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Electrical vehicle modeling: A fuzzy logic model for regenerative braking

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ABSTRACT

This paper presents a fuzzy logic model of regenerative braking (FLmRB) for modeling EVs' regenerative braking systems (RBSs). The model has the vehicle's acceleration and jerk, and the road inclination as input variables, and the output of the FLmRB is the regeneration factor, i.e. the ratio of regenerative braking force to the total braking force. The regeneration factor expresses the percentage of energy recovered to the battery from braking. The purpose of the FLmRB development is to create realistic EV models using as least as possible manufacturers intellectual property data, and avoiding the use of EV on-board sensors. To tune the model, real data was gathered from short and long-distance field tests with a Nissan LEAF and compared with two types of simulations, one using the proposed FLmRB, and the other considering that all the braking force/energy is converted to electric current and returned back to charge the battery (100% regeneration). The results show that the FLmRB can successfully infer the regenerative braking factor from the measured EV acceleration and jerk, and road inclination, without any knowledge about the EV brake control strategy.

1. Introduction

Electric vehicles (EVs) have become a commercial transportation solution. According to the Electric Vehicles Initiative (http://www.iea.org), the aggregated goal for all countries with known deployment targets is 7.2 million in EV sales for 2020. However, nowadays autonomy is still one of the major obstacles to massive adoption of EVs, resulting in practice on EVs use being restricted to urban areas. In this context, the research and development of EV modeling and simulation tools, particularly aimed for road traffic analysis, plays an important role. For example, the implementation of algorithms for best route followed by EVs could lead to energy savings and to the improvement of vehicle autonomy range. A major advantage of EV systems is the possibility of energy regeneration during breaking. However, the amount of regenerated energy depends on how the vehicle implements the distribution of braking energy among the braking sub-systems, i.e. it depends on the amount of energy that is recovered to the battery pack and on the amount of energy released as heat in the mechanical brake system. Energy regeneration requires time to restore movement into energy. Large deceleration rates imply the major use of mechanical brakes (Ehsani et al., 2010), decreasing the degree of energy regeneration.

This paper proposes a fuzzy logic approach for modeling the braking force distribution in EV RBS. The EV model used here is an improvement of the model proposed in (Maia et al., 2011). There are three main advancements. First, motivated by the fact that there are no equal batteries, the real voltage and current information is used for battery modeling instead of using a general lookup table built for the battery model being used (that typically would be provided by the manufacturer). Second, a better approximation is employed for the computation of the equivalent mass of the vehicle's rotating parts, giving a more accurate result. Third, a generic fuzzy logic framework is proposed for modeling existing regenerative braking systems, specifically for designing a FLmRB which models the distribution of total braking torque between mechanical non-regenerative torque (e.g. friction-based) and regenerative torque. The results of the proposed FLmRB were compared with real-world data obtained with a Nissan LEAF in road tests. Although the FLmRB has been designed and verified with a Nissan LEAF EV, the FLmRB framework is targeted to design suitable models for any EV by adjusting the fuzzy logic rules using human expert knowledge, or by using an intelligent optimization method, such as the hierarchical genetic algorithm proposed in (Mendes et al., 2013), to learn/improve the structure and parameters of the fuzzy model.

The paper is organized as follows. Section 2 introduces related work. In Section 3, the EV model is given. The FLmRB framework is designed in Section 4. In Section 5, simulations, experiments with a Nissan LEAF EV and corresponding results are presented. Finally, Section 6 gives concluding remarks.

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Nomenclature

α	inclination angle of the road (upward-sloping or downward-sloping) [rad]
β	ratio of regenerative braking force to the total braking force
η_b	battery efficiency
η_m	motor efficiency
η_t	transmission and gears efficiency
μ_{rr}	coefficient of rolling resistance of the tire
ω_{rad}	motor angular speed [rad/s]
ω_{rpm}	motor angular speed (revolutions per minute)
ρ	air density [kg/m^3]
τ_g	torque required by gearbox/transmission [N m]
τ_b	braking torque [N m]
τ_{max}	motor maximum tractive torque [N m]
τ_{mechF}	braking torque on front wheels [N m]
τ_{mechR}	braking torque on rear wheels [N m]
τ_{mech}	mechanical braking torque [N m]
τ_{min}	motor maximum braking torque [N m]
τ_{reg}	regenerative braking torque [N m]
τ_{req}	torque required from the motor [N m]
τ^+_{req}	torque required from the motor on traction events [N m]
τ^-_{req}	torque required from the motor on braking events [N m]
A	frontal area of the vehicle [m^2]
a	vehicle acceleration [m/s^2].
C	battery capacity [A h]
C_d	vehicle's drag coefficient
E_{oc}	open circuit voltage [V]
F_{ad}	aerodynamic drag force [N]
F_{hc}	hill climbing force [N]
F_{la}	linear acceleration force [N]
F_{rr}	rolling resistance force [N]
F_{te}	tractive effort [N]
G	gear ratio
g	acceleration due to gravity [m/s^2]
I_{bat}	battery current [A]
φ	jerk, the derivative of acceleration [m/s^3]
K_0	battery parameter
K_1	battery parameter
K_2	battery parameter
K_3	battery parameter
K_4	battery parameter
m_c	curb weight (vehicle mass with battery pack) [kg]
m_I	vehicle equivalent mass increase due to the angular moments of the rotating components [kg]
m_v	total vehicle mass, with load and occupants masses [kg]
P_{acc}	power consumed by accessories [W]
P_{req}	required power from battery [W]
r	wheel radius [m]
R^+_{in}	battery internal resistance [Ω]
R^-_{in}	battery internal resistance [Ω]
SOC	battery state of the charge
SOC_0	SOC at beginning of the test
T_a	set of linguistic terms defined for the acceleration a [m/s^2]
T_φ	set of linguistic terms defined for φ [m/s^3]
T_α	set of linguistic terms defined for α [rad]
T_β	set of linguistic terms defined for β
V_t	battery pack terminal voltage [V]
v	vehicle speed [m/s]

2. Related work

Several works have proposed approaches for implementation of braking strategies. In Aleksendrič et al. (2012), an intelligent control strategy to control the pressure of the brake actuator using artificial neural networks is proposed and implemented in an microcontroller. While the aim of the method was to improve the braking process, it cannot be applied to quantify the distribution of the total braking torque between mechanical non-regenerative torque, and regenerative torque in electronic braking systems in EVs. García et al. (2013) presented five control strategies for energy management systems in fuel cell vehicles. Although fuel cell vehicles are unable to perform energy regeneration, this drawback was reduced by combining the fuel control system with an energy store system, such as a battery, a supercapacitor, or a combination of both. By placing focus on regenerative braking, Cheng and Ye (2011) proposed a GA-based neural network to design an energy recovery system for an electric motorcycle. Zhang et al. (2010) designed a regenerative braking force controller based on fuzzy logic using desired braking force, vehicle speed, and battery state of the charge (SOC) as the inputs, and the ratio of the regenerative braking force as the output. It also uses battery temperature to produce a compensation coefficient in order to limit the regenerated current. A control strategy using a couple of fuzzy logic controllers is studied by Chu et al. (2011b) for adjusting the braking force allocation. As input information, it is used the brake pedal displacement, and the slip ratio of the wheel, not being useful in traffic simulators.

Other similar proposals for new or improved regenerative braking strategies can be found by Xu et al. (2011) and Nian et al. (2014). The works cited above in this paper propose either new strategies to perform regenerative braking or some improvement to some already existing RBS. However, there is a lack of an RBS modeling methodology that can be applied in a variety of existing (and specific) EVs for building an RBS model of the distribution of total braking torque between mechanical non-regenerative torque (e.g. friction-based) and regenerative torque. The goal of the work presented in this paper is to develop a methodology for building models of RBS strategies, rather than developing a RBS strategy.

3. Electric vehicle modeling

This section briefly presents how the EV was modeled and which characteristics were included in the model. The EV model herein formulated, shown schematically in Fig. 1, is based on Larminie and Lowry (2003) and Ehsani et al. (2010). The modeling architecture can be adapted to be used in traffic simulators, such as the SUMO simulator (Krajzewicz et al., 2012), or simulators which are based on Simulink. The system has three subsystems: *Wheel & Gear Subsystem*, *Power Driver Subsystem*, and *Energy Storage Subsystem*. The subsystems will be presented in the following subsections.

3.1. *Wheel & Gear Subsystem*

The *Wheel & Gear Subsystem* takes from the vehicle drive data, the time-referenced speed v and (road) inclination angle α as input variables and produces five outputs: torque required by gearbox τ_g, motor angular speeds ω_{rpm} and ω_{rad}, acceleration, a, and derivative of the acceleration, the Jerk, φ. To obtain τ_g, the mechanical force F_{te} needed to produce the desired speed at inclination α has to be calculated. This mechanical effort F_{te}, i.e. the force transmitted by the motor to the gearbox/transmission and from this to the vehicle