Modeling IVC-based Energy Savings of Electric Vehicles

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***Abstract*—In this paper we present an easy-to-implement model that allows to determine the potential energy savings of regenerative braking (also: recuperation) for Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) by exploiting Inter-Vehicle Communication (IVC). The proposed model has been designed to be applied within different braking scenarios: approaching traffic lights, stop-and-go, emergency brakes, or platooning, among others. Furthermore, the model has been implemented in MATLAB allowing not only to simulate numerous braking scenarios but also to extend it by adding IVC-related parameters like latency or packet-loss. The corresponding results can be carried over to large-scale scenarios by taking into account different equipment rates of both the number of EVs and the availability of Intelligent Transportation Systems (ITS).**

***Index Terms*—Electric Vehicles; Recuperation; Regenerative Braking; Physical Model; Inter-Vehicle Communication;**

I. Introduction and Related Work

Due to the lack of direct CO_2 emissions, Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) are not only believed to alleviate the global warming phenomenon but also to considerably lessen the degree of dependence on fossil fuels like petroleum and natural gasses. Intelligent Transportation Systems (ITS) include the possibility to efficiently exchange information among vehicles and between vehicles and various types of infrastructure, and offer a broad range of applications [1].

In a previous article, we showed that by using Green Light Optimal Speed Advisory (GLOSA) systems the CO_2 emission can be significantly reduced [2]. However, in certain cases it is not possible for the driver to accelerate in order to pass the current green phase or decelerate in order to pass the next green phase.

While Inter-Vehicle Communication (IVC) was shown to be able to help improve traffic safety [3], [4], the positive impact on the environment and comfort is also an important factor in successfully bringing this technology onto the market.

This particularly applies to EVs and HEVs when considering their limited battery capacity and the corresponding range anxiety. In this context, regenerative braking means recovering energy while decelerating or coasting, and recharging the vehicle's battery, thereby saving energy and increasing the driving range. Obviously, the required braking force depends on the driving situation, e.g., considering a vehicle approaching a traffic light or an emergency brake at the tail of a traffic jam. From a technical point of view, the recuperation module might only induce a maximum braking force (also: decelerating momentum); if this force is insufficient, conventional (disc or drum) brakes are required. Such braking systems transform kinetic energy into thermal energy (caused by friction), which in contrast cannot be stored for future use.

There exist various approaches to increase the efficiency of the braking/recuperation process among others in [5] and [6]. However, this article will focus on the potentials enabled by ITS: the earlier an IVC-based application can suggest an optimal speed trajectory, the more energy can be saved.

In this article, we will first introduce a model allowing to calculate the optimal speed trajectory in order to achieve the best energy balance depending on the driving situation. Based on that, a MATLAB implementation of the proposed model has been implemented to investigate different driving situations. It will be shown that the amount of driving situations where conventional brakes are required can be reduced by IVC-based applications—allowing to maximize the retrieved energy.

The remainder of the article is as follows. First, the derivation of our physical model is presented in Section II. In Section III, simulation results for a vehicle approaching a traffic light are shown. Finally, the paper is concluded in Section IV and potential future work is discussed.

II. Physical Model

In this section, we describe the physical model used to calculate the optimal speed trajectory to reach a desired speed level in the most energy-efficient way.

A. The Vehicle's Kinetics During Freewheeling

In the following, the calculation of the energy flows—based on the forces affecting the vehicle during freewheeling—are shown. Note, that the potential energy which is caused by the downhill force is neglected.

$$F_{\text{Accel}} = m \cdot a \tag{1}$$

$$F_{\text{Air}} = \frac{1}{2} \cdot c_A \cdot \rho \cdot A \cdot v(t)^2 \tag{2}$$

$$F_{\text{Roll}} = c_R \cdot m \cdot g \tag{3}$$

While F_{Accel} denotes the force accelerating the car, F_{Air} and F_{Roll} denote the air- and rolling resistance, respectively. The parameters m, c_A, ρ, A, c_R, and g are specified in Table I.

Table I
PARAMETERS AND THEIR VALUES

Parameter	Symbol	Value
Air drag coefficient	c_A	0.32
Air density at 20 °C	ρ	1.2041 $^{kg}/_{m^3}$
Car's cross sectional area	A	$2\,m^2$
Rolling resistance coefficient	c_R	0.015
Vehicle weight	m	1400 kg
Gravitational acceleration	g	9.81 $^{m}/_{s^2}$
Efficiency factor recuperation	η	0.6

Based on the laws of motion the following differential equation can be derived:

$$m \cdot \frac{\mathrm{d}v(t)}{\mathrm{d}t} = -\frac{1}{2} \cdot c_A \cdot \rho \cdot A \cdot v(t)^2 - c_R \cdot m \cdot g \tag{4}$$

For the sake of readability we substitute all constant values to rewrite (4) as follows:

$$\frac{\mathrm{d}v(t)}{\mathrm{d}t} = -c_1 \cdot v(t)^2 - c_2, \text{ where} \tag{5}$$

$$c_1 := \frac{c_A \cdot \rho \cdot A}{2 \cdot m} \text{ and}$$

$$c_2 := c_R \cdot g$$

For a given initial speed v_0, the following function will solve the differential equation (5):

$$v(t) = \sqrt{\frac{c_2}{c_1}} \cdot \tan\left[\arctan\left(v_0 \cdot \sqrt{\frac{c_1}{c_2}}\right) - \sqrt{c_1 \cdot c_2} \cdot t\right] \tag{6}$$

Now, let an initial speed v_0 and a target speed v_1 be given, and let the forces affecting the car be restricted to air- and rolling resistance (also: freewheeling). The time t_1 after which the vehicle will reach v_1 can be derived using the following equation:

$$t_1 = \frac{\arctan\left(v_0 \cdot \sqrt{\frac{c_1}{c_2}}\right) - \arctan\left(v_1 \cdot \sqrt{\frac{c_1}{c_2}}\right)}{\sqrt{c_1 \cdot c_2}} \tag{7}$$

Given t_1, the distance the vehicle will cover (again by freewheeling, only) can be determined by $s(t) = \int v(t)\,\mathrm{d}t$. By introducing the following three constants we present a closed-form solution in (13). Let

$$k_1 := \sqrt{\frac{c_2}{c_1}}, \tag{8}$$

$$k_2 := \arctan\left(v_0 \cdot \sqrt{\frac{c_1}{c_2}}\right), \text{ and} \tag{9}$$

$$k_3 := \sqrt{c_1 \cdot c_2}, \tag{10}$$

then we can compute the distance as follows:

$$s(t_1) = \int_0^{t_1} k_1 \cdot \tan\left(k_2 - k_3 \cdot t\right) \mathrm{d}t \tag{11}$$

$$= \left[\frac{k_1}{k_3} \ln\left|\cos\left(k_2 - k_3 \cdot t\right)\right|\right]_{t_0=0}^{t_1} \tag{12}$$

$$= \frac{k_1}{k_3} \ln\left|\cos\left(k_2 - k_3 \cdot t_1\right)\right| - \frac{k_1}{k_3} \ln\left|\cos\left(k_2\right)\right| \tag{13}$$

Summing up, with a given t_1 (equation (7)) we can compute the distance $s(t_1)$ the vehicle has covered until it reaches v_1, when considering rolling and air resistance only.

B. Calculation of the Potential Energy Savings

The energy balance of braking vehicles can be represented as follows:

$$E_{\text{Kin}} = E_{\text{Roll}} + E_{\text{Air}} + E_{\text{Recu}} + E_{\text{Brake}}, \text{ where} \tag{14}$$

$$E_{\text{Kin}} = \frac{1}{2} \cdot m \cdot v^2(t_0), \tag{15}$$

$$E_{\text{Roll}} = c_R \cdot m \cdot g \cdot v(t), \tag{16}$$

$$E_{\text{Air}} = \frac{1}{2} \cdot c_A \cdot A \cdot \rho \cdot v^3(t), \tag{17}$$

and E_{Recu} and E_{Brake} denote the energy that is recuperated or wasted by the mechanical brakes, and t_0 marks the start of the maneuver.

Obviously, the main goal of regenerative braking is to minimize the power consumed by the rolling and air resistance and to recuperate most of the remaining kinetic energy while avoiding braking mechanically.

In the following, we assume an IVC-based application being able to inform the driver/vehicle about the following parameters

- v_{end}, the target speed to reach
- s_{end}, distance to the point when v_{end} has to be reached,

for example when approaching a speed limit sign. Now let's assume that a vehicle—currently driving at speed v_0—needs to reduce its speed to v_{end} and let the only forces decelerating the vehicle be the rolling and air resistance. The distance which the vehicle will cover can be calculated according to (7) and (13). Based on the calculated $s(t_1)$ and s_{end}, the following three cased can be distinguished:

1) $s(t_1) < s_{\text{end}} \rightarrow$ no speed reduction required, keep current speed or even increase speed.
2) $s(t_1) \approx s_{\text{end}} \rightarrow$ no further speed reduction required, roll- and air resistance sufficient during freewheeling.
3) $s(t_1) > s_{\text{end}} \rightarrow$ speed reduction required, roll- and air resistance insufficient, initiate optimal recuperation.

In the following, we only focus on the third case. Since the air resistance depends quadratically on a vehicle's speed—see (2)—it is recommended to recuperate as much energy as possible with the highest recuperation torque available at the beginning of the braking maneuver, while freewheeling in the end phase. Figure 1 shows an example speed trajectory, where the speed of the car is reduced from v_0 to v_{free} by using recuperation (phase I) and further to v_{end} with freewheeling (phase II), respectively. Here, the speed level v_{free} denotes the velocity which a vehicle has to possess to reach the destination point s_{end} with the target speed level v_{end}—by freewheeling.

In general, the maximal recuperation energy can be determined based on the kinetic energy, see (15). Since the vehicle's speed v_0 needs to be reduced by some term Δv, the maximal possible recuperation energy is given by:

$$E_{\text{Brake}} = \frac{1}{2} \cdot m \cdot v_0^2 - \frac{1}{2} \cdot m \cdot v_{\text{free}}^2 \tag{18}$$

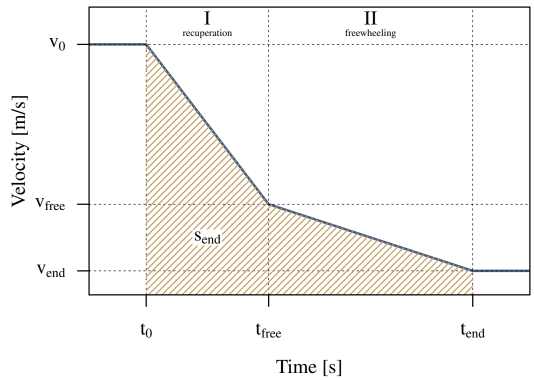


Figure 1. Scheme of generic regenerative braking maneuver

In order to obtain v_{free}, s_{end} is inserted in (13) to calculate a time t, first. Inserting t into (6) allows to reveal v_{free}—by doing so, v_0 in k_2 of (9) is no longer constant but turning into v_{free}.

Next, the actual recuperable energy is determined. Let a time interval $[t_0; t_1]$, the rotational speed of the engine $n\,(v(t))$, and the maximal recuperation moment $M_{\text{Recu}}(n)$ be given (cf. Figure 2). Then the recuperation energy can be calculated as follows (cf. [7]):

$$E_{\text{Recu}} = \int_{t_0}^{t_1} \eta \cdot P_{\text{Recu}}\,\mathrm{d}t \tag{19}$$

$$= \int_{t_0}^{t_1} \eta \cdot 2 \cdot \pi \cdot n\,(v(t)) \cdot M_{\text{Recu}}\,\mathrm{d}t$$

$$= \eta \cdot \frac{R_{\text{w2e}}}{r} \cdot M_{\text{Recu}} \cdot \int_{t_0}^{t_1} v(t)\,\mathrm{d}t$$

$$= \eta \cdot \frac{R_{\text{w2e}}}{r} \cdot M_{\text{Recu}} \cdot s_{\text{end}} \tag{20}$$

In (20), R_{w2e} denotes the ratio between wheels' and engine's rotations while r is the radius of the wheels.

Note, that if $E_{\text{Brake}} > E_{\text{Recu}}$ the vehicle might not recuperate the whole energy until arriving at the destination. In this case, conventional brakes are required to reach the given speed level v_{end} and $E_{\text{Brake}} - E_{\text{Recu}}$ is transformed into heat.

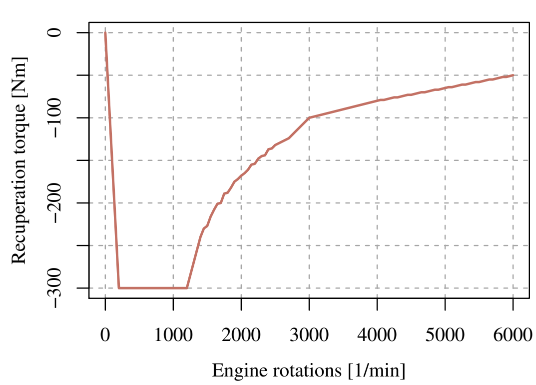


Figure 2. Maximal recuperation torque depending on the vehicle's speed

III. Simulation

The presented model has been implemented in MATLAB (R2014b) allowing to study the effects of various braking scenarios. Each scenario is parametrized by providing a start and end velocity v_0 and v_{end} as well as the distance s_{end} when the given speed level v_{end} has to be reached. In addition to that, a further parameter is required: the distance s_{inf} left to the destination when the driver/vehicle retrieves information on the new speed level.

Figure 3 summarizes the results for the following experiment: The vehicle has an initial speed of $14\,\mathrm{m/s}$ and a traffic light is positioned $500\,\mathrm{m}$ away, while the vehicle has no chance to pass the traffic light in any green phase ($v_0 = 14\,\mathrm{m/s}$, $v_0 = 0\,\mathrm{m/s}$, $s_{\text{end}} = 500\,\mathrm{m}$). Based on that, three different distances s_{inf} are considered: $500\,\mathrm{m}$, $300\,\mathrm{m}$, and $100\,\mathrm{m}$.

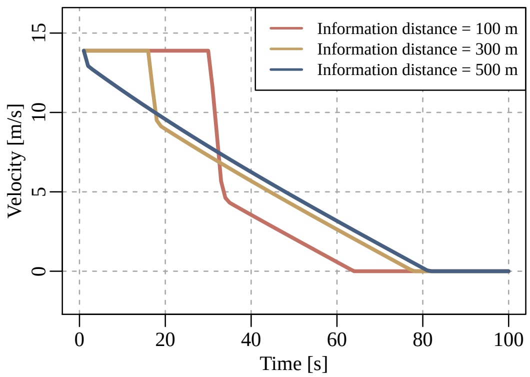
We assume that drivers will remain at the current velocity and will only start decelerating at the time they are informed. The different points of information can be interpreted as the point of receiving a message via IVC or visually recognizing a switching traffic light, respectively.

Figure 3a shows the most efficient driving strategies given a certain information distance. When informed late (red line, $100\,\mathrm{m}$), the optimal approach is to first fully recuperate (brake) and then freewheel to the traffic light. With increasing information distance (yellow line), the driver is able to shorten the recuperation interval and to increase the duration of freewheeling leading to a better energy balance. In the ideal scenario (blue line), the driver can almost exclusively freewheel the remaining distance. Note, that all three trajectories cover the same distance, however, the red and yellow trajectories arrive at the traffic light earlier due to the fact that they spent more time driving with a higher (constant) velocity.

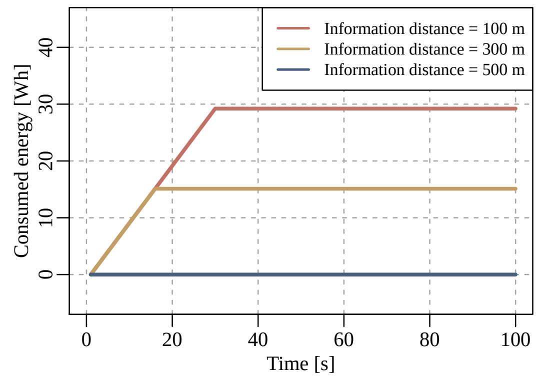
Figure 3b shows the required energy to carry out the optimal driving strategies shown in Figure 3a. As can be seen, holding the current velocity by overcoming air and rolling resistances drains the battery. The later a driver is informed, the longer they remain at a suboptimal driving strategy, missing the opportunity to recharge the battery.

In Figure 3c we draw the energy fed back to the battery through recuperation. The more sharply the vehicle brakes (not using the mechanical brakes), the more the battery is recharged. Intuitively this might lead to the conclusion that it is desirable to recuperate as much and as strong as possible, however, Figure 3d shows that the total energy balance for the traffic light approach is negative for all but the blue line, where the vehicle almost does not recuperate at all. At shorter information distances, the vehicles were not able to recuperate as much energy as they consumed earlier holding their velocity v_0. Our results show that with sufficiently long information distance s_{end}, a vehicle is able to reach $v_1 < v_0$ with a positive energy balance recharging the battery and thus increasing the driving range.

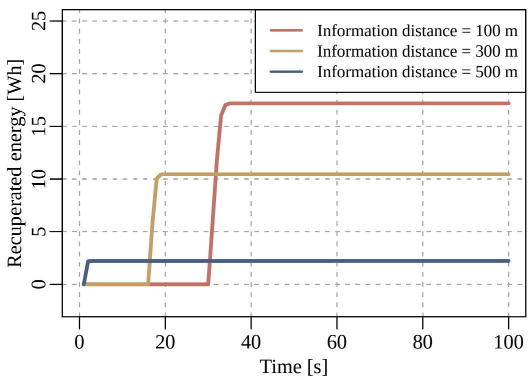
Please note, that the effect of choosing the best point in time to change from recuperation to freewheeling becomes more prominent at larger speeds, as the air resistance has a cubic influence on the consumed energy.



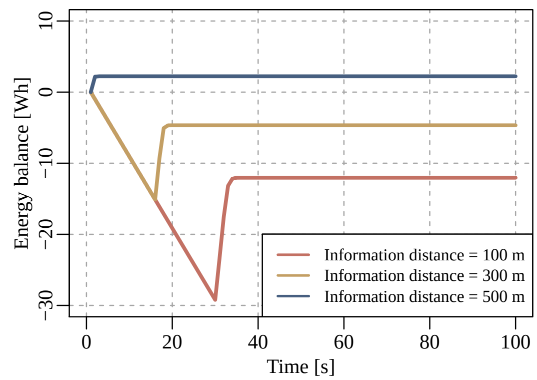
(a) Speed profiles



(b) Consumed energy



(c) Recuperated energy



(d) Energy balance

Figure 3. Simulation results for efficiently approaching a traffic light with different times of information

IV. Conclusion and Future Work

In this paper, we presented a model to calculate the optimal speed trajectory for vehicles that need to achieve a desired speed level within a certain information distance. Inter-Vehicle Communication can increase this information distance and thereby improve the energy balance of EVs and HEVs as shown by our model. Our simulation results showed that we can considerably reduce the consumed energy if vehicles are informed about a braking maneuver in time.

As future work, we want to integrate our model into our Veins-based [8] simulation framework [7] to study the impact of optimal speed trajectories on greater vehicle fleets. This allows us to investigate the effect of small scale braking maneuvers in denser traffic, e.g., when a vehicle informs succeeding cars about upcoming decelerations in a timely manner. This furthermore enables research towards electrified platoons and thereby energy efficient strategies for autonomous vehicles.

V. Acknowledgment

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