Chapter 16
Dynamic Performance Enhancement of Hybrid Tricycle by Design of Efficient Transmission System

Amol Waddamwar, Suyog Kulkarni, and P. R. Dhamangaonkar

Abstract The revolution from gasoline-powered vehicles to electric vehicles (EVs) has been a gradual process to stabilize climate change due to global warming and maintain our standard of living. Zero emission of harmful exhaust gases is a good sign for our health. EVs have several benefits than petrol/diesel vehicles like less noise pollution, low maintenance cost, and low cost of fuel per km. Efficycle is a sustainable hybrid eco-friendly trike which can be driven by human power by pedaling and/or by power from an electric motor. It has a tadpole configuration having a capacity of two commuters. In this paper, we focused on enhancement of vehicle dynamic performance by optimum selection of transmission system components. Proper design of electric drive to overcome required torque on all terrains and comfortable drive is vital to maximize battery discharge time.

Nomenclature

A	Frontal area = 2.09 (m^2) Cd = Drag coefficient = 0.4
GCW	Gross combined weight (Kg) Fa=Aerodynamic force (N)
Fg	Gradient force (N)
FGrad	Total resistance force on gradient Road (N)
FLevel	Total resistance force on level road (N)
Fr	Rolling force (N)
Θ	Inclination of 5^0
μ	Rolling coefficient = 0.01

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ρ Density of air = 1.225 (Kg/m^3)

16.1 Introduction

Every year, pollution level is increasing due to continuous increase in the number of vehicles running on fossil fuels, a non-renewable energy source. Hence, the world is moving to electric vehicles as a mobility solution. However, there are different problems, such as low range and lower torque capacity, going with the electric vehicle. Efficycle is a hybrid version, which can run on electric motor using battery power and/or on human power using pedaling. It is a trike having tadpole configuration and carrying capacity of two commuters. This solution does not limit the range of vehicle and can be proved as a better replacement of fueled vehicles contributing toward the environment sustainability.

As efficycle is a hybrid vehicle, there are three possible drives—electric, manual, and hybrid. Here, battery power decides the driving range for electric mode. On the other hand, there is a demand for human power for pedaling in manual mode. However, integration of all three modes in a single system, switching among different modes, energy consumption rate of battery and reduction in human efforts are critical parameters in the design. Considering all these factors, design of transmission system for hybrid vehicle plays a vital role. Also, while designing the transmission, it is important to consider the aspects such as simplicity in design, ease in availability of parts, weight of vehicle, cost, manufacturing feasibility, and serviceability. In this paper, detail design and validation of transmission system for efficycle is discussed.

16.2 Literature Review

Deepanjan Majumdar et al. had revealed that e-rickshaws are energy efficient than other forms of motorized public road transport vehicles in the state. Proper implementation of e-rickshaws has a potential to address the issue of environmental pollution due to transportation as specific CO2 emission for e-rickshaws was found to be 19.129 gm/passenger-km [1].

Prof. S. U. Gunjal et al. have worked on delta configuration of human-powered hybrid trike. In his work, driver seats are in longitudinal direction. This configuration mainly increases the length of vehicle and power train chain. Increase in vehicle length tends to instability of vehicle during cornering and moreover, increase in weight of vehicle [2]. From the above literature work, our principal objective is to develop efficient hybrid transmission for tadpole configuration to improve its dynamic performance and validate it by performing several tests to meet design targets.

16.3 Transmission System

The main aim is to enhance vehicle dynamic performance by reducing vehicle weight and optimizing transmission system. Kerb weight of vehicle is 95 kg. This trike is a rear wheel drive vehicle, powered by electric motor drive and manual pedaling. To reduce driver fatigue and use battery power efficiently, we focused on calculating optimum gear ratio for manual as well as electric drive, wheel selection, and chain selection. We have considered three types of forces: rolling force, aerodynamic force, and gradient force in calculation to get required torque on rear wheel, optimum gear ratio, and maximum vehicle speed. Also, dynamic testing of the vehicle was done on a 100 m acceleration test track. We have targeted to achieve a maximum vehicle speed of 40 km/hr with hybrid drive (motor + pedaling).

16.3.1 Resistance Force, Torque

This is a hybrid trike, which has three drives: manual, electric, and hybrid. To calculate required torque and gear ratio, forces on the rear wheel and maximum vehicle speed are calculated separately for each drive. In manual drive, the power generated by a healthy person to drive a bicycle ranges from 375 to 25 W with two hours of continuous running [3]. So, we have 375 W per driver for manual drive (total 750 W). We have BLDC motor of 400 W, 48 V, and maximum 1500 rpm. By considering 10% motor winding loses, useful motor power is 360 W and 1350 rpm. Therefore, for hybrid drive, we have a total 1110 W of power.

16.3.2 Rear Wheel Selection

Wheel selection is the most important part in any vehicle design as they are the only contact between the road surface and the vehicle. Road shocks are first absorbed by tires and then transmitted to suspension. Wheel tires are chosen in such a way that it must provide traction in all kinds of surfaces without slipping. The rear wheel has been chosen precisely to improve the vehicle's performance. Based on the targeted top distance traveled, rear wheel has been chosen as a 28" bicycle wheel. Disadvantage of selecting a 28" wheel is an increase in required torque value.

16.3.3 Resistance Force Calculation [4]

For total resistance force calculation, we have considered three forces like rolling force, aerodynamic force, and gradient force. On level road, we have neglected

Table 16.1 All drive summary

Parameter	Manual	Electric	Hybrid
Power (W)	750	360	1110
Level Road			
Total resistance force (N)	78.99	52.52	99.60
Torque (N-m)	28.09	18.68	35.42
Max speed (Km/hr)	34.20	24.62	40.10
Gradient Road			
Total resistance force (N)	233.50	233.50	233.50
Torque (N-m)	83.03	83.03	83.03
Max speed (Km/hr)	11.56	5.55	17.11

gradient force as no inclination, whereas on gradient road we have neglected aerodynamic force as vehicle speed is less. Using following equations, resistance forces, required torque, and maximum speed for all drives is calculated as shown in Table 16.1.

$$\text{GCW} = 245\ \text{kg} \tag{16.1}$$

$$\text{Radius of rear wheel} = 0.356\ \text{m} \tag{16.2}$$

$$\text{Rolling force} = \mu \times \text{m} \times \text{g} \tag{16.3}$$

$$\text{Aerodynamic force } (Fa) = \rho \times A \times \text{Cd} \times (\text{Cw} + 1) \times (V \times V) \div 2 \tag{16.4}$$

$$\text{Gradient force (Fg)} = m \times g \times \sin\theta \tag{16.5}$$

$$\text{Level road (FLevel)} = \text{Fr} + \text{Fa} \tag{16.6}$$

$$\text{Gradient road (FGrad)} = \text{Fr} + \text{Fg} \tag{16.7}$$

16.3.4 Manual Drive

The vehicle can be driven by the drivers in both single passenger mode and dual passenger mode as shown in Fig. 16.1. The drivers can power the vehicle using the two crank wheels (having 52 teeth, 196 mm diameter) in the front portion of the vehicle frame. These two crank wheels deliver the power to the intermediate shaft

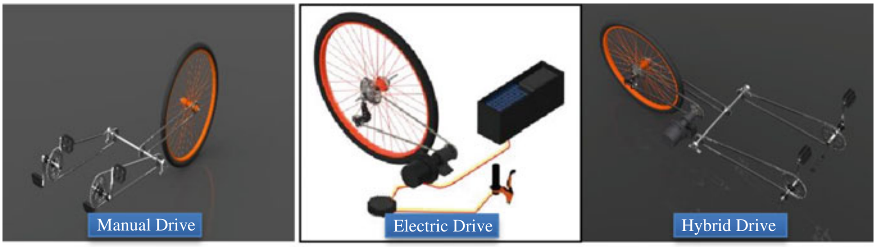

Fig. 16.1 Transmission system

mounted in the rear part which ultimately drives the rear wheel through freewheels (16 teeth, 72 mm diameter). The overall manual transmission has a single speed gear assembly. Roller chain and sprockets are a very efficient method (efficiency 98%) of power transmission compared to belts. The aim of the drive-train model is to deliver the power produced by the drivers to the driving wheel most efficiently. The manual drive is divided into two chain drives (front and rear) using an intermediate shaft.

16.3.4.1 Manual Gear Ratio

While selecting gear ratio, to reduce the fatigue of the driver, it is important that there should be maximum distance traveled per sprocket revolution with optimal driving effort. Sprocket and freewheel are selected of 52 and 16 teeth, respectively, to deliver maximum rpm. So, the gear ratio for front manual chain drive will be 3.25. For rear chain drive, we have selected a gear ratio of 1.0.

16.3.4.2 Manual Chain Selection [5]

From a table of power rating of simple roller chain, 8 A chain was selected for both front and rear manual chain drives. Table 16.2 shows the chain selection summary.

Table 16.2 Chain selection summary

Parameter	Front chain	Rear chain
Rpm	78	255
Torque (Nm)	28.80	17.72
Power transmitted (kW)	0.235	0.458
kW chain rating	0.332	0.647
No. of chain links	142	134
Chain type	8 A	8 A

16.3.5 Electric Drive

The electrical transmission of the vehicle consists of a BLDC motor and freewheels. The BLDC motor of 48 volts and 400 W (1500 rpm) is powered by a lithium polymer battery of 48 volts and 35Ah. The motor is mounted on the left side of the vehicle frame and battery is on the right when viewed from the front side. The max rated torque of the selected motor is 2.7 Nm. To maximize torque, there is a need to select the proper gear ratio to get required speed reduction and torque on level road as well as on gradient road. With an electric drive, we got a maximum speed of 24.62 km/hr. Rpm of motor 1500 but considered rpm as 1350 due to 10% electric losses.

Electric drive required reduction calculations are as follows:

Level Road:

Total resistance force = 52.52 N (Table 16.1) Torque = 18.68 Nm (Table 16.1)

Maximum rpm = 184

$$\text{Level road reduction} = 1350 \div \text{Max rpm} = 1350 \div 184 = 7.34 \tag{18.8}$$

Gradient Road:

Total resistance force: 233.50 N (Table 16.1) Torque = 83.03 Nm (Table 16.1)

Maximum rpm = 42

$$\text{Gradient road reduction} = 1350 \div \text{Max rpm} = 1350 \div 42 = 32.14 \tag{18.9}$$

From calculation for electric drive, required speed reduction on level road and gradient road is 7.34 and 32.14, respectively. Available gearbox ratio options are 6.0, 10.37, 11.6, 14.3, 15.7, and 16.6. We have selected a planetary gearbox of 10.37. Output of a selected geared motor is 130 rpm and 25.2 Nm. To match required reduction on level as well as gradient road, there is a need of 12 speed (11-52 T) cassette but not available in market. So, we have selected a 9 speed (11-32 T) cassette derailleur using a shifter to get required speed reduction and torque. Cassette offers steps in gear ratios which ensure efficient use of motor.

For electric drive, 8 B chain type selected by calculation as kW rating is 1.59 kW.

16.3.6 Maximum Acceleration Calculations

$$\text{Mass of vehicle, } m = 245 \text{ kg} \tag{16.10}$$

$$\text{Total resistance, } R = \text{Fr} + \text{Fa} \tag{16.11}$$

$$\text{Tractive force, } F = (\text{torque} \times \text{Gear ratio} \times \text{transmission efficiency}) \div \text{r} \quad (16.12)$$

$$\text{Acceleration} = (F - R) \div m \text{ considering } F = m \times a \quad (16.13)$$

Using Eqs. (16.10), (16.11), (16.12), and (16.13), calculated maximum acceleration for each drive,

Manual Drive:

Total resistance, $R = 78.99$ N

Tractive force, $F = (57.6 \times 3.25 \times 0.9) \div 0.356 = 473.79$ N
Aeleration $= (473.79-78.99) \div 245 = 1.61$ m/s^2

Acceleration with Electric Drive:

Total resistance, $R = 52.52$ N
Tractive force, $F = (2.43 \times 10.37 \times 1.5 \times 0.9) \div 0.356 = 95.66$ N
Acceleration $= (95.66 - 52.52) \div 245 = 0.18$ m/s^2

Acceleration with hybrid drive:

Total resistance, $R = 99.60$ N

Tractive force,
$F = ((2.43 \times 10.37 \times 1.5) + (57.6 \times 3.25)) \times 0.9) \div 0.356 = 569.43$ N
Acceleration $= (569.43 - 99.60) \div 245 = 1.91$ m/s^2

16.4 Validation [6]

Efficycle is not a standard vehicle which is available in the open market. It is a customized version developed for competition and can be used for general or special purpose. Hence, there are no specific standard norms for testing of this vehicle. But this vehicle is developed according to the rulebook released by competition authority. Tests discussed in the validation section conform to the rulebook of the competition and results were verified with our design targets.

Vehicle is tested for several tests such as acceleration test, durability test, utility test, maneuverability test, and gradient test to ensure enhancement of vehicle's dynamic performance by selecting optimum gear ratio to overcome each terrain torque requirement.

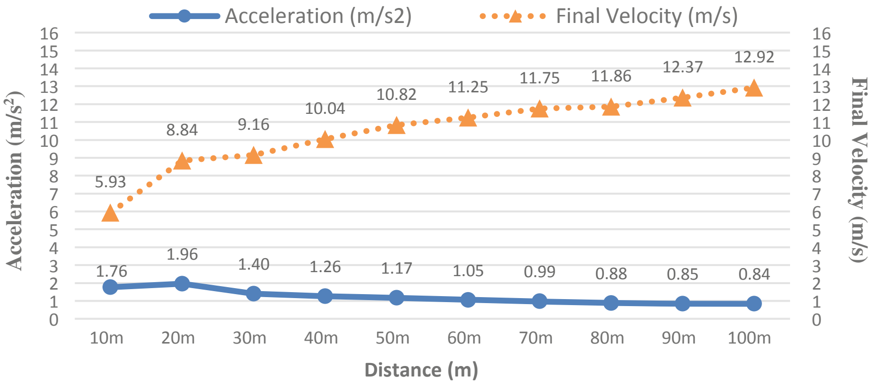

Fig. 16.2 Distance versus time, velocity, and acceleration

16.4.1 Acceleration Test

Vehicle needs to travel 100 m distance as fast as possible using hybrid drive with optimized electric drive gear ratio. We have conducted five acceleration tests using hybrid drive. From results, average speed is equal to 12.92 m/s whereas calculated max speed is 11.14 m/s. It means drivers applied more power than 375 W per driver which we have considered for calculations. It has taken an average 15.48 s time to cover 100 m distance as shown in Fig. 16.2.

16.4.2 Durability Test

To check the durability of a vehicle in a race condition, the track is designed to have a lot of turns, bends, gradients, and various kinds of obstacles. Total length of the circuit was around 2 km. Vehicle had run for 1.5 h along with 30 vehicles. It completed 17 laps using hybrid drive, i.e., the vehicle traveled 34 km distance in 1.5 h with average speed of 23 km/hr. After 1.5 h long run, vehicle was inspected subsystemwise and no damage or breakdown was observed.

16.4.3 Maneuverability Test

To check the maneuvering capability of a vehicle in a non-race condition, vehicle is driven on a leveled surface path full of turns and bends. Vehicle has taken 54 s to cover approx. 200 m track using hybrid drive.

16.4.4 Utility Test

To check the utility capability of a vehicle in a non-race condition, a rough track is designed with full of turns, bends, gravels, potholes, and other obstacles. Vehicle was loaded with the 20 kg payload in the utility box during the test. Vehicle has taken 34 s to travel 150 m track using hybrid drive.

16.4.5 Gradient Test

To check gradeability of a vehicle to climb inclination of 5°, this test was performed. Vehicle has taken 4 s to cover 25 m of length of track using hybrid drive.

16.5 Conclusion and Future Scope

The vehicle has three transmission drives: manual drive, electric drive, and hybrid drive. At first, we calculated resistance forces, torques, and maximum speed for each drive. These calculated values were taken as input for selection of type of chain, gear ratio, rear wheel size, motor and battery ratings, and motor gearbox. We have selected a 9-speed cassette (11-32 T) to get required torque values which ensure the efficiency of electric drive. Maximum vehicle speed was observed as 34 km/hr, 25 km/hr, and 40 km/hr with manual drive, electric drive, and hybrid drive, respectively.

Vehicle dynamic performance checked with acceleration test, durability test, utility test, maneuverability test, and gradient test to ensure enhancement of vehicle's dynamic performance. From the acceleration test, the vehicle reached a top speed of 47 km/hr (18% more than design target) by selecting proper motor gear ratio whereas we targeted 40 km/hr speed at time of design. From durability test, vehicle had completed 17 laps (34 km) in 1.5 h with average speed of 23 km/hr using hybrid drive without any system breakdown. Vehicle successfully overcomes a 5° gradient required torque of 83 Nm using hybrid drive and covered 25 m in 4 s of time. Vehicle showed satisfactory results on all kinds of terrain surfaces.

Multiple gear ratios can be used in manual drive (for driving as well as driven wheel) using gear shifter to get multiple speed options, and it will help to minimize driver initial torque requirement. Moreover, an electronic gear change sensor system can be designed to autochange of gear ratio as per torque requirement. Further vehicle dynamic performance can be improved by reducing vehicle weight by 5~1 0 kg to reduce torque requirement.

This hybrid trike can be used in urban cities for daily use by office employees, students, etc. Also, this can be useful for internal movement in a company campus.

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