EPOS – System Optimization Beyond Propulsion

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Introduction

The electrification and automation of the automotive industry pose new requirements on the energy and environmental features of vehicle systems and subsystems. All systems of the vehicle need to be optimized to meet these requirements.

In braking, this means an increased focus on electrically actuated brake systems that can reduce both costs and energy. In this work, the energy consumption of Haldex's Electro-Mechanical Brake (EMB) system is studied. The system is an innovative non-pneumatic brake system, designed to meet the safety and environmental requirements of tomorrow. The energy and the energy related cost savings of using this system, in favor of a traditional pneumatics-based brake system, are estimated for a number of heavy vehicles and drive cycles using an approach based on the interaction between physical testing and dynamic simulation.

The system simulation models used in the analysis are physics-based and are developed to fully capture the dynamic behavior of the brake system. Hence, the models are not limited to energy consumption analysis. They can be used freely in any system design activities, such as in the evaluation of concepts and control strategies. In this work, the simulation models have been used together with test results to deliver a deeper understanding of the EMB system and the different considerations in brake design.

Considerations in brake design

To correctly estimate the energy consumption and savings of using the EMB system, it is important to understand how the system will be used when installed in a vehicle. The energy consumed will be highly influenced by the vehicle's application and the driver's behavior. Hence, different drive cycles and brake patterns need to be considered in the brake design and analysis.

Drive cycles are defined as velocity profiles mimicking the driver behaviors of certain vehicle types. The definitions of some drive cycles of interest are shown in Table 1.

Table 1. Drive cycle definitions.

Drive cycle	Top speed (km/h)	Period (s)	Retardation (m/s^2)
City	30	77	-0,83
Refuse	43	95	-0,85
Construction	58	233	-1,01
Regional distribution	60	750	-0,98
Long-range	90	7200	-1,00

The drive cycles of the table are ordered with increasing speed and frequency. The city bus and refuse truck drive cycles are low-speed profiles with frequent braking, whereas the long-range profile is a high-speed profile with infrequent braking. This variety of drive cycles will help indicate how different factors influence the overall energy consumption during the drive cycle. A typical example of such a factor is the system idling, i.e. when the system isn't in use, and its effect on the efficiency of the system. This will be a dominant contributor to the energy consumption for applications with infrequent braking, i.e. long-range, but will have limited impact on drive cycles with frequent braking.

The brake behavior of the driver will also influence the energy consumed over a drive cycle. Figure 1 (a) shows the typical shape of a brake force request from a manual driver in a vehicle without brake blending.

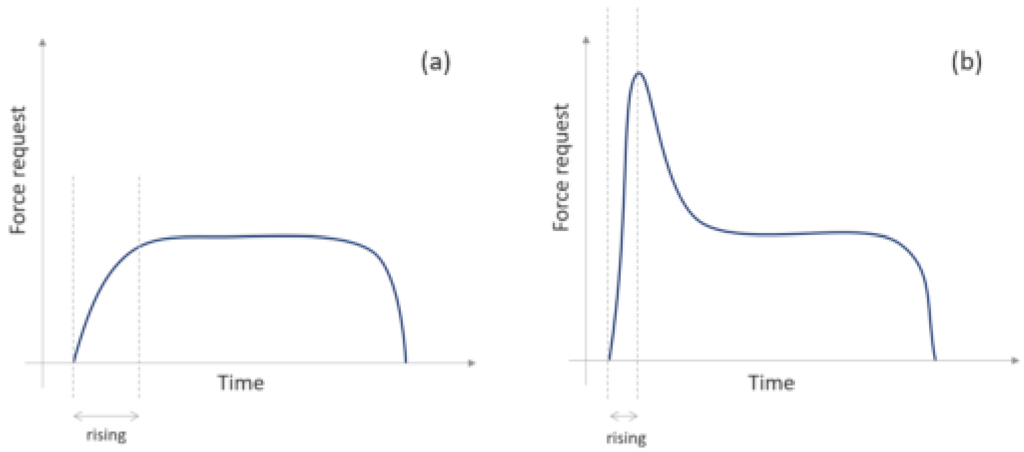

Figure 1. Figures a-b show the brake force requests of a manual and an automated/blended driver respectively.

The rising of the brake request is often a slow process that can take up to 2 seconds depending on the situation and driver. While the slow rising assures a soft and controlled brake experience, it impacts the energy consumption of the brake system negatively as it prevents energy saving functionalities due to the need of controlling the motor torque dynamically over a longer period of time.

Figure 1 (b) shows the corresponding shape of a brake force request for a vehicle with brake blending active. While the underlying brake request from the driver for this case may look similar to that of (a), the brake force request must now compensate for the power limit of the vehicle motor at high velocities. This results in the pulse-like brake request shown in Figure 1 (b). The typical relation between a brake torque request and a motor torque request during a brake event with brake blending is further examined in Figure 2. The motor torque request characteristics shown are given by the power limitation at high rotational speeds and the torque limitation at lower speeds. The brake torque request compensates for the available motor torque to fulfill the brake request of the driver. This relation applies for all applications where brake blending is used. Hence, the behavior shown in Figure 1 (b) can be expected to show also in autonomous vehicles. While the brake torque request from the autonomous driver may be shaped differently, the shape of the actual brake force request will be affected by the motor limitations similarly as for the regular vehicle. Hence, the force request can be expected to show a similar, pulse-like, behavior both for manual and autonomous drivers. This pulse-like behavior needs to be considered in brake design activities as it may have a negative impact on the energy savings of using brake blending.

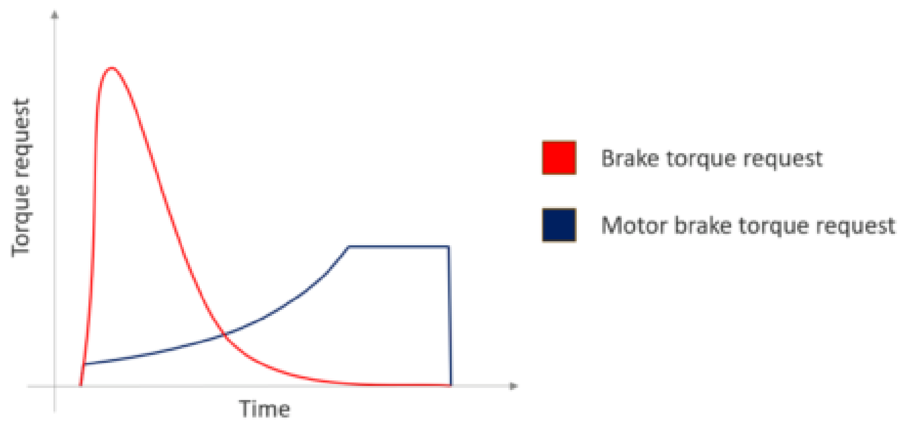

Figure 2. Typical relation between the brake torque request (foundation brake) and motor torque request (driveline) during a brake event with brake blending.

The energy consumed by the brake system is further influenced by the driver's behavior at standstill. Some common brake patterns at standstill are shown in Figure 3: parking brake, mild brake, and hold brake.

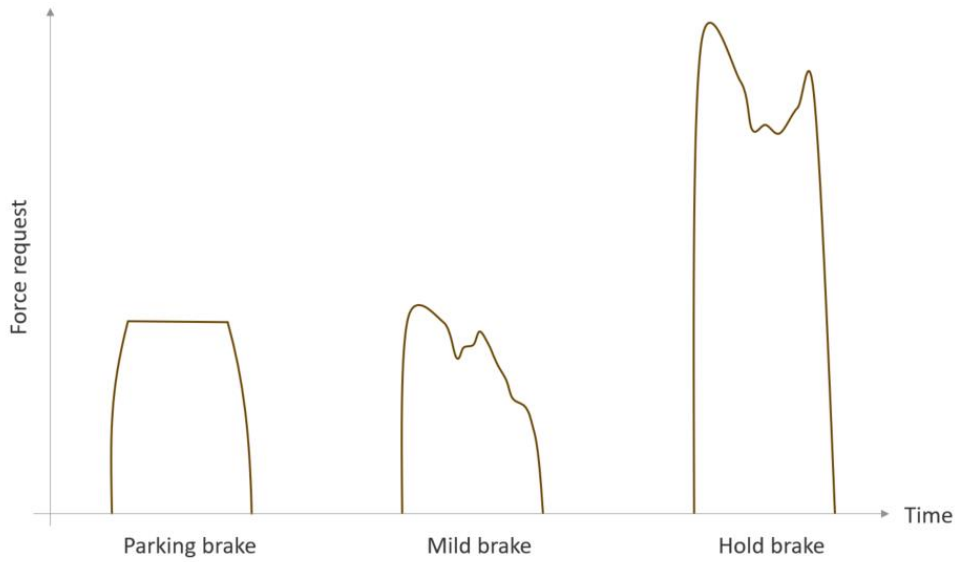

Figure 3. Brake patterns at standstill to consider.

The first case resembles the force request of a parking brake event, where the brake is locked at a steady force, using an internal locking mechanism. The impact on the power consumption is low for this case. Besides the power needed for the initial actuation of the brake, no power is required to hold the requested force while locked. The mild brake and hold brake patterns occur in red-light situations and in other situations where the parking brake is left open, and the driver uses the brake pedal to hold the vehicle. Mild brake means just enough brake to hold the vehicle and hold brake means full braking. As indicated by the brake patterns of Figure 3, the driver often fails to hold a steady force request during mild brake and hold brake situations. There are several explanations for this, such as the lack of reference speed at standstill and the low level of force feedback in typical truck brake pedals. The mild brake and hold brake patterns have a much higher impact on the power consumption than the parking brake case, due to the varying force request that may prevent the brake from locking.

Model development

To analyze the dynamic behavior and the energy consumption of the EMB system, a system model comprising a detailed brake axle model, a simplified vehicle, and a driver, is developed in Modelica[1]. Modelica is a leading object-oriented, equation-based, and acausal modeling language, well-suited for dynamic modeling and simulation of physical systems.

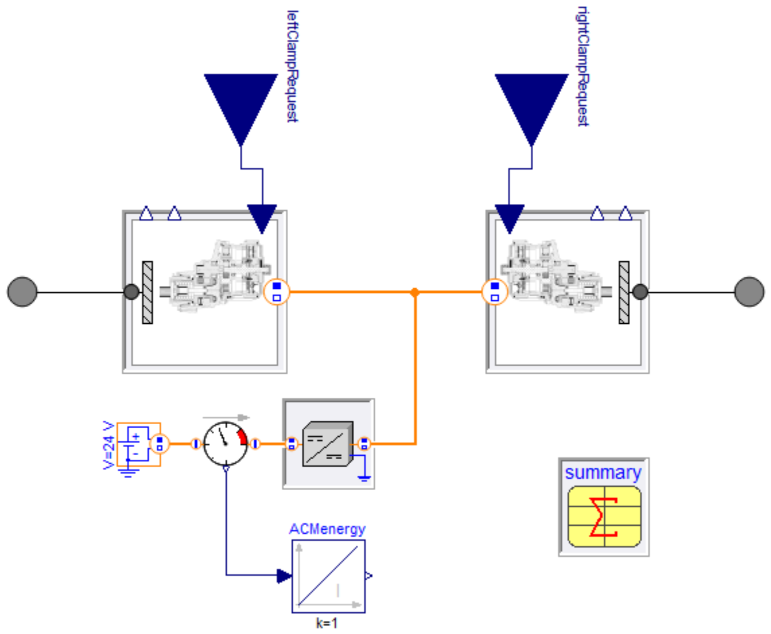

Figure 4. The brake axle model modelled in Modelica.

The outline of the brake axle model is shown in Figure 4. It consists of an Axle control module (ACM) connected to two brakes, each consisting of a Caliper control module (CCM) and a caliper. The ACM, charged by the vehicle battery, is the energy reservoir of the brake axle that powers the CCMs.

The CCM actuates and controls the caliper. It is modeled by an electrical motor with inverter, a gear, and a ball ramp that translates the rotational movement of the motor into the translational movement required for the clamping.

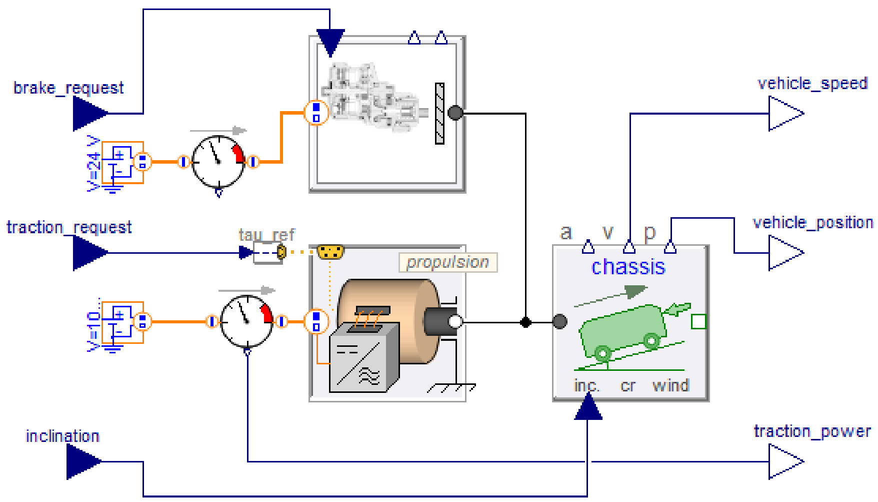

Figure 5. The vehicle model with motor, chassis, and detailed brake axles.

The vehicle model used is shown in Figure 5. It consists of a simple chassis model, an electrical motor, and the brake axle model described previously. The chassis is a simple standard vehicle from the Modelica Standard Library[2], defined as a moving mass with losses related to rolling resistance, aerodynamic drag, and inclination. The electrical motor is a detailed standard model from Modelon's Electrification Library[3]. It models the propulsion system of the vehicle and supports both positive and negative torques. The latter is important when studying brake blending effects, i.e. when the vehicle drivetrain is used in combination with the friction brakes to achieve the retardation during a brake event.

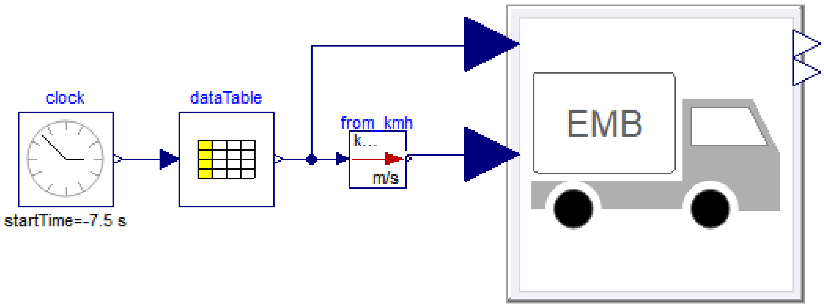

Figure 6. The controlled vehicle testbench based on the vehicle described previously.

The complete vehicle system model in Figure 6 is achieved by combining the vehicle model with a driver model that follows a specified speed and inclination profile, while considering the speed and brake control characteristics discussed previously. The driver model consists of a PD controller that generates traction and brake requests in accordance with the brake blending strategy used. The brake blending strategy can be turned off and altered by modifying parameters such as the max power and max torque used by the vehicle motor during braking. The driver also models standstill behavior, i.e. the use of the parking brake at zero velocity.

Model validation

The system model is validated on component, subsystem, and system level. Component validation, such as the validation of the EMB motor and inverter model characteristics, is performed using measurement data from component tests. Subsystem models, such as the brake and axle models, are validated in a similar way using the test rigs available at Haldex. In addition to capturing the dynamic system behavior, emphasis of the validation is put on correctly mimicking the component and system losses, as this will have a major effect on the energy consumed by the system.

The complete system model is validated using measurement data from vehicle tests obtained in collaboration with an OEM of the automotive industry. In these tests, a test driver follows the velocity profiles of the drive cycles discussed previously, using a vehicle equipped with EMB axles.

The test is then reproduced in the simulation environment by using the recorded velocity profile of the physical driver as input for the modeled driver. The outcome is compared to the results from the physical test to build an understanding for how well the results correlate. The brake force requests from the driver, delivered brake force, and energy consumption of the system over the drive cycle are a few of the signals of interest.

Figure 7 and Figure 8 shows the simulated and measured clamp force and the energy consumed during a refuse drive cycle. The parking brake is applied at standstill. The vehicle testbench shown in Figure 6 has been used in the simulation environment together with the recorded velocity and inclination profiles from the physical test.

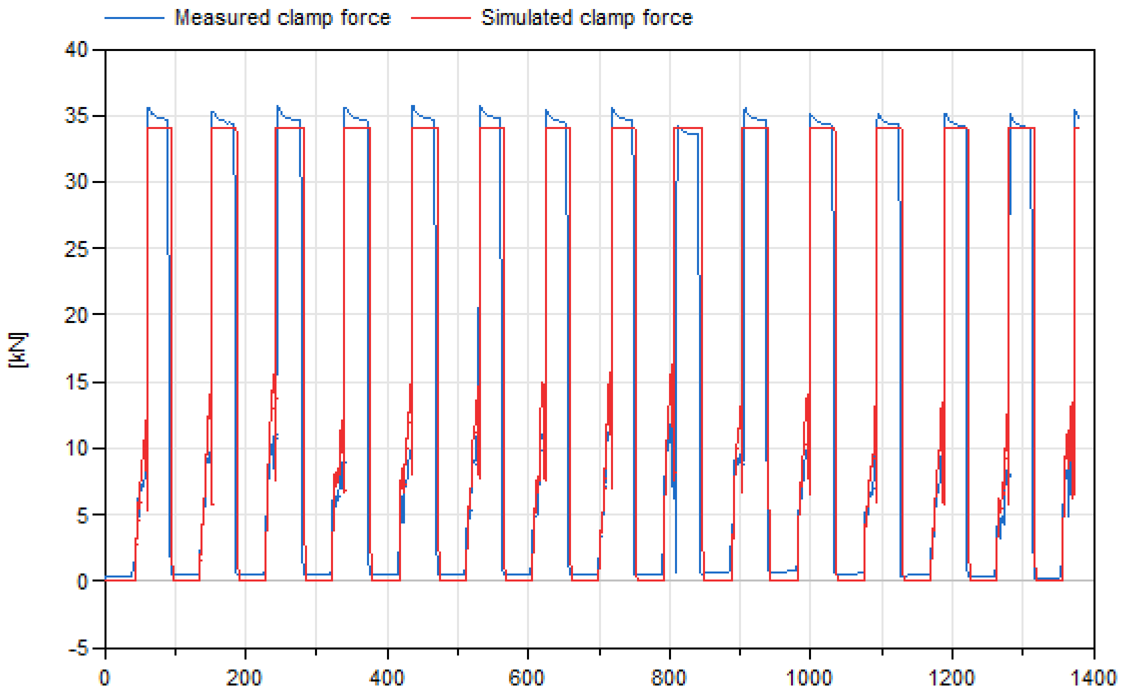

Figure 7. Measured and simulated clamp force of the refuse drive cycle.

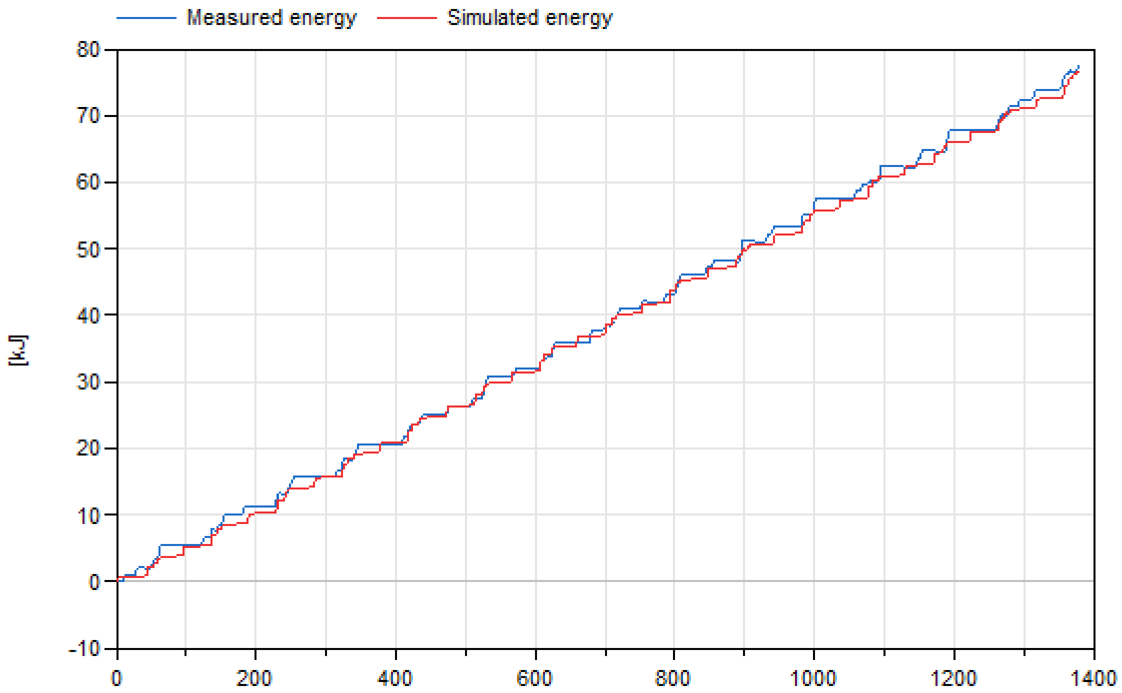

Figure 8. Measured and simulated energy consumption of the refuse drive cycle

In addition to the validation of the full vehicle model, the same test data is also used to perform analysis on the isolated axle model. In this case, the recorded brake request generated by the physical driver is used as input to the simulated brake axle. Again, simulation results, such as delivered brake force and the energy consumed, are compared to their measured equivalents. Figure 9 and Figure 10 shows the results from an axle validation case of a construction drive cycle. The parking brake is applied at standstill. Here, the recorded clamp force from the measurement is used as input to the brake axle simulation. The spike seen at the end of each parking brake event in Figure 9 is due to noise in the measurement data.

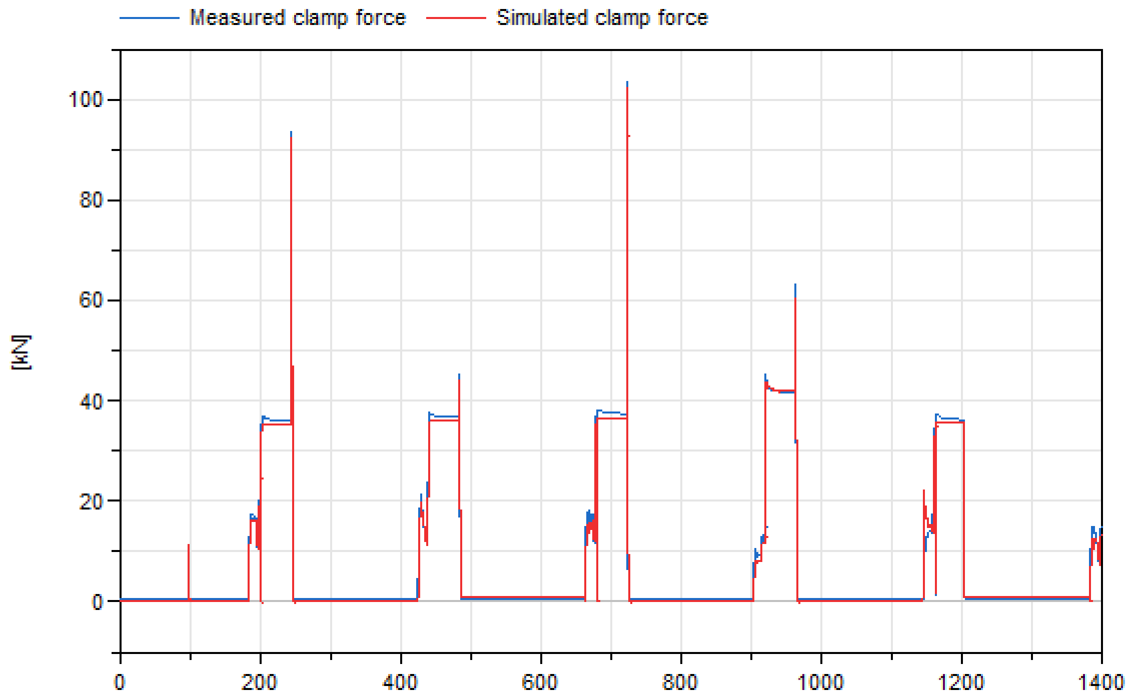

Figure 9. Measured and simulated clamp force of the construction drive cycle

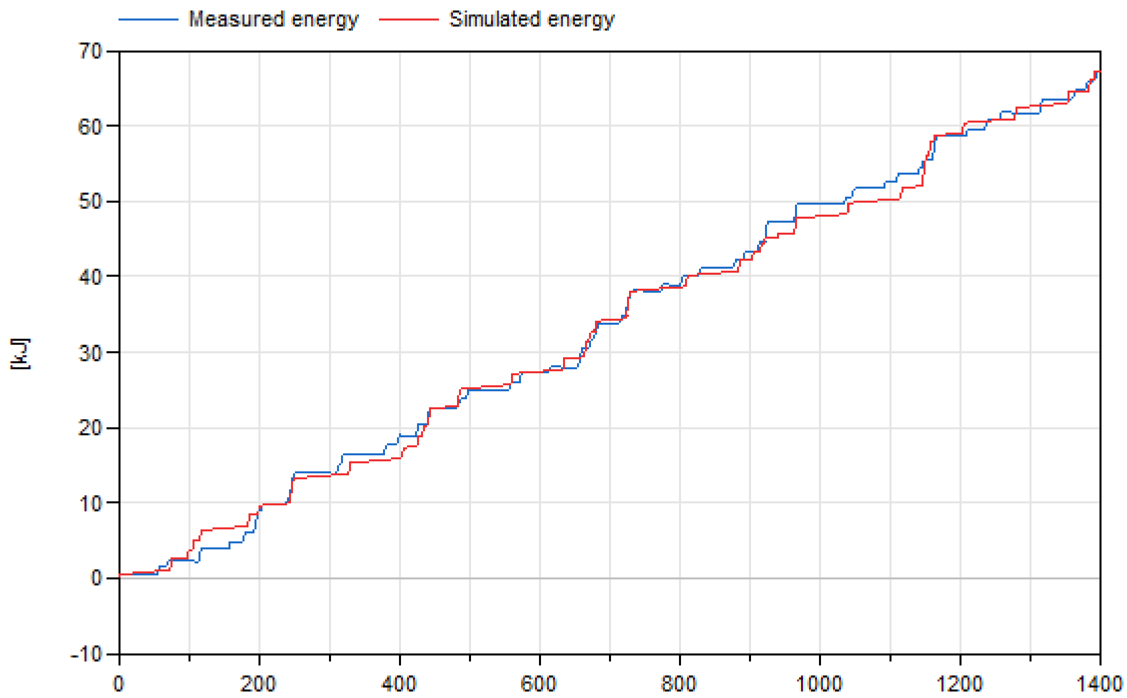

Figure 10. Measured and simulated energy consumption of the construction drive cycle

The quality of the model validation is improved by the dual use of the test data, as it simplifies identification of external factors that may influence the correlation between the simulated and measured systems.

Data from eight vehicle drive cycle tests, with parking brake at standstill, are compared to the simulation results from both the full system and the brake axle test setups. The validation indicates a good correlation between the simulated and measured systems, with a mean energy deviation of < 1% for the population of tests.

Similar validation efforts show good correlation between simulations and measurements also for drive cycle tests with mild brake and hold brake patterns at standstill. It is, however, clear from the measurement results, that mild brake or hold brake situations are harder to reproduce with a real-world vehicle and driver, than the corresponding parking brake situation. This is due to the lack of driver references, such as speed and force feedback, discussed previously. Mild brake and hold brake situations are equally hard to reproduce in simulation using the full system model. Hence, the model validation of such situations is limited to tests using the isolated brake axle model.

Energy consumption analysis

The energy consumption of the EMB system in relation to a traditional pneumatics based Electrical Brake System (EBS) is studied using a similar approach as for the full system validation. The test vehicle, same vehicle as in the validation work, equipped with EBS axles are used for the physical testing and the driver follows the same set of drive cycles as discussed previously. The recorded velocity profiles and force requests from these measurements serve as inputs to the EMB simulation testbenches mimicking the full vehicle and the brake axle.

The measured energy consumed by the EBS system is compared to the simulated EMB energy for each test. A typical result is shown in Figure 11. The figure shows a comparison between the measured energy consumed by the EBS system and the simulated energy consumed by the EMB system during a construction drive cycle.

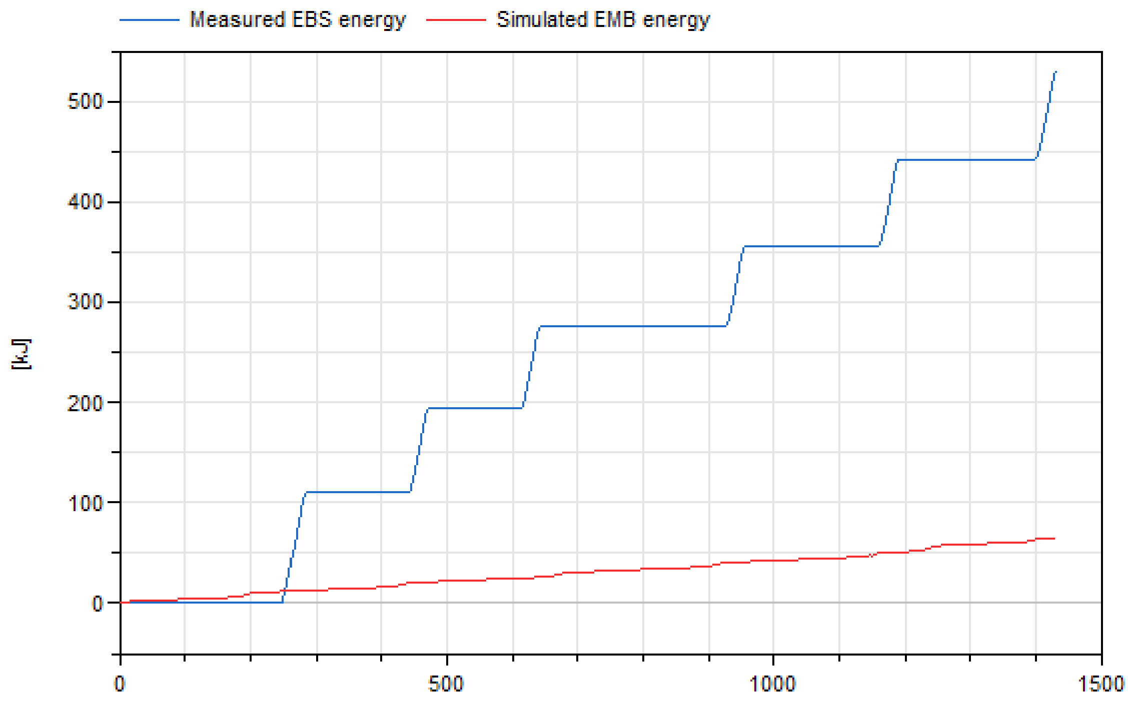

Figure 11. Measured EBS energy compared to simulated EMB energy for a construction drive cycle.

The results from the comparison indicate that the EMB system consumes about 10-20% of the energy of a traditional EBS system. An energy saving of 80-90%.

Energy savings per vehicle type

The energy consumption measurements described previously were conducted using a designated vehicle and a limited number of drive cycles. The analysis can now be extended to other vehicle types and drive cycles by using simulation.

The vehicle definitions are shown in Table 2.

Table 2. Vehicle definitions used in the energy consumption analysis.

Vehicle	Mass (kg)	Axles
Ebus 12m 4x2	12000	2
Ebus 18.2m 6x2	19500	3
Waste mgmt 6x2	22000	3
MD truck	21000	2
Long-haul 6x2	35000	3

Energy savings are calculated assuming a fixed EMB/EBS energy ratio of 15%. This is a reasonable value given the concluded energy consumption ratio between EMB and EBS of 10-20%. Energy and cost savings per drive cycle (row) and vehicle type (column) are shown in Table 3. The cost savings are estimated assuming an energy price of 0.3 €/kWh and an annual driving distance of 80000 km.

Table 3. Annual cost saving per drive cycle (row) and vehicle type (column)

Annual savings (€)	Ebus 12m 4x2	Ebus 18.2m 6x2	Waste mgmt 6x2	MD truck	Long-haul 6x2
City	407,65	645,22	613,57	472,34	760,03
Refuse	492,48	704,61	724,69	534,65	833,33
Construction	123,58	186,66	190,38	135,68	205,37
Regional distribution	100,57	148,16	149,19	102,27	154,48
Long-range	55,11	82,42	82,50	55,20	82,87

Brake blending

The energy consumption and savings of using the EMB system in vehicles together with brake blending have also been modeled, validated, and analyzed using the described process. The results indicate that the energy savings remain in the same range as for vehicles without brake blending, 80-90%.

In addition, the results indicate that while brake blending saves energy due to the regeneration, it has a minor effect on the brake energy consumption both for EBS and EMB. The reason for this is twofold. Firstly, the system idling power consumption remains the same both with and without brake blending. The second reason is related to the pulse-like behavior of the brake force request discussed in Figure 2. A typical clamp force of the measured EBS system is shown in Figure 12. The first pulse of the figure is related to how the brake request compensates for the motor power limitation at high velocities. The second pulse comes from an increasing brake request from the driver close to standstill.

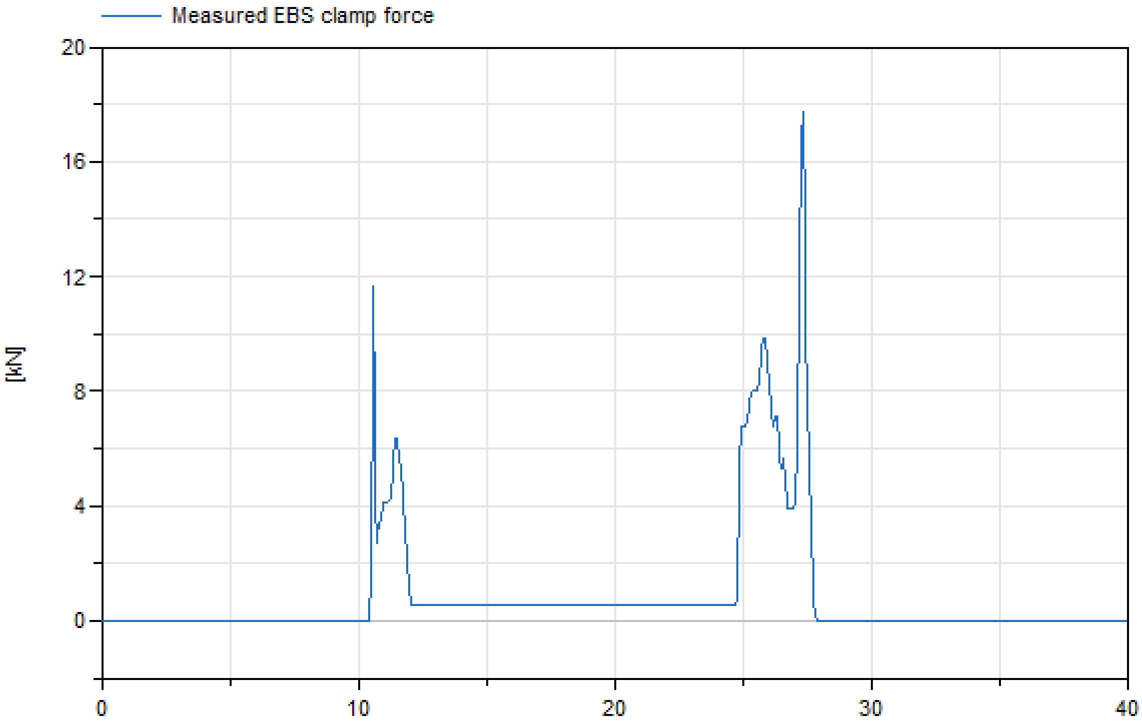

Figure 12. Measured EBS clamp force for a construction test with brake blending

While the overall brake force request is lower for brake blending cases, the pulse-like behavior shown has a negative effect on the power consumption of the brake system.

Conclusions

The stronger focus on the energy and environmental aspects of the brake system requires adoption of development methods and processes that allows for analysis of those effects in addition to the already strong focus on safety features. This means adopting a knowledge-driven and cross-functional process that aligns with the business goals and provides early feedback on design proposals with respect to energy, environment, and safety.

In this work, such a simulation-driven process was developed for analyzing the dynamic behavior, energy consumption, and savings of using the EMB system. The results from the analysis show that the EMB system consumes about 80-90% less energy than a traditional pneumatics based EBS system. While the results confirm the outcome from a previous study[4], where energy savings of about 83% were achieved with a city bus, they also indicate the potential of making even larger cost savings with other vehicle-drive cycle configurations as shown in Table 3.

The analysis based on the simulation models has delivered extended insights into the system and its use cases. Studies of the different considerations in brake design, discussed earlier, have led to a number of improvement suggestions to further reduce the power consumption of the system. The strong interaction between testing and simulation has been essential to these studies, as it has delivered a deeper knowledge of the complexity of the EMB system and results that would have been impossible to achieve with testing or simulation alone.

The analysis of the power consumption during red-light situations, mild brake or hold brake, is an example where this has proven valuable. As discussed previously, such situations are hard to reproduce in testing due to the lack of driver references at standstill which can lead to large deviations in energy consumption. Measurement results from mild brake and hold brake situations, show that the energy consumption can deviate up to 100% for comparable tests. This large variation is a consequence of the lever effect of brake systems that makes the energy consumption sensitive even to small deviations in the boundary conditions. The interaction between the real-world testing and simulation has been a necessity for reducing the impact of these conditions in the analysis. In addition, the simulation-based process has been an enabler for studying the impact of alternate lock mechanisms and control strategies targeting more efficient locking of the brakes during such situations. Analysis shows that there are several ways for the control software to limit the power consumption at standstill even with varying force requests. However, those improvements are yet to be implemented.

Understanding the system behavior and energy consumption during different situations are key enablers for future design improvements and for optimizing the brake behavior in heavy vehicles. The analysis done in this work shows that the EMB system can play an important role in the overall vehicle system optimization. Not only with respect to energy efficiency and safety features, but also with respect to other aspects such as tire and brake pad wear. Such improvements would mean further cost reductions and lower particle emission levels. The full vehicle system optimization aspects of using the EMB system needs to be further investigated. The simulation-driven process and the brake system knowledge developed in this work are good starting points for those investigations and will continue to support the future innovation of brake systems.

References

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[3] The Modelon Electrification Library - https://modelon.com/library/electrification-library/

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