Modelling and Simulation of a Hybrid Powertrain System for a Commercial Vehicle

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Abstract - *The project presents an extensive modelling and simulation of two different configurations of Hybrid powertrain system for a commercial vehicle. The two configurations that were chosen for this study were Series Hybrid configuration and P2 Parallel configuration.*

The aim of this paper is to increase the fuel economy of existing conventional trucks in the market. A hybrid powertrain of a Light Commercial Vehicle (LCV) of about 7 tonnes is modelled and simulated to increase the fuel economy. It is proven that Series Hybrid configuration fails to improve the economy in commercial vehicles because of high torque demands from the motor, because of which engine runs continuously for a long time to sustain the depletion of energy from the battery. Whereas, in P2 parallel configuration, losses from an individual generator used in series configuration is eliminated and the advanced control strategy is developed which makes optimum usage of battery and engine for both running and charging purposes and the flow of energy improves the fuel economy of hybrid trucks compared to conventional one. From our simulation results, it was found that the Series hybrid configuration gave a mileage of 6.23 kmpl whereas P2 parallel hybrid configuration was able to achieve mileage of 10.79 kmpl.

1. INTRODUCTION

Diesel engine technology is setting new standards for reducing vehicle emissions and fuel consumption. The hybrid-electric vehicle technology also achieves these goals, especially for congested traffic conditions. Hybrid Electric Vehicle (HEV) are vehicles that are powered by two prime movers, typically an electric motor and an Internal Combustion engine, including the diesel engine. Today's diesel HEVs combine the latest advances in hybrid vehicle technology with the inherent efficiency and reduced emissions of modern clean diesel technology to produce dramatic reductions in both emissions and fuel consumption. Specifically, Diesel-Electric hybrid technology is being used increasingly to improve the performance of vehicles. The term diesel-electric hybrid is also used to describe an HEV that combines the power of a diesel engine with an electric motor. This paper describes the modelling, simulation of Series and P2 Parallel hybrid powertrain for Light Commercial Vehicle (LCV). Series configuration is achieved through two speed reduction gearboxes along with the final drive. In series type, only the Electric Motor is powering the wheels and engine's role is to charge the battery. The first gear in the series type is to provide maximum torque and the second gear to provide maximum brake power.

Now, in parallel configuration of HEV is achieved through a multi speed reduction gearbox. The engine and an electric motor are connected through same shaft separated by clutch and similarly electric motor and transmission are also separated through another clutch. This parallel HEV provides four basic mode of operation namely electric mode, HEV mode, engine/charge and regenerative mode. The selection of mode depends upon the requirement of the vehicle, a feasible control strategy of parallel HEV is developed for operation of the vehicle in the city, highway and high-power requirement conditions. The advantage of parallel hybrid electric vehicle over series hybrid is the higher fuel mileage. The operational flexibility and better performance of the developed hybrid vehicle makes it a good choice for a parallel HEV.

Previously study of fuel economy has been done based on the JE05 driving cycle in a research paper of fuel economy improvement of small delivery hybrid trucks conducted by National traffic Safety and Environmental Lab, Japan. The mileage of small delivery hybrid trucks in catalog specifications were given better compared to diesel trucks, but users reported that diesel trucks were better in terms of mileage. In the experimental test, a vehicle of GVW around 7 tonnes was considered whose fuel economy was 7 Kmpl in hybrid mode and 7.7 Kmpl in diesel mode which shows the reduction in fuel economy in urban mode was 9 %.

1.1 WORLD HEV SCENARIO:

Recently, there has been an increasing interest in the development of parallel hybrid electric vehicles. The Americas held the major share of the global hybrid commercial vehicle market. North America was the major contributor to the market in the Americas, making it the top manufacturing country in this type of automobile. The country has been registering strong demand as the government and companies in the private sector are working to promote battery electric vehicles, using eco-friendly transport, and expanding distributor networks to increase the availability of hybrid vehicles. The passenger hybrid electric vehicle (Toyota Prius) uses an epicyclic gear box as an electromechanical transmission. The dual configuration allows power to be transmitted through two parallel shafts from the prime mover of the driving wheels. In this arrangement, the engine power is split into two parts, on through the ring gear to the output shaft and the other through the sun gear to electric generator. Some of the electricity generated by the generator is used to drive the electric motor and remaining is used to charge the batteries.

The new type of technology is being implemented for Indian conditions for LCV (Light Commercial Vehicle) with a new parallel configuration and control strategy is described in this paper.

1.2 Benchmarking

In this paper, we have studied the importance of hybrid powertrain concepts and its consequences for commercial vehicle. When we talk about selecting the type and architecture of powertrain, we see conventional vehicles, pure electric vehicles and hybrid electric vehicles competing. Conventional engine vehicles consume good amount of fuel because of which our dependence on petroleum increases, at the same time environment also suffers with emissions. Pure EVs produce no emissions, but when its battery gets discharged after a specified low range from fully charged condition, it requires 7-8 hours to get charged fully again. As the full range is too low and the charging time is very high in current Electric Vehicle, there is always the range anxiety situation. Because of these reasons, consideration for Hybrid electric vehicles comes into picture. It reduces emissions and fuel consumption from conventional vehicles and removes range anxiety from pure EVs.

The focus of this project is to increase the fuel economy of a commercial vehicle from existing commercial vehicles of GVW 7 tons approx. For that purpose, fuel mileages of hybrid and conventional trucks from an SAE paper are taken as benchmark. In India, due to huge number of vehicles, roads are usually densely packed especially in cities in traffic conditions. That is why focus has been put on improving the fuel economy in urban conditions. For that IDC has been used at low speeds. The model is created in GT-suite for Series Hybrid and P2 Parallel Hybrid configurations and simulated in Indian driving cycle with low speeds. The SAE paper used for benchmarking showed the fuel economy of 7.7 kmpl for conventional truck of 6.5 tons. With Series Hybrid model, we didn't achieve a good fuel economy and we only managed to get it to somewhere over 6 kmpl which looks surprising at first, but with detailed study, it is found that Series Hybrid isn't good for commercial vehicles because of high torque requirements, that is why motor pulls lot of energy from the battery and it forces engine to recharge the battery. Another possibility is that engine maintains the SOC of the battery when it falls to certain extent, but for that engine will have to run at all times at some nominal torque request conditions, which will consume lot of fuel. Also, presence of generator reduces the efficiency of system even more.

So, plan was to improve upon this system by making certain changes with the power flow, components and control strategy. If we manage the power flow in such a manner that engine only, motor alone and engine motor combined operate at certain conditions, our powertrain would be very efficient. That is why, for pure EV mode in the system, engine and motor need to be disconnected, for that clutches need to get added to the system. This system is P2 Hybrid system, in this configuration, motor can provide negative torque to the engine to make it reach its idle rpm, charge the battery and positive torque to run the wheels. In HEV mode, engine and motor work in harmony to give the maximum fuel efficiency. P2 model and its control strategy is developed and simulated in Indian driving cycle at lower speeds. Fuel economy improved from 7.7 kmpl of conventional truck of 6.5 tons to 10.79 kmpl.

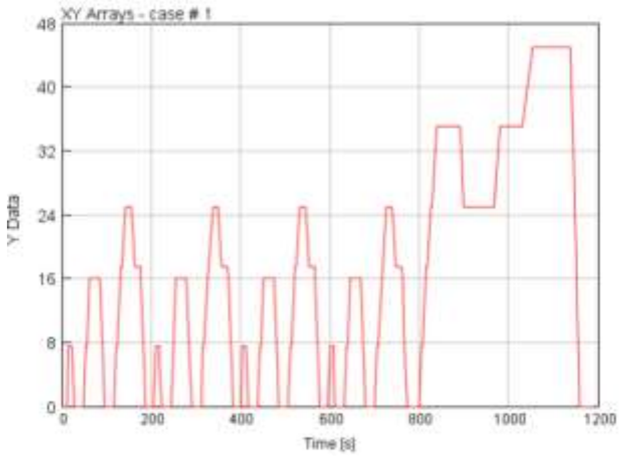


Fig – 1: A typical Indian Driving Cycle

1.3. Powertrain Configurations based on Power Flow Path

P0 Configuration - In this configuration, the electric machine is connected with the I.C. engine through a belt, on the front-end accessory drive (FEAD).

P1 Configuration - In this configuration, there is no belt drive compared to P0, hence increasing the torque transfer as there isn't any belt slip. Also, the battery gives better efficiency and costs much higher.

P2 Configuration - The electric machine is side attached or integrated between the internal combustion engine and the transmission; the electric machine is decoupled from the I.C. engine and it has the same speed as the I.C. engine.

P4 Configuration - The electric machine is connected through a gear mesh on the rear axle of the vehicle; the electric machine is decoupled from the I.C engine and is located in the rear axle drive or the wheel hub.

2. Powertrain Calculations

To develop a suitable powertrain, we need to calculate the wheel Torque. For the vehicle to move, it needs to overcome Rolling, Gradient, Acceleration and Aerodynamic Resistances. Hence, we are calculating the total resistance at different vehicle speeds.

Data Assumed: -

1) GVW of vehicle =7300 Kg
2) Rolling coefficient between road surface and wheel = 0.008
3) Air density, p = 1.225 Kg/m^3
4) Coefficient of drag, Cd = 0.608
5) ϴ = Maximum gradient = 20% = 11.85 degrees = 0.20699 radians
6) Frontal Area, A = (Height * Width) + 2*(ground clearance * tyre width) = (2.05*2.68) + 2*(0.192*0.235) = 5.056 m^2
7) Transmission efficiency = 0.85
8) Motor efficiency = 0.9
9) Wheel diameter = 17.51 inch = 0.445 m

Hence, Total Resistance (N) = Rolling Resistance (R_r) + Gradient Resistance (R_g) + Aerodynamic Resistance (R_a) + Acceleration Resistance (R_{ac})

For vehicle speed = 14 Kmph (speed which can be achieved at maximum gradient)

Tractive Effort, Ft = Total Resistance * Transmission efficiency * Motor efficiency

Now, since this is the speed (14 Kmph) which can be achieved at maximum gradient, the maximum torque required by the motor will be at this speed.

Therefore, Motor Torque = Motor Power / Wheel Speed (in radians)

Now, since we know that, Power = Force * speed

So, we can calculate power required by the motor = Tractive effort * linear speed

Therefore, on calculating further, Motor Torque = Motor Power/Wheel Speed (radians)= **4914.22 Nm**

For vehicle speed = 80 Kmph (maximum speed that can be achieved)

At maximum speed, motor will be delivering maximum power.

Motor Torque at maximum speed = Motor Power / Wheel Speed = **878.68 Nm** [7]

3. Vehicle Modelling in GT-Suite

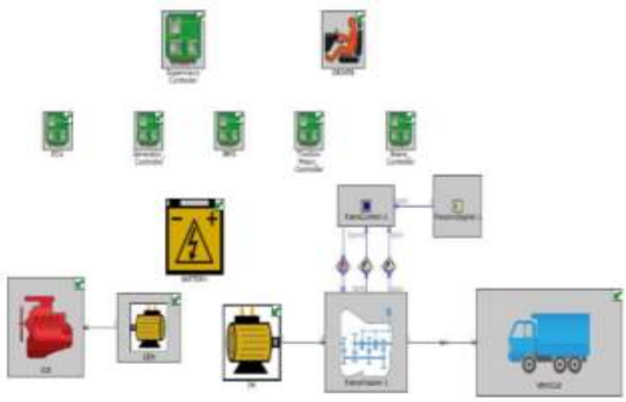


Fig -2: Series Hybrid Configuration in GT-Suite

The model represents a series hybrid commercial vehicle that has traction motor powering the rear wheels, and a constant speed genset engine is connected to a smaller generator. The control strategy proposed for this model is very simplified. First, the "driver" component calculates a required power to follow a required driving cycle, which is passed to the traction motor, which is passed to the traction motor to move the vehicle. Then, based on the battery state of charge level, the ICE generator combination charges the battery. This is how series hybrid model works.

Engine Signals receive signals from supervisory control and runs at that required rpm when battery SOC falls below given level. Engine is also connected to ICE-Gen Gearing. This link connects engine and generator with particular gear ratio. IC Engine controller also enables us to enter properties, engine type, engine displacement, inertia, idling speed, fuel density and also, its BMEP and BSFC maps.

In Supervisory controller, it Signals receives signals from driver for vehicle acceleration and traction power demand and battery for SOC level. Regenerative Brake controller and Charge Level-State Charge take up these input data and send output signals to traction motor and engine. Charge Level-States determines when to switch the engine on and when to turn it off depending upon the battery SOC condition. Depending upon that, it sends the signals to ignition to turn the engine on whenever it is required.

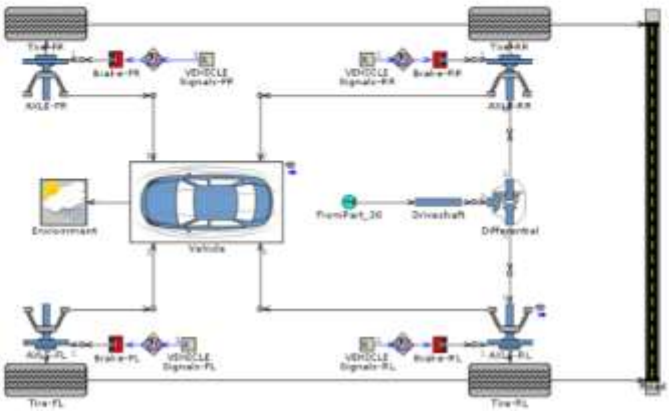


Fig -3: Vehicle Model

Vehicle model consists of several components like environment, tires, axle, differential, driveshaft, road etc. This helps us to define the road conditions, environmental conditions, vehicle dimensions, vehicle brake conditions. Brake-RR controller takes the value of brake pedal position and applies required amount of brakes on the tires. Road controller helps us to define road elevation, road grade, road curvature radius etc.

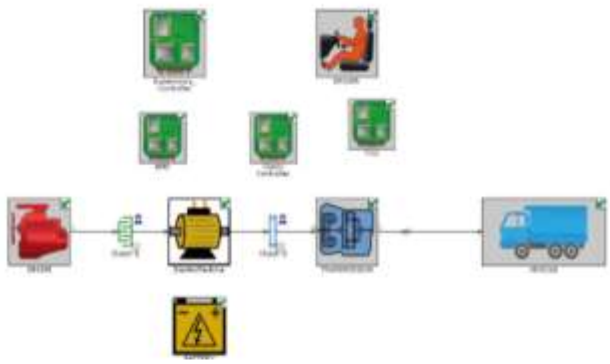
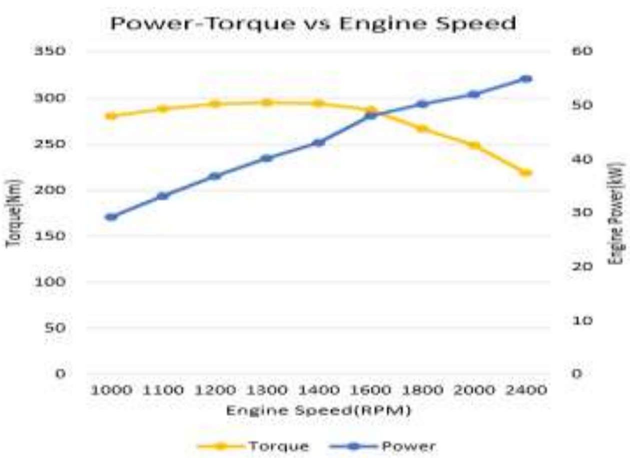


Fig -4: P2 Hybrid Configuration Model

This is P2 parallel Hybrid model on GT-Suite. So, we have two clutches in this system, one clutch is situated between engine and electric machine and another clutch is situated between transmission and electric machine. Whenever vehicle is stopped or it isn't moving, clutch-2 is open, and clutch-1 is closed and with the help of regenerative energy, motor starts the engine, which in turn does the idle charging of the battery. So, here system works in HEV mode. Now, when clutch-1 is open, engine is disconnected from the electric machine, and system works in EV mode.



Graph -1: Power-Torque Characteristics of the Engine as generated using the Engine Model in GT-Suite

4. Control Strategy

Hybrid electric powertrain control doesn't work like in case of conventional vehicles with only IC engine. In case of pure IC engine, engine supplies power at all times, basically focus is put on changing the fuel air ratios depending upon the driving cycle, vehicle speed, accelerator position etc. But in case of HEVs, things get more complicated because we hybridize the system with electric motor. There are different modes for different operating, SOC and driving conditions where powertrain works in pure EV mode, pure engine mode, HEV mode and regenerative mode. This is all governed by ECM control system and the strategy that it uses is known as HEV control strategy. GT-Suite gives user the freedom to develop their own control strategy and run the simulation to get the optimum fuel consumption.

State 1: At the start, vehicle runs in State 1 when battery's SOC is greater than 0.35, it works in pure EV mode. Here clutch 1 is open because there is no power flow from engine and clutch 2 is closed because motor is transmitting power to transmission gearbox.

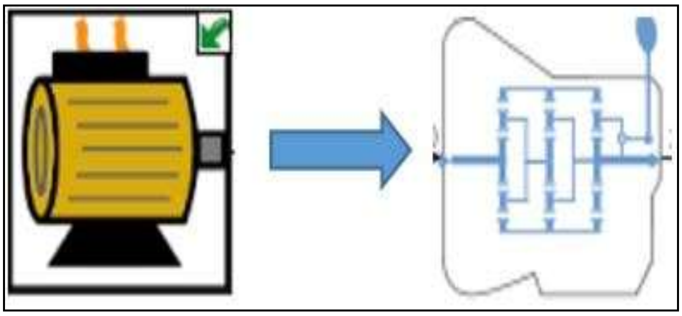


Fig -5: State 1: When Vehicle is running on pure EV mode

State 2: Vehicle runs in pure EV mode till the time battery SOC reaches 0.35. Now there are two conditions, first one is vehicle is not moving and the other one is when vehicle is moving. In the condition when vehicle is stopped, engine is still switched off and the motor produces negative torque with the help of regenerative energy and starts the engine. Here clutch 1 is closed and clutch 2 which is present between motor and transmission is open because there is no power flow from motor to wheels.

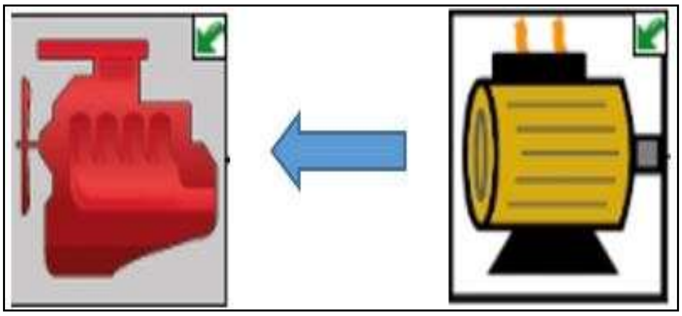


Fig -6: State 2: Clutch 1 is closed, and motor starts the engine

State 3: As soon as engine reaches 750 rpm, which is the engine idle speed, engine starts to charge the battery. For that it, it supplies torque enough to charge the battery. At the same time motor is also charging the battery and clutch 2 is closed. This mode is idle charging mode, because engine is utilizing its energy to charge the battery.

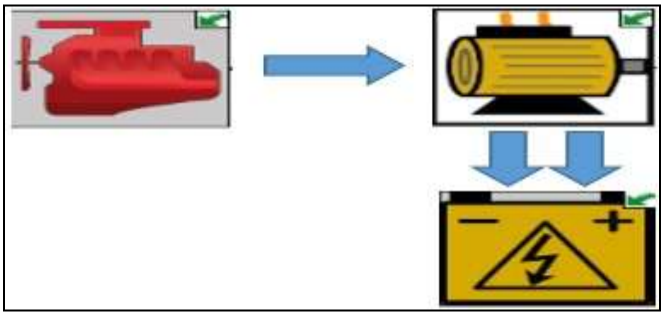


Fig -7: State 3: Idle Charging

State 4: In the 2nd condition, vehicle is moving and SOC is below 0.35, here clutch 1 is starting to get connected, and motor is developing power to start the engine. For that, motor needs to overcome engine friction torque and the torque request from the driving cycle because it has to run the vehicle also. Clutch 2 is closed here.

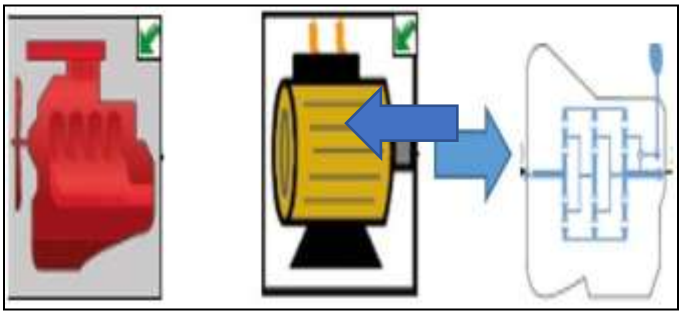


Fig -8: State 4: Engine Started

State 5: If brakes are released from state 4, then, vehicle will start to move, this is where HEV mode is seen, Motor charges the battery from regenerative energy, engine overcomes the resistance of the road and drives the vehicle and also charges the battery. If brakes are applied again and vehicle gets stopped, state 5 goes back to state 4.

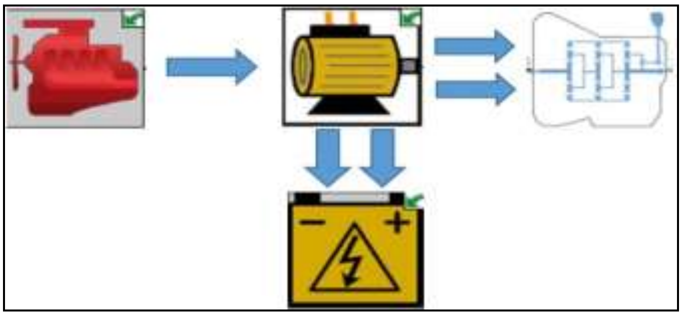


Fig -9: State 5: HEV Mode

State 6: In case, driver torque provided by the engine isn't able to overcome engine friction torque, then motor supplies the driver torque and as well as starts the engine by overcoming engine friction torque in backward direction. When driver torque becomes greater than friction torque, state 6 goes to state 5.

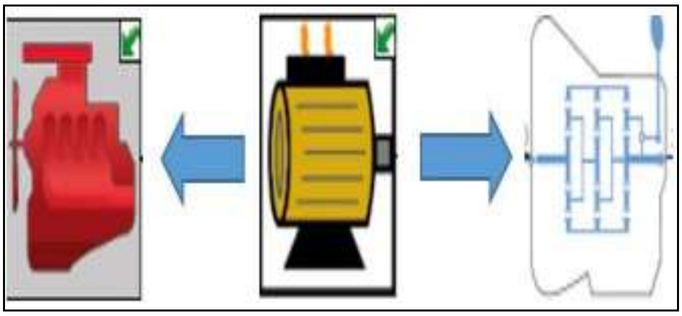
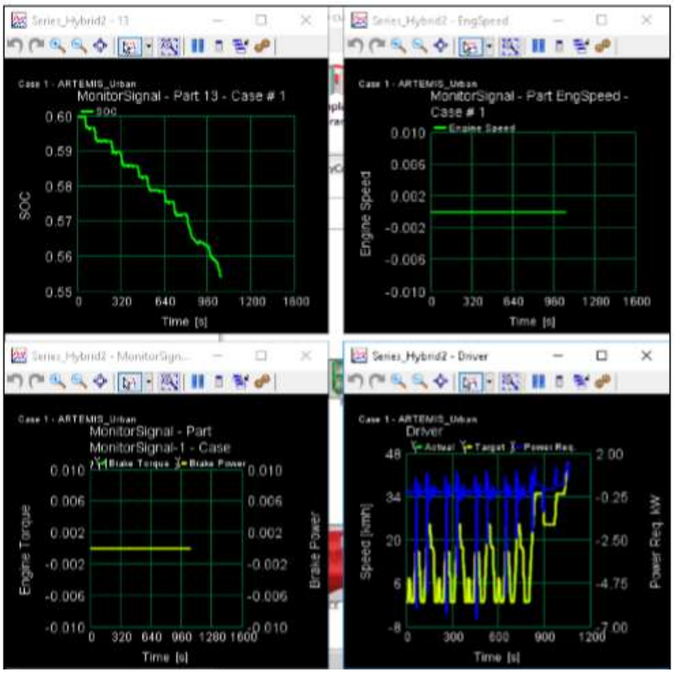


Fig -10: State 6: HEV Mode (Regenerative Braking)

State 7: This is the case where the driver is changing the transmission gear, so the engine state and motor state is off. Since, there is a transition of gear number, so there is no engine torque request as well as motor torque request.

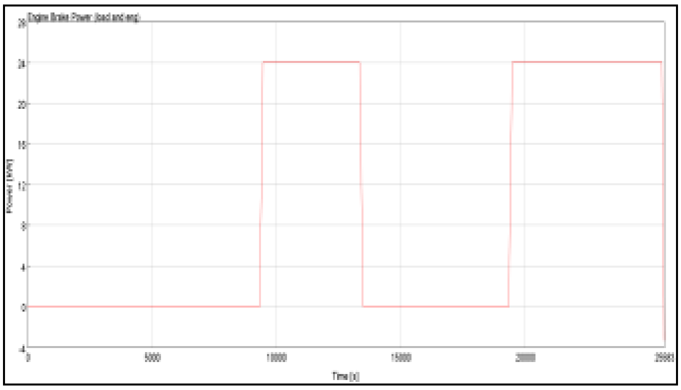
5. Simulating the Model



Graph -2: Live Graph Being Monitored During Simulation

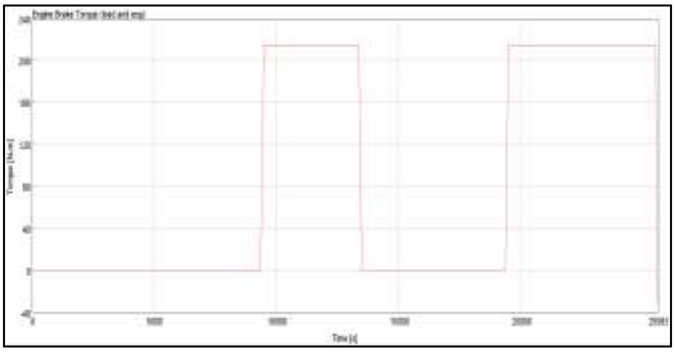
5.1 Simulation of Series Configuration

Simulation is run on GT-suite at Indian Driving cycle, and different results were obtained of different important parameters.



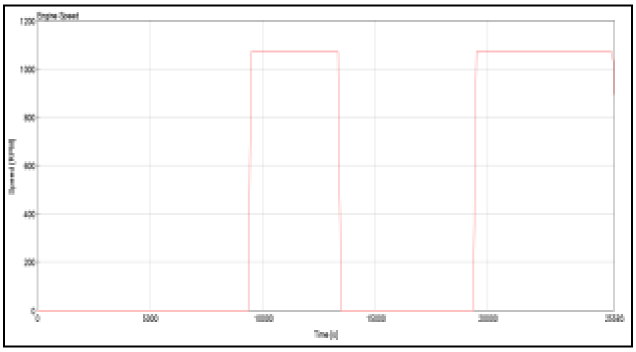
Graph -3: Engine Brake Power vs Time

Engine requires 24kW of brake power to charge the battery at that rate.



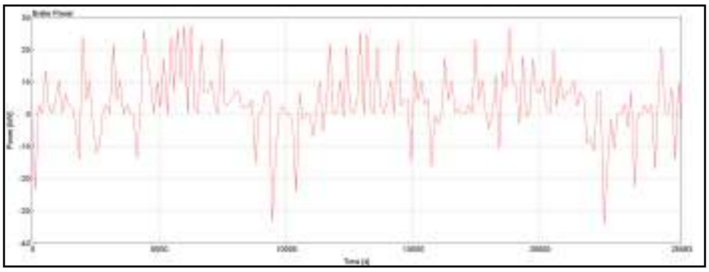
Graph -4: Engine Brake Torque vs Time

Engine requires 214 Nm of torque to take the battery SOC from 0.32 to 0.6 SOC level.



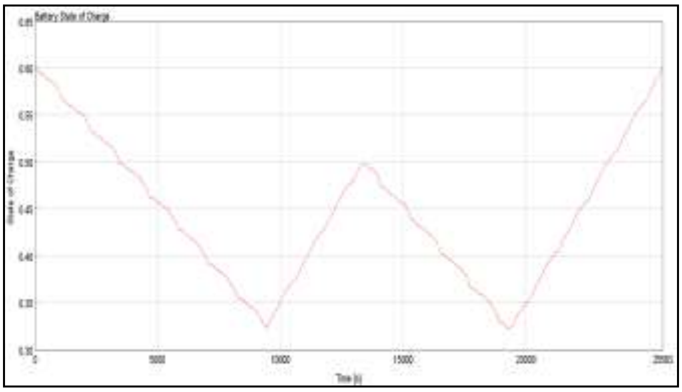
Graph -5: Engine RPM vs Time

Engine is running when battery SOC is reaching 32%, and charges it again to 0.6 and stops, again runs till SOC reaches 0.6 from where it started.

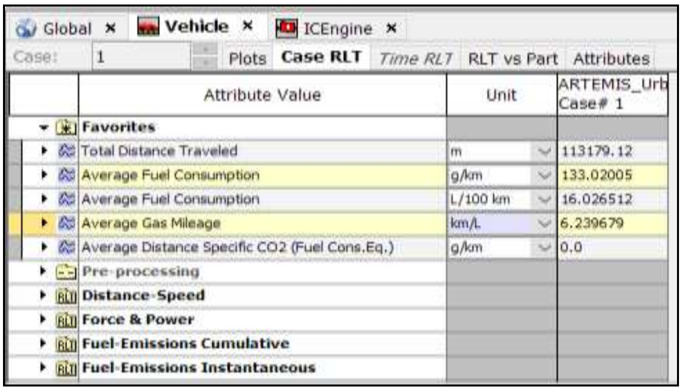


Graph -6: Motor Power vs Time

Motor is always powering the wheels. Motor reached a maximum power of 27.63 kW



Graph -7: Battery SOC vs Time



Global × | Vehicle × | ICEngine ×

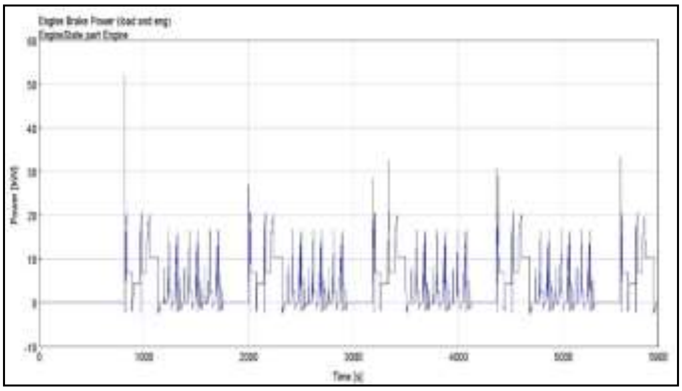
Case: 1 | Plots | Case RLT | Time RLT | RLT vs Part | Attributes

Attribute Value	Unit	ARTEMIS_Urb Case# 1
Favorites		
Total Distance Traveled	m	113179.12
Average Fuel Consumption	g/km	133.02005
Average Fuel Consumption	L/100 km	16.026512
Average Gas Mileage	km/L	6.239679
Average Distance Specific CO2 (Fuel Cons.Eq.)	g/km	0.0
Pre-processing		
Distance-Speed		
Force & Power		
Fuel-Emissions Cumulative		
Fuel-Emissions Instantaneous		

Fig -11: Mileage of Series Hybrid Configuration

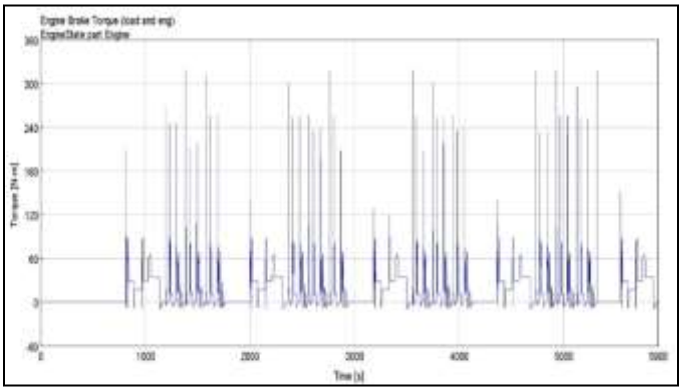
5.2 Simulation of P2 Configuration

Simulation is run on GT-suite at Indian Driving cycle, and different results were obtained of different important parameters.



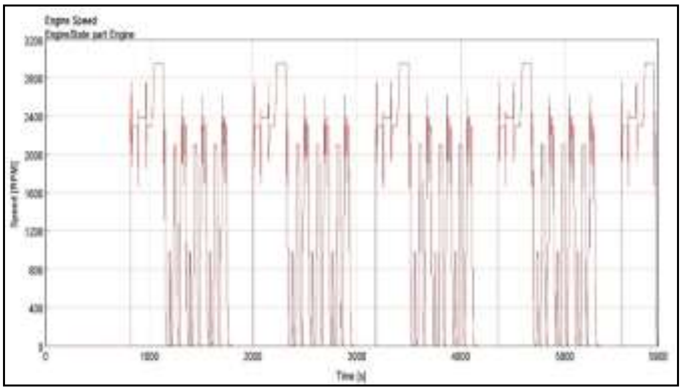
Graph -8: Engine Brake Power vs Time

The graph shows variations in engine power in response to the drive cycle, at the start engine is not running, as soon as SOC reaches 0.35, engine is started by the electric motor with the negative torque.



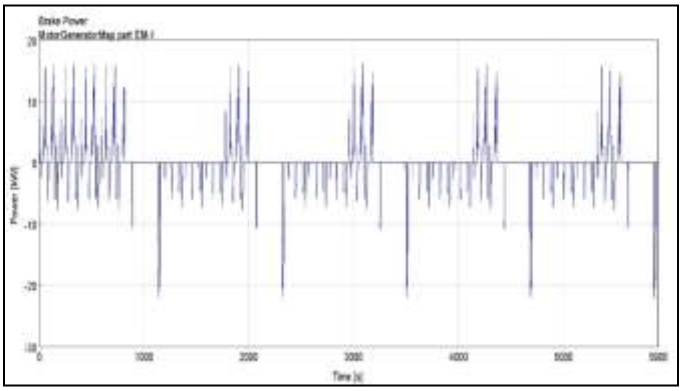
Graph -9: Engine Brake Torque vs Time

Engine torque is shown at different instances in response to the torque request from the supervisory controller.



Graph -10: Engine RPM vs Time

Engine speed is shown at different instances in response to the driving cycle.



Graph -11: Motor Power vs Time

Motor power is shown as per the control strategy, note that, sometimes motor providing positive power, sometimes it is not transmitting any power, sometimes negative power is evident, that is due to regenerative energy.

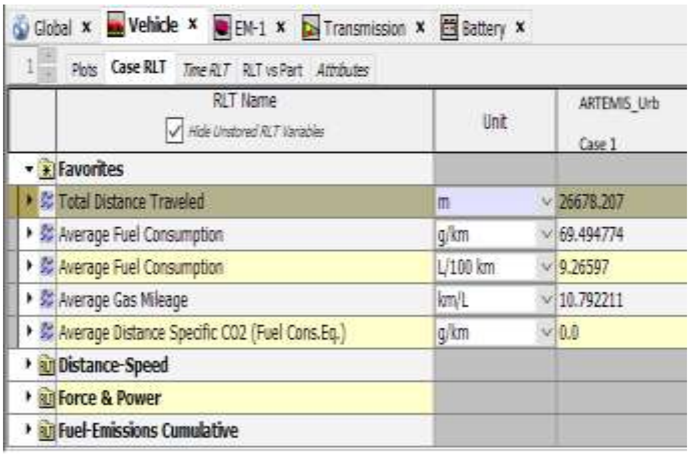


Fig -12: Mileage of P2 Hybrid Configuration

6. Results

SI. No.	Parameters	Series Hybrid	P2 Parallel Hybrid
1	Fuel Mileage (kmpl)	6.23	10.79
2	Motor maximum Power consumption (kW)	28	18
3	Engine maximum Power consumption (kW)	24	32
4	No of Gear Ratios	2	5

Table -1: Power and Mileage Comparison between P2 and Series Configurations

From the table we can see that P2 parallel hybrid gave a mileage of 10.79 kmpl compared to series hybrid of 6.23 kmpl. This way, this P2 Hybrid architecture even by being slightly more complex proved to be far more efficient than Series Hybrid and conventional diesel for commercial vehicles in urban Indian driving cycle. In urban conditions, P2 Hybrid obtains around 40% more fuel economy than conventional diesel truck in Japan which gave mileage of around 7.7 kmpl.

7. Conclusion

After performing the simulation and several studies, it was concluded that the powertrain system needed to come up with a more sophisticated and different control strategy, where we can't just rely entirely on motor to do the entire job of running the wheels and engine for charging the battery. We needed to combine all these ideas together and we came to the conclusion that removing the generator from the system and allowing engine to transmit its power towards battery for charging and towards transmission for powering the wheels through motor will help the system to perform with even better efficiency because that will allow system to adjust more flexibly as per its requirements. P2 Parallel Hybrid model and its controllers were modelled. Generator was removed from the previous model to reduce the losses from generator. [8]

Moreover, once available energy in the battery falls below certain extent, system can turn into either pure engine mode or HEV mode. If motor is turned off, engine will alone run the power flow towards battery and to the wheels, and motor connected to the clutch will run because of engine powering it and not by using the energy from the battery. Like this, engine, motor and regenerative energy work in harmony to overcome high torque requirements when engine is not running very often, which improves fuel economy.

References

[1] M. Ivantysynova and P. Banejee, "Development of a Torque-Based Control Strategy for a Mode-Switching Hydraulic Hybrid Passenger Vehicle," SAE Technical Paper, 2018. https://doi.org/10.4271/2018-01-1007

[2] M. Ehsani, Y. Gao and S. E. Gay, "Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design. Second Edition (Power Electronics and Applications Series)," CRC Press, Taylor and Francis Group, 2009.

[3] "Autonomie," [Online]. Available: www.autonomie.net.

[4] "www.x-engineer.org," [Online].

[5] I. Guwahati, "Introduction to Hybrid and Electric Vehicles," 8 Feburary 2013. [Online]. Available: https://nptel.ac.in/courses/108103009/3.

[6] "Rolling Resistance," [Online]. Available: www.nptel.ac.in.

[7] H. Naunheimer, B. Bertsche, J. Ryborz and W. Novak, "Automotive Transmissions Fundamentals, Selection, Design," Springer-Verlag Berlin Heidelberg , 2011.

[8] N. Okui and T. Niikuni, "A Study of Fuel Economy Improvement of Small Delivery Hybrid Trucks," SAE Technical Paper, 2014. https://doi.org/10.4271/2014-01-2903

[9] "Specification," [Online]. Available: https://trucks.cardekho.com/en/trucks/tata/sfc-709ex/specifications.

[10] M. Bradley, "Hybrid-Electric Drive Heavy-Duty Vehicle Testing Project - Final Emissions Report," Defense Advanced Research Projects Agency, 2000. http://www.walshcarlines.com/pdf/Navc9837.pdf

[11] J. Gray.United States of America Patent US 6,876,098 B1, 2005.

[12] J. J. Bowman.United States of America Patent US 8,783,396 B2, 2014.

[13] "GT-Suite About Us," [Online]. Available: www.gtisoft.com/gt-suite-applications.

[14] Yang, X., Shen, Y. Runge-Kutta Method for Solving Uncertain Differential Equations. J. Uncertain. Anal. Appl. 3, 17 (2015). https://doi.org/10.1186/s40467-015-0038-4.

Definitions/Abbreviations

BMEP – Brake Mean Effective Pressure
BSFC- Brake specific fuel consumption
DOH- Degree of Hybridization
ECU- Engine control unit
EM- Electric motor
EV- Electric vehicle
FHEV- Full Hybrid vehicle
HEV- Hybrid electric vehicle
ICE- Internal Combustion engine
IDC- Indian Driving Cycle
LCV- Light Commercial Vehicle
MHEV- Mild Hybrid electric vehicle
PHEV- Plug-in Hybrid vehicle
RPM – Revolutions Per Minute
SOC- State of Charge