

Assessing the Regeneration Potential for a Refuse Truck Over a Real-World Duty Cycle

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ABSTRACT

The majority of a refuse truck collection cycle consists of frequent Stop and Go events while moving from one household to another. The nature of this driving mission creates the opportunity to reduce fuel consumption by capturing and re-using the kinetic energy normally wasted during braking. This paper includes the evaluation of the brake energy available for regeneration from the conventional drivetrain; the description of the impact of the vehicle variable mass and auxiliary loads; a model validation over a real-world duty cycle; and the potential for an increase in fuel efficiency through hybridization of the drivetrain. The Hydraulic Hybrid (HH) technology is selected since it has a large power density. Special attention is paid to two main issues related to refuse truck modeling: i) the fact that each time the trash bin is picked up, the vehicle mass increases in a discrete manner; ii) the load from the additional auxiliary Power Take-Off unit used to lift and compact the refuse. The model of the complex vehicle system is validated with data from real-world refuse collection duty cycles in Texas.

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INTRODUCTION

Refuse trucks are part of an urban infrastructure. The nature of the refuse collection consists of hundreds of stops in front of individual homes or businesses. Accelerating the Class 8 truck weighing 15+ tons after every stop requires a significant amount of energy. Delivering such energy to the wheels entails high fuel consumption as well as a release of pollutant emissions into city areas [1]. Powertrain hybridization provides the direct means to decrease both the pollution emitted and the energy consumption by capturing the vehicle kinetic energy during the frequent decelerations and re-using it for acceleration.

Due to the significant weight of the vehicle, refuse truck hybridization requires a technology with high power density to handle high rates of energy flow. Hydraulic Hybridization (HH) is well suited for such an application as it uses the Pump/Motor (P/M) with a much higher power to weight ratio than its electric motor/generator counterpart [2]. For storage purposes, an HH vehicle can use a bladder type accumulator filled with elastomeric foam, which can achieve 95% of the round trip efficiency [3]. With regard to refuse truck maintenance, the personnel are previously trained to deal with safety concerns since pressurized hydraulic circuits already exist on the truck i.e. auxiliary hydraulic circuits for refuse pick-up, compacting and brake system.

The objectives of this paper are to develop a vehicle system simulation of the conventional refuse truck and to later use the simulation to assess the potential of the regenerative braking of the hydraulic hybrid configuration during a real-world refuse collection cycle. The paper is organized as follows. The conventional and the HH vehicle models are described first. Next, the analysis of the refuse collection duty cycle is performed and the distinction between the two driving modes, e.g. collection and trip to landfill is made. An additional consideration is given to the modeling of the vehicle weight increase and the Power Take-Off (PTO) operation during refuse collection. Model predictions for the conventional vehicle are validated with real-world measurements. Finally, the energy audit is performed using the validated model to analyze the potential of regenerative braking. The paper concludes with a comparison of the conventional versus the HH fuel consumption over a real-world driving cycle and offers insights into potential for further improvements.

VEHICLE MODEL

The vehicle model is based on an integrated vehicle simulation platform created in Simulink, and a hydraulic driveline and storage components that were originally developed for a smaller, class 6 truck [4, 5]. For the class 8

refuse truck simulation, the model was appropriately modified and new components were scaled as needed. [Table 1](#) gives the refuse truck specifications.

Table 1. Refuse truck specification

Engine	Description	8.3L – 6cyl
	Max. Power	218kW @ 2450rpm
	Max. Torque	1240Nm @ 1320rpm
Transmission	Design	5speed
	Gear ratios	4.59 2.25 1.54 1 0.75
	Differential	6.14
Vehicle	Curb weight	16,000 kg
	Air drag	0.75
	Frontal area	6.5 m ²
	Tire radius	0.53 m

Since the detailed description of several components was not available, certain approximations were made based on measured real world data. As for the engine model, the available 7.6L engine fuel consumption map was scaled up to match the peak power of the 8.3L engine used in the real vehicle. The main approximations refer to the shift logic, weight increase and the PTO power demand. The shift logic was generated from the real-world data thorough application of basic principles for developing gear shift lines.

The models are integrated into a forward looking simulation. The virtual driver is modeled as a PI controller, which compares the actual and desired vehicle speed and gives a separate command for acceleration and deceleration. The acceleration command is mapped together with the engine speed in order to provide the fueling command. The engine output torque is a function of the engine speed and the fueling command. The engine speed ω_e is computed from the dynamics [equation \(1\)](#) where I_e is the engine inertia, T_e is the engine torque and T_i is the impeller torque from the torque converter.

$$\omega_e = \frac{1}{I_e} \int (T_e - T_i) dt \quad (1)$$

The refuse truck is equipped with a 5-speed automatic transmission. The torque converter is modeled by [equation \(2\)](#) using the capacity factor and the torque ratio curves;

$$T_i = \left(\frac{f_k(SR)}{\omega_e} \right)^2 \quad (2)$$

where f_k is the capacity factor function and SR is the speed ratio between the engine speed and the turbine (transmission input), i.e. $SR = \omega_{\text{turbine}} / \omega_e$. The torque converter includes a lockup clutch and is controlled based on the vehicle speed and driver's demand. It is limited to lock only on the second

and higher gears. The gearbox is modeled as a finite state machine, where different gears represent different states. A blending function is added to simulate inertia and the torque phase during the gear shift.

The vehicle is modeled as a single point mass system while the pitch plane dynamics are ignored. The resistive forces include air drag and rolling resistance. The latter depends on the vehicle weight and can change during the driving cycle. The vehicle also contains a brake model, which modulates the braking forces on the vehicle depending on the driver signal.

HYDRAULIC HYBRID CONFIGURATION

The parallel hydraulic hybrid powertrain is modeled by integrating additional components into the conventional powertrain. By adding a secondary power source after the conventional transmission, the propulsion system is able to assist the engine or recover the vehicle kinetic energy during deceleration. The engine downsizing or the engine shut downs are not considered in this study.

The HH system shown in [Figure 1](#) consists of a variable displacement axial piston Pump/Motor (P/M), a 38L high pressure hydraulic accumulator (140-300bar) and a low pressure reservoir (2-5bar). The P/M is coupled to the driveshaft with the gear ratio of 1.5. An additional vehicle weight of 500kg is considered to account for the hydraulic hybrid system. The P/M displacement command varies the flow and torque. The modeling is based on the updated Wilson theory [6], where the theoretical flow and torque are calculated and then multiplied by the volumetric and torque efficiencies. The coefficients in the expression for losses are calibrated to match the state-of-the-art P/M design developed for the propulsion [7]. More details about the P/M implementation and modeling can be found in [8, 9]. The hydraulic accumulators act as a hydro-pneumatic energy storage device. The nitrogen gas is stored in the bladder and compressed whenever the hydraulic fluid enters the accumulator, thus acting as a pneumatic spring. The differential equation for temperature is derived from the energy conservation expression. Since the hydraulic system works under high pressures, the ideal gas equations cannot be used. Instead the gas pressure is related to the gas temperature and specific volume by the Benedict-Webb-Rubin equation for real-gas [6]. The accumulator is modeled with an elastomeric foam on the gas side to increase the thermal time constant [8, 10] and to achieve high conversion efficiencies in the ~95% region.

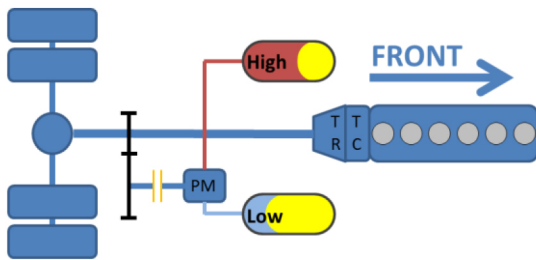


Figure 1. Powertrain scheme

Hybrid powertrain architecture offers flexibility in operating two power sources in the most efficient manner while satisfying all the constraints imposed on the vehicle powertrain. Most commonly the main interest in developing the supervisory control is to maximize fuel economy [11]. Even though advanced optimization algorithms for the supervisory control are required to evaluate the maximum benefit [12], the heuristic based control strategy is an intuitive, robust and simple alternative suitable for the initial system analysis and the characterization of interactions within the system. The strategy for a parallel system aims to recuperate the vehicle kinetic energy until the accumulator is full, and to reuse it immediately to accelerate the vehicle until the hydraulic accumulator is depleted. Several constraints were implemented to ensure the P/M speed range and to avoid P/M frequent on/off operations.

DRIVE CYCLES

The duty cycle of refuse collection consists of frequent stop and go conditions as the truck moves from one household to another to empty the trash bins. This is followed by a high speed drive to landfill. Figure 2 shows a speed trace recorded during real world refuse truck operation. The data were acquired on conventional refuse truck operating in a suburban area in Texas, with a majority of single family households. The data acquisition technique was similar to [13]. During the refuse collection, the vehicle is normally accelerated to a speed of about 20km/h and then stopped within the next 20 meters. The aggressiveness of this mission is driven by the productivity requirement, i.e. the desire to collect the refuse from the prescribed area in the shortest time possible. Once the refuse has been collected, the truck needs to be unloaded at the landfill. Therefore, the refuse truck driving cycle can be divided into two driving modes: collection and approach. The division between the two modes is possible by using the GPS data, where collection neighborhoods are identified. The driving character can also be identified through the speed trace, where speeds much higher than 20 km/h for a longer period of time clearly indicate approach to landfill. Figure 2 illustrates a sequence of two collection cycles. It also shows the vehicle weight increase during the collection. The vehicle weight increases in discrete steps as the trash bins are picked up, while during

the approach the weight remains constant. After the unloading at the landfill the vehicle weight is reset.

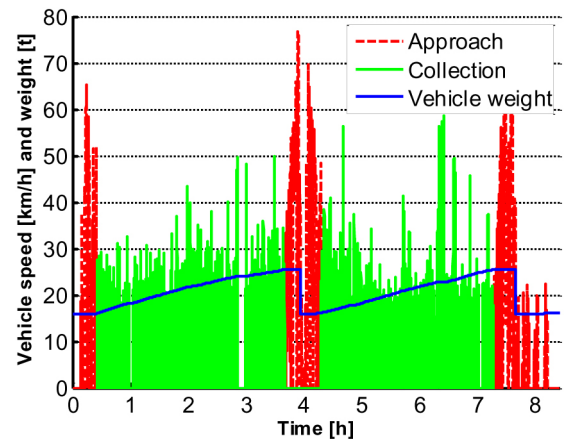


Figure 2. Refuse truck duty cycle divided into approach and collection parts: the sequence comprises approach, collection, trip to landfill, approach, collection and second trip to landfill.

To gain further insight, the speed distribution on the same cycle is shown in Figure 3, including the histogram and its cumulative representation. During this drive cycle, about 45% of the time the vehicle is stopped. Then as the speed distribution gradually increases to 20 km/h, about 84% of the cycle cumulative time is already covered. The remaining 16% in the speed distribution consists of speeds above 20km/h. The rest of the available drive cycles show a similar distribution to the one shown in Figure 3.

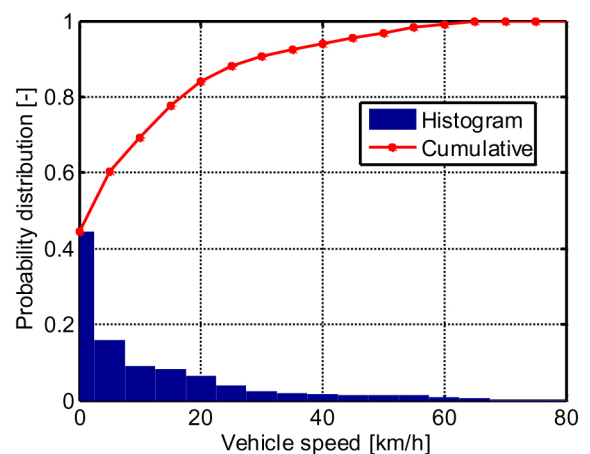


Figure 3. Refuse collection cycle characteristics

WEIGHT INCREASE ESTIMATION

The refuse truck curb weight is approximately 16 tons and the added weight of the collected refuse typically reaches an additional 8 tons (+50%)! This weight increase cannot be ignored since it has a significant impact on the vehicle energy usage. In order to estimate the vehicle weight, several