THE INFLUENCE OF GEAR RATIO ON THE EXHAUST EMISSION AND FUEL CONSUMPTION OF A PARALLEL HYBRID VEHICLE POWERTRAIN

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Abstract : Hybrid electric vehicles are becoming the major substitute for internal combustion engine vehicles because hybrid electric vehicles are noteworthy in terms of efficiency, durability and acceleration capability. Hybrid vehicles offer improved fuel economy and greenhouse gas reduction compared to vehicles with internal combustion engines only. The purpose of this study is to investigate the influence of gear ratio of gearbox unit, differential, and torque coupling unit in fuel consumption and exhaust emission of parallel hybrid powertrain. Study was carried out in MATLAB/SIMULINK environment. Five gear ratio combinations are simulated which includes gearbox unit, differential and torque coupling unit. From the simulation it noted that It is noted that 10% fuel economy improved and 8% of CO_2, 11% of CO, 2% of HC, and 4% of NOx reduction achieved by using proper gear ratio in powertrain components.

***Index Terms* - Hybrid Vehicle, Gear Ratio, Fuel Consumption, Exhaust Emission.**

I. Introduction

Hybrid vehicles offer improved fuel economy and greenhouse gas reduction compared to vehicles with internal combustion engines only. Several hybrid constructions have been applied on the vehicles in the automotive industry because of these benefits. Improve vehicles' fuel economy, such as reducing vehicles weight, reducing rolling resistance, reducing aerodynamic resistance, downsizing the engine, etc. however, each of these suggested approaches has benefits and drawbacks may constrain it. Still hybrid vehicle need improvement in their various components to achieve better performance.

Previous study shows the improvements on fuel consumption and exhaust emission can be obtained by not only the hybridization of conventional vehicles but also correct determination of gear ratio in the powertrain components [1] . In previous study they considered three speed gearbox, torque coupling unit, differential and their results shows that when low gear ratio on torque coupling unit is considered then it is more significant compared to higher ratio in gear box and differential. In this study we are considering five speed gearbox, differential and torque coupling unit with different values of gear ratio for evaluation of exhaust emission and fuel consumption in parallel hybrid powertrain.

1.1 Parallel hybrid electric vehicle

The parallel hybrid electric vehicle allows both the engine and electric motor to deliver power in parallel to drive the wheels. Since both the engine and electric motor are usually coupled to the drive shaft of the wheels via two clutches, the propulsion power may be supplied by the engine alone, by the electric motor alone or by both. The electric motor can be used as a generator to charge the battery by regenerative braking or absorbing power from the engine when its output is greater than that required to drive the wheels. The parallel hybrid needs only two propulsion devices the engine and the electric motor.

Power flow in parallel hybrid vehicle is show in Fig. 1.1. which illustrates the four operating modes of the parallel hybrid electric vehicle. In parallel hybrid electric vehicle during startup or full-throttle acceleration, both the engine and electric motor proportionally share the required power to propel the vehicle. Typically, the relative distribution between the engine and the electric motor is 80–20%.

During normal driving, the engine solely supplies the necessary power to propel the vehicle, while the electric motor remains in the off mode. During braking or deceleration, the electric motor acts as a generator to charge the battery via the power converter. Also, since both the engine and electric motor are coupled to the same drive shaft, the battery can be charged by the engine via the electric motor when the vehicle is at light load. Recently, the Honda Insight has adopted a similar power flow control.

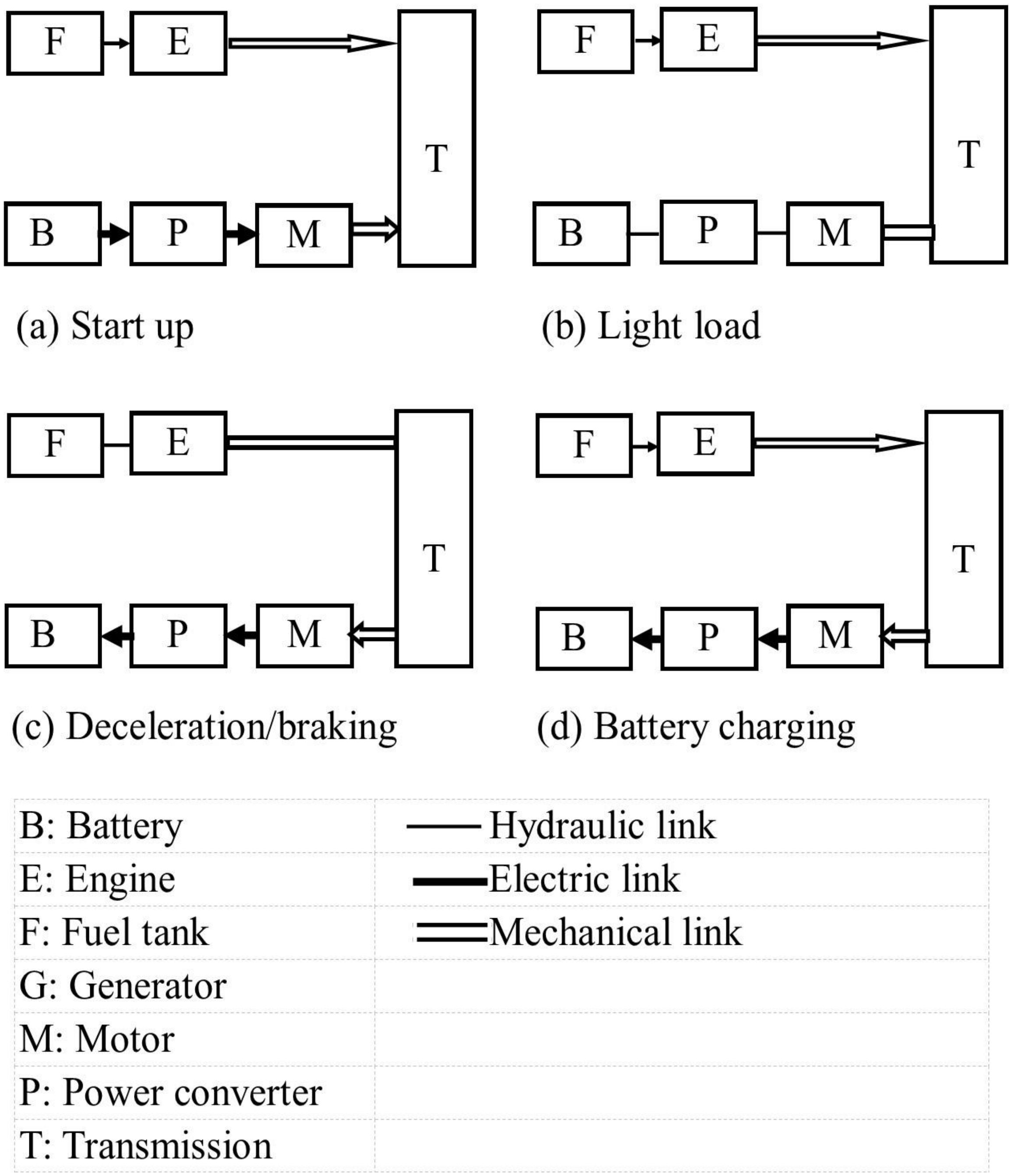

Fig. 1.1 Parallel hybrid electric vehicle power flow

II. Methodology

In this study we used MATLAB/SIMULINK to simulates parallel hybrid powertrain. NEDC drive cycle is used as input parameters for simulations. The fuel consumption, exhaust emissions are determined according to the power requirement of internal combustion engine and electric motor. In this study five different gear ratio combinations are simulated and these combinations are arranged by using alternator ratio in fifth stage of gearbox unit, torque coupling unit, and differential. Fuel consumption and emission of $CO_{2,}$ CO, NO_x, and HC are checked on NEDC (New European Driving Cycle) cycles.

2.1 Description of vehicle model

In this study, the powertrain of the vehicle is considered as parallel hybrid which consists of an ICE (Internal combustion engine) and an EM (Electric motor). Powertrain configuration of the parallel hybrid vehicle and its main components are shown in the Fig. 1.2. The ICE and EM are connected with TCU to transfer power to the wheel via the GU and the differential. GU is the five-stage transmission that is located after the TCU.

The main assumption for the motion equation of the powertrain of the vehicle model are as follows: equations are arranged for the longitudinal movement of the vehicle, tire radius is assumed to be constant, and tire slip, system vibration, damper are neglected. The vehicle moves according to the speed and acceleration inputs od NEDC. Using the inputs of the NEDC, the resistance for F_R, grading resistance F_{st} , air resistance F_L , and acceleration resistance F_a , which creates torque demand on the vehicle tires. To meet the demand required energy is produced by the engine and electric motor.

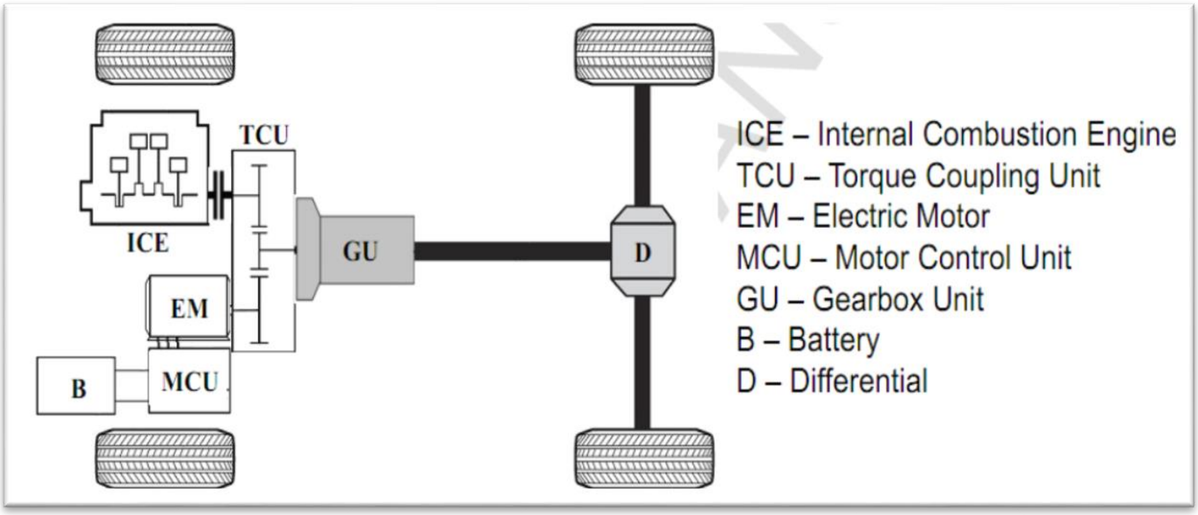

Fig. 1.1 Configuration of Parallel hybrid electric powertrain [1]

$$F_R = m \times g \times f_R \tag{1}$$

$$F_{st} = m \times g \times \sin \delta \tag{2}$$

$$F_L = ½ \times \rho_a \times A \times C_w \times V^2 \tag{3}$$

$$F_a = \lambda \times m \times a \tag{4}$$

The parameters given in the above equations are defined as follows: m is total mass of vehicle, g is the gravitational acceleration, f_R is the rolling resistance coefficient, δ is the slope angle of road, ρ is the density of air, C_w is the aerodynamic coefficient of the vehicle, A is the projection area of the vehicle, and λ is the coefficient of the effect of rotating masses. Velocity (V) and acceleration (a) of the vehicle taken from the NEDC. These parameters are selected after investigating the vehicle specification from Toyota yaris (2020). According to NEDC the road is considered to be horizontal thus the slope of the road is taken as zero. Input parameters for the vehicle model listed in Table 1.1

Table 1.1 Input parameters for vehicle model

Parameters	**Value**
Vehicle mass (m)	1565 kg
Coefficient of rolling resistance (f_R)	0.012
Aerodynamic drag coefficient (C_w)	0.33
Projection area of the vehicle (A)	2 m^2
Coefficient of the effect of rotating masses (λ)	1.1
Density of air (ρ)	1.22 kg/m^3
Dynamic tire radius (r_{dyn})	0.4 m

Instantaneous torque (M_T) and power (P_T) demands on the traction tires of the vehicle are given in Eqs. (5) and (6), respectively.

$$M_T = (F_R + F_{st} + F_L)\, r_{dyn} \tag{5}$$

$$P_T = (F_R + F_{st} + F_L)\,V \quad (6)$$

2.2 Description of internal combustion engine and electric motor

In order to evaluate the fuel consumption and the exhaust emission rates of ICE, engine model is established in Simulink environment, which neglects the effect of driver. Fuel consumption and emission are calculated according to speed and torque request of ICE. The parameters of ICE, EM and Battery are shown in Table 1.2, Table 1.3 and Table 1.4 respectively. These parameters are taken from vehicle Totoya yaris (2020).

Table 1.2 ICE parameters

Fuel type	Petrol
Maximum power at 6000 rpm	51 kW
Maximum torque at 4300 rpm	95 Nm

Table 1.3 EM parameters

Electric motor type	Permanent magnet, synchronous
Maximum output	45 kW
Maximum torque	169 Nm
Battery type	Nickel-metal hydride

Table 1.4 Battery parameters

Battery type	Nickel-metal hydride
Battery voltage	200 V
Battery output power	21 kW

2.3 Simulink model of parallel hybrid powertrain

The components of parallel hybrid powertrain are created in Simulink by block diagram and the simulation of the system is performed for vehicle speed and acceleration inputs of NEDC cycle. Simulink is used for simulation because it is fast solving analysis that has short time step for a long simulation time, flexibility for combining component subsystems, and simplicity for evaluating and comparing results.

Input parameter data sets are connected with the vehicle block, which is composed of the equations for the resistance force acting on vehicle and the torque-speed demand on tires. EM and ICE should provide the torque demand of the vehicle, which is calculated in the TCU block, angular velocity of ICE and EM are equal to the angular velocity of TCU. Torque and speed relations are defined in following equations when ICE and EM operating together.

$$T_{TCU} = T_{EM} + T_{ICE} \quad (7)$$

$$W_{TCU} = W_{EM} = W_{ICE} \quad (8)$$

Simulink blocks of the simulation interface is shown in Fig. 1.2. Simulation time is taken as 1200 s for one NEDC profile.

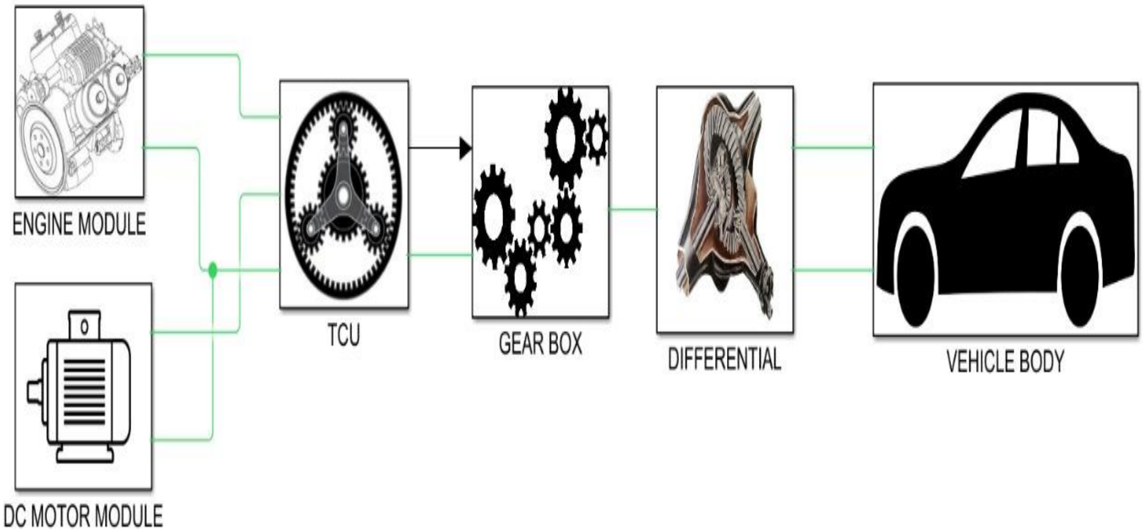

Fig. 1.2 Simulink structure of the parallel hybrid powertrain

2.4 DESIGN PARAMETERS AND SIMULATION METHOD

Hybrid vehicle need single or multi-speed gearbox related to its type such as series or parallel hybrid [1] .Single speed gearbox is proper for electric and series hybrid vehicles because they use only electric motor for traction [1] . Therefore, in order to provide the requirements for reaching the maximum speed and grading in these vehicles, a single speed gearbox with fixed ratio and final gear ratio is used. However, multi-speed gearbox is necessary for reaching top speed, grading and economic driving requirement in parallel hybrid vehicles because they use both ICE and EM for traction. Five speed GU is considered in this study according to the vehicle parameter and NEDC requirements.

Torque and speed requirement of ICE and EM are determined by gear ratios between power sources and drive wheels. Five gear ratio options that includes differential gear ratio I_D , TCU gear ratio I_{TCU} , and five speed GU gear ratio from I_{GU1} to I_{GU5} are shown in Table 1.5. Value of the gear ratio are taken from Toyota yaris (2020). There are five options are used to check the fuel consumption and exhaust emission from vehicle. Option 0, 1 and 2 are used to check the changes on the fifth gearbox ration when I_{TCU} and I_D have same value. Options 3 and 4 are used for the evaluation of the effects of the differential gear ratio and TCU gear ratio, respectively.

Table 1.5 Gear ratio options of powertrain components

	I_D	I_{GU1}	I_{GU2}	I_{GU3}	I_{GU4}	I_{GU5}	I_{TCU}
Option 0	4.29	3.54	1.91	1.31	1.02	0.85	1.12
Option 1	4.29	3.54	1.91	1.31	1.02	0.90	1.12
Option 2	4.29	3.54	1.91	1.31	1.02	0.75	1.12
Option 3	4.35	3.54	1.91	1.31	1.02	0.75	1.12
Option 4	4.12	3.54	1.91	1.31	1.02	0.75	1.20

Vehicle can be operated in three different modes related to vehicle speed and torque demand. Operation modes of power sources are expressed as:

- **EM only:** ICE is shut down when the vehicle speed is under 10 km/h.
- **ICE only:** EM is shut down, ICE operates at higher speed than 10 km/h and torque demands are under 55 Nm.

Both EM and ICE: Torque is produced by both EM and ICE when torque demand is higher than 55 Nm.

III. Result and discussion

Operation characteristics and torque demand in the ICE are calculated by the simulation for one cycle time of NEDC. Vehicle speed, engine power and specific emission rates of CO, HC, and NO_X are the input parameters for the fuel consumption and exhaust emission calculations. Fuel consumption and exhaust emission rates are calculated for each step time in the unit of l/100km and g/km respectively. Simulation results of different gear ratio option are show for fuel consumption (Fig. 1.3, and exhaust emission (Fig. 1.4, Fig. 1.5, Fig. 1.6, Fig. 1.7) are explained below.

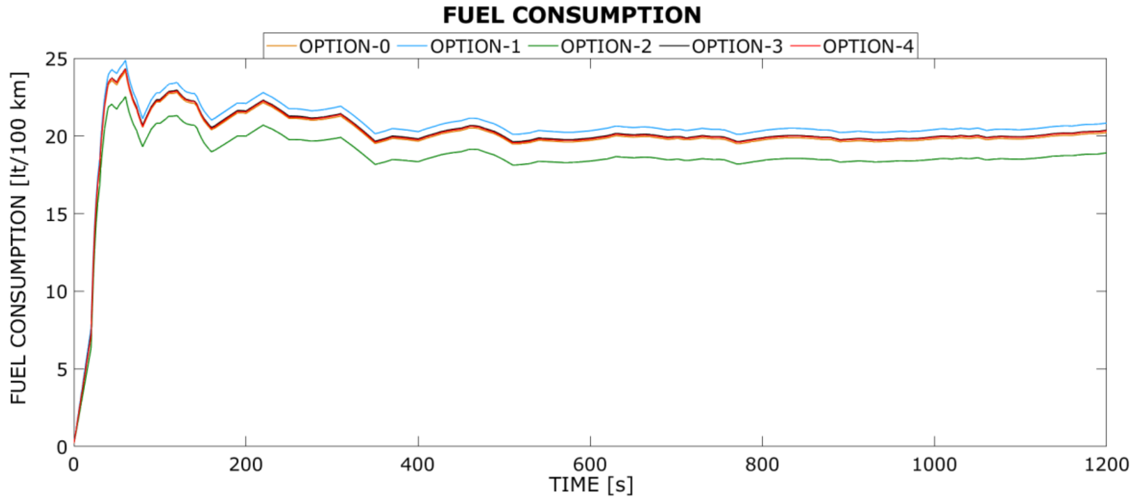

Fig.1.3 Fuel consumption

The gear ratio option 1 shows the higher fuel consumption about 25 l/100km while option 2 shows low fuel consumption about 22 l/100km. The higher fuel consumption in option 1 observed due to increasing gear ratio in 5th stage of gearbox. The lower fuel consumption is observed in option 2 due to lowering gear ratio in 5th stage of gearbox. Between 100 to 500 seconds fuel consumption rate is varying according to speed demand.

When vehicle starts to move then it required higher torque therefore with higher torque the fuel consumption also increased. Here result shows that in all options the fuel consumption is higher upto 100 seconds after that it is slightly decreased and after 400 seconds no more variation in fuel consumption in observed because after 400 seconds torque is reduced.

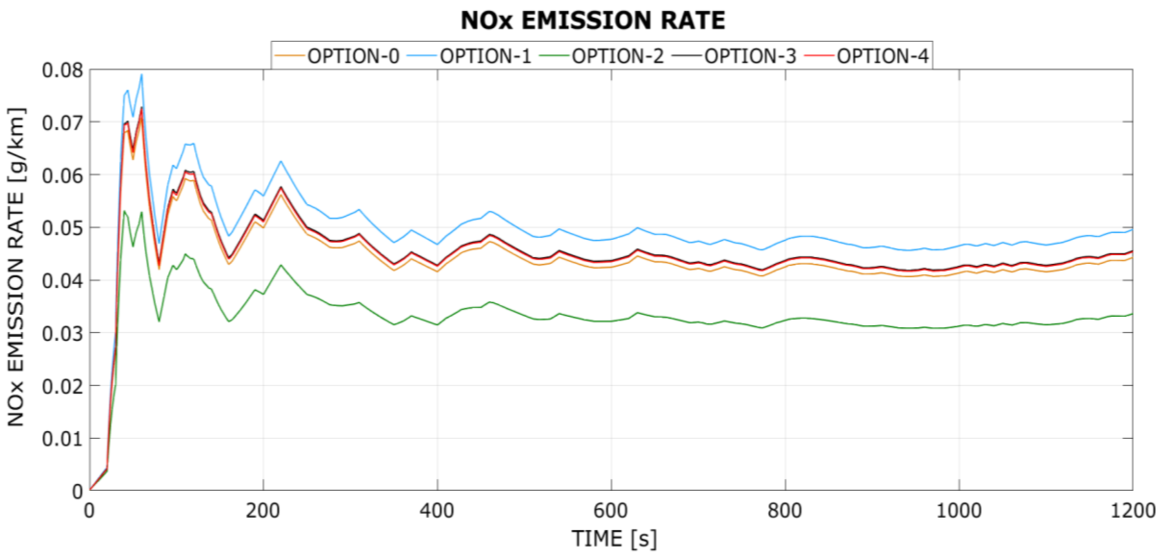

Fig. 1.4 NOx Emission

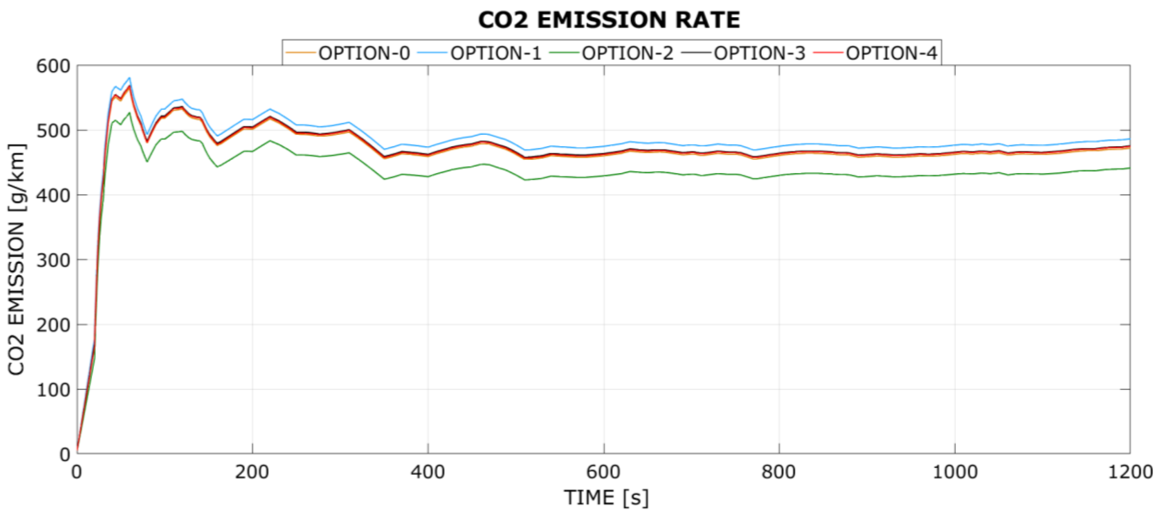

Fig. 1.5 CO_2 Emission

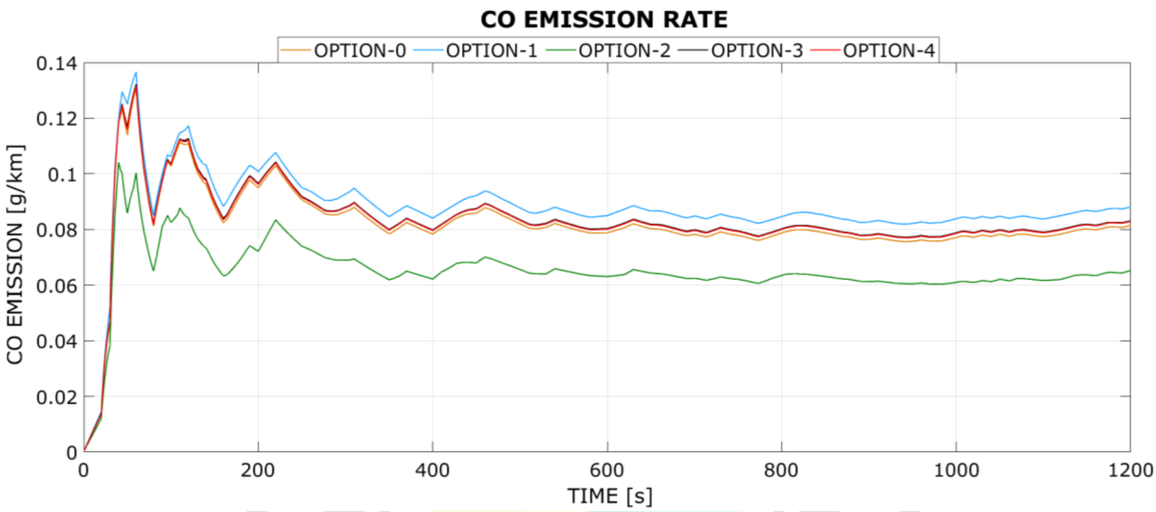

Fig. 1.6 CO Emission

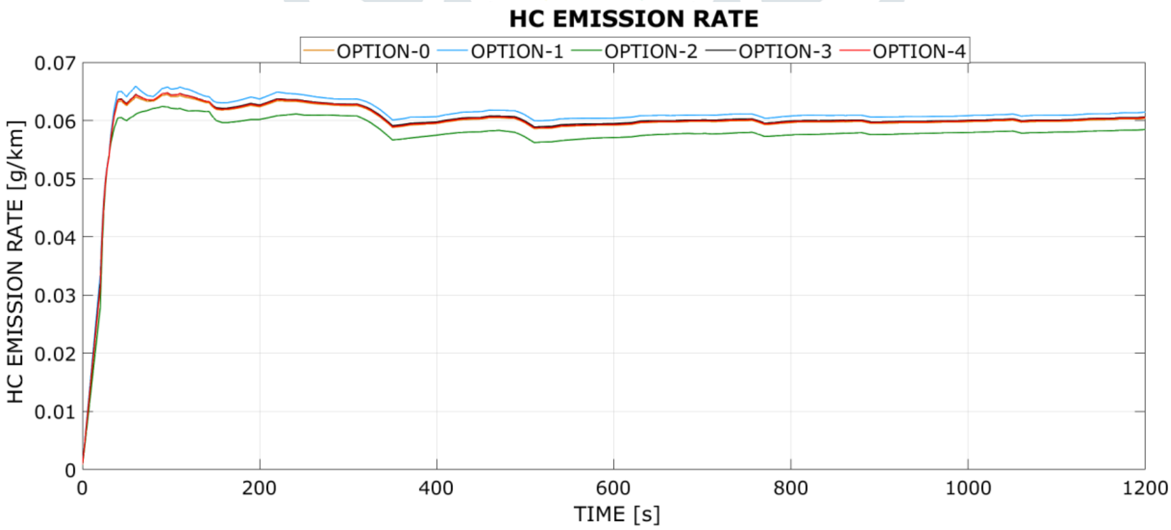

Fig. 1.7 HC Emission

The results of exhaust emission are presented in Fig. 1.4, Fig. 1.5, Fig. 1.6, Fig. 1.7 according to ICE operation. CO2 emission reach up to 500 g/km for each gear ratio options. Highest CO2 emission observed in option 1 due to increasing gear ratio of 5^{th} stage of gearbox which resulting higher fuel consumption therefore emission also increased. The maximum CO, HC, and NOx are 0.14 g/km, 0.07 g/km and 0.08 g/km respectively. All the highest emissions are observed in option 1 due to higher fuel consumptions. Option 1 have maximum value of CO_2 emission while option 2 have lowest CO_2 emission. After 400 seconds emission level slightly changes in all option at the end of the cycle. Up to 200 seconds vehicle moves slowly with higher torque from ICE which results in higher emission rate. It is observed that the change in gear ratio of 5^{th} stage gearbox affect the level of HC emission. Option 1 have highest HC emission due to increasing gear ratio in gearbox. While lowest HC level is observed in option 2 due to decreasing gear ratio in gearbox. It is also observed that the change in TCU and differential ratios does not affecting much more.

The amount of CO_2 emission originated from this simulation is compared with real world data as follows. According to European Regulation No: 443/2009, 2018 is 130 g/km. Some car manufactures exposed the CO_2 emission from their vehicles as 78 g/km, 86 g/km, 94 g/km, 108 g/km for Toyota prius 1.8, Toyota C-Hr 1.8, Suzuki Baleno 1.2, ford Mondeo 2.0 respectively. Therefore level of CO2 emission originated from this simulation are within the limit given by the European Regulation.

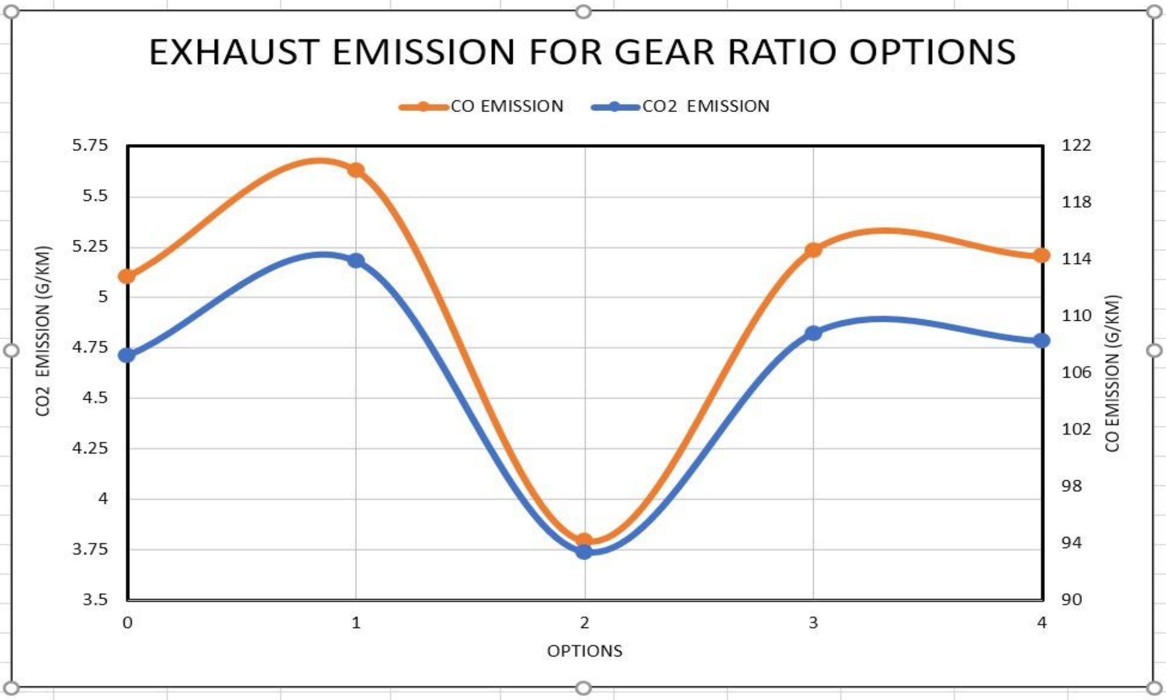

Fig. 1.8 Exhaust emission for gear ratio options

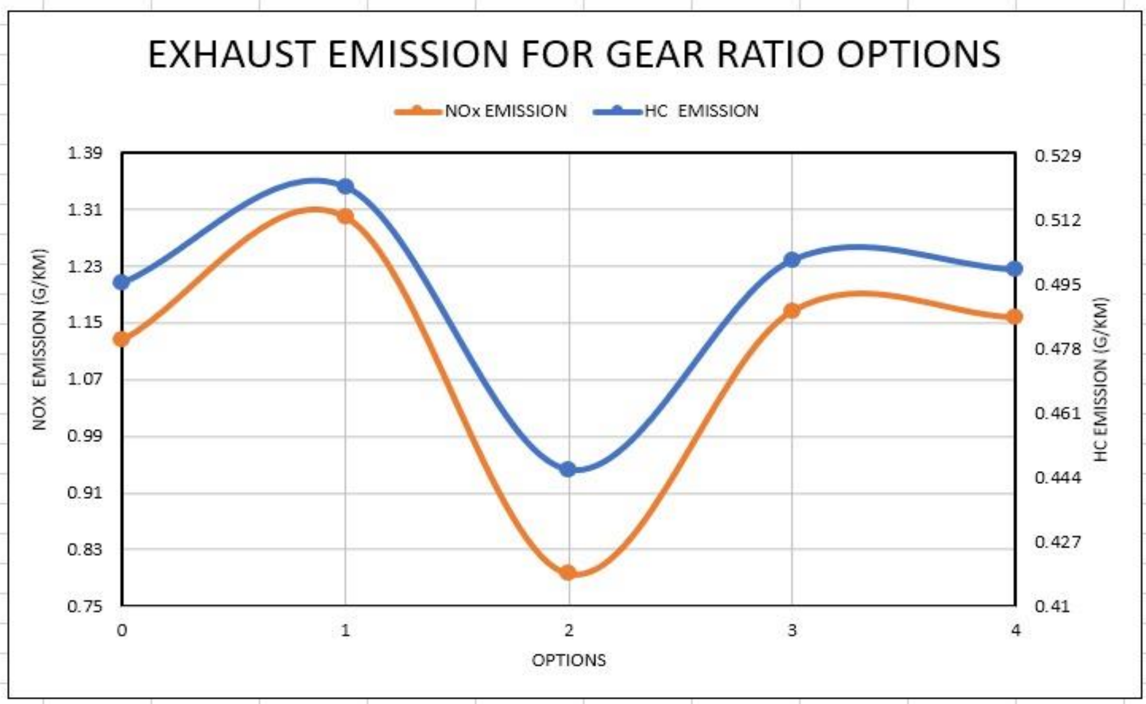

Fig. 1.9 Exhaust emission for gear ratio options

The results of the exhaust emission of each gear ratio options are shown in Fig 1.8 and Fig. 1.9. Simulation results indicates that the lowest emission found from option 2, 94 g/km for CO_2 and 5.1 g/km for CO.

IV. CONCLUSION

Simulation of a parallel hybrid powertrain was carried out in MATLAB- Simulink to reduce the fuel consumption and exhaust emission for different values of gear ration in differential, GU and TCU. The general conclusions are summarized as follow:

Decreasing gear ratio of the 5th speed in Gearbox resulting lower torque therefore due to lower torque fuel consumption also decreased. Increasing or decreasing gear ratio in differential and TCU does not affect much more in fuel consumption and exhaust emissions. Reducing gear ratio of 5th speed in gearbox is shown by option 2. This option gives best results for fuel consumption of 18 l/km and exhaust emissions are 94 g/km of CO_2 , 5.1 g/km of CO, 0.0495 g/km of HC, and 1.14 g/km of NOx. It is noted that 10% fuel economy improved and 8% of CO_2 , 11% of CO, 2% of HC, and 4% of NOx reduction achieved by using proper gear ratio in powertrain components.

V. Acknowledgment

I hereby would like to Acknowledge the in valuable support of my project guide Prof. Jitendra K Chauhan, Department of Mechanical Engineering, PIET, Vadodara. He helped me through his invaluable suggestion and support throughout the project and has been an unending source of inspiration for me. I am also thanked other faculty members who have directly or indirectly helped me whenever it was required by me. I owe my special thanks to, my friends for supporting and encouraging me in all possible ways and also all faculty members of Mechanical Engineering Department for the knowledge they imparted me throughout my Project.

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