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System Level Modelling and Simulation of an Electric Bicycle

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Abstract – **This paper considers the use of electric bicycles as a means of transport of zero emissions, low congestive kind of transportation in a typical daily use in Sofia, Bulgaria. The paper presents a system level model of a parallel topology ebike, using a BLDC motor and Li-ion battery. The control system is implemented in Stateflow, while the remaining block uses the new Simulink Drivetrain library. Simulation results for key electrical and mechanical parameters are presented for a daily trip to work. Comparison of the SOC of the battery with and without energy recovery is also presented. This model is used to evaluate the specific requirements and possible tradeoffs when constructing such a vehicle.**

Keywords – **Drives, Electric Bicycles, Power electronics, EPACs**

I. INTRODUCTION

Europe is the second largest user of bicycles, as a means of transportation, with constant sales around 20 million bicycles per year [1]. However, a closer look at statistics shows that Electrically Power-Assisted Bicycle (EPACs) sales have increased 17 times for just 10 years and are around 1.7 million per year, which is about 10% of total sales. Bulgaria is the fifth largest producer of bicycles in Europe, but ranks among the last on their use, especially electric bikes. In Sofia the use of this kind of transportation has the potential to lower traffic congestion and local pollutant emissions. An added benefit is that being a southern country it has around 25% more sunny days, less rainy days and softer winter, compared to Rotterdam, Netherlands (the second largest consumer of EPACs) [2]. The environmental conditions are quite favorable for using electric bicycles as the main means of transportation. It is the main goal of this paper to investigate the possible advantages of using an ebike in Sofia, Bulgaria, as a means for daily travel.

It is the aim of this paper to evaluate the use of an electric bicycle on a typical daily trip to work. Thus, it deals with the modelling of an electric powered bicycle. Using the new Simulink/Drivetrain block, the system models a parallel ebike system, powered by a typical Li-Ion battery and a BLDC motor. The control algorithm is idealized and based on a Stateflow algorithm. The two cases with and without energy recovery are separately considered.

Previous research on the topic includes [3], where the efficiency of different control algorithms is presented, but without a model of the whole system. In [4] a series electric bicycle architecture is considered and different control strategies and their influence on the SOC of the battery is presented with simulation and experimental verification. A hybrid energy storage simulation is presented in [5], where the human cyclist only sets the desired torque. As a driving cycle the Portuguese standard NP EN 1986-1 is used, while in this paper the actual road conditions are taken into consideration, when presenting the simulations. A detailed modeling of the human torque production is presented in [6].

The paper is structured as follows: the next section presents the block diagram of the system level modeling of an ebike together with the main assumptions for each of its components. In Section III simulation results are presented for a complete road trip in Sofia including the SOC of the battery, Human and Motor torque and other system parameters. Finally, in section IV a summary of the proposed model and possible future iterations are presented.

II. MODEL ASSUMPTIONS

The construction of an electrified vehicle involves the complicated interaction between mechanical and electrical subsystems. The block diagram of the modeled system is shown in Figure 1.

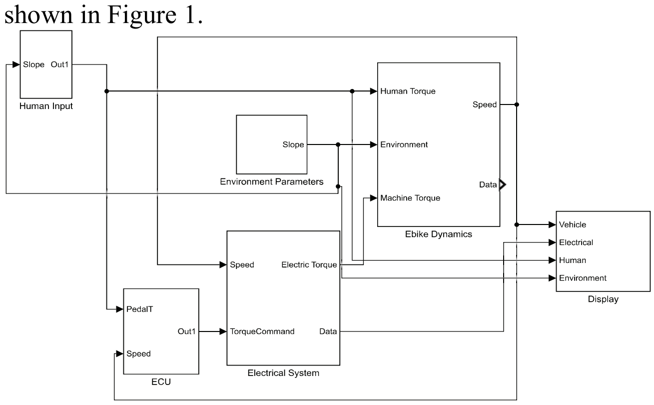

Figure 1. Block diagram of the modeled ebike

It consists of:

- Electrical subsystem - models the battery (Li-Ion is used) and BLDC Motor. The inverter controlling the motor is idealized, so the block only requires a reference for the torque.
- Electric Control Unit (ECU) - a control algorithm is implemented in Stateflow. It regulates the speed of the vehicle by varying the amount of torque reference given to the motor drive. The control algorithm takes as inputs the torque from the pedals and the vehicle speed. The motor is active only under 25km/h as is the law in Europe.

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• Environment block - supplies data for the grade of the route and the wind velocity. The grade is obtained on the basis of real data for a typical route in Sofia, Bulgaria. The wind velocity is taken as constant.

• Ebike dynamics block - implements a 1D model of the bike (rolling resistance and aerodynamic drag) and the gear mechanism for combining the two torques.

• Human input block - supplies data for the pedaling torque, obtained from the human cyclist. This torque is obtained from the crank radius, foot speed and the power supplied by the human rider [7], [8].

A brief description of each of the blocks is presented next.

A. Layout

Human power is taken as a simple exponential model, although more complicated models can be used [9]:

$$P = 85 + \frac{400}{t^{0.25}} \quad (1)$$

where P is the human power [W] and t is the time[s].

The average propulsive force that is applied to the pedal is calculated as:

$$F_{Ped} = P / S \quad (2)$$

where S – foot speed (m/s) or cadence.

Finally, as the torque applied to the pedal is pulsating and depends on the position of the foot, a typical sinusoidal variation is assumed and presented as:

$$T_{ped} = F_{Ped} R_{crank} \left| \sin\left(\Theta_{Ped} + \Theta^{*}\right) \right| \quad (3)$$

where R_{crank} - crank radius (m), Θ^{*} - Initial crank angle (rad), Θ_{Ped} -current crank angle (rad).

B. Environment block

The road slope has an influence on the human cadence, which results in torque ripple. To take into account this fact the human cadence has been modeled as a first order low pass filter as presented in [6]. The associated time constants prolong the simulation time, without giving much more insight into the system level modeling approach adopted here. A new approach is used here, where the function between the human cadence and road slope is taken as:

$$S = 1.6 + \frac{i}{5} \quad (4)$$

where i[deg] is the road incline. Assuming an average non-athlete human cadence of 50[rpm] the speed in [m/s] is calculated as 1.6[m/s] for a typical crank length of 160[mm].

The presented model of the human torque input is implemented as a Matlab function (with slope and time as inputs and Torque as output) in the human input block of the mode.

GPS data are used [10] in order to obtain accurate data for the slope along the road. The data are then imported in Matlab as 1-D Lookup table in Environment Parameters block and shown in Figure 1.

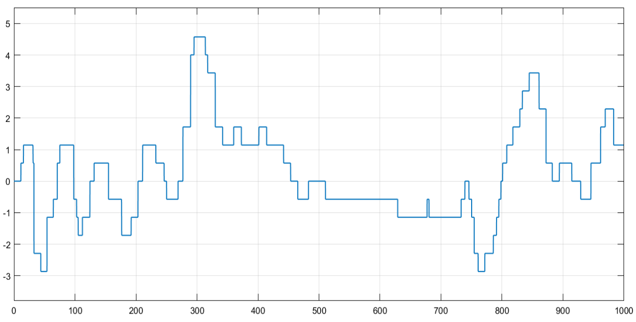

Figure 2. Road Grade in degrees

C. Electric Control Unit

The Control algorithm implemented in Stateflow is shown in Figure 3. The inputs are the pedal torque and vehicle speed and the output is the torque setpoint to the motor controller. The algorithm implements a simple hysteresis-band control of the motor torque setpoint.

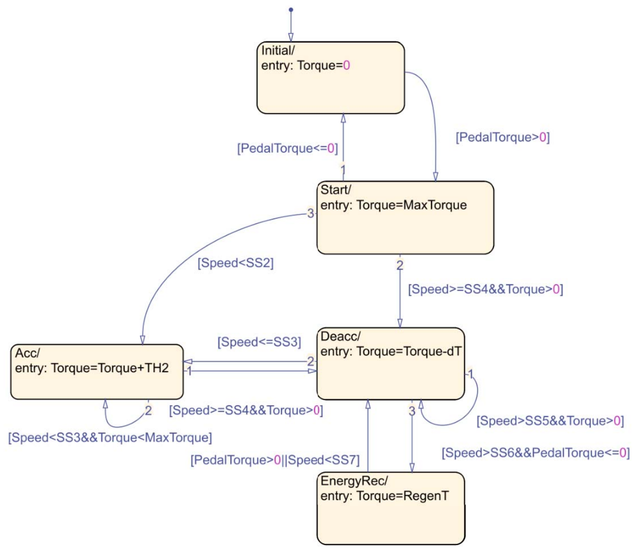

Figure 3. ECU control algorithm

In order to start the motor there must be torque input form the human cyclist. As such the electric bicycle is a of a pedelec type. If the Speed is above 25km/h the motor is shut down, as is the law in Europe. The model assumes that the cyclist requires maximum assistance from the motor, so the algorithm adjusts the torque command in order to regulate the speed around the maximum allowable speed.

A possible energy recovery is implemented in state EnergyRec, if the PedalTorque is less than 0 (the human has stopped pedaling) and the speed is high enough. In order to have PedalTorque less than zero a check is made in the human torque function comparing the current road slope to a set value. The idea is to emulate the possibility when the downward slope is too steep for the cyclist to stop pedaling and the excess energy to be recovered in the battery. This is an idealized situation but will be sufficient to check the potential advantage of energy recovery.

The model can be modified as in [5] to include mechanical braking, but the idea is to get a preliminary idea on the ideal possible energy recovery.

D. Electrical subsystem

The motor is taken from Simulink/Drivetrain library as a mapped motor, with parameters shown in Table 1. The torque/speed diagram of the motor, shown in Figure 3 is set by obtaining representative values from the available direct drive motors from Crystalite G25 rear wheel motor [11]. It should be noted that the motor controller is not modeled at the switching level, only its overall efficiency is set. This considerably speeds up the model simulation, which is useful for obtaining early data on the system behavior.

TABLE 1. MOTOR PARAMETERS

Motor and drive overall efficiency [%] @ 23.3rad/s 11.6Nm	86
Iron losses [W]	0
Torque control constant [s]	0.02

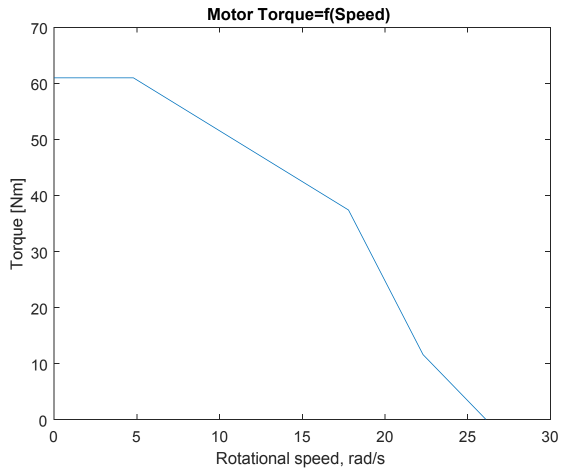

Figure 4. Used motor torque/speed diagram

The Datasheet Battery model from Simulink/Drivetrain block is used for the battery. Battery output voltage is determent from a lookup tables for a single cell of open-circuit voltage and the internal resistance, which are functions of the state-of charge (SOC) and battery temperature. This allows for the characterization of the cell performance at various operating points. The battery is assumed to be constructed from 9 cells in series and 2 stacks in parallel, with nominal battery of 10Ah. Initially the battery is assumed to be fully charged.

E. Ebike dynamics block

A 1D Vehicle body is used to model the bike dynamics and its main parameters are shown in Table 2. In order to simplify the model the bike is assumed to have ideal tires although rolling resistance can easily be included if more elaborate simulation model is needed. The data are obtained from available data on ebikes, presented in [12].

TABLE 2. BIKE PARAMETERS

Mass [kg]	120
Drag coefficient	1
Frontal Area [m^2]	0.8

III. RESULTS

A. No Energy Recovery

The motor must not be active for speeds over 25km/h. The model assumes that maximum pedal assistance is required, and the cyclist is moving at this top speed at all times, regardless of road slope. For such a case the human and motor torques are shown in Figure 3.

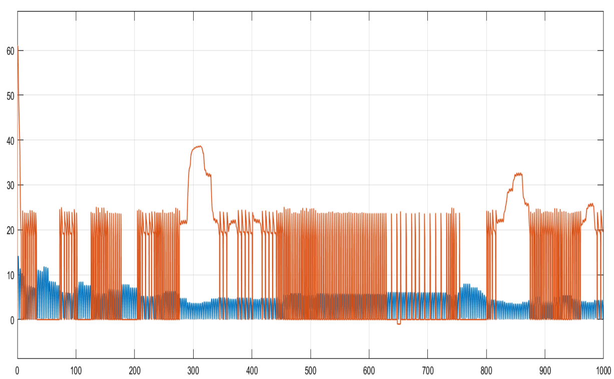

Figure 5. Human applied torque (blue)[Nm} and motor torque(orange)[Nm] without energy recovery

The resulting vehicle speed and road slope for such a case are shown in Figure 6.

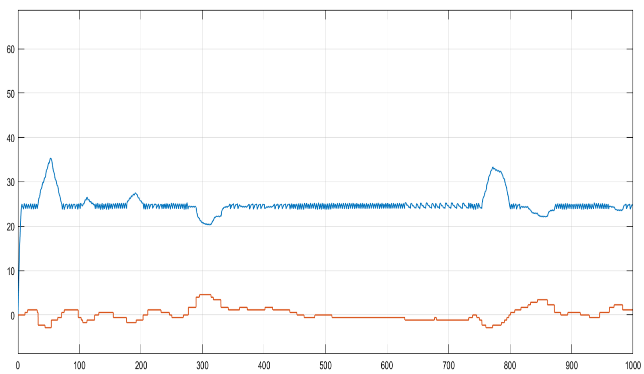

Figure 6. Vehicle speed (blue) [km/h] and road slope (orange)[deg] for the trip

The required motor power for this case is shown in Figure 7.

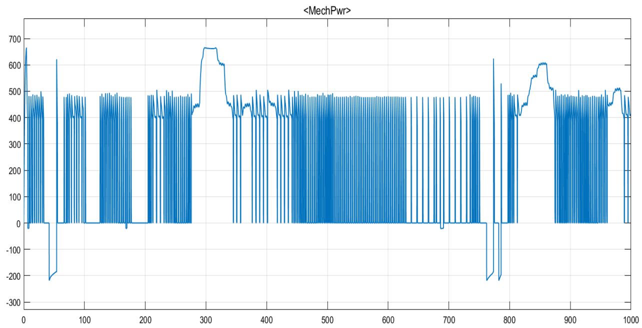

Figure 6. Motor power [W]

B. *With Energy Recovery*

If the control algorithm is augmented with the capability of energy recovery, which is activated only when the road slope is over 1[deg] the vehicle speed comparison is shown in Figure 7. The remaining Ah capacity in the battery for the case with and without energy recovery is shown in Figure 8.

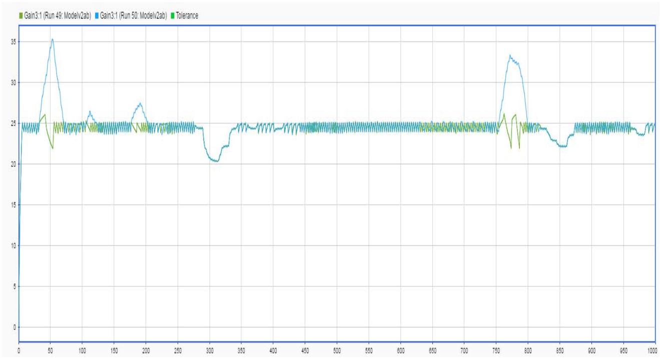

Figure 7 Vehicle speed with (green) and without (blue) energy recovery [km/h]

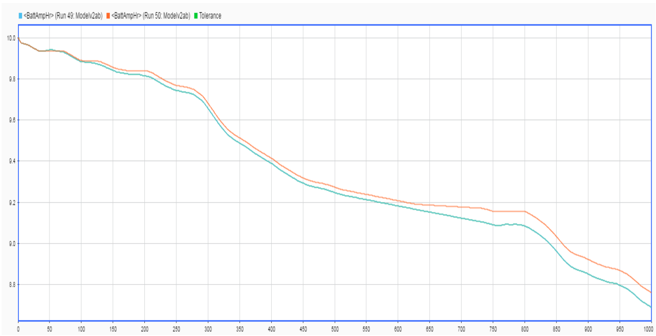

Figure 8. Battery AH capacity remaining [Ah] without energy recovery [green] and with energy recovery [orange]

It should be noted, that if a period when the speed is reduced to zero (for example stopping at traffic lights) is included in the actual driving cycle, the potential for energy recovery will be larger, but also the speed of the vehicle will be lower.

The case presented here is a preliminary result, which will be modified with experimental data. Despite this it can be seen that the added benefit of including an energy recovery is not large, probably in the range of 10% at most, probably less in the final variant.

However, it should be noted that not all electric motors that are sold are capable of energy recovery – the most attractive being the direct drive front or rear wheel motor. The freewheeling device installed in geared motors and center hub ones does not allow for regenerative braking.

IV. Conclusion

This paper considered the multi-domain nature of modeling an EPAC. A model of a parallel EPAC, consisting of a BLDC motor and Li-Ion battery is constructed in Simulink using the new Drivetrain block.

The presented model separately discussed regenerative and non-regenerative braking and its influence on the SOC of the used battery. It also presented a new approach to model the human cadence ripple induced by road slope and its influence on the overall operation of the system.

A physical system will be realized using the data acquired.

Acknowledgment

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