Fuel Efficiency Improvement in HEVs Using Electromechanical Brake System

Mohammad Khodabakhshian, Jan Wikander, Lei Feng

Abstract—Today, two of the main concerns in transportation industry are reducing fuel consumption and emissions, and tough regulations are put on the vehicle manufacturers in these regards. One of the main approaches towards reducing CO\textsubscript{2} emissions is hybridization of the powertrain system. Substantial R\&D in this area over the last couple of years has resulted in rather optimal components and control strategies, and hence that further substantial improvements are difficult. This motivates research on other energy consuming vehicle subsystems, e.g. pneumatic and hydraulic systems.

In this paper, the brake system of a hybrid city bus is studied. A complete electrification of the primary brake system would eliminate the use of low efficiency pneumatics for braking. It is therefore interesting to investigate how much energy can be saved by using electrically actuated and controlled primary brakes. The study is based on simulations in Autonomie which is a MATLAB/SIMULINK based vehicle simulation software package. Different representative driving cycles are studied. It is shown that fuel consumption can be reduced in the range of 0.5 to 1.5\% by substituting the pneumatic brake system with a mechatronic one. This may seem limited, but can, combined with substitution of also other less efficient subsystems with their mechatronic counterparts, result in a substantial environmental and economic improvement.

I. INTRODUCTION

Today, two of the main concerns in transportation industry are reducing fuel consumption and emissions. For passenger cars, European parliament environments committee has decided to put the limit of 130 g/km CO\textsubscript{2} by the end of 2012. A target of 95 g/km CO\textsubscript{2} has also been defined for 2020 [1]. For the heavy vehicles, the CO\textsubscript{2} limit of 1.5 g/Kwh is defined in Euro 6 standard which will be effective from 2014 [2]. Achieving these levels requires great efforts from automotive manufacturers. One of the main approaches towards reducing CO\textsubscript{2} emissions is hybridization of the powertrain system. In hybridization, two main aspects are usually being considered. The first aspect is component design and sizing, and the second aspect is the power management strategy for controlling the powertrain. Research in the latter area has been very active in recent years and has resulted in several different control strategies for hybrid powertrain systems [3].

However, the demands on fuel efficiency and emission reduction require improvement beyond the powertrain. One possibility is to reduce or even omit the energy being consumed by auxiliary subsystems, such as braking and steering. Many of these systems are pneumatic or hydraulic and not at all optimal for energy efficiency. The potential of improved auxiliary subsystems in terms of decreasing fuel consumption has already been presented in [4]. The potential of a particular subsystem with respect to fuel reduction depends on vehicle type and driving scenario. Examples of such auxiliary subsystems are steering and braking systems. The potential fuel efficiency improvements of electrohydraulic and electromechanical steering systems are discussed in [5].

In this paper, the brake system of a hybrid city bus is studied. The corresponding driving cycles include many stop-and-go sequences, and hence braking performance is essential. A complete electrification of the primary brake system would eliminate the use of low efficient pneumatics for braking. It is therefore interesting to investigate how much energy can be saved by using electrically actuated and controlled primary brakes. The potential of electromechanical brake systems in reducing fuel consumption has, as far as we have seen, not yet been properly evaluated.

In the current work, energy consumption of an electromechanical brake system is investigated and compared to the energy consumption of a pneumatic brake system for the case of a hybrid city bus. The investigation is based on modeling and simulation.

The paper is structured as follows: Section II gives a brief introduction to brake systems used in heavy vehicles. In section III, the modeling, the modeled vehicle, the driving cycles and the simulation environment are described. Simulation results are presented and discussed in section IV. The paper is concluded in section V.

II. BRAKE SYSTEM IN HEAVY VEHICLES

Brake systems in hybrid heavy vehicles usually consist of three main brake sources: service brake (also called fundamental or primary brake) a secondary brake system, and finally the energy recuperating brake system. The service brake can provide enough braking torque, but not over longer time periods due to overheating of brake pads. On the other hand, using the service brake too scarcely will cause brake glazing, i.e. a low friction layer that reduces braking performance. The secondary brake systems (retarders) needed to overcome the overheating problem are used in different combinations and are of different types, such as hydrodynamic retarders, engine compression retarders, engine exhaust retarders, and electromagnetic retarders (eddy-current brakes). Retarders mounted before the gearbox (like exhaust and compression retarders) are called primary retarders.

Usually, mathematical models of retarder’s torque characteristics are not available, and instead retarder maps relating brake torque to retarder speed can be used. An example of a retarder map is shown in Fig. 1.
Given the different brake systems, brake blending strategies are used to distribute the brake command from the brake pedal to the different brake systems such that good braking performance is achieved, while taking different brake system constraints and also maintenance aspects into account. In the case of a hybrid vehicle, an additional brake blending target is to recuperate as much energy as possible while adhering to overall vehicle energy management strategies.

In this study, the conventional pneumatic primary brake system is replaced by an electromechanical brake system to investigate the achievable energy consumption reductions. Electromechanical brake systems (EMB) are based on electromechanical actuators and communication networks instead of conventional pneumatic or hydraulic devices. Apart from energy related advantages, EMB systems also have better controllability enabling better integration with vehicle traction and stability control. Other advantages of the EMB systems are elimination of complex and heavy piping, reduced number of components, and enhanced diagnostic capabilities of the brake system. Example of EMBs are presented in [7] and [8]. The particular EMB system studied here is a prototypical system developed by Haldex [9]. Due to a mechanical self-enforcing mechanism of the EMB system, the electrical energy consumed during braking is very low. A more detailed discussion on electromechanical brake systems is presented in [10] and [11].

III. MODELLING

A. Vehicle Specification

The vehicle simulated in this study is a parallel hybrid electric city bus. The electric motor is used for moving from standstill up to 20 km/h. In higher speeds, the diesel engine is engaged for propulsion and charging of batteries. For a typical city driving cycle it is claimed by the manufacturer that this can reduce fuel consumption by 35% (which corresponds to around 26 l/100km) and emissions up to 50%. The architecture of the system is shown in Figure 2.

The batteries are based on active temperature controlled lithium cells. Each cell has individual charge control. The Electric motor (Integrated Starter Alternator Motor (I-SAM)) which is also used as the generator is a permanent magnet motor which runs on changing current. Some of the vehicle specifications are shown in Table I.

<table>
<thead>
<tr>
<th>Specification of Hybrid Bus</th>
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<tbody>
<tr>
<td>Final drive ratio</td>
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<tr>
<td>Wheel radius</td>
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<tr>
<td>Frontal area</td>
</tr>
<tr>
<td>Drag coefficient</td>
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<tr>
<td>Vehicle mass</td>
</tr>
<tr>
<td>Diesel engine</td>
</tr>
<tr>
<td>Power output/Torque</td>
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<tr>
<td>Electric motor Power output/Torque</td>
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<td>Transmission</td>
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B. Driving cycles

Simulation of different driving cycles will clearly produce different results. It is hence important to use representative driving cycles. To avoid confusion and make results comparable, standardized driving cycles such as SORT are designed (SORT – Standardized On-Road Test cycles developed by the International Association of Public Transport). The SORT cycles as well as the so called New York City bus driving cycle are used as important references for bus companies for evaluating the energy aspects of bus operation. SORT cycles have been developed mainly for standard buses (12m). In this paper, SORT1 (Fig. 3) and the New York City bus (Fig. 4) driving cycles have been used.
C. Modelling and simulation

To model the power train system of the hybrid bus, different software packages were considered and compared. A similar comparison has also been done and reported in [12]. For the presented work the simulation tool “Autonomie” has been used [13]. Autonomie is a modeling and simulation tool developed by Argonne National Laboratory in collaboration with General Motors (GM). The software is used for analysis of powertrain systems and especially for fuel consumption evaluation of different technologies and system configurations under transient test conditions.

The full model of the simulated vehicle including driver, controller and powertrain system is shown in Fig. 5. The powertrain system model is shown in Fig. 6. A short explanation of the main components of the model is presented in Table II.

D. Electromechanical brake model

A simple model of the electro mechanical brake system is explained here. The model presented here is based on the wedge brake models presented in [14], [15] and [16]. This model is used to understand the behavior of the system in terms of energy efficiency. In the simulation environment, a more complex model which is closer to reality is considered. Schematic view of the brake system is shown in Fig. 7.

The normal force on the wedge \( F_{\text{Normal}} \) is calculated as:

\[
F_{\text{Normal}} = K_{\text{wedge}} x_{\text{wedge}} \tan \alpha
\]  

(1)

where \( x_{\text{wedge}} \) is wedge displacement, \( K \) is caliper stiffness and \( \alpha \) is wedge angle. When the disk is rotating, the brake force \( F_{\text{Brake}} \) is calculate as

\[
F_{\text{Brake}} = \mu F_{\text{Normal}} = \mu K_{\text{wedge}} x_{\text{wedge}} \tan \alpha
\]  

(2)

The axial force on the wedge from the reaction force \( F_{\text{Axial}} \) is

\[
F_{\text{Axial}} = -F_{\text{Normal}} \tan \alpha
\]  

(3)

So the total axial force on the wedge \( F_{\text{Wedge}} \) is calculated as:

\[
F_{\text{Wedge}} = (\mu - \tan \alpha)F_{\text{Normal}} + F_{\text{Motor}} = (\mu - \tan \alpha)K_{\text{wedge}} x_{\text{wedge}} \tan \alpha + F_{\text{Motor}}
\]  

(4)
When the disk is stopped, $F_{Wedge}$ is:

$$F_{Wedge} = -Kx_{Wedge} \tan^2 \alpha + F_{Motor} \tag{5}$$

The brake torque can be calculated as:

$$M_{Brake} = 2\mu F_{\text{Normal}}r_d \tag{6}$$

where $r_d$ is disk radius.

### E. Brake Blending

The controller being used for the brake system is a rule-based controller which is based on the default controller used in Autonomie. The logic behind the controller is explained here.

The default state (1) of braking is to brake using mechanical braking without using the electric motor. If SOC, chassis deceleration and gear number are below a specified threshold and motor speed and chassis speed are above a certain threshold, the brake will go to state 2. In state 2, the mechanical brake is deactivated and all the brake torque will be provided using the electric motor. If the brake demand is larger than the maximum torque that the electric motor can provide, and battery and electric system can handle (e.g., in the strong deceleration situations), the brake system will transit to state 3. In this state, mechanical braking will augment the electrical motor braking. If the brake demand reduces to less than the maximum capability of electrical system, the brake will go back to state 2. If in state 2 or state 3 the gear ratio is 0 (neutral gear), the regenerative brake is deactivated and only the mechanical brake is working. If any of the conditions necessary to switch from state 1 to state 2 breaks then the brake state will be either state 4 or state 5. If the brake demand is greater than the maximum regenerative brake, then it will be in state 4, otherwise state 5 will be active. The difference in state 4 and 5 is the way different brake torque portions are calculated. While either state 4 or state 5 are active and some specific conditions for SOC, motor and vehicle speed, vehicle deceleration and gear ratio happens, the system will go to regenerative state (state 2 or 3). If the conditions change, system will go to pure mechanical brake state (state 1). The mechanical brake part is using a simple logic. The priority is using engine brake at the beginning and in case that brake demand is quick (sudden brake) and if the electric motor and the engine brake cannot provide the needed torque, the fundamental brake will run. A schematic of the control rules is shown in Figure 8. The conditions are shown in Table II.

![Figure 7. Wedge brake schematic](image)

![Figure 8. Schematic of brake controller](image)

<table>
<thead>
<tr>
<th>Model</th>
<th>Conditions</th>
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<tr>
<td>A</td>
<td>(SOC)&lt;(SOC below which the engine is turned on) &amp;&amp; (chassis speed)&lt;(chassis speed below which charging is forbidden) &amp;&amp; (motor speed)&lt;(motor speed below which charging is forbidden) &amp;&amp; (Chassis deceleration)&lt;(Chassis deceleration above which charging is forbidden) &amp;&amp; (brake demand)&lt;(maximum regenerative brake)</td>
</tr>
<tr>
<td>B</td>
<td>(Torque demand)&gt;(electrical system capability)</td>
</tr>
<tr>
<td>C</td>
<td>(SOC)&lt;(SOC below which the engine is turned on)</td>
</tr>
<tr>
<td>D</td>
<td>(SOC)&lt;(SOC below which the engine is turned on)</td>
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<tr>
<td>E</td>
<td>(t-Ts)&lt;(Ts)</td>
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<tr>
<td>F</td>
<td>(gear ratio)==(neutral)</td>
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<td>G</td>
<td>(gear ratio)==(neutral)</td>
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<tr>
<td>H</td>
<td>(t-Ts)&lt;(Ts) &amp;&amp; (SOC)&lt;(SOC below which the engine is turned on) &amp;&amp; (chassis speed)&lt;(chassis speed below which charging is forbidden) &amp;&amp; (motor speed)&lt;(motor speed below which charging is forbidden) &amp;&amp; (Chassis deceleration)&lt;(Chassis deceleration above which charging is forbidden) &amp;&amp; (brake demand)&lt;(maximum regenerative brake)</td>
</tr>
<tr>
<td>I</td>
<td>(t-Ts)==(Ts)</td>
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IV. SIMULATION AND RESULTS

The results of comparing simulations using a conventional brake system configuration and an electromechanical brake system configuration are presented here. The results are presented for the New York City bus driving cycle and the SORT1 cycle.

In Fig. 9 and Fig. 10, the mechanical brake torque demand and regenerative brake torque demand are shown for SORT1 and New York City bus cycle respectively. The brake usage in the case of using a pneumatic brake system is basically the same (in simulation) as using an electromechanical brake system, although because of different response times, there will be minor differences in a real case.

The energy consumption of the pneumatic brake system and the electromechanical brake system are shown in Fig. 11 and Fig. 12 for SORT1 and the New York City bus cycle respectively.

The energy source of the conventional brake system is the air compressor. In the vehicle under study, the compressor is a 6 kW compressor with duty cycle of 18%. The required energy for the brake system is assumed to be a portion of the compressor energy. This assumption is reasonably close to real conditions according to the real world data from SORT1 as provided by the vehicle manufacturer. By substituting the conventional primary brake system with an electromechanical brake system, the amount of brake energy consumed by the compressor will be saved. This amount of energy is small compared to the size and power of the propulsion system, but still worth to consider for future vehicle optimization. The main reason for the low energy consumption of the electromechanical brake system is the self-energized mechanism. By using Equation (3) in equilibrium and Equation (4), the characteristic brake factor can be written as:

$$ C = \frac{F_{\text{brake}}}{F_{\text{motor}}} = 2 \times \frac{\mu K \tan \alpha}{(\mu - \tan \alpha) K \tan \alpha}$$

As can be seen in the Equation (7), by choosing the right value for $\alpha$, the characteristic brake factor will be infinite; hence the motor force required for braking is theoretically zero. Only small amount of energy is consumed by electric motor for position controlling to prevent locking of the brake and also to release the brake.

Even though a dominating portion of the mechanical brake energy is absorbed by the retarder(s), the energy needed for the pneumatic brake system is still non-negligible. It is however important to note that both the fuel consumption and the brake intervention is different in different driving cycles. Hence, the energy saving potential varies substantially depending on driving cycle.

Summary of the results are:

- Using an electromechanical brake system can improve fuel efficiency with 0.5-1.5% depending on driving cycle, brake strategy and retarder specifications.
- The results are obtained by considering the worst case scenarios for compressor energy consumption and according to the given component and system specifications. Deviations from these conditions will change the results.
- The limited – but still important – improvement is mainly due to the regenerative braking and due to that the engine retarder is the main mechanical brake source.
- The powertrain type of the current work is parallel hybrid. In a conventional bus case (no regeneration), the improvement in fuel efficiency will be larger since some of the brake torque provided by the regenerative brake system in this case must be provided by the pneumatic brake system.
- Substituting the pneumatic brake system with an electromechanical system, increases fuel efficiency to an extent worth considering. However, by substituting all of the pneumatic subsystems with electro-mechanical devices (door opening, kneeling, etc.), the overall improvement of fuel efficiency will be considerable. Such an improvement is difficult to achieve by modifying solely the hybrid driveline since it is already rather optimal.
Application of an electromechanical brake system in a hybrid city bus is investigated in this paper. The main focus has been on energy aspects i.e. fuel consumption reduction.

A city bus is chosen as the case study mainly because of the driving cycles that city buses undergo i.e. driving cycles with a lot of stop-go sequences. The simulations were done for different driving cycles of a parallel hybrid city bus, i.e. a vehicle which is designed to avoid the need for mechanical braking as far as possible. The results still show 0.5 to 1.5 percent decrease in fuel consumption depending on driving cycle.

The accuracy of results may be improved by considering a more accurate model of the pneumatic brake system, but this will most likely not change the overall conclusions about achievable energy consumption reduction.

The brake system is only one of the auxiliary sub-systems which can be replaced by more efficient mechatronic ones. By substituting several of the less efficient subsystems with electromechanical systems the overall improvement of fuel efficiency will be considerable. This can be a subject for future research.

REFERENCES


