

Management of Kinetic and Electric Energy in Heavy Trucks

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04/12/2010Erik Hellström, Jan Åslund and Lars Nielsen
Linköping University

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ABSTRACT

Hybridization and velocity management are two important techniques for energy efficiency that mainly have been treated separately. Here they are put in a common framework that from the hybridization perspective can be seen as an extension of the equivalence factor idea in the well known strategy ECMS. From the perspective of look-ahead control, the extension is that energy can be stored not only in kinetic energy, but also electrically. The key idea is to introduce more equivalence factors in a way that enables efficient computations, but also so that the equivalence factors have a physical interpretation. The latter fact makes it easy to formulate a good residual cost to be used at the end of the look-ahead horizon. The formulation has different possible uses, but it is here applied on an evaluation of the size of the electrical system. Previous such studies, for e.g. ECMS, have typically used a driving cycle, i.e. a fix velocity profile, but here the extra freedom to choose an optimal driving pattern is added.

INTRODUCTION

Hybridization allow recovery of brake energy, optimization of the energy distribution between engine and motor, and reduction of losses due to idling and clutching, and may allow downsizing of the heat engine [1]. These possibilities may yield better fuel economy and lower emissions despite the fact that a vehicle with a hybrid powertrain typically is heavier than with a conventional powertrain.

Another upcoming technology is look-ahead control where, with a conventional powertrain, there is a possibility to save fuel by taking information about the upcoming road topography into account. Fuel-optimal algorithms that utilize such information have lately been evaluated experimentally [2]. A system that adapts the velocity to the road topography

was also recently launched by Daimler Trucks North America in collaboration with NAVTEQ [3].

Combining these two ideas in a hybrid powertrain gives extra degree of freedom in the power flows, and information about the road topography is valuable for selecting the power distribution in an optimal way. The power to mass ratio of heavy trucks leads to that significant downhills, where the vehicle accelerates without engine propulsion, and significant uphill, where the vehicle decelerates despite maximum engine power, are common on highways. Therefore the optimal control law is expected to be position-variant and, for the hybrid case, the energy management of both kinetic and electrical energy is important. These are features that distinguishes the problem from related work on passenger cars [4, 5, 6] and light-duty vehicles [7, 8] where predefined drive cycles are used or time-invariant feedback controllers are derived from stochastic control.

The purpose of this paper is to study fuel-optimal management of kinetic and electric energy in heavy trucks traveling on open roads. The main contribution is the formulation of fuel equivalents that relate a change in time, kinetic energy, or electrical energy to a change in consumed fuel. The following sections present background on the scenario, the problem objective, and a model for the relevant dynamics. The potential gain in fuel economy is then investigated and it is demonstrated that simultaneous management of kinetic and electrical energy is important. After that, the fuel equivalents are derived. These equivalents are used to formulate a look-ahead control scheme that efficiently solves the minimum-fuel problem. Finally, powertrains with different sizes of the electrical system are compared to a conventional powertrain by computing the optimal solution.

BACKGROUND

For heavy trucks up to class 7, hybridization has been identified as a technology that could improve fuel economy substantially [9, 10, 11]. The ideal candidates are vehicles mainly operating in urban areas with stop-and-go conditions, such as transit buses and delivery trucks. For these applications, e.g., engine downsizing and regenerative braking are expected to yield good results.

For the heaviest trucks in class 8, weighing more than 15 tonnes, there is less room for improvement. These trucks typically travels on open road at operating points with high efficiency and significant downsizing requires heavy motors due to the high power requirements [9, 10]. On the other hand, they are a large consumer of fuel, e.g., in the U.S. class 8 trucks consume about 68% of all commercial truck fuel used, and 70% of this amount is spent traveling on open road with a trip length of more than 100 miles [9]. Thus, any technology that improves truck efficiency will have the best benefit for this class. The first targets for class 8 trucks are applications where the drive pattern yields an expected good utilization of the hybridization, such as regional delivery or drayage applications [12]. When such hybrid powertrains matures, long-haul applications are further developments.

OBJECTIVE

To achieve cost reductions, the objective is to minimize the fuel mass M required for a drive mission with a given maximum trip time T_0 :

$$\begin{aligned} &\text{minimize } M \\ &\text{subject to } T \leq T_0 \end{aligned} \quad (PI)$$

The control inputs are the torques from the combustion engine and from the electrical motor, respectively, together with the brakes, and the gear shifts. The control signals are fueling u_e , electrical motor voltage u_m , brake torque u_b , and gear selection u_g . The road slope is a function of position, and it is therefore natural to use spatial coordinates. A simple model may then have, e.g., velocity and state of charge as states.

Table 1. Longitudinal forces.

F_a	Air drag	$\frac{1}{2}c_w A_a \rho_a v^2$
F_r	Rolling resistance	$mg c_r \cos \alpha$
F_g	Gravitational force	$mg \sin \alpha$

A straightforward way to handle the trip time constraint is to include time as an additional state [13].

TRUCK MODEL

A model for the dynamics of a hybrid electrical truck is formulated [14, 1]. For the longitudinal motion, kinetic energy is used as state. This has been shown to be beneficial in the case of a conventional powertrain since it allows for simple integration and linear interpolation on coarse grids [13]. It is later shown that this formulation is suitable for a hybrid powertrain as well.

LONGITUDINAL MOTION

The prime movers are a combustion engine and an electrical motor. The torques from the engine T_e and the motor T_m torque are given by

$$T_e = f_e(\omega, u_e), \quad T_m = f_m(\omega, u_m) \quad (1)$$

where ω is the rotational speed, u_e is the engine fueling, u_m is the motor voltage, f_e is a lookup table originating from measurements, and f_m is specified below. The torque from the engine and motor is assumed to be combined between the crankshaft and the transmission by direct coupling. The torque at the flywheel is then

$$T_t = T_e + T_m \quad (2)$$

The components of the driveline, such as propeller shafts and drive shafts, are assumed stiff and no clutches are modeled. The combined conversion ratio of the transmission and final drive, denoted by i , and their efficiency, denoted by η , are functions of the gear number u_g . The models of the resisting forces are given in Table 1.

Use the relation $v = \frac{r_w}{i} \omega$ where r_w is the effective wheel radius and the mass factor $c_m = 1 + \frac{i^2 \eta I_1 + I_2}{m r_w^2}$ where I_1 , I_2 are lumped inertia before and after the transmission respectively. The dynamics for the velocity v is then

$$\frac{dv}{dt} = \frac{1}{c_m m} \left(\frac{i \eta}{r_w} T_t - \frac{u_b}{r_w} - (F_a + F_r + F_g) \right) \quad (3)$$

where all model parameters are explained in Table 2. By introducing kinetic energy $e = \frac{1}{2} m v^2$ and noting

Table 2. Truck model parameters.

$I_{1,2}$	Lumped inertia	c_w	Air drag coefficient
m	Vehicle mass	A_a	Cross section area
r_w	Wheel radius	ρ_a	Air density
g	Gravity constant	c_r	Rolling res. coeff.

that $\frac{de}{ds} = mv \frac{dv}{ds} = m \frac{dv}{dt}$ where s is position, the model is finally written as

$$c_m \frac{de}{ds} = \frac{i\eta}{r_w} T_t - \frac{u_b}{r_w} - (F_a + F_r + F_g) \quad (4)$$

BUFFER DYNAMICS

The amount of energy in the electrical buffer is denoted by b . The dynamics is governed by the power P_b , and the convention is that when P_b is positive, energy flows from the buffer, and energy is stored in the buffer when P_b is negative. The dynamics becomes

$$\frac{db}{dt} = v \frac{db}{ds} = -P_b \quad (5)$$

The power P_b equals the motor power. Thus

$$\eta_m P_b = \omega T_m \quad (6)$$

where η_m is the motor efficiency that is less than unity when P_b is positive and greater than unity when P_b is negative.

An electrochemical battery is used as the buffer in the evaluation later on. The battery is modeled by an internal resistance model [15]. This is an equivalent circuit that consists of a voltage source, with open-circuit voltage U_{oc} , in series with a resistor with resistance R_i . The battery voltage U is

$$U = U_{oc} - R_i I_b \quad (7)$$

where the current I_b is determined by

$$I_b = \frac{1}{2R_i} \left(U_{oc} - \sqrt{U_{oc}^2 - 4R_i P_b} \right) \quad (8)$$

The battery voltage is limited to an interval $U \in [U_{min}, U_{max}]$ which yields limits for the maximum current and power for discharging and charging respectively.

FUEL CONSUMPTION

The mass flow of fuel $\dot{m}$ is determined by the fueling level u_e and the engine speed ω ,

$$\dot{m} = \frac{n_{cyl}}{2\pi n_r} \omega u_e = \frac{n_{cyl}}{2\pi n_r} \frac{i}{r_w} v u_e \quad (9)$$

where n_{cyl} is the number of cylinders and n_r is the number of engine revolutions per cycle. The consumed fuel mass per unit distance is $\dot{m}/v$.

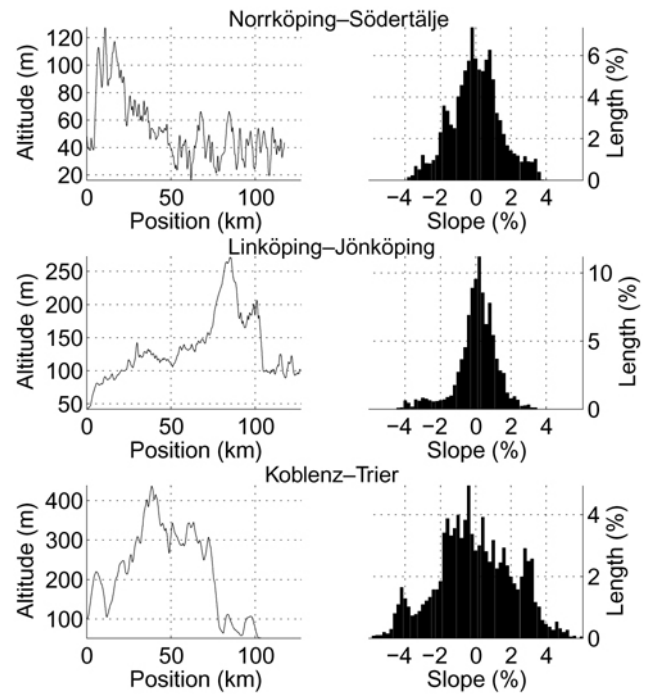


Figure 1. Altitude profile (in one direction) and distribution of road slope values (in both directions) for three different routes.

RECOVERING BRAKE ENERGY

The fuel economy can be improved by reducing the brake energy. A preliminary analysis is made to investigate the potential gain and the requirements on a storage system in terms of energy, power, and efficiency. It is demonstrated that, with an additional energy buffer, management of both kinetic and buffer energy is important.

The scenario considered is highway driving. The desired velocity profile is constant speed adjusted for the desired trip time. However, constant speed is not feasible for a heavy truck on all road topographies since in significant downhills the vehicle accelerates without engine power and in significant uphill the vehicle decelerates despite maximum engine power [13]. Braking is typically required to limit the

speed with respect to legal and safety requirements or to adapt the speed to a preceding vehicle.

Figure 1 shows two routes from Sweden and one from Germany. From the altitude profile and road slope distribution it is clearly seen that these routes have different characteristics, and this leads to different usage of the brakes.

The numerical results in this section are obtained with a 360hp conventional powertrain controlled by a cruise controller (CC), and a gross weight of 40 tonnes.

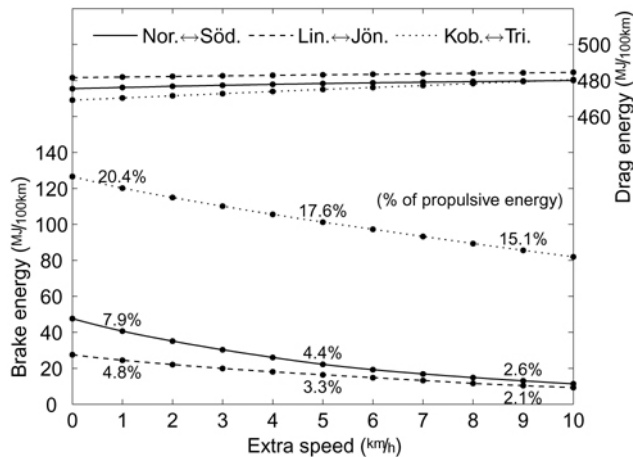


Figure 2. Energy consumed by drag and brake forces with CC and different values for the extra speed allowed in downhills.

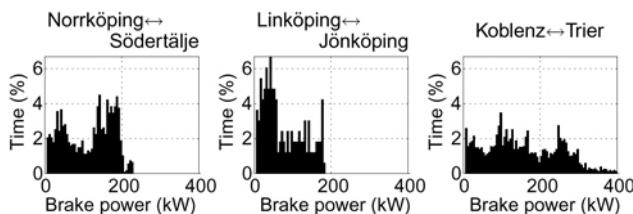


Figure 3. Distribution of brake power for three routes.

POTENTIAL GAIN

In Figure 2 the energy requirements for traveling the routes in Figure 1 back and forth are shown. The set speed is 80km/h and the extra speed allowed in downhills is varied along the horizontal axis. The percentages of brake energy in relation to the total propulsive energy show the maximum gain in fuel economy with reduced braking. The values differ much and have the intuitively negative correlation with the extra speed allowed in downhills.

BRAKE POWER

The required brake power for a certain speed for a given slope is given by the forces in Table 1. A 40 ton truck in a 2%

downhill requires about 70kW brake power to keep 90km/h and 260 kW in a 4% downhill. The distribution of the brake power for traveling the routes in Figure 1 back and forth are shown in Figure 3. The set speed is 84km/h with 5km/h extra speed allowed in downhills.

A generator that cover the power range would weigh several hundred kilograms considering a reasonable specific power. There are also constraints, depending on the placement, that limit the physical size of the motor.

STORAGE SYSTEM

Reducing the brake energy on highways can be achieved by using kinetic energy as a buffer or adding a device for regenerative braking. Utilizing kinetic energy requires that there is an interval in which the velocity is allowed to vary and some energy is lost due to increased air drag. Devices for recovering energy may be of different types such as electrochemical or electrostatic. Losses occur when charging and discharging the buffer, and the mass of the device will increase the drag.

A 40 ton truck in a 2% downhill requires, per kilometer, about 0.78 kWh brake energy to keep 90km/h and 2.9 kWh in a 4% downhill. This corresponds to the capacity of a 3.9 kWh and 14.4 kWh battery respectively with a 20% usable charge range. A significant amount of energy can also be stored as kinetic energy. With the same numbers as above, a velocity interval 80±5km/h correspond to a buffer of about 0.7 kWh which is equivalent to the capacity of a 3.5 kWh battery.

Efficiency

Utilizing kinetic energy as a buffer is, intuitively, more efficient than a device for regenerative braking. Here, a simplified analysis is done to compare these strategies quantitatively. Consider a road segment of length L_1 , with sufficient slope α for the vehicle to accelerate without engine propulsion and assume that $T_e = 0$ and $\cos \alpha \approx 1$.

Assume that the recovering device is capable of absorbing the sufficient amount of energy ΔW in order to keep constant kinetic energy e_0 . With the drag forces $F_d(e) \approx F_r + F_a$, the amount becomes

$$\Delta W = (F_g(\alpha) + F_d(e_0))L_1 \quad (10)$$

which is a negative quantity in this case. The stored energy is $-\eta_s \Delta W$ where η_s is the storage efficiency. Given that the efficiency is equal when discharging, then $-\eta_s^2 \Delta W$ is the amount of energy that can be used in the future. If this energy is used to overcome the driving resistance on a level road, then