



Conceptual design and operating modes comparison of parallel, series and hydro-mechanical hydraulic hybrid power train with hydraulic hybrid auxiliary system

Sohrab Pakdelbonab^{1*}, Afshin Kazerooni², Gholamhassan Payganeh³, Mohsen Esfahanian⁴

¹ PhD Student of Mechanical Engineering Department, Shahid Rajaei Teacher Training University, Tehran, Iran

² Assistant Professor of Mechanical Engineering Department, Shahid Rajaei Teacher Training University, Tehran, Iran

³ Associate Professor of Mechanical Engineering Department, Shahid Rajaei Teacher Training University, Tehran, Iran

⁴ Associate Professor of Department of Mechanical Engineering, Isfahan University of Technology, Isfahan, Iran

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ABSTRACT

Global restrictions on the use of fossil fuels in the transportation sector and the commitment to rapid response to the climate change have created a strong incentive to develop fuel-efficient and low-emission vehicle systems. Hydraulic hybrid power train technology is one of the temporary solutions introduced to optimize internal combustion engine (ICE) operation and regenerate braking energy. The hydraulic hybrid power train system (HHPS) has a higher power density than the electric one. So, it is used in heavy vehicles, agricultural and construction machinery that need a high-power density to accelerate or recover the braking energy. In some trucks, such as refuse collection trucks, fire trucks and delivery trucks, a high percentage of the ICE energy is consumed by the auxiliary systems. In this type of trucks, the hydraulic hybrid power train systems are not very efficient. This paper introduces a hydraulic hybrid auxiliary system (HHAS) concept to manage the energy consumed by the auxiliary system in refuse collection trucks. In the first part of the paper, the configurations and operating modes of series, parallel and hydro-mechanical HHPS are discussed and compared with the HHAS concept. In the following, the conventional refuse collection truck model and refuse truck equipped with HHAS model was developed in MATLAB/SINMULINK and simulated in Tehran refuse collection truck driving cycle. The simulation results show that by using the HHAS concept, the fuel consumption is reduced by 15 percent.

1. Introduction

Due to a rise in the urban and interurban fleets, a large part of the world's fossil fuel resources are consumed by passenger cars and heavy vehicles. Fossil fuel resources in the world are limited and they will run out someday in the future. On the other hand, excessive consumption of fossil resources by vehicles leads to the production of various greenhouse gases such as carbon dioxide.

These greenhouse gases have a negative effect on weather conditions as well as human health. Today, the biggest challenge for the world's auto-manufacturers is to design and produce vehicles that are not dependent on fossil fuels. The idea of using electrical energy in a variety of vehicle systems, including propulsion, steering, cooling, and auxiliary systems, is the best solution to this challenge. But currently, the low energy density of electrical energy sources such as batteries and

*Sohrab pakdel bonab

Email Address: pakdel.srttu@gmail.com

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super capacitors compared to fossil fuels, low life cycles, high charging time, high cost, and also lack of infrastructure for electric vehicle usage have placed restrictions on auto-manufacturers and users. However, these restrictions are expected to be lifted in the near future and thus, electric vehicles will be extended to all urban and interurban fleets.

In conventional vehicles, the power required to propel the vehicle is supplied by ICE. The ICE is connected to the wheels by a mechanical transmission system. The direct mechanical coupling of the ICE to the wheels or the final users restricts the operation of the ICE, so that the ICE cannot operate in the high efficiency area[1]. The idea of using a secondary energy source and a power converter besides the ICE called hybrid powertrain is one of the temporary solutions commercialized in recent decades to manage the energy consumption of the ICE and recover braking energy. Figure 1 shows the concept of hybrid powertrain.

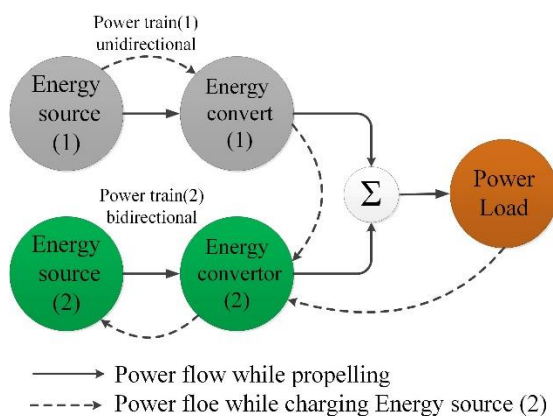


Figure1: The concept of hybrid power train

As shown in figure 1, the energy source and power converter 1, i.e., the ICE, is a unidirectional system that supplies the propulsion power of the vehicle and is not able to recover energy. But the power source and power converter 2 is a bidirectional system. This means that it is involved in providing propulsion power and can recover and store the energy through the ICE or the wheels when braking. If the energy source and secondary power converter is of electric type, it is called electric hybrid power train and if the energy source and secondary power converter is of hydraulic type, it is called hydraulic hybrid power train. Electric hybrid power train uses batteries or super capacitors as an energy store and motor-generators to convert electrical energy into mechanics or vice versa. HHPS uses the hydraulic accumulator to store hydraulic energy and hydraulic pump-motor to convert hydraulic energy to mechanics or vice versa. The purpose of the hybrid power train is to

disconnect the direct mechanical connection of the ICE from the wheels in order to operate the ICE in the optimal area and also to recover the braking energy.

The HHPS system has a higher power density than the electric one[2]. So, it is used in heavy vehicles, agricultural and construction machinery that need a high power density to accelerate or recover braking energy. This system has a high potential in reducing fuel consumption, pollution, the cost of installing hybrid equipment, and increasing vehicle performance in heavy vehicles. One of the early studies on HHPS to recover the kinetic energy was conducted by [3]. In this study, using a combination of flywheel and hydraulic accumulator, it was concluded that more than 50% of the kinetic energy could be recovered by the hydraulic system. In 1973, Elder and Otis proposed a computer model for the series HHPS [4]. This model could be used for a variety of passenger cars, vans, and buses. Reddy et. al. carried out a study on a parallel hydraulic hybrid bus using a constant displacement Pump/motor[5]. Matheson simulated a hydraulic hybrid system and designed an appropriate control strategy for a military vehicle at Monash University in Australia[6]. This project was done using MATLAB/SIMULINK software. A novel hydraulic hybrid vehicle with wheel motors to improve vehicle power performance and fuel economy has been proposed by [7].

The hydraulic power train system consists of three main configurations: series, parallel, and hydro-mechanical. System design, energy efficiency, environmental pollution, control strategy, and performance of each of these configurations are different depending on the vehicle class as well as its usage[8, 9]. In some urban fleets, such as the refuse collection fleet, vehicles perform a unique mission. In this fleet, conventional diesel trucks are usually used. These trucks have high frequent stops in their driving cycle. Also, a significant part of the ICE energy is used to supply the power of the auxiliary system. In recent years, various types of hybrid configurations have been introduced for this fleet[10, 11], but they seem to be inefficient and uneconomical.

This paper presents a novel concept for energy management of the auxiliary system in refuse collection trucks. This system is highly efficient and economical for refuse collection truck where a large part of the ICE energy is consumed in the auxiliary system. In the first part of the paper, the configurations of the hydraulic hybrid power train system are discussed. Then hydraulic hybrid auxiliary system configuration is described. In the

next step, the model of the conventional refuse truck and refuse truck equipped with HHAS was developed in MATLAB/SINMULINK. The simulation results in Tehran refuse collection truck driving cycles show impressive improvements of fuel economy.

2. Types of hydraulic hybrid power train configuration

The choice of HHPS configuration is one of the important parameters in system design and implementation of the hybrid control strategy. The HHPS has three main configurations. These architectures have intrinsic differences in power transmission efficiencies and effectiveness in ICE. The types of HHPS configurations are as follows.

2.1. Series Hydraulic Hybrid Power Train

In the series hydraulic hybrid configuration, the mechanical connection between the ICE and the wheel is eliminated[12]. The Power transmission of this configuration is similar to a hydrostatic transmission. Figure 2 shows an overview of the series hydraulic hybrid configuration.

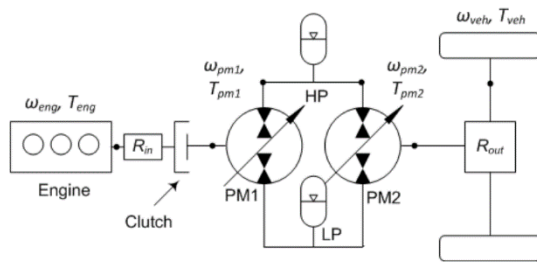


Figure2: Series hydraulic hybrid configuration

In this configuration, the rotational speed and torque of the wheels are independent of the rotational speed and torque of the ICE. Therefore, in terms of rotational speed and output torque, the ICE has the freedom to operate in the optimal area or at a constant speed[12]. In this configuration, the ICE is coupled to the pump/motor 1 and the mechanical power of the ICE is converted to hydraulic power by the hydraulic pump. According to the required power of the wheels, the hydraulic power is divided. In power distribution, if the required power of the wheels is less than the output power of the pump/motor 1, the additional power is stored in the hydraulic accumulator. If the required power of the wheels is more than the output power of the pump/motor 1, the energy stored in the accumulator is used to compensate for the required power of the wheels. If the output power of the pump/motor 1 is equal to the required power of the wheels, all hydraulic power is converted to mechanical power by pump/motor 2. However, in this structure, the output power of the

ICE must be transmitted by a hydrostatic system, which has a lower efficiency compared to the mechanical transmission. Also, in the braking mode, the pump/motor 2 converts the kinetic energy of the vehicle to hydraulic power and stores it in the hydraulic accumulator. In this system, the pump/motor 2 is coupled to the final differential. It supplies the driving propulsion of the vehicle. Hence, the size of the pump/ motor 2 is selected in such a way that it is able to supply the driving propulsion of the Vehicle. This system has the following unique features:

- 1- All the ICE-generated power is transmitted by the hydrostatic power transmission system.
- 2- The ICE-generated power is converted to hydraulic power and then to the mechanical power again. So, the efficiency of this system is lower than the mechanical system.
- 3- The size, weight, and cost of this system are high, but its control strategy is simple.

Table 1 shows the operating modes of the series HHPS configuration.

Table1: Operating modes of the series HHPS configuration

Modes	Operation of the modes
Series	ICE operates at efficient point
ICE off	ICE gets off and PM2only supplies the power load of the vehicle
Braking	PM2 regenerates the braking energy

Given the low energy density of the hydraulic accumulator[2], if the required power of the wheel is high, the accumulator cannot supply this power for a long time. Thus, the duration of the ICE off mode will be short. Moreover, in series mode, if the percentage of energy stored in the accumulator or the energy consumed from the accumulator is higher, the state of charge of the accumulator reaches the maximum or minimum in a short time. In these cases, the series HHPS's performance is not optimal.

2.2. Parallel Hydraulic Hybrid Power Train

In this configuration, the ICE is mechanically connected to the wheels and its power is transmitted to the wheels through a high efficient mechanical transmission. Figure 3 shows an overview of the parallel HHPS configuration

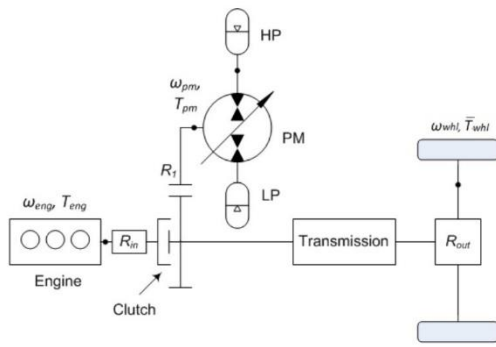


Figure3: Parallel hydraulic hybrid configuration

As shown in figure 3, due to the mechanical coupling of the ICE to the wheels, the rotational speed of the ICE depends on the rotational speed of the wheels[13]. In this configuration, the hydraulic pump/motor is connected to the ICE by transfer case. The hydraulic pump/motor converts the excess torque of the ICE into hydraulic power and stores it in the accumulator. If needed, the power stored in the accumulator is converted into mechanical power by the pump/motor to supply the required propulsion power. In this configuration, the ICE torque is independent of the wheel torque, hence the ICE has the freedom to operate in the optimal area in terms of output torque, but its speed is restricted[14]. Due to the use of the mechanical transmission system, the efficiency of the transmission is higher than the series structure. Table 2 shows the operating modes of the parallel HHPS configuration.

Table2: Operating Modes of The Parallel HHPS configuration.

Modes	Operation of the modes
Parallel	ICE operates along maximum torque
ICE off	ICE gets off and PM only supplies the power load of the vehicle
Braking	PM regenerates the braking energy

In this configuration, due to the low energy density of the accumulator, the operating time in the ICE off mode is not long.

In recent decades, Bosch Rexroth has introduced and commercialized the (HRB) system[15]. In this system, the pump/motor is coupled to the output gearbox by transfer case. This system recovers only the braking energy compared to the parallel HHPS. This system is suitable for vehicles with frequent stops in the driving cycle. In this system, the braking energy is recovered and stored in the hydraulic accumulator and reused in acceleration mode. This system is relatively simply design and is installed as an option on the vehicle. Figure 4 shows a configuration of HRB system.

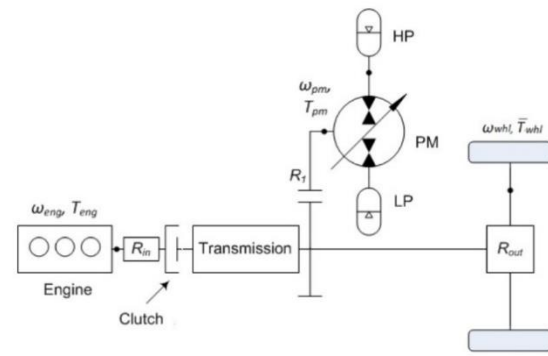


Figure4: Hydrostatic regenerative braking configuration

This configuration is considered a subset of the parallel HHPS configuration in which it is not possible to charge the accumulator by the ICE. Table 3 shows the operating modes of the HRB.

Table3: Operating modes of the HRB configuration.

Modes	Operation of the modes
Braking	PM regenerate braking energy
Acceleration	Braking energy is used to supply the acceleration power

As shown in the table above, this configuration does not have the ICE off Mode.

2.3. Hydro-mechanical Hydraulic Hybrid Power Train

The hydro-mechanical transmission is a combination of mechanical and hydrostatic transmission. In this system, the ICE-generated power is transmitted to the wheel through both the mechanical and hydrostatic transmission[13]. Hence, the advantage of both the high efficiency of the mechanical transmission and the continuous variable transmission of the hydrostatic system are combined. In this system, the percentage of the transmitted power through mechanical and hydrostatic transmission varies. This configuration is widely used in heavy vehicles, especially agricultural and construction machinery[16]. This system is not used in passenger vehicles due to the high volume and weight of the system. The hydro-mechanical transmission is a continuous variable transmission with a wide range of gear ratios between the ICE and the wheels. The hydro-mechanical transmission system has different types including input-coupled, output-coupled, and combined coupled. In the input-coupled type, a planetary gear is coupled to the final differential. If the hydro-mechanical transmission system uses the accumulator to store hydraulic power in order to manage the ICE operation, the system will be called Hydro-mechanical HHPS. Figure 5 shows

the configuration of the input-coupled hydro-mechanical HHPS.

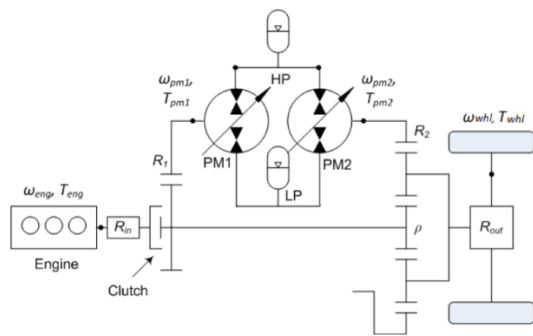


Figure5: input-coupled hydro-mechanical HHPS configuration.

This configuration is in fact a combination of series and parallel HHPS configuration with the advantages of these two configurations. In this configuration, the torque and rotational speed of the ICE are completely independent of the torque and rotational speed of the wheels. It allows the ICE to operate at any operating area and offers the freedom to operate the ICE more efficiently. Table 4 shows the operating modes of the hydro-mechanical HHPS configuration.

Table4: Operating modes of the hydro-mechanical HHPS.

Modes	Operation of the modes
HMT	ICE operates at most efficient area
Parallel	ICE operates along maximum torque
Series	ICE operates at most efficient area
ICE off	ICE gets off and PM2 supplies only the power load of the vehicle
Braking	PM2 regenerates the braking energy

As shown in the table above, this configuration includes parallel and series Modes.

3. Hydraulic Hybrid Auxiliary System Configuration

All configurations mentioned above do not work efficiently for some fleets. For example, the refuse collection truck fleet performs a unique mission. In this fleet, Trucks have highly frequent stops in their driving cycle. This fleet usually uses class 3 to 5 conventional trucks. The power train of these trucks is the diesel ICE. In these trucks, the ICE is responsible for supplying the propulsion power together with the auxiliary system power. Figure 6 shows the configuration of the conventional refuse collection truck.

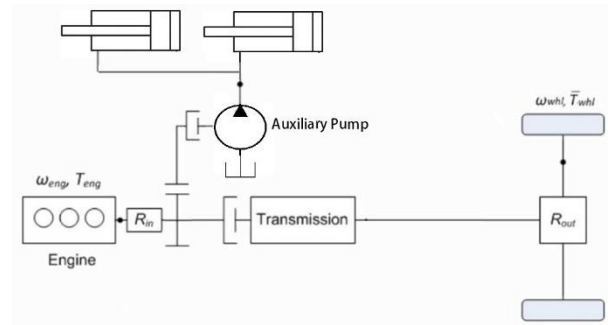


Figure6: Conventional refuse collection truck configuration.

Refuse collection trucks travel through the residential areas and streets, stop at loading stations to collect refuse by a mechanized system. Figure 7 shows the pattern of the refuse collection driving cycle.

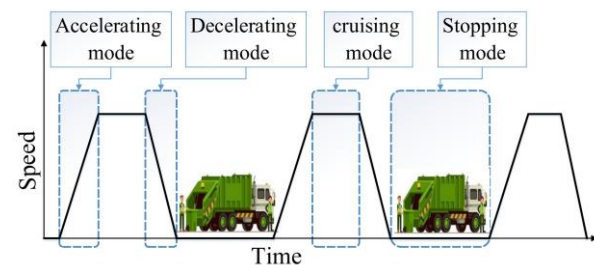


Figure 7: Pattern of the refuse collection driving cycle

As shown in figure 7, the refuse collection truck driving cycle includes acceleration, cruise, deceleration, and stop at loading station modes, which are recursive throughout the driving cycle with a short interval. During the driving cycle, a large percentage of the truck's kinetic energy is lost in the deceleration mode by the frictional braking system. In the stop mode, the auxiliary system energy is supplied by the auxiliary hydraulic pump. The hydraulic pump is connected to the ICE through power take-off (PTO) shaft and gearbox. Hence, in this type of trucks, the ICE is coupled to the wheel at driving mode and coupled to the hydraulic pump at stop mode.

In the refuse collection truck, due to the low consumed power of the auxiliary system and the incompatibility of the ICE-generated power with the auxiliary power, the ICE operates in an area with lower efficiency. As mentioned earlier, direct coupling of the ICE to the final consumer, such as wheels or hydraulic pumps, restricts the performance of the ICE and consequently reduces the efficiency of the ICE. Table 5 shows the operating modes of a conventional refuse collection truck.

Table5: Operating modes of the conventional refuse collection truck

Modes	Operation of the modes
Driving	ICE supplies the propulsion power.
Auxiliary	ICE supplies the auxiliary power.
Braking	The braking system converts the vehicle's kinetic energy into the heat energy.

Refuse truck hybridization requires a technology with high power density to handle high rates of energy flow. HHPS 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. Most studies proposed the parallel HHPS and HRB system for braking energy recovery and ICE management[10, 17]. A study shows that refuse collection truck in Stuttgart uses more than 58% of the ICE energy to supply the auxiliary system power and, less than 48% to supply the driving power. Also, with the use of HRB technology, the energy consumed to supply the driving power is reduced by approximately 20%[10]. Figure 8 shows the distribution of energy consumption in a conventional refuse collection truck and the truck equipped with the HRB system.

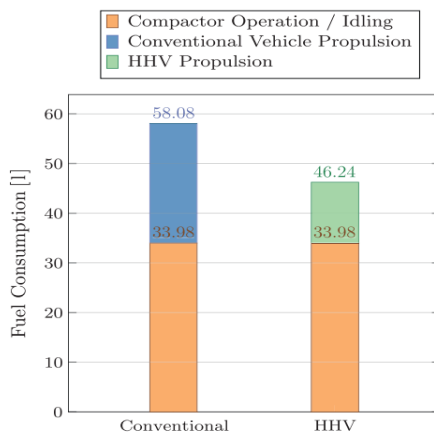


Figure 8: Distribution and comparison of the consumed energy in conventional and hybrid refuse collection trucks[10].

Considering the above result, the energy management of the auxiliary system is important, since more than half of the energy is consumed at the stop mode by the auxiliary system. All types of HHP configurations manage and reduce just the energy used in the driving mode. Hence, these configurations are not efficient and economical for vehicles that consume a significant portion of the energy in the stop mode. This paper proposes a hydraulic hybrid auxiliary system (HHAS) in order to manage the energy of the auxiliary system. The aim of this concept is to regenerate the braking

energy and reuse it in a hydraulic auxiliary system. Figure 9 shows the concept of the HHAS.

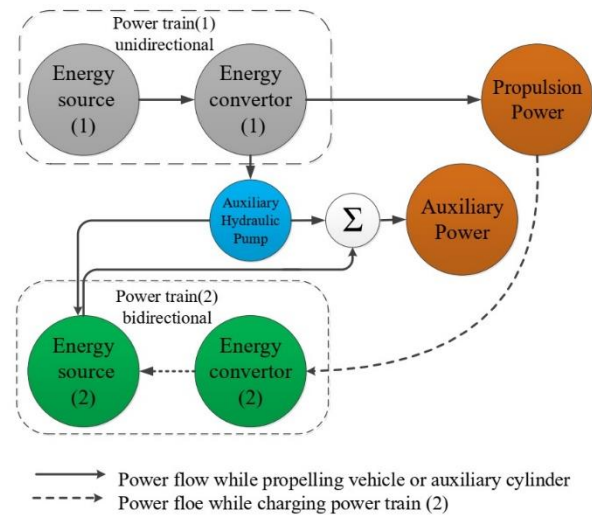


Figure 9: concept of the HHAS.

In this concept, the hydraulic pump is used as a secondary energy convertor, which is inexpensive and simply designed compared to a hydraulic pump/motor used in all types of HHP configurations. The hydraulic pump acts as unidirectional system and converts the mechanical energy (braking energy) into a hydraulic energy. Figure 10 shows the configuration of refuse collection truck equipped with the HHAS.

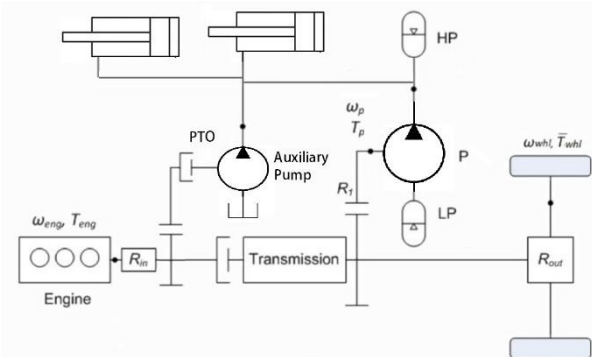


Figure 10: The Refuse collection truck configuration equipped with the HHAS.

As shown in figure 10, The pump is located after the gearbox and is connected to the drive shaft by torque transfer case. the transfer gear ratio might be applied to prevent the pump from over-speeding and make it more efficient. In the braking mode, the vehicle's braking energy is recovered by the pump and stored in the hydraulic accumulator. then, the stored energy is used in the auxiliary system. If the stored energy is not sufficient to supply the required auxiliary system energy, the driver activates the PTO shaft and the energy of the auxiliary system is supplied by the ICE. When the PTO shaft is active, it is possible to charge the

accumulator through the auxiliary hydraulic pump. Table 6 shows the operating modes of HHAS.

Table6: Operating modes of the HHAS configuration.

Modes	Operation of the modes
Driving	ICE supplies the propulsion power.
Hybrid auxiliary	Energy source 2 supplies the auxiliary power.
Auxiliary	ICE supplies the auxiliary power
Braking	PM2 regenerates the braking energy

4. Modeling the Hybrid Auxiliary System

A physics-based simulation of the truck's systems is a necessary prerequisite for performing a comprehensive design of a suggested concept. To calculate the fuel consumption and approve technical feasibility of the concept, the truck components model and system integration was implemented in MATLAB/SIMULINK using a platform previously developed by the researchers at Vehicle, Fuel & Environment Research Institute[2]. First, a conventional refuse collection truck model was developed to simulate a dynamic behavior and fuel consumption. Then, the HHAS model was developed and added to the conventional model. Finally, the fuel consumption results were compared.

4.1. The Conventional truck Model:

In this study, the 6-ton Isuzu was selected as the target vehicle. Table 7 shows the conventional refuse collection truck specifications.

Table7: Isuzu truck specification[18].

Engine	Description	2999 cc - 4 cylinder.
	Max. Power	120kW @ 2800 rpm
	Max Torque	382 Nm @ 1600 rpm
Transmission	design	Manual -5 Speed
	Gear ratios	4.2,3,1.7,1,075
	Differential	4.1
Vehicle	Gross mass	6000 kg
	Air drag	0.75
	Front Area	4.3 m ²
	Tire radius	0.43 m

The truck model is based on a forward-looking vehicle system simulation. Figure 11 shows the model of conventional refuse collection truck.

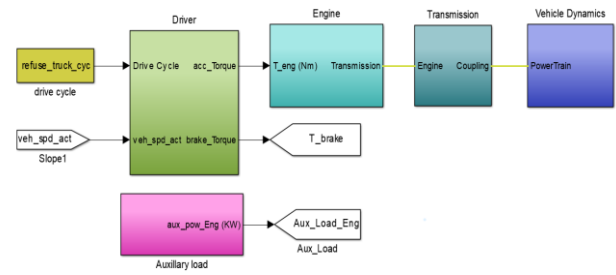


Figure 11: Conventional refuse collection truck model.

In this model, the virtual driver is modeled as a PI controller, which compares the actual and reference driving cycle speed and sends a separate command for acceleration and deceleration pedal. The acceleration command was mapped together with the engine speed in order to provide the fueling command. Figure 12 shows the fuel map of the ICE.

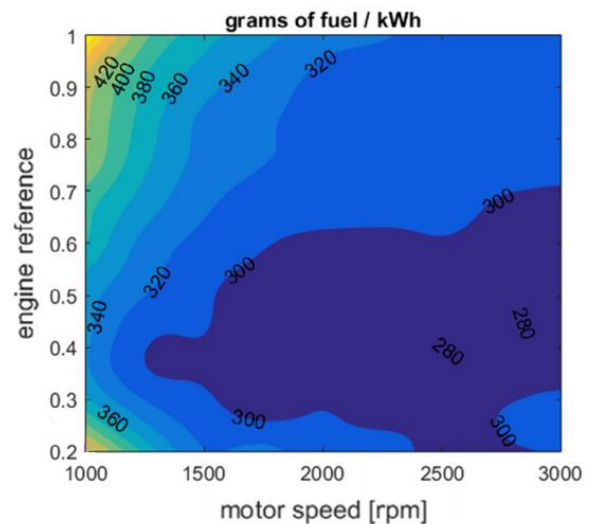


Figure 12: The fuel map of ICE as function of motor speed and equivalent engine throttle[19]

The ICE output torque is a function of the ICE speed and the fueling command. The truck transmission is modelled as a finite state machine, where different gears ratio represents different states. The truck is modelled as a single point mass system. The truck mass varies during the driving cycles. The truck is unloaded and weighs the least when traveling from the parking lot to the first loading station. The truck mass discretely increases in any stop at the loading station. When the tank capacity of the truck is filled, the truck moves to the unloading site. At this time, the truck weighs the most. At the unloading site, the trucks unload the collected refuse into large trailers. After unloading the refuse, the truck returns to the parking lot or to the urban refuse collection district if its mission is not completed. At this time, the truck weighs the least.

The resisting forces include rolling resistance and air drag. The braking model simulates the braking forces depending on the deceleration command. The required auxiliary power is computed based on the loading cycle of auxiliary system measured during the real world refuse truck operation and detailed specification of components of auxiliary system. The loading cycles is the pressure of auxiliary hydraulic circuit versus time. The model validation performed through a fuel consumption comparison between the simulated and the field measured data. The results indicate that the error was less than 8 percent.

4.2. The HHAS Model:

The hydraulic hybrid auxiliary system includes a hydraulic pump, a single-speed transfer case, a hydraulic reservoir and, a hydraulic accumulator. This system was modelled based on specification of the components and was integrated into the conventional model. The HHAS is able to regenerate the braking energy during the braking mode. The size of components was designed in such a way to regenerate a maximum braking energy till the accumulator reaches the maximum state of charge. The stored energy is immediately reused to supply the auxiliary power. Hybridization of the auxiliary system offers a flexibility in controlling the ICE operation, regeneration of braking energy, and the ICE shut-down. Due to a limitation of ICE in conventional trucks, the ICE shut-down is not considered. Figure 13 shows the forward-looking model of the refuse collection truck equipped with the HHAS.

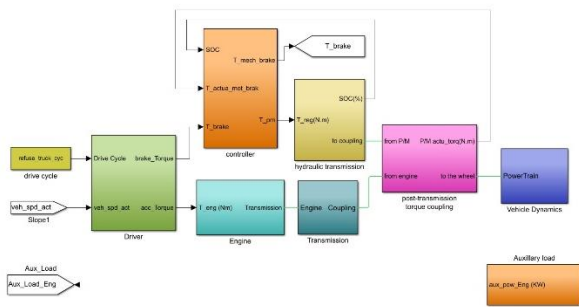


Figure 13: model of the refuse collection truck equipped with the HHAS.

4.3 Fuel Economy Results:

The developed models were simulated in Tehran refuse collection truck driving cycles. Since the amount of fuel consumption depends on the truck speed, truck mass and road grade, this driving cycle was extracted simultaneously with the road grade and the truck mass cycles. Figure 14 shows Tehran

refuse collection truck driving cycle together with mass cycle.

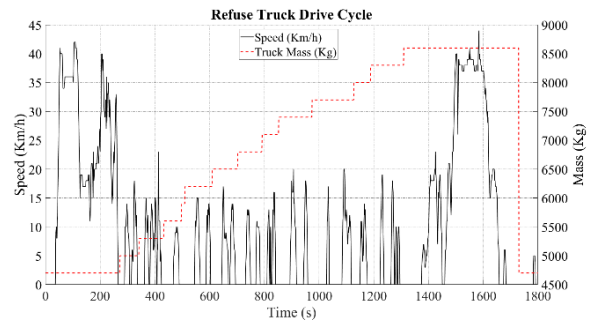


Figure 14: Tehran refuse collection truck driving cycle together with the truck mass[20].

As shown in figure 14, The mass of refuse collection truck varies during its mission, so the truck mass and road grade cycles were considered in the simulation.

In this simulation, the initial SOC of the accumulator was considered 75 percent. The fuel economy improvement of refuse collection truck equipped with HHAS over the conventional truck is shown in Table 8.

Table 8: Comparison of fuel economy in conventional refuse collection truck and refuse truck equipped with HHAS.

Truck	Fuel Consumption (let/100 Km)	Fuel Consumption Reduction (%)
Conventional refuse collection truck	32.4	-
Refuse collection truck equipped with HHAS	27.5	15

The results demonstrate impressive improvements of fuel economy over Tehran refuse collection truck driving cycle.

5. Conclusion

this study compared the conceptual design and operating modes of series, parallel and hydro-mechanical hydraulic hybrid power train systems with a hydraulic hybrid auxiliary system. The aim of HHAS is to regenerate the braking energy and manage the energy consumed in the auxiliary system. The hydraulic hybrid auxiliary system includes a hydraulic pump, a single speed transfer case, a hydraulic reservoir and, a hydraulic accumulator. The pump is located after the gearbox and is connected to the drive shaft by transfer case. In the braking mode, the vehicle's braking energy is recovered by the pump and stored in the hydraulic accumulator. In the stop mode, the stored

energy is used in the auxiliary system. The size of the HHAS components was designed in a way to regenerate a maximum braking energy. The fuel economy improvement on the order of 15% and simply designed configuration highlights an important advantage of the HHAS in comparison with configurations discussed above.

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