A more efficient braking system for heavy vehicles

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Electric powertrains increase efficiency in road vehicles and enable zero tailpipe emissions, but introduce practical limitations in on board energy storage capacity, due to the low energy density in battery systems when compared with chemical fuels in tanks. The increased powertrain efficiency and lower on-board energy storage levels place focus on other energy consumers in the vehicle system, such as the braking system. Our measurements indicate that a conventional pneumatic electronic braking system for heavy vehicles consumes 2-3% of the mission energy in a typical city bus cycle for a battery electric vehicle. The newly developed electromechanical braking system offers a more efficient energy conversion for the braking function, consuming 0.4-0.7% of the mission energy under similar driving conditions. This work focuses on an energy analysis of the conventional and the novel system in the context of a city bus application. The data is sourced from measurements of a battery electric bus, driven on a proving ground in tests repeated three times, in unladen condition. The measurements include comparative tests for the vehicle equipped with a traditional electro-pneumatic braking system and the same vehicle equipped with the new electro-mechanical braking system.

1. Introduction

The energy used by the longitudinal actuators in a battery electric bus were studied experimentally, by driving an emulated city bus schedule featuring frequent stops on a proving ground. An illustration of the test vehicle is shown in figure 1. Energy consumption in battery electric city buses has been

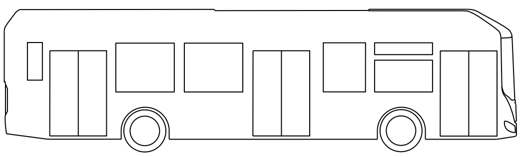

Figure 1: The object under study, a low floor 4x2 battery electric bus.

studied in [1], which does not go into detail on the energy use of the braking system. One work that does investigate the pneumatic system in heavy vehicles is [2], but the authors unfortunately hide the axes on significant results.

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Table 1: Vehicle properties.

Property	value	unit
Unladen mass	12800	kg
Pneumatic tank energy	256	kJ
Capacitor bank energy	44	kJ

2. Methodology

A test vehicle, powered by a battery electric powertrain, was run over a 5 km loop on a proving ground, starting and stopping in the same location. This cycle was repeated three times in succession for each of the tested braking systems, the reported cases are in an unladen vehicle state. The tests were performed on separate occasions, as the same vehicle was used with both systems.

2.1 Test cycle

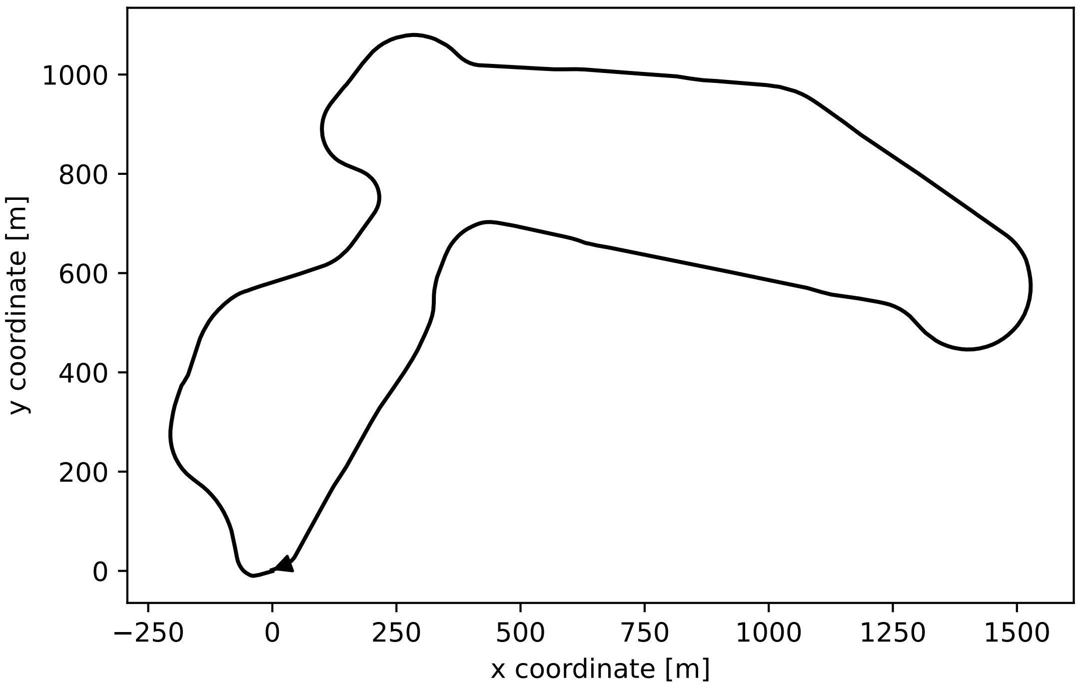

Figure 2: The test track coordinates, the arrow indicates the driving direction and location of the start and finish for each test.

The loop is driven on an asphalt road, forming a closed circuit, as depicted in figure 2. Tests are driven at targeted speeds of 8.5 m/s, the lateral acceleration content is minimal, and the longitudinal accelerations are in the 1 m/s^2 range. The velocity and altitude profile of the track are depicted in figure 3. At each stop a halt brake function is activated in the EBS case, which applies a service brake pressure of 200 kPa, roughly 17 % of the system capability. On steeper inclines this system retains a slightly higher pressure. In the EMB case this functionality is emulated by the use of its parking brake function, which uses a clamping force equal to 25 % of the system capability.

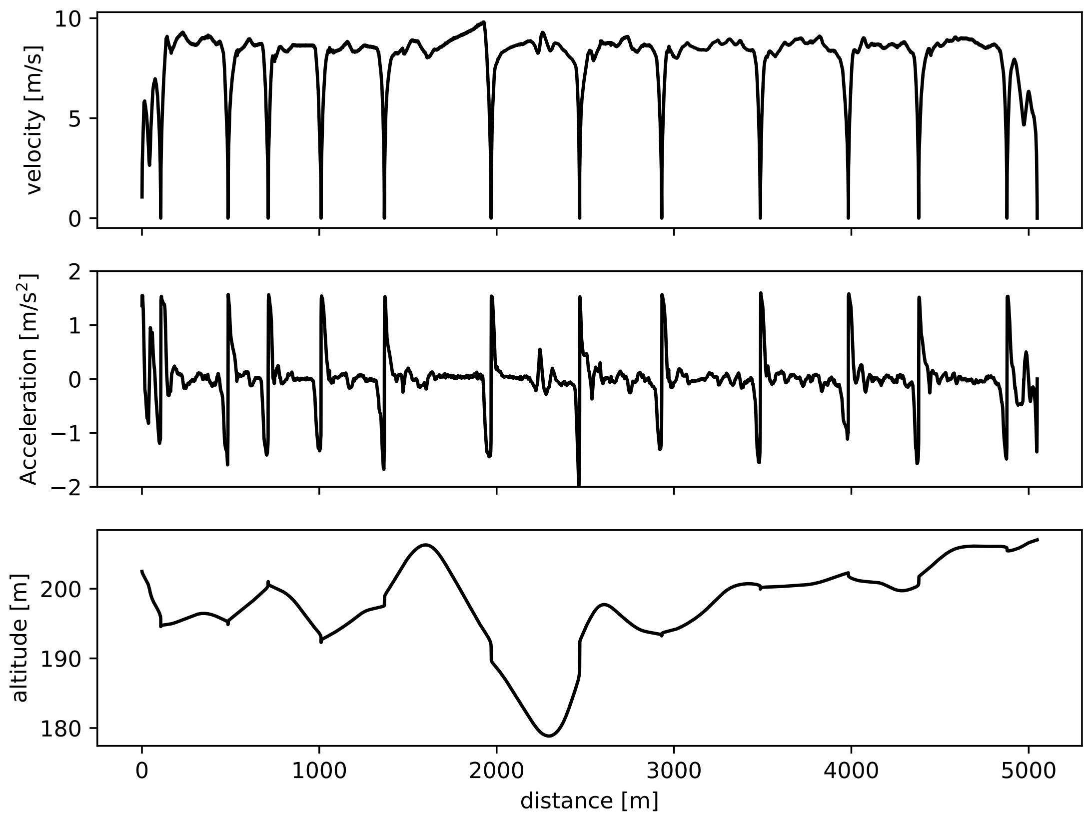

Figure 3: The test cycle velocity, acceleration and altitude, the discontinuities on each stop location are caused by the GPS receiver altitude drift, indicating low accuracy in altitude.

2.2 Experimental setup and data

The energy converted by the longitudinal actuators were gathered at a sample rate of 10 ms on the vehicle CAN-bus, together with two GPS devices at 10 ms and 100 ms respectively.

The longitudinal actuators in the vehicle, including the two braking system variants, are depicted in figure 4. These are a) the powertrain, b) the compressed air system, and c) the EMB system.
The data gathered by the CAN-logger is saved in a vendor-proprietary message based binary format. After completion of the experiments, the data is converted to ASCII values, utilizing the CAN message data specification in order to generate sampled physical value data at a 10 Hz rate. This data is subsequently processed and displayed in section 4.

2.3 Experimental uncertainty

As the experiments are performed with a human driver over several different days, the repeatability of the experiments is not perfect. For example, some average driving speed disparities can be seen in the comparison tests, where the EBS runs are on average performed with a slightly lower driving speed than with EMB. The number of stops performed in the EBS case is 13, and in the EMB case 10, when counting the final stop at the take off location, as indicated by the arrow in figure 2.

The EMB system consumption is measured from the low voltage (24 V), which means that the losses stemming from the conversion from high voltage to low voltage systems is not captured in this measurement. The reasoning behind this choice is that many other consumers that are out of scope for this work would be included in the measurement if it was performed on the high voltage side of the DC/DC converter. The efficiency of such converters is typically >95 %.

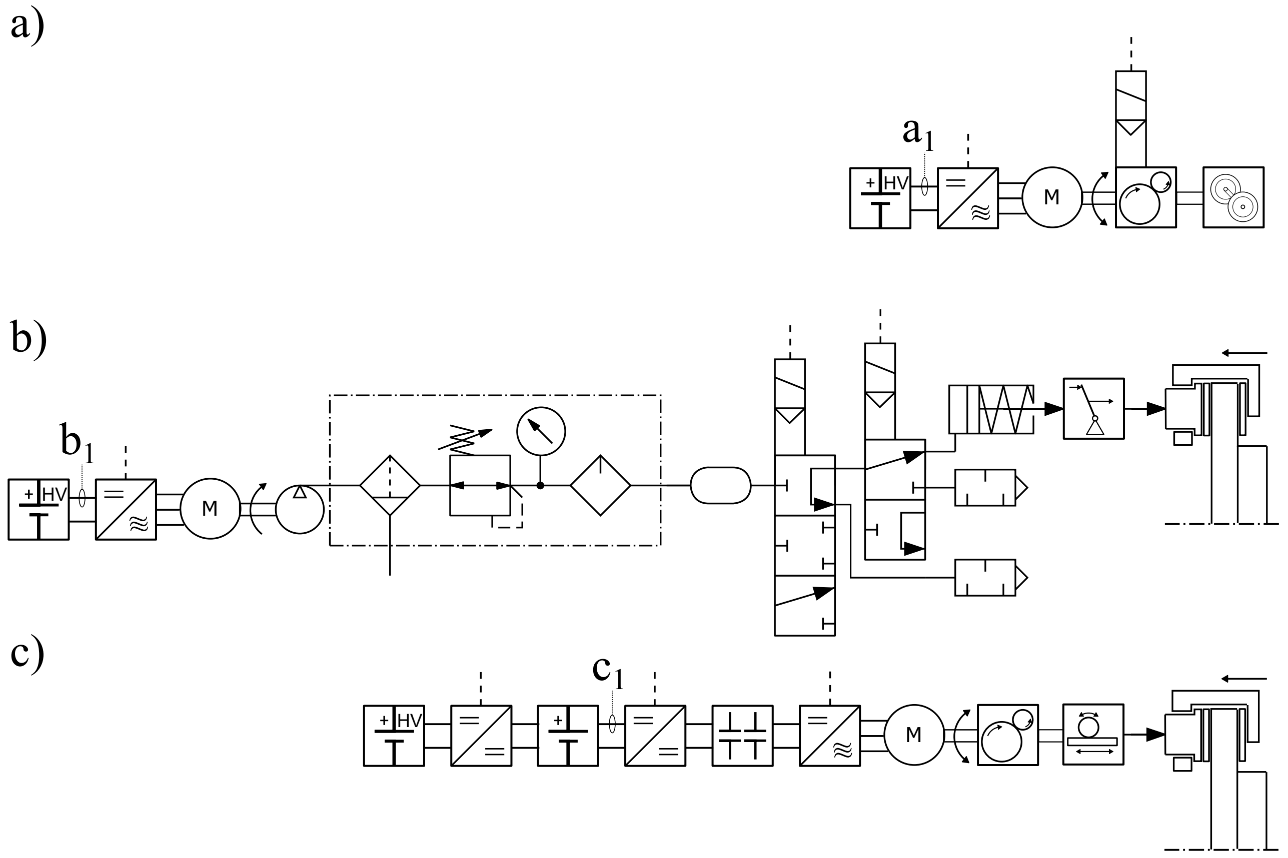

Figure 4: Diagram of the actuators under study. a) is the traction system, b) is the EBS system, and c) is the EMB system. The points $\{$a,b,c$\}_1$ indicate where the energy used is measured by the actuator in question as voltage at the terminals of the device times current flowing into the device.

Other consumers of compressed air exist in the vehicle, such as air-suspension and other body-functions, the use of these functions have been minimized, by not utilizing for example the kneeling function. Still some consumption of compressed air exists in excess of that used by the EBS system. The consumption of these systems is captured implicitly, by subtracting the air use that remains in the EMB case from the EBS cases in Section 5.

It should be noted that most of the braking effort, slowing the vehicle down, is performed by the regenerative braking from the powertrain. The controller requesting this action is not identical between the two systems. This may affect the acceleration levels and velocities triggering powertrain and braking system actions, but efforts have been made to align their actions.

3. Analysis

The energy used by each actuator over a cycle is

$$W_{*_1} = \int_{t_0}^{t_1} P_{*_1} \mathrm{d}t \tag{1}$$

where * is the actuator, the value is calculated numerically using Simpson's rule. The total energy consumed by the longitudinal actuators in the vehicle is defined as

$$W_{tot} = W_{a1} + W_{b1} + W_{c1} \tag{2}$$

The maximum available energy inside the pneumatic reservoirs, from the common gas law and assuming isothermal expansion would be

$$W_p = p_t V_t \ln \frac{p_a}{p_t} + (p_t + p_a) V_t \tag{3}$$

where $*_t$ denotes the reservoir, and $*_a$ denotes atmosphere. The energy stored in the capacitor bank is

$$W_c = \frac{1}{2}U^2C \tag{4}$$

4. Results

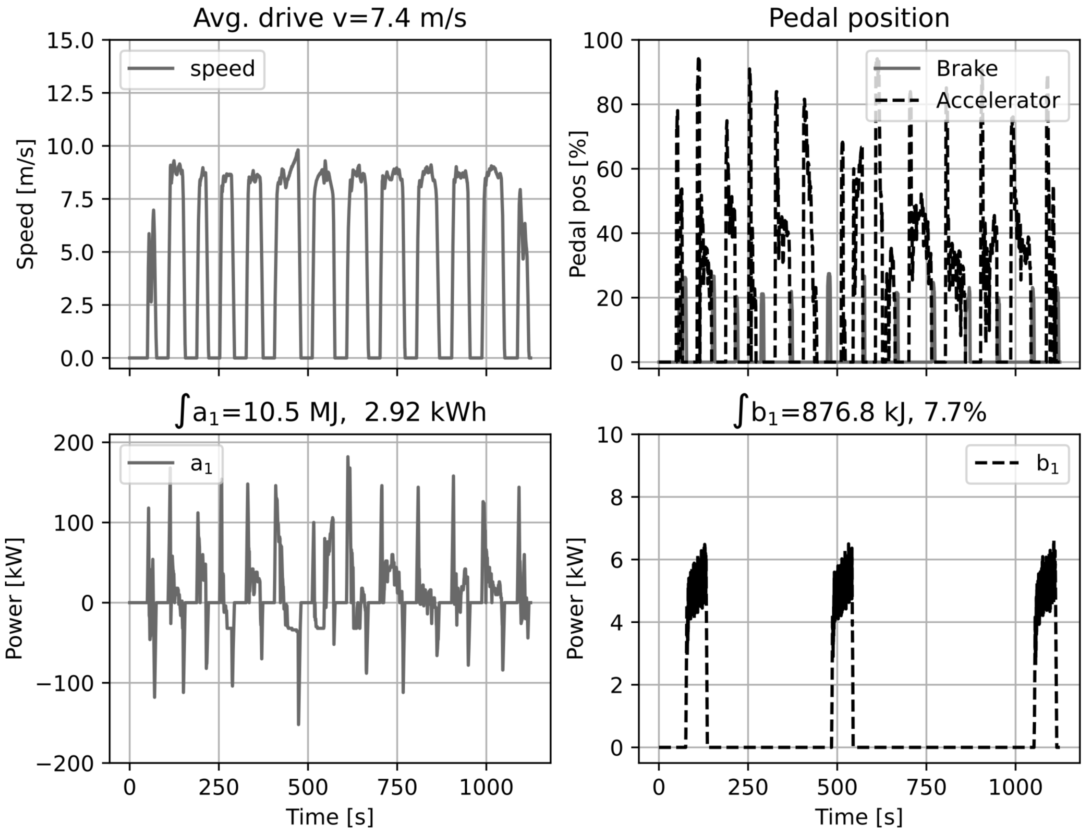

Figure 5: EBS run 3

Figures 5-6 show the third run with each vehicle configuration, as this allows the systems in the vehicle approach operating temperature, the earlier repeat runs are included in the appendix, Figs. 7-10. Each result plot includes the calculated energies converted by the longitudinal actuators during the the run. On the top left is the velocity as measured at the wheels, the top right shows pedal positions used by the driver. The lower left shows the powertrain power, which is both positive for tractive effort and negative for regenerative braking, the lower right shows the pneumatic compressor, and where applicable also the power consumed for charging the capacitor bank energy storage in the EMB case.

The measured energies consumed by the powertrain and braking systems over all runs for the three cases are presented in Tab. 2. This table also contains some information regarding irregularities in the driven cycles, stemming from the use of a human driver.

5. Discussion

In the EBS case, the b_1 actuator consumed on average 587 kJ, with the pneumatic electronic braking system removed and the electromechanical braking system installed, the energy consumption of b1 was reduced to 276 kJ on average. This indicates that the energy used to actuate the pneumatic brakes was 311 kJ, as measured at the terminals of the compressor system. In comparison to the powertrain energy, in the EBS case was 10.6 MJ, the pneumatic braking system used 2.8% of the total energy

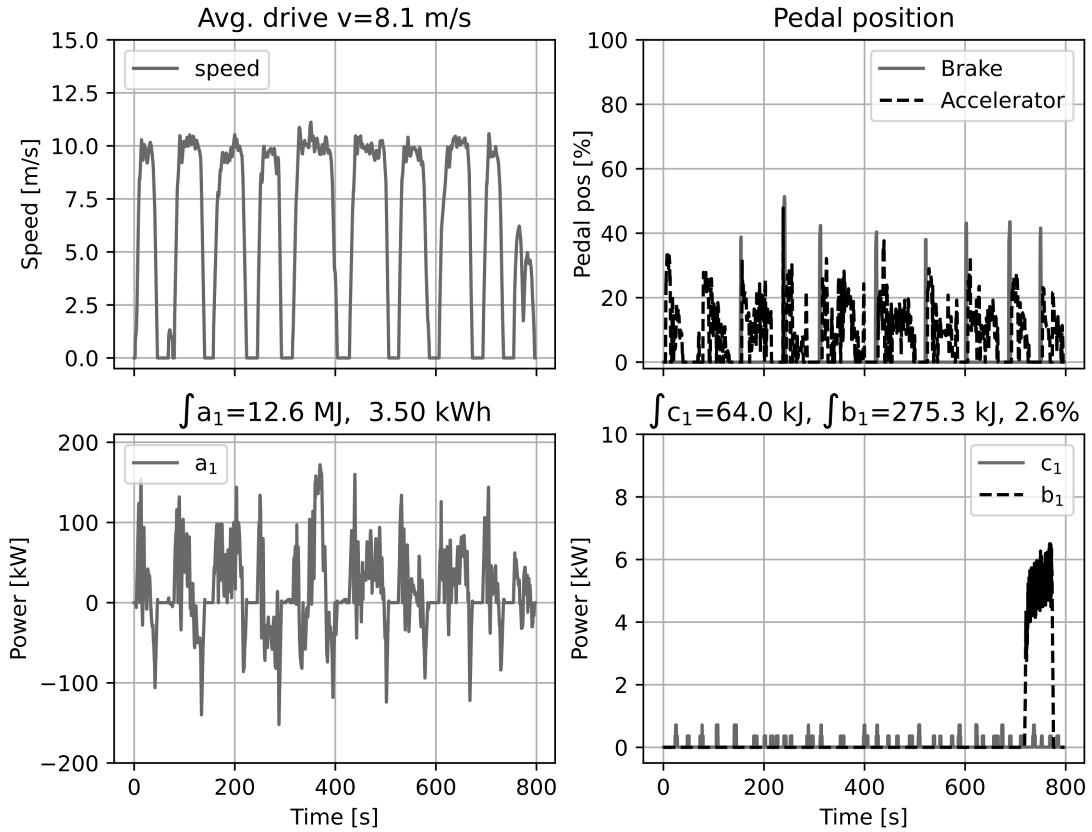

Figure 6: EMB run 3

for the measured actuators, a_1 and b_1. The remaining compressed air energy may be used in body functions, one example being pneumatic suspension.

In comparison, the EMB system used 62 kJ for a similar mission, albeit with fewer stops and higher average driving speeds, leading to higher powertrain energy consumption. Here the energy consumption in the b_1 system is 276 kJ, leading to a total b_1+c_1 energy use of 338 kJ, significantly lower than the average of the EBS runs. If calculated as a fraction of the total mission energy, the c_1 system used 0.45% of the energy for the measured actuators a_1, b_1 and c_1.

This indicates that the electromechanical braking system is clearly more efficient than the pneumatic electronic braking system, but the comparison is slightly unfair as fewer stops were performed and the powertrain energy was higher. So if a careful extrapolation effort is undertaken and the EMB system consumption, c_1, is scaled up by a factor relating to the number of stops, 1.3, its consumption could have been 81 kJ, and b_1 from EMB is scaled up by the same factor, giving 359 kJ. These numbers, if combined with a powertrain consumption from the EBS case of 10.6 MJ, would have resulted in 0.73% of the total energy used by the EMB system, and 3.25% used by b_1. Alternatively, the average amount of energy used by the EBS can be estimated per bus stop and compared to the same metric measured for the EMB system. Such a calculation gives values of 24 kJ/stop and 6 kJ/stop for the EBS and EMB systems respectively.

According to these results the electromechanical energy conversion in the EMB system is more efficient than the combined air compressor and EBS system, by a factor between 3 and 4, while performing the duties of stopping and holding a battery electric city bus stationary, during the stops on a typical city bus driving schedule.

The amount of compressed air used by other systems on the bus was not studied in detail in this work. It is, however, interesting to observe that, according to the energy use measured, the EBS only accounted for around 60% of the total compressed air use. Further experiments are needed to identify which systems are responsible for this additional compressed air energy use.

Table 2: Averages over 3 runs.

	EBS	EMB	unit
a1, powertrain	10.6	13.5	MJ
b1, compressed air	587	276	kJ
c1, EMB	-	62	kJ
b1+c1 % of total	5.2	2.5	%
Velocity	7.4	8.5	m/s
Stops	13	10	-
Ambient temperature	12	6	°C

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2. B. Karanja and P. Broukhiyan, "Commercial vehicle air consumption: Simulation, validation and recommendation," Master's thesis, KTH, Machine Design (Dept.), 2017.

Appendix

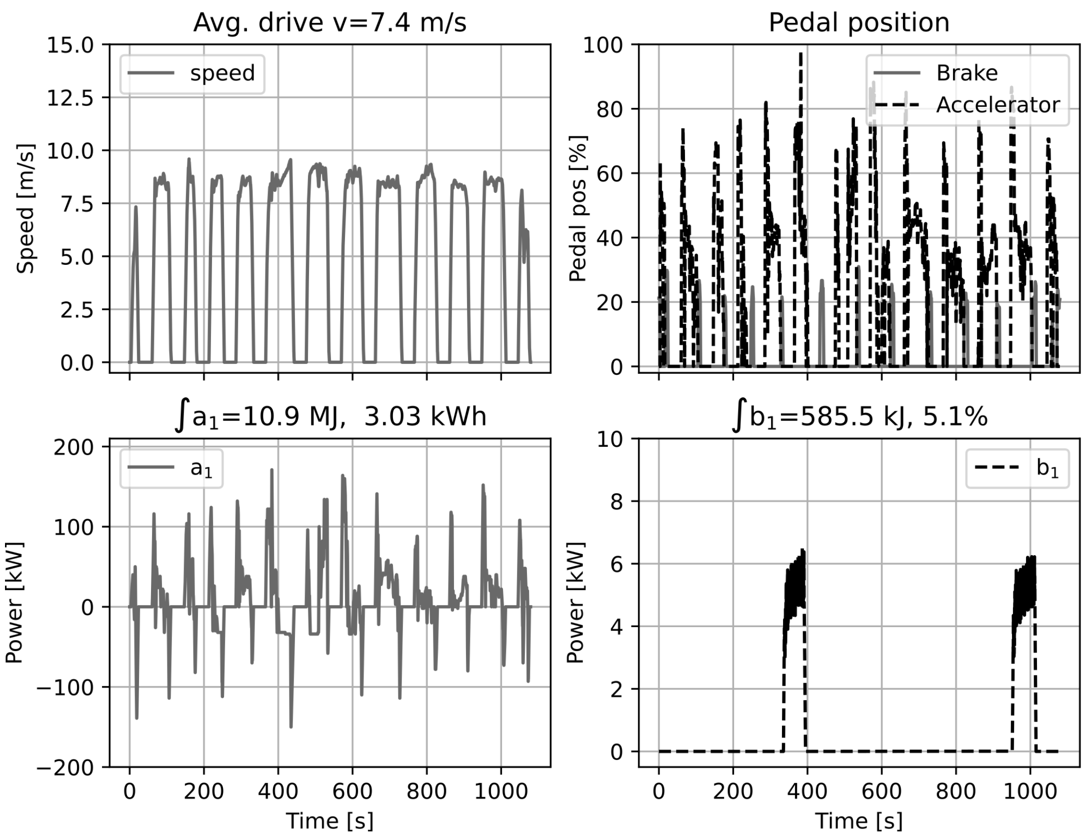

Figure 7: EBS run 1

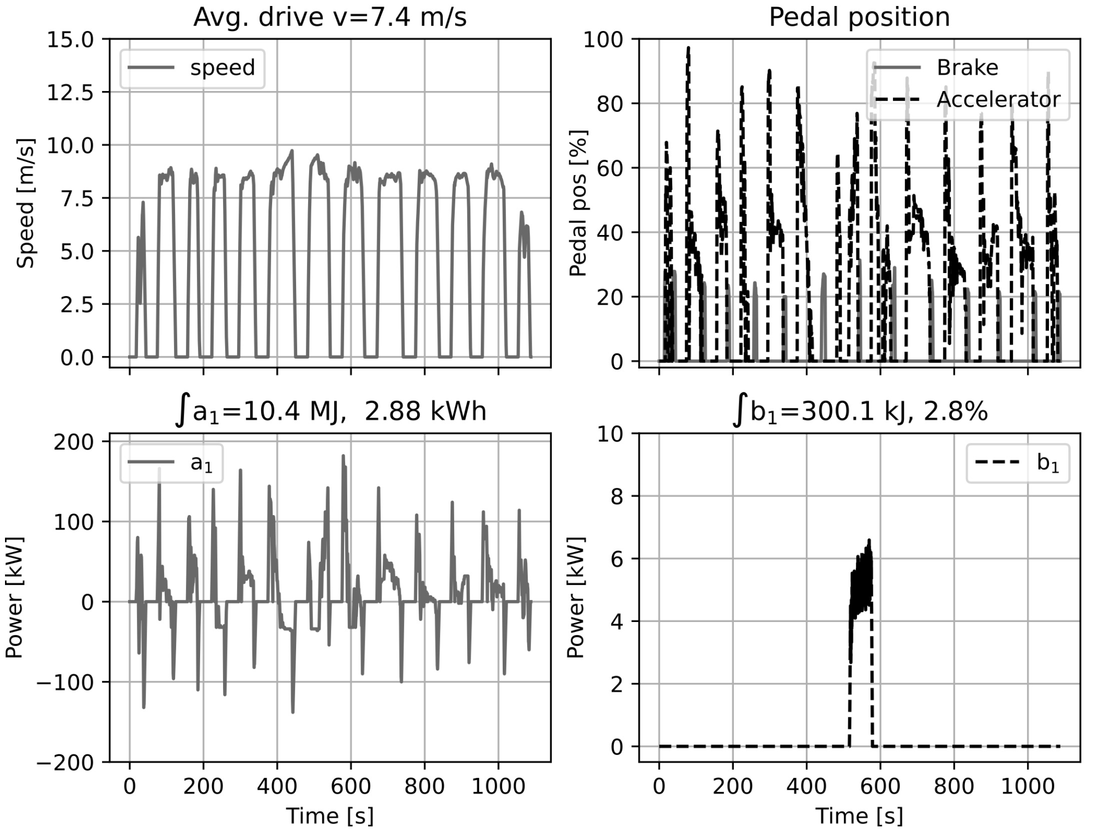

Figure 8: EBS run 2

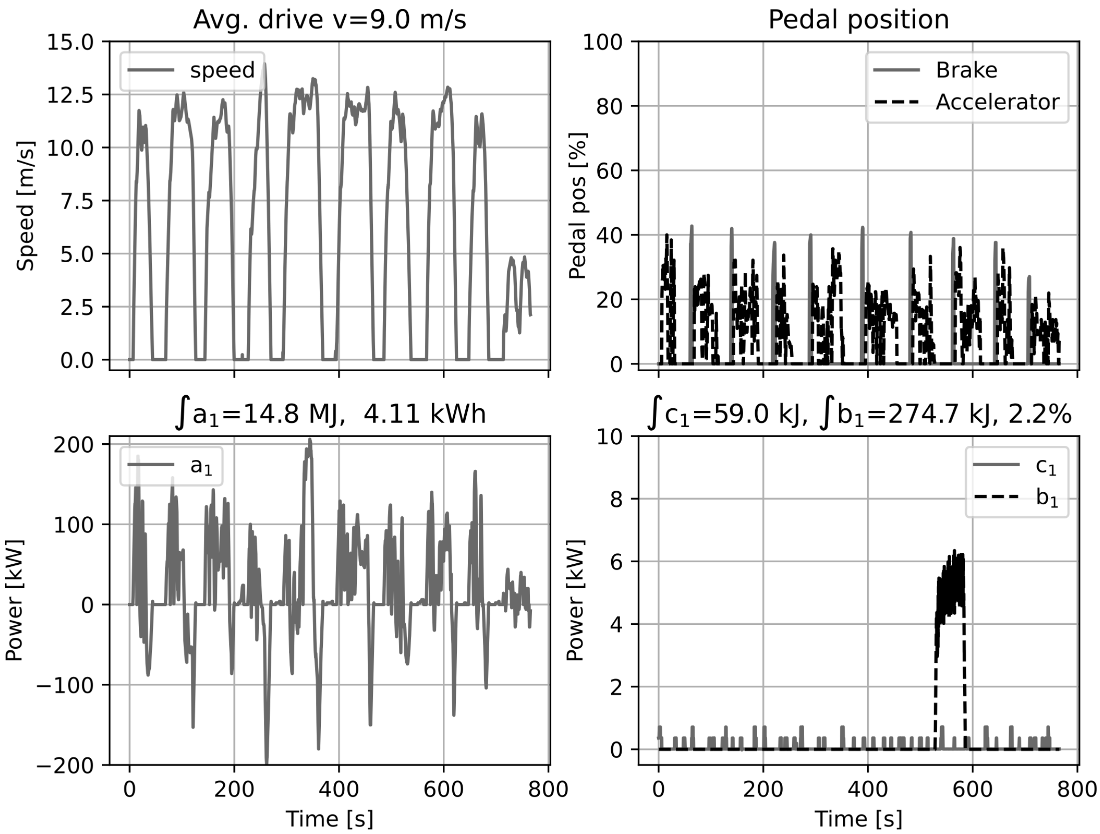

Figure 9: EMB run 1

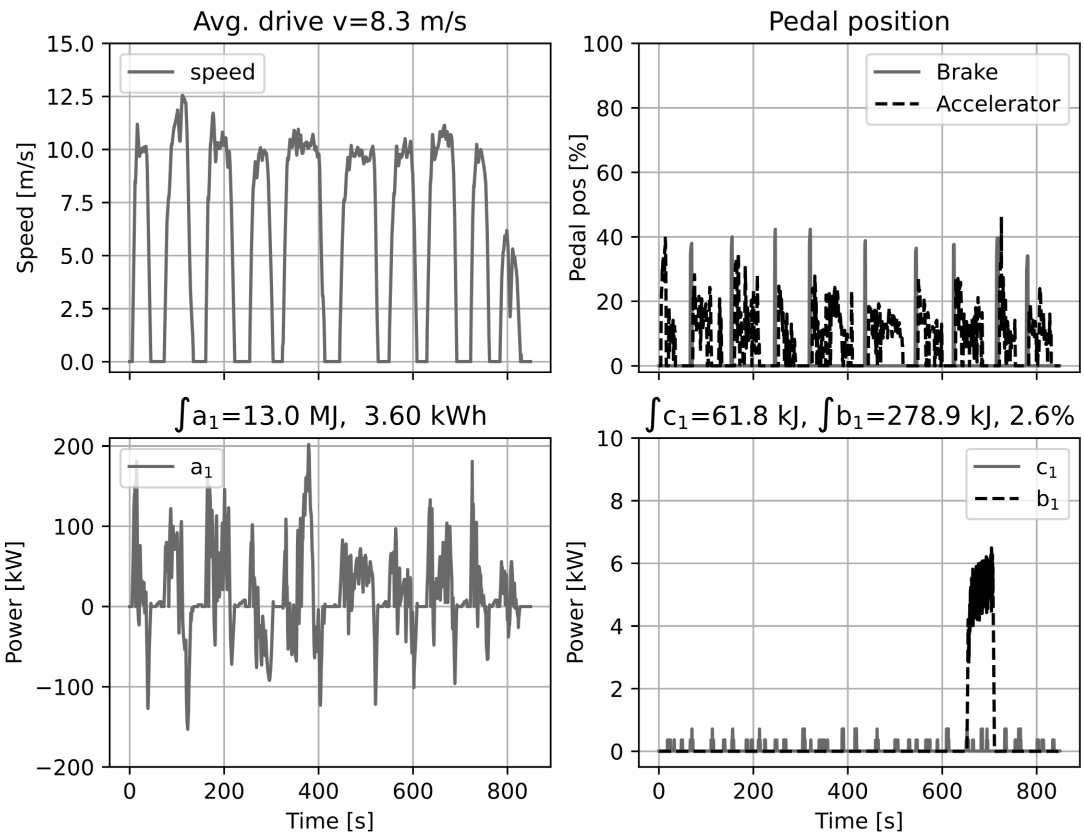

Figure 10: EMB run 2