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## Performance Comparison for Series and Parallel Modes of a Hybrid Electric Vehicle

Halit Yaşar<sup>1</sup>, Gökhan Canbolat<sup>2\*</sup>

### ABSTRACT

Recently, the studies in the automotive sector has concentrated on hybrid electric vehicle. The better results in fuel economy and vehicle performance values have been achieved with the hybrid electric vehicle technology. In this study, the fuel consumption and vehicle performance values are compared to the series and parallel hybrid electric modes of a conventional street sweeper by using AVL Cruise. Nowadays, there are many driving cycles used in the analysis of fuel consumption and vehicle performans. However the current driving cycles are not appropriate for the vehicles designed for a particular functions (carrying, lifting, sweeping etc.) such as street sweepers in terms of velocity and functionality. For this reason, a driving cycle is constructed by taking into consideration the daily tasks of the street sweepers with the help of AVL Cruise. The series and parallel hybrid electric configurations of the street sweeper were analyzed separately. Consequently, the demanded power (kW) from the internal combustion engine and its fuel consumption (L/h) were investiageted under the specific operating conditions in the driving cycle. The simulations show that the series hybrid mode has better fuel economy and vehicle performance.

**Keywords:** Hybrid Electric Vehicle, Simulation, Fuel Consumption, Vehicle Performance

### 1. INTRODUCTION

Since the efficiency of electric motors is higher than the internal combustion engines, many studies are being done on hybrid electric vehicles. But the current world conditions and technology have not been able to found a suitable environment to pass all-electric vehicles. Therefore, automotive companies have concentrated on hybrid electric vehicles before the all-electric vehicles. To ensure the sustainable development of the automotive industry, the research and development of electric drive systems with clean energy become a national consensus [1].

Hybrid electric vehicle technology is much more complex than conventional vehicles. Basically, the hybrid electric vehicles can be divided into series and parallel hybrid vehicles [2]. The design of the hybrid electric vehicles requires more effort and time than conventional vehicles. Simulation software packages have become indispensable in vehicle design. There are many simulation packages such as AVL Cruise, Amesim, Advisor, Adams, Msc Easy 5, Psat, etc. [3].

In the literature, there are a great number of studies Hybrid Electric Vehicle (HEV) vehicle simulations performed by using ADVISOR [2, 4-16]. In addition, AVL Cruise software developed

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for this area has taken place in many automotive projects. AVL Cruise is a simulation program used in the design of vehicle and vehicle drive systems. Cruise enables modeling for vehicle design and optimization in specific applications such as fuel consumption, emission, acceleration and driving cycle tests. Previous works have shown the validity of AVL Cruise software and some works are presented here. Briggs et al. [3] studied that simulating of non automotive vehicles is highly hard according to passenger cars. A diesel-electric hybrid bus and an Internal Combustion Engine (ICE) triggered forklift is studied in the paper and concluded that the standard driving cycles are appropriate for this vehicle. Teixeira et al. [17] compared the the vehicles powered by electric motors to engine powered vehicles in terms of carbon dioxide emission and fuel economy. They presented that electric vehicles consumes the energy near four times lower than conventional vehicles at the standart driving cycle conditions. W<sub>1</sub> et al. [18] focused on fuel consumption reduction by changing the power systems of steering. The results demonstrate that a 1% vehicle fuel economy improvement can be achieved in a vehicle with a steering system which has electro hydraulic power compared to vehicle which has hydraulic power steering system. In addition, a 1.7% vehicle fuel economy improvement can be achieved using a full electric power steering system in a FTP-75 driving cycle. Oh et al. [19] conducted modeling of vehicles powered by gasoline and diesel ICE for testing 10 passenger cars in 7 types of driving mode. The simulations are performed by variance of driving modes and the types of vehicles, and the accuracy of the simulations results are verified by the chassis dynamometer. It is informed that the accuracy of simulations in termes of fuel economy and CO<sub>2</sub> emission are found compatible with test data results.

There is no HEV simulation study on street sweepers. In this article, an appropriate driving cycle was developed for Hybrid Electric Street Sweepers (HESS) by using Random Cycle Generator (RCG) of AVL Cruise. The series and parallel hybrid configurations of the HESS were simulated in this driving cycle. AVL Cruise simulations were performed to compare the

series and parallel hybrid drivetrain configurations based on fuel consumption and vehicle performance.

## 2. THE DRIVETRAIN SYSTEMS OF HYBRID ELECTRIC VEHICLES

HEV are defined as vehicles with more than one energy source. Hybrid electric vehicles mainly consist of an ICE which generates the power, an energy storage system and an EM.

HEVs are mainly divided into two main configurations, serial and parallel [4]. In series hybrid electric vehicles, the ICE is used in the generating electric energy and EM is used for driving the vehicle (Figure 1.). The lack of a coupling system between the EM and the ICE in series hybrid electric vehicles facilitates the design of these vehicles. ICEs are used for the generating the electrical energy that will drive the vehicle. In addition, the most important advantage of series hybrid electric vehicles is that the internal combustion engine is operated at a constant speed, resulting in low fuel consumption and high efficiency.

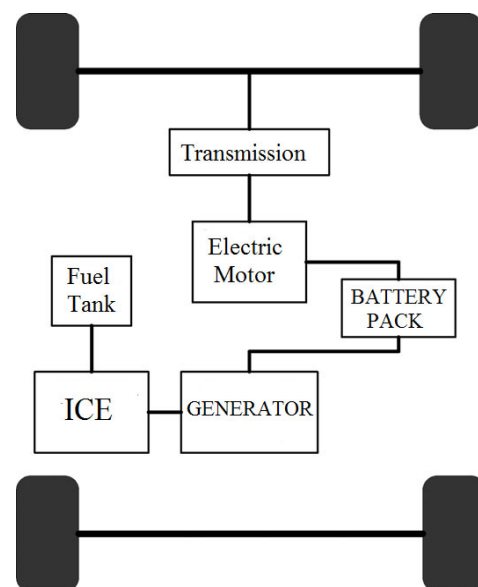


Figure 1. Series hybrid configuration

Another configuration is parallel hybrid electric vehicles (Figure 2.) In parallel hybrid configuration, the vehicle can be driven by an

ICE or EM or together depending on changing driving conditions. Parallel hybrid configuration is more complex than series hybrid configuration. In a parallel hybrid configuration, a power split unit is required to separate the ICE and EM. Depending on changing driving conditions, EM or ICE can be driven at different times.

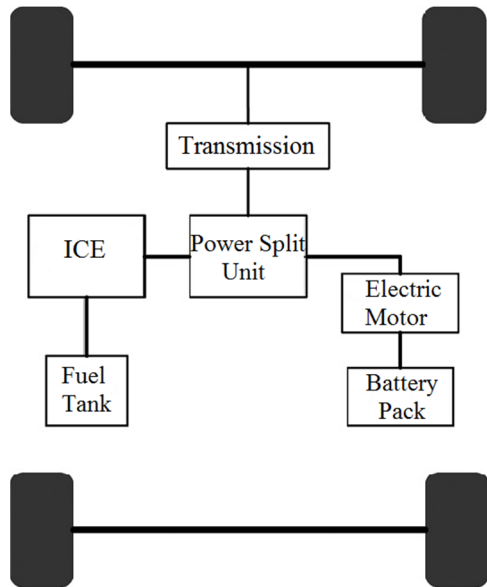


Figure 2. Parallel hybrid configuration

### 3. MODELING AND SIMULATION

In recent years, simulations have become a common tool used in vehicle design. In this study, the powertrain of a hybrid electric street sweeper is modeled. A driving cycle suitable for the daily operating conditions of street sweepers was created by using AVL Cruise software.

#### 3.1. Creating an Appropriate Driving Cycle

Driving cycles are needed when examining vehicle performance, fuel consumption and exhaust emissions. Driving cycles are used to compare goals. Because they are useful to estimate the exhaust emissions, fuel economy and performance [20]. In the the past a few decades, countries developed a variety driving cycles for urbans (Federal Test Procedure 72 (FTP-72), the New European Driving Cycle

(NEDC), Japan 10 15 Mode and highway driving cycles like US 06, Highway Fuel Economy Test (HWFET)) [21].

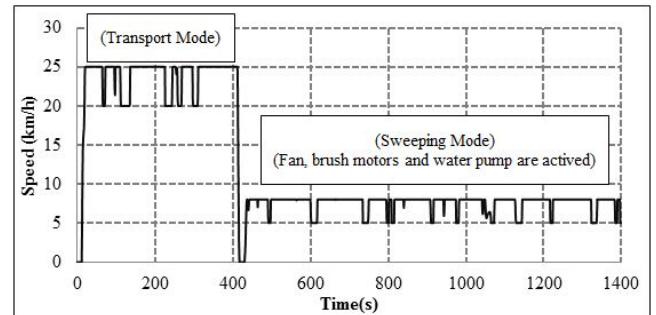


Figure 3. The vehicle velocity according to driving cycle

Figure 3. shows the driving cycle created for the hybrid electric street sweeper. This driving cycle was created by taking into account the daily tasks and operating conditions of the vehicle. The driving cycle consists of 1400 s and two driving modes (Transport and Sweeping). In the cycle, the range of 0-400 s represents the transport mode and during this mode, the speed of the vehicle is set at maximum 25 km / h. Also during the transport mode the vehicle only moves from one location to another without sweeping. In the driving cycle, the range of 400-1400 s represents the sweeping mode, during sweeping mode fan, sweeping and water pump motors are operated. During the sweeping mode, the average speed of the vehicle is set at 8 km / h, which is the most efficient sweeping velocity obtained from the field conditions.

In order to reflect the actual values, brakes and accelerations were added in driving cycle. The fluctuations seen in the cycle are the result of the added brakes and accelerations.

#### 3.2. Hybrid Electric Street Sweeper

Hybrid electric vehicles have better fuel economy, lower emissions and energy efficiency than conventional vehicles. In recent years, many hybridizations studies on heavy vehicles and electric propulsion systems have been developed for these vehicles [22].

Table 1. The basic characteristics for the hybrid electric street sweeper

Vehicle Mass (kg)	2500
Frontal Area ( $m^2$ )	$A_f=2,2$
Drag Coefficient	$C_D=0,65$
Rolling Resistant Coefficient	$\mu_r=0,01$
Vehicle-Width (mm)	1400
Vehicle-Length (mm)	3700
Vehicle-Height (mm)	1650
Wheel-Radius (mm)	320
Air Density ( $kg/m^3$ )	1,25
Maximum Speed (km/h)	25

The general characteristics of the vehicle modeled in this study are given in Table 1. In addition, the 3-D model constructed with Solidworks software is presented in Figure 4.

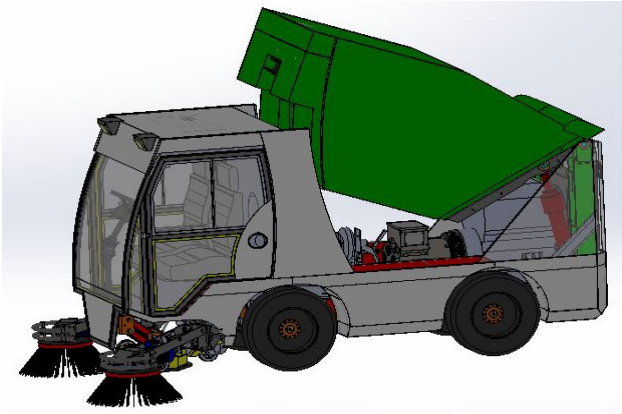


Figure 4. Hybrid electric street sweeper

In this study, a four-stroke and turbocharged diesel engine was selected for the hybrid electric street sweeper. As a result, it is predicted that the most suitable engine in terms of performance and geometry is a Mitsubishi diesel engine. The technical characteristics of the ICE were given in Table 2. The selected internal combustion engine is modeled with AVL Cruise and interpolations were made for different speeds (rpm).

Table 2. The technical specifications of internal combustion engine

Internal Combustion Engine	Mitsubishi
Type	4-stroke, cylinder in line, direct injection, turbocharged
Number of cylinders	4
Displacement volume ( $cm^3$ )	3331
Compression ratio	17:1
Bore (mm) - Stroke (mm)	94 - 120
Engine Power (kW/rpm)	36,8 / 1500
Engine Torque (Nm/rpm)	196 / 1500

Once the internal combustion engine was selected, the required step is the choice of the appropriate generator. The demanded torque values in the vehicle must be calculated correctly and the generator selection is important. In this study, a Gensan alternator was chosen by considering the vehicle's sweeping functions as well as the torque required to move the vehicle. The technical characteristics of the selected generator are given in Table 3.

Table 3. The technical specifications of generator

Generator	GENSAN
Continuous Power (kVA)	30
Standby Power kVA)	33
Speed (rpm)	1500
Frequency (hz)	50
Voltage (V)	231/400

During the sweeping mode shown in the driving cycle, generator selection is made by taking into account that the electric motor, fan motor, brush motors and water pump are activated.

Table 4. The technical specifications of the motor which drives the vehicle

AC Motor	3-Phase, 2-Pole, Asynchronous Motor
Power (kW)	15
Speed (rpm)	3000
Current (A)	28,6
Torque (Nm)	48,8
Cos (φ)	0,89
Efficiency (η)	%89
Mass (kg)	81

When selecting the electric motor; air, rolling, acceleration resistance forces acting on the vehicle are taken into account.

### 3.3. The Modeling of The Series and Parallel Hybrid Electric Configurations

Vehicle control algorithm for the hybrid electric street sweeper vehicle according to the driving cycle and the daily operating conditions is created. AVL Cruise models are constructed for the series and parallel hybrid modes of vehicle. Figure 5. and Figure 6. represent the series and parallel hybrid electric vehicle models. The model was created by using AVL Cruise software. Each box in the models represents one module and each module can be arranged according to the requirements of the user. The blue and red lines in the models show the mechanical and electrical connections, respectively. In addition to mechanical and electrical connections, each module is connected to each other via a communications network. Modules communicate with information by networks with each us. This control algorithm is the result of the operating conditions of the vehicle, which is also determined by the driving cycle.

It is seen in the Figure 5. that the HEV is driven only by the EM. The internal combustion engine-generator module is only used to generate the electrical energy required for the electric motors. In addition, the sweeping components are controlled according to the driving cycle.

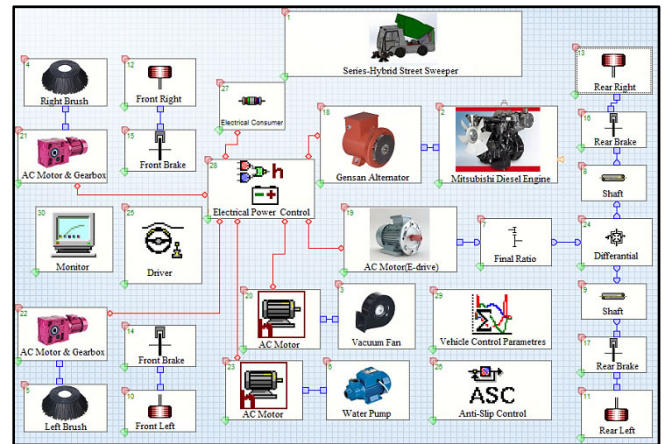


Figure 5. Series hybrid electric model by using AVL Cruise

Figure 6. shows the AVL Cruise model for the parallel hybrid electric road sweep vehicle. As it seen in the model, a parallel hybrid electric vehicle can be driven by an internal combustion engine or an electric motor with the aid of a power split unit. The vehicle can also be driven simultaneously with the ICE and the EM to meet the demanded total power according to the driving conditions.

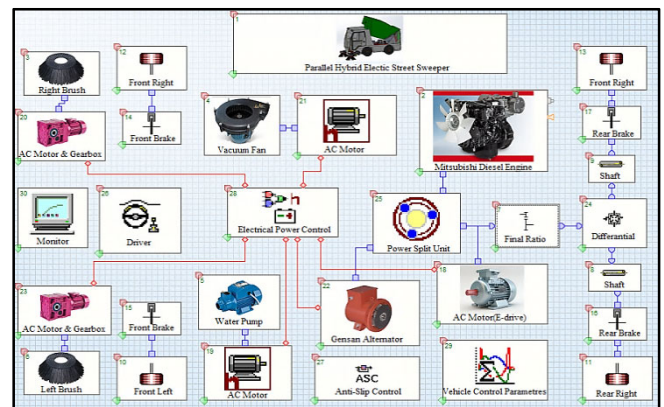


Figure 6. Parallel hybrid electric model by using AVL Cruise

In order to compare the series and parallel hybrid mode in respect of the fuel consumption and vehicle performance, the vehicle was driven only by the electric motor during sweep mode, but in transport mode the electric motor is used for series hybrid mode and the internal combustion engine is used for the parallel hybrid mode.

#### 4. SIMULATION RESULTS

The simulations were conducted to compare series and parallel hybrid electric street sweeper in terms of fuel consumption and vehicle performance. According to the driving cycle, the sweeping components are operated through the sweeping mode and driven by the electric motors. Detailed technical informations about the used electric motors are supplied from the manufacturers and integrated into AVL Cruise software. In addition, during sweeping mode, the vehicle is powered by an EM in series and parallel hybrid modes, since the sweeping components are active and the velocity of the vehicle is very low. Therefore, the fuel consumption and vehicle performance values for the series and parallel hybrid modes will be same during the sweeping mode, so the comparisons will be detailed for the transport mode.

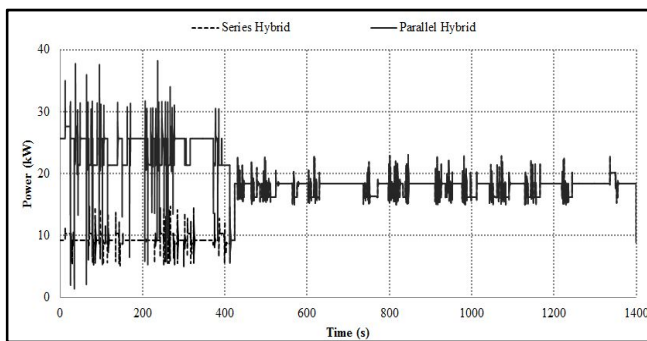


Figure 7. The demanded power according to driving cycle for series and parallel cases

Figure 7. shows the required power (kW) values for series and parallel hybrid cases. The range of 0-400 s represents the transport mode, and during this process, the average power values required for serial and parallel hybrid situations are 10 and 25 kW respectively. These results with AVL Cruise simulations show that for the series hybrid situation, 60 % less power is required. The fluctuations shown in Figure 7. are the result of accelerations and brakes added to the driving cycle and are intended to reflect the real values. The power values indicate that less power is demanded for the series hybrid mode because the vehicle is driven only by EM during the series hybrid mode. AVL Cruise simulations clearly

demonstrate that EMs have higher efficiency and torque at lower speeds than ICE.

During the sweeping mode (400-1400 s), as shown in Figure 7. sweeping components (brush, water pump and vacuum fan) are activated and the vehicle is driven by electric motor only. During this mode the internal combustion engine is only used for generating electricity with the aid of the alternator and operated at constant speed (1500 rpm). The total demanded power during the sweeping mode is 18 kW, which can rise to 23 kW according to the driving cycle conditions.

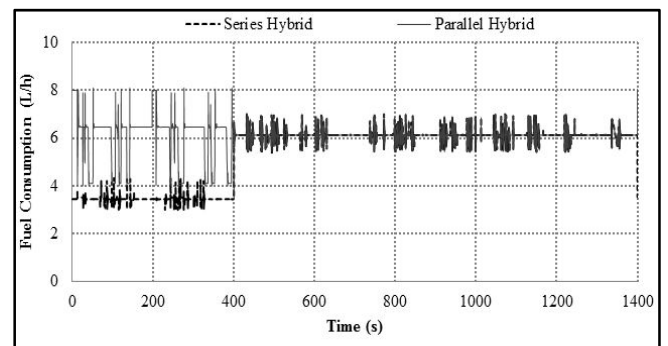


Figure 8. Fuel consumption variation for series and parallel hybrid cases according to driving cycle

Figure 8. presents the fuel consumption values of the HESS according to the driving cycle. During transport mode, the sweeping components are not activated. During this mode, average fuel consumption values for serial and parallel hybrid situations are seen as 3.8 L/h and 6.2 L/h respectively. When for the sweeping mode in the driving cycle, the sweeping components start to be driven by EMs, in addition to which the vehicle is driven only by an EM. During sweeping mode, the average fuel consumption value is 6 L / h.

#### CONCLUSION

In this paper, simulation on series and parallel hybrid configurations of a hybrid electric street sweeper were carried out by using AVL Cruise. The powertrain of the vehicle is modeled and the control algorithm of the vehicle is presented according to driving cycle (transport and sweeping mode). The control block diagrams of

the vehicle in terms of mechanical, electrical and informational connections were constructed to reflect the real driving conditions.

Due to the fact that the current driving cycles are not appropriate for such vehicles, necessitates to create of a appropriate driving cycle for the daily working and speed conditions of the street sweepers increased. For this reason an appropriate driving cycles for street sweeper is created by considering the real operation conditions of these vehicles.

The simulation results clearly show that fuel consumption and emissions in series hybrid configuration were lower compared to the parallel hybrid case. The reason is that the ICE runs at a constant speed in series hybrid mode during the transport mode. On the other hand, the engine speed is variable in parallel hybrid mode. Therefore, the high combustion efficiency provides the lower fuel consumption.

### ACKNOWLEDGMENTS

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