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An investigation on the fuel savings potential of hybrid hydraulic refuse collection vehicles

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ABSTRACT

Refuse trucks play an important role in the waste collection process. Due to their typical driving cycle, these vehicles are characterized by large fuel consumption, which strongly affects the overall waste disposal costs. Hybrid hydraulic refuse vehicles offer an interesting alternative to conventional diesel trucks, because they are able to recuperate, store and reuse braking energy. However, the expected fuel savings can vary strongly depending on the driving cycle and the operational mode. Therefore, in order to assess the possible fuel savings, a typical driving cycle was measured in a conventional vehicle run by the waste authority of the City of Stuttgart, and a dynamical model of the considered vehicle was built up. Based on the measured driving cycle and the vehicle model including the hybrid powertrain components, simulations for both the conventional and the hybrid vehicle were performed. Fuel consumption results that indicate savings of about 20% are presented and analyzed in order to evaluate the benefit of hybrid hydraulic vehicles used for refuse collection.

1. Introduction

The worldwide collection and transport of solid waste requires large amounts of fossil fuels and has a significant influence on our climate, see e.g. Fruergaard et al. (2009) and Eisted et al. (2009). In particular, refuse trucks play a vital role in the daily waste disposal routine. They are used to collect different kinds of solid waste in urban areas everywhere in the world. In order to guarantee clean neighborhoods, the refuse trucks must satisfy a variety of requirements, most importantly reliability and efficiency, but also manoeuvrability and the satisfaction of the driver's power demand. Additionally, the waste compactor system needs to match the operational task and the vehicle type. Typically, refuse collection vehicles are powered by conventional diesel engines. Although modern engines allow for relatively efficient vehicle operation, refuse collection vehicles consume extremely large amounts of fuel compared to the travelled distance as shown by Nguyen and Wilson (2010). This is due to the typical driving profile during waste collection: refuse trucks must stop frequently in order to pick up the waste containers, which results in long idling times, see Gaines et al. (2006). In urban areas, a dense household population leads to short distances between consecutive containers. During the vehicle stops at these waste containers, the diesel engine needs to be in idling mode in order to power the compactor system. As a consequence, refuse trucks are characterized by an extremely low mileage per gallon (Larsen et al., 2009; Nguyen and Wilson, 2010). Additionally, refuse trucks have a significant impact on the environment due to their diesel exhaust emissions and the brake dust resulting from the typical stop-and-go behavior, see e.g. Kuusimäki et al. (2002) and Larsen et al. (2009).

For all these reasons, refuse collection vehicles are interesting candidates for advanced powertrain concepts as noted by Baseley et al. (2007). Their efficiency can be increased by improving the conventional powertrain components, e.g., down-sizing of the diesel engine or the development of more efficient transmissions. More recent approaches include hybrid powertrain solutions, where the conventional powertrain is supplemented by an alternative propulsion system consisting of a second energy converter and a second power source. Hybrid electric vehicles are a well investigated topic in research (Guzzella and Sciarretta, 2007), with a clear focus on passenger vehicles. However, hybridization concepts aiming at commercial vehicles have recently become more popular, e.g. Baseley et al. (2007) and Wu et al. (2004). Several truck manufacturers already offer hybrid electric refuse trucks with various powertrain concepts. These electric hybrid vehicles use one or several electrical machines in combination with an electrical battery, usually on a basis of Lithium-Ion cells. The additional electrical powertrain allows for regenerative braking, i.e., conversion of the braking energy into electrical energy. The recuperated energy is

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stored in the battery and used at a later time instant to propel the vehicle. Furthermore, there exist plug-in variants that can be charged over night. Depending on the hybrid vehicle architecture, the state of charge (*SOC*) and the applied energy management strategy, hybrid electric refuse trucks can also be operated in a zero-emission mode, during which both vehicle propulsion and compactor operation is performed by the electrical machine and the diesel engine can be turned off. While hybrid electric vehicles (HEVs) offer a variety of advantages over conventional vehicles, they also suffer from the high complexity of the electrical components. This leads to high costs, in particular during vehicle acquisition because of the expensive batteries, but also thereafter because of the high requirements regarding maintenance and the expensive spare parts.

Hybrid hydraulic vehicles (HHVs) offer similar advantages as their electric counterparts, but differ by using hydraulic propulsion technology. This leads to cheaper components. Additionally, the hydraulic propulsion system can easily be retrofitted into an existing conventional powertrain. Since most refuse trucks already use a hydraulic compactor system, the maintenance personnel is usually familiar with hydraulic components and can therefore perform minor repairs on the hybrid vehicle. HHVs are a current topic in academic research, see e.g. Bender et al. (2013) and Kaszynski and Sawodny (2011), but various manufacturers also offer commercial solutions. However, previous work used artificial driving cycles in order to evaluate the possible fuel savings when comparing the HHV to the conventional diesel vehicle (Baseley et al., 2007; Kaszynski and Sawodny, 2011; Bender et al., 2013). This makes it difficult for authorities and private waste management companies to decide on whether they can expect fuel savings on their collection routes that justify the higher vehicle acquisition and maintenance costs.

In order to analyze the costs involved in municipal waste disposal, various models for the waste collection process have been developed in the past, e.g. Hirsch (1965), Wang et al. (1996) and Sonesson (2000). The impact of waste transportation on the environment for different scenarios and collection strategies was analyzed by Beigl and Salhofer (2004), Salhofer et al. (2007) and McLeod and Cherrett (2008). Wilson and Baetz (2001b) and Wilson and Baetz (2001a) model the waste collection process using probability distributions. However, none of these models can be used to assess the possible fuel savings obtained from hybrid refuse trucks since they do not include detailed vehicle models. In this work, we investigate the possible fuel savings based on a driving cycle derived from real-world measurements including vehicle velocity, vehicle mass, road grade and compactor activation phases. This allows for a precise assessment of the possible fuel savings achieved through the use of hybrid hydraulic refuse trucks, enabling the waste management contractor to decide on whether hybrid hydraulic refuse trucks pay off.

The paper is organized as follows: the measurement setup and the derived driving cycle are illustrated in Section 2. In Section 3, we present the developed dynamical vehicle model with its conventional and hybrid components. The obtained simulation results are presented and analyzed in Section 4. Finally, Section 5 provides concluding remarks and an outlook on future work related to this research.

2. Driving cycle acquisition

During the development and analysis of advanced powertrain concepts, simulation models can be used to obtain valuable insights at an early development stage. However, such simulations only deliver realistic results if both the used vehicle model and the used driving cycle (consisting of e.g. velocity, mass and road grade) match the considered vehicle and its typical application profile. Therefore, driving cycle acquisition is a first crucial step in order to determine the possible fuel savings of hybrid hydraulic refuse trucks. Only by using the real driving cycle within simulations, reliable conclusions regarding the expected fuel consumption can be delivered. For refuse trucks, the driving cycle includes not only the velocity and road grade, but also the time-varying mass and the activation phases of the compactor.

2.1. Vehicle measurements

In order to obtain realistic driving cycle data, a conventional refuse truck was equipped with data logging hardware and additional sensors including a differential GPS to obtain precise position information, and a MEMS barometer for altitude measurements based on the atmospheric pressure. Signals corresponding to the vehicle's powertrain such as velocity, chosen gear or engine speed were accessible through the standard vehicle controller area network (CAN) bus. Additionally, the current vehicle mass is measured through the air suspension of the wheels and also made available on the CAN bus. Fig. 1 illustrates the measurement setup.

Together with the waste management authority of the City of Stuttgart, Germany (AWS), a collection route was chosen that contained both typical collection phases in urban neighborhoods and typical transfer phases from the collection area to the waste incineration plant. The chosen route also includes high road grades, which lead to high power demands during vehicle operation. After the measurement hardware was installed, the vehicle was operated on its usual collection routes and driving cycle data was collected from December 2012 until February 2013.

2.2. Driving cycle

From the recorded vehicle data, the complete driving cycle can be derived. Fig. 2 illustrates the complete driving cycle corresponding to a complete working day of the refuse truck. The position plot clearly shows the urban collection area in the northeast as well as the long transfer to the waste incineration plant in the south via the highway. There were two major collection phases performed within the magnified collection area. The corresponding intervals

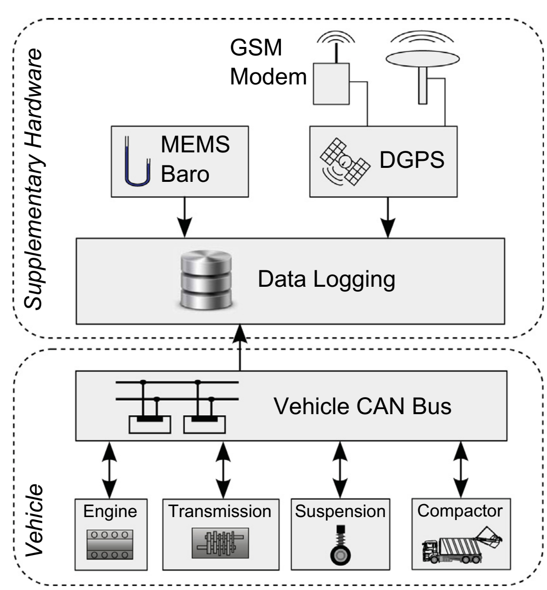

Fig. 1. Measurement setup for the acquisition of the refuse truck driving cycle.