as a function of just $\tau_{ice}(t)$, hence becoming a single-variable optimization problem; the constraints can also be reformulated to depend on $\tau_{ice}(t)$ only and incorporated in $J(\tau_{ice}(t))$. The control problem becomes a *single variable, unconstrained* optimization problem, and a solver based on the *golden-ratio method* has been implemented for its resolution speed and the capability of dealing with non continuous cost function. Being the controlled variable τ_{ice} , the actuator is the throttle, a viable solution since ride-by-wire technology is now popular on motorbikes (see for instance Beghi et al. 2006); this reflects on a controlled throttle request signal in the simulation environment.

5 VIRTUAL ENVIRONMENT

The implemented virtual environment has two main goals:

1. provide a flexible, easily integrable tool for *dynamic simulation* of a (simplified) model of the hybrid motorbike;

2. test the proposed control algorithms on a realistic scenario.

The core of the simulation tool is *VI-BikeRealTime*, a professional modeling, post processing and real-time analysis environment for motorcycle models. One of its main features is the SIMULINK interface, which allows to perform software-in-the-loop and hardware-in-the-loop activities: together with the availability of a great number of customizable parameters and output channels (more than 350 outputs), the tool is able to provide all the quantities needed to evaluate the dynamic behaviour of the vehicle.

The key feature of the SIMULINK interface is the presence of a *virtual rider*, which emulates the behaviour of a real driver and allows to close the loop of the dynamic simulation, giving a reliable feedback on the performance of the control strategies in a realistic scenario, before the "real-world" tests. In this sense, it is important for our purposes to *limit* the performance of the virtual driver, implemented as a *maximum performance* driver, to emulate situations of city-driving, as to build ad-hoc tracks to replicate realistic paths; a SIMULINK model of the electrical machine has been implemented to get a complete dynamic system representing the hybrid vehicle, with particular efforts on the representation of the power management system.

5.1 Virtual rider

The virtual rider is able to "ride" a virtual vehicle model through a number of different manoeuvres in order to allow users to accurately evaluate the dynamic behaviour. The main advantage is the capability of dealing with closed-loop manoeuvres, which allows to test the effectiveness of control algorithms from the point of view of the final user (the rider): this is achieved by a combination of a static and an accurate *dynamic solver* (Frezza et al., 2003) that, given the model parameters of the motorbike and the track, is able to solve in real-time a set of equations which emulate a real-driver behaviour (Frezza and Beghi, 2006; Frezza and Beghi, 2003; Frezza et al., 2004; Saccon et al., 2008), in terms of applied longitudinal and lateral forces, driveline following and management of crucial elements as steering, throttle, brake and many more.

The virtual rider must be provided with *speed* and *gear-shifting* references for a specific track: since it is implemented to give the maximum performance during the ride, the two references have to be manipulated in order to limit the driver capabilities and emulate a city-ride route.

5.2 Tracks

A fundamental aspect of a reliable vehicle simulation is the choice of the track: the driver's and vehicle behaviour are deeply affected by the features of the route. For the target of interest, the track has to be able to catch the main features of urban and extra-urban mobility, typical for this kind application. The provided tool has the capability of building a reliable road model, made up of single small blocks that can be characterized in terms of orientation, regularity, grip and other parameters, and when combined, the principal features of the track are specified, e.g. curves position and inclination angles, overpasses, chicanes and many more. In the design stage, a weighted combination of curvature and tension (local measure of the total path length) determines the trajectory that the virtual driver will follow along the circuit: this is clearly another crucial parameter to specify the virtual rider's behaviour.

5.3 Hybrid engine

The hybrid engine, with both the endothermic engine and electric motor, is implemented has an *external* SIMULINK system with respect to the core block representing the motorbike/rider dynamics. In fact, simply adding the torque supplied by the electric motor to the one given by the *integrated* model of the internal-combustion engine leads to a wrong calculation of the throttle signal and an increasing error in tracking the speed reference: as stated before, the speed reference must be given in advance to the solver, which at each time step calculates the throttle signal w.r.t. the torque that has to be supplied in the next step to match the desired speed (feed-forward action). From the solver point of view, the *whole* input torque is supplied by the endothermic engine, hence leading to a wrong computation of the throttle signal that reflects on a bad tracking of the speed reference that the internal PID controller is not able to prevent and on wrong behaviour of the virtual rider (e.g. using brake instead of engine braking, or following the wrong trajectory). Implementing the hybrid engine as an external system allows to provide the right torque value to the solver in the feed-forward step, obtaining correct results for throttle and speed signals.

Another remarkable advantage of our implementation is the *throttle partialization* management. Both the engine models are *map-based*, i.e. their dynamics is represented by a collection of look-up tables which relate the main quantities (e.g. RPM to supplied torque). Each engine is provided with maps relating the maximum and minimum suppliable torque to the current RPM value (for the electrical machine, the minimum torque is null, since it doesn't contribute to engine braking): from the throttle value applied on the previous step and the current RPM value, the

endothermic torque and the new throttle value are calculated, and the last one is used to scale the electric torque to get the correct value. To compute the partialized torque, a linear interpolation is used, but the implemented model gives the possibility to use more accurate partialization maps, if available.

The subsystem includes a block to select the charge and boost intervals, as described in sections 4.1–4.2.

5.4 Battery pack

The system implemented to model the accumulators follows what has been shown in Section 3: for the real-time operation of interest, the most significant information is the *power* that they can provide when the electrical machine acts as a booster, and store when it acts as a generator.

During the boost phase, the absorbed power is computed as

$$P_{boost}(t) = P_{batt}^D(t) = \tau_{em}(t) \cdot \text{RPM}(t) \cdot \eta_{em}^{-1} \quad (9)$$

with η_{em} the efficiency of the electrical machine. The spent energy (hence $SOC(t)$) is then computed integrating $P_{batt}^D(t)$. Note that the dynamics of the electric motor is supposed instantaneous, acceptable hypothesis in this early stage design.

When working as a generator, it is necessary to have a real-time estimate of the instantaneous charge power $P_{charge}(t) = P_{batt}^C(t)$, to have the charge current regulated as a function of $SOC(t)$. Based on an approach similar to the one described in section 3.1, the implemented model describes $P_{batt}^C(t)$ as a polynomial function calculated with (1): some correspondent values for $v_{batt}^C(t)$ and $i_{batt}^C(t)$ are extrapolated from the data-sheet, giving a set of points for $P_{batt}^C(t)$ and, using polynomial fitting, the function

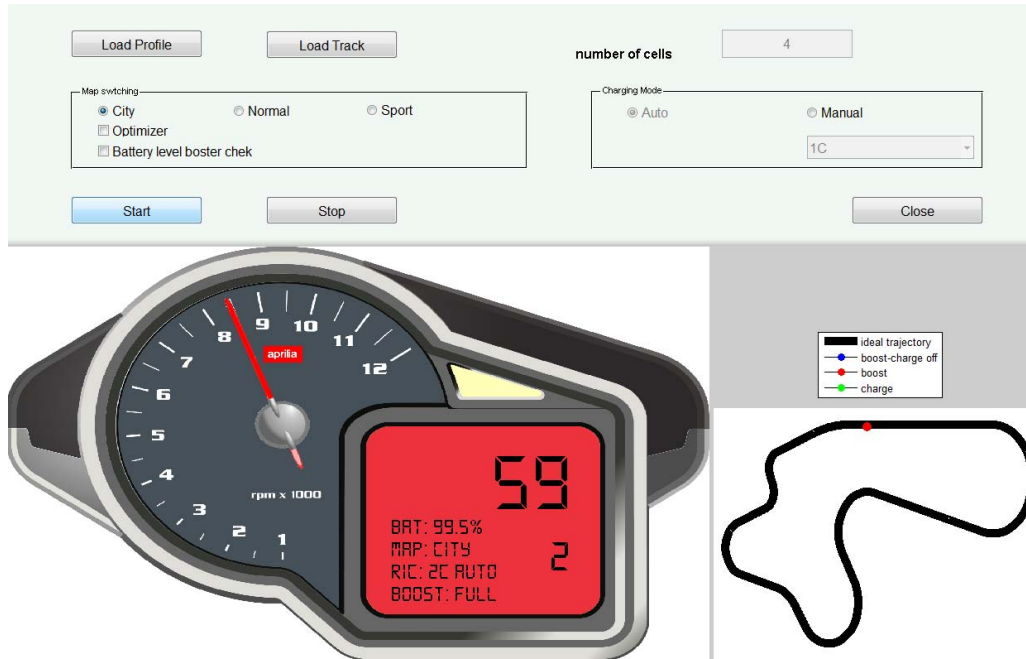
$$P_{batt}^C(t) = \sum_{k=0}^n p_k \cdot SOC(t)^k \quad (10)$$

is computed. For $SOC(t) < SOC_{lim}$ the function is monotonic, as for $SOC(t) \geq SOC_{lim}$, hence it is possible to look at the inverse map to get the time instant \bar{t} relative to a value of P_{batt}^C : being T_s the sample time, the estimation of the charging power is computed from (10) as $P_{batt}^C(\bar{t} + T_s)$. The estimate is then integrated to obtain $E(t)$ and the correspondent $SOC(t)$.

5.5 Graphical User Interface

A GUI has been implemented to set the principal parameters for our test purposes: number of battery cells, track and rider profiles, control strategies, rider's driving style. The GUI allows to modify the control strategy and driving behaviour in real-time,

Figure 7: Graphical User Interface screenshot.



while a user friendly representation of the hybrid motorcycle current operation mode and set-up is provided through a dashboard (Figure 7).

6 SIMULATION RESULTS

The proposed control strategies have been tested on the previously described virtual environment. The targets of the simulation are two:

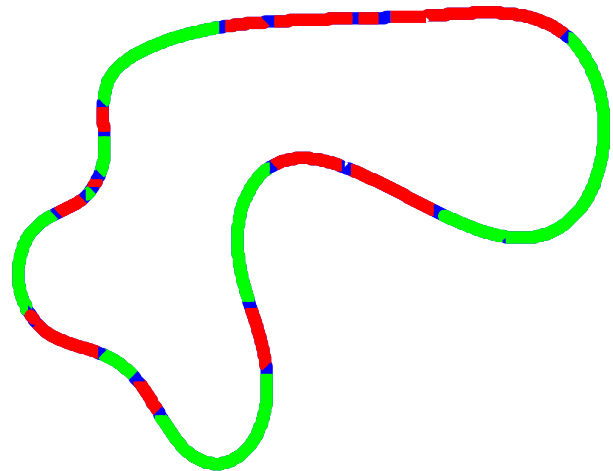
1. validate the chosen battery battery-pack, made up of 4 Kokam Li-Poly cells, on a realistic track: starting $SOC = 1$, the goal is to end a lap with the SOC as close to 1 as possible;
2. test the improvements in driving performance due to the electric boost contribution.

The last point cannot be directly verified: as previously stated, the solver of the virtual rider needs a speed reference to track. Hence, in order for the comparisons to be reliable, the rider has to be provided with the same speed reference, whatever the chosen motorbike (pure endothermic or hybrid) and control strategy are. In this sense, the comparison will be carried out on the *throttle demand* rather than the applied boost: given the same speed profile, a lower throttle demand corresponds to an improvement due to the boost action, so the target becomes emissions reduction.

The gear-shift map is realized to limit the virtual rider's performance and emulate the typical RPM profile of urban driving paths, favouring up-shifts to keep low running speeds. The designed track, 1793

meters long, contains both urban and extra-urban features, with close brakings and accelerations phases together with long straights and fast bends: in Figure 8 the track is shown, with highlighted boost and charge intervals.

Figure 8: Simulation test track: in red the boost intervals, in green the charge ones.



In Figure 9 the pure endothermic and the hybrid motorbike performance, with adaptive boost and charge switching strategies, are compared. The throttle request for the hybrid vehicle is lower than the demand of the endothermic one during almost all the accelerations, and this correspond to different applied boost torque values. In Figure 10 the two proposed control strategies are compared on the same speed reference. The advantages of the adaptive torque splitter are ev-

ident: the electrical machine is much more exploited, with remarkable throttle demand, and consequently emission, reduction, in particular during long accelerations. The boost supply is also more regular using the optimal control strategy, thanks to the effectiveness of the cost function. Regarding the State Of

Figure 9: Pure endothermic and hybrid motorcycle with adaptive boost comparison.

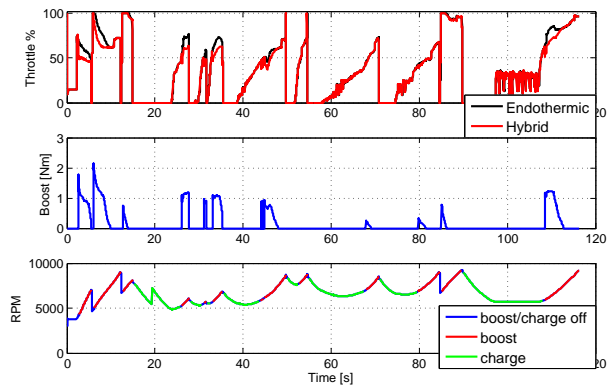
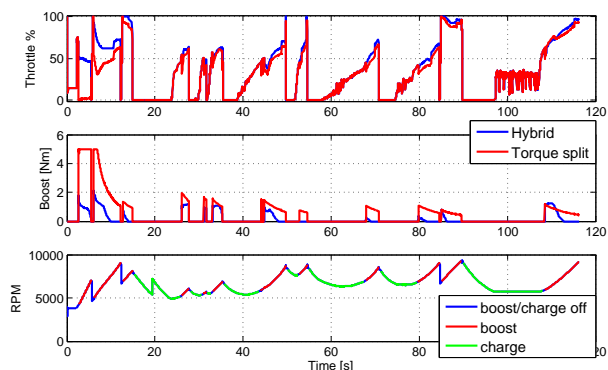


Figure 10: Different control strategies for hybrid motorbike comparison.



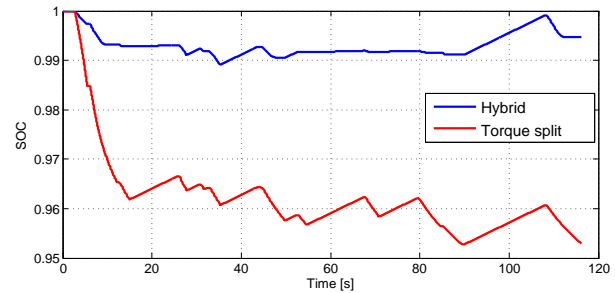
Charge of the battery, Figure 11 shows the battery exploitation with the two different strategies: the optimal control keeps the SOC around 95% (the fixed SOC_{ref} , assuring a better use of the accumulators capabilities: both the strategies satisfy the target of almost-full charge at the end of the path. Note that with torque split strategy the SOC does not increase significantly because of the reduced lap time: the second part of the track has extra-urban features and doesn't allow a full charge, while the first strategy shows a more conservative approach.

All the simulations have been carried out in real-time, thus demonstrating the applicability of the power management system strategies on real vehicles.

7 CONCLUSIONS AND FUTURE WORKS

A virtual, dynamical environment for the design of hybrid motorcycles has been implemented. A new

Figure 11: Battery exploitation comparison.



battery model has been proposed, using information available from data-sheets, and two adaptive control strategies have been studied to assure increase in performance and optimal power management. The battery model and control strategies have been included in a flexible SIMULINK interface and integrated with a virtual rider tool for testing purpose: simulations have been carried out to validate the battery sizing and the effectiveness of the control.

Next steps will be the improvement of electrical machine and battery models, including more dynamical features, software-in-the-loop tests to verify the implementation of control algorithms and battery management on a real ECU and software-in-the-loop tests to assess the behaviour of the real electric motor.

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