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Methodology for Retrofitting Electric Power Train in Conventional Powertrain-based Three Wheeler

Kiran B Pattar**, Praveen Kumar R H, Rahul Raj K Jain, Sharanbasappa S Patil
Department of Mechanical Engineering, PES Institute of Technology, India.

P A P E R I N F O

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A B S T R A C T

India is a country of 1.32 billion population with 221 million registered vehicles on the road. Of these, 933950 three wheelers entered service in the year 2015-16 (114% increase from 2005-06). With atmospheric pollution and emission norms in mind, it is essential that we bring down the emission of vehicles. Tail pipe emission reduction is one of the ways to achieve that but, it is a difficult process. This paper explores the alternative. This work describes a methodology for retrofitting the conventional drivetrain of a vehicle with an electric power unit. This work describes the development of a real world drive cycle for three wheeler auto rickshaws in Bengaluru city. For this, the micro trip generation method is employed, which captures the driving conditions encountered by the vehicle on a regular working day. A Bajaj RE 4 stroke CNG vehicle is used as the test vehicle throughout the process. A GPS based data logging system VBOX 3i is used for data acquisition. The vehicle dynamics are simulated to determine the power rating required for the electric motor to retrofit the IC engine using one dimensional longitudinal acceleration analysis. Coast down test results determine aerodynamic drag and rolling resistance coefficients. Dyno test helps us to understand the torque requirements for the electric motor to be retrofitted. The results of the mathematical model and the dyno test are then used to find a suitable electric motor. The adopted methodology in this work can be used to find the suitable power train replacement for any vehicle.

1. Introduction

Three wheeled auto rickshaws are one of the cheapest means of private transport in India. Three wheeled goods carrier are preferred to transport small to medium loads within the city limits. According to a recent survey, there are on average 50000 auto rickshaws in tire 1 cities (cities having more than 4 million population). In the financial year 2016-2017, 402,034 passenger three wheelers (8.83% drop from 2006-07) and 109,624 commercial three wheelers (12.75% hike from 2006-2007) were sold [1]. The sale of these vehicle is expected to fluctuate between -5% and 5% in the upcoming years. It is thus safe to say that the three wheelers will not be out of service any time in the near future in the country.

Threats of global warming and the fear of limited fossil fuel resources have forced the nations all around the globe to implement emission norms for the fuel powered vehicles in their country. In India, Bharat

* Corresponding author
E-mail address: pattar.kiranb@gmail.com
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Stage is the norms that any vehicle trying to enter the market needs to abide by India implemented Bharat Stage IV nationwide in 2017. Bharat Stage IV is based on Euro 4 implemented in Europe. As notified by the Government of India, during the next phase of emission norms implementation, Bharat Stage V will be skipped and there will be implementation of Bharat Stage VI by 2020 [2]. This places stricter emission standards on the upcoming models and a durability mileage (The maximum distance that a vehicle can serve before it is scrapped) on existing vehicles.

The tail pipe emission reduction can be done in either of the two ways; we can either alter the engine capacity like upscaling or downscaling, or we can completely retrofit the fossil fueled power train with a nonpolluting one like an electric power unit. This work outlines the procedure followed in the latter approach. It comes up with a suitable electric motor to retrofit the existing IC engine based system and perform on par with it. Bajaj RE 4 stroke CNG is used as the test vehicle for the study. All the tests are performed on the same vehicle.

2. Drive Cycle Development

Drive cycles are velocity time profiles which represents the driving conditions experienced by the vehicle during a regular driving shift. They are employed to simulate the driving conditions experienced by a vehicle on a regular on-road trip and on a dynamometer during initial vehicle prototype testing. This is done to derive information about pipe emissions and fuel consumptions for the vehicle under driving conditions.

A part of this paper deals with finding the real world driving cycle for three wheelers in Bengaluru city. The data for this driving cycle was derived from real life driving data which was recorded with the help of a GPS based data logging system ‘Racelogic VBOX 3i’. Microtrip generation method was employed to capture the various traffic conditions and to record driver behavior over the period of the driving cycle [3]. Eight micro trips were recognized with varying traffic conditions. The number of similar driving conditions are chosen based on the probability of the vehicle encountering the particular traffic condition. The final concatenated drive cycle developed for Bengaluru city for the three wheeler, shown in Fig. 1 that contains 79 minutes of data and covers a total distance of 26.7 km. The maximum achieved speed was 57.9 kmph and the average speed was found out to be 20.3 kmph.

Table 1. *Microtrip details.*

Route NO	Path taken	Duration	Distance
1	PESU-Nayandahalli Flyover	205s	731.64m
2	Nagarbhavi-Summanahalli	332s	745.3m
3	Summanahalli- Goraguntepalya	576s	5133.2m
4	Goraguntepalya- Yeshwanthpur	568s	1968.9m
5	Yeshwantpur- Malleshwaram	821s	5678.3m
6	Malleshwaram- Majestic	602s	3074.1m
7	Majestic-Chamrajpet	671s	2331.4m
8	Chamrajpet-PESU	1077s	5724.6m

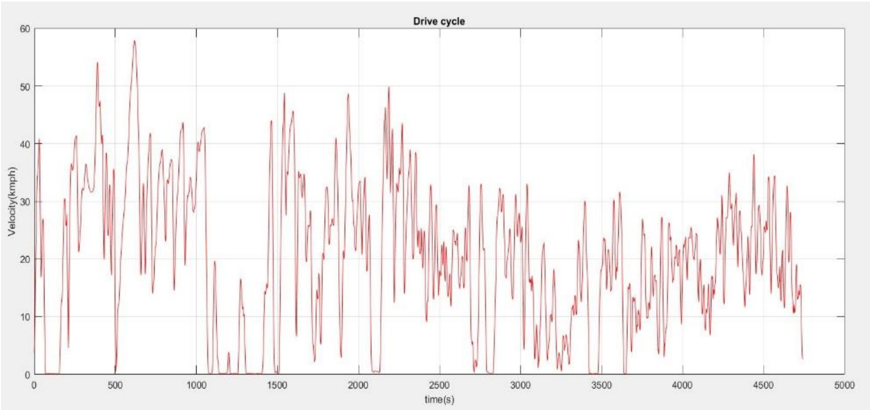

Fig. 1. *Bengaluru city driving cycle for three wheeler*.

3. Vehicle Dynamics Simulations

Complex workings of an automobile can be expressed with the help of simple fundamental laws of mechanics, which are governed by equations. We use this equation to create a mathematical model of our test vehicle in MATLB. Since this paper deals with electrification of three wheeler power train, which does not require studies on multiple axis movement studies, we restrict our study to one dimensional longitudinal acceleration analysis.

The force that propels the vehicle forward is called the Tractive force F_{TR}. This force is developed by the power unit (IC engine or electric motor), which flows through the power train then onto the wheels. Tractive force generated by the vehicle power unit should be able to overcome the following resistances [4]:

- F_{rr} = Force due to tire rolling resistance.
- F_{AD} = Force due to aerodynamic drag.
- F_G= Force to overcome inertia while negotiating slope.
- F_I=Inertial forces (acceleration, deceleration).

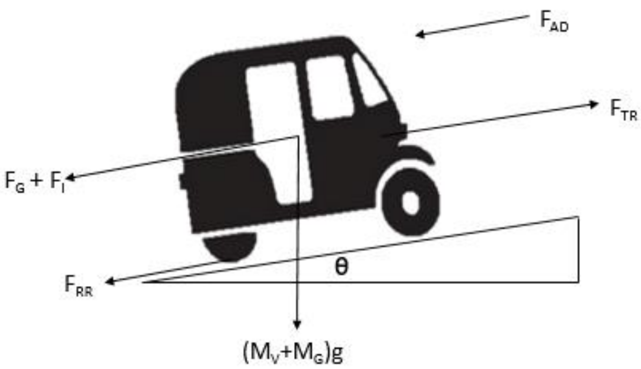

Fig. 2. *Forces acting on the vehicle along longitudinal direction*.

3.1 Rolling and Aerodynamic Resistances

3.1.1 Rolling resistance

The resistance offered by the rolling action of the wheels is affected by the design of tires, inflation pressure, vehicle weight, speed of vehicle, and Coefficient of rolling resistance (C_{rr}). This Coefficient of rolling resistance (C_{rr}) gives the rolling resistance per unit weight of the vehicle. C_{rr} depends on the design of the tire and inflation pressure. Hence, the rolling resistive force can be used as a variable of speed of the vehicle, the equation governing the resistive force is given in Eq. (1).

$$F_{rr} = (M_v + M_P) \times g \times cos\theta \times C_{rr} \tag{1}$$

3.1.2 Aerodynamic drag

Aerodynamic drag is the result of vehicle and air interaction. As the vehicle moves, it displaces the air in front of it. Due to the inertial properties of air, it offers resistance to the motion of the vehicle. This resistance is termed as Aerodynamic drag. Aerodynamic drag depends on vehicle speed, area of contact, the shape of the vehicle, and density of air surrounding the vehicle. With all the other quantities being the physical quantities, the effect of shape of the vehicle can be quantified with help of a non-dimensional quantity called Aerodynamic drag coefficient C_{AD}. Aerodynamic drag force is governed by the following Eq. (2).

$$F_{AD} = \frac{1}{2} \times D_{air} \times C_{AD} \times A_f \times (V_{vehicle} \pm V_{wind}) \tag{2}$$

3.1.3 Coast down test

Aerodynamic and rolling resistances are commonly tested by the deceleration method of road testing, commonly referred to as the coast down test. Using this method, the vehicle is accelerated to a certain speed, preferably its top speed, then the drive is disconnected from the engine and the vehicle decelerates. The variations of vehicle speed and distance traveled with time are continuously recorded. The deceleration of the vehicle is due to the combined effects of the rolling resistance of the tires, driveline resistance and aerodynamic resistance, which can then be derived from the coast down test data. From the derived deceleration and taking into account the effects of the inertias of all rotating components in the driveline, including the tires, the total resisting force acting on the moving vehicle can be found out. With the effects of the driveline resistance neglected from the total resisting force, the rolling resistance and the aerodynamic resistance can be determined. Coast down test for the current vehicle was found out using the same GPS based data logging system ‘Racelogic VBOX 3i’, which was used to develop the drive cycle.

When the vehicle decelerates from V_1 to V_2 in distance S meters, the total resistance force is given by Eq. (3).

$$F_x = (\gamma_m \times M_v + M_p) \times a_x, \tag{3}$$

where γ_m mass factor whose value varies from 1.04 to 1.06 and a_x is deceleration in longitudinal direction.

The resisting force F_x that causes deceleration of the vehicle is sum of the rolling resistance F_{rr} and the aerodynamic drag F_{AD}.

$$F_x = F_{rr} + F_{AD} \tag{4}$$

$$F_x = Mgcos\theta C_{rr} + \frac{1}{2}D_{air}C_{AD}A_f(V_{vehicle} \pm V_{wind}).$$

Solving Eq. (3) and Eq. (4), we get the values for Aerodynamic drag coefficient and rolling resistance coefficient.

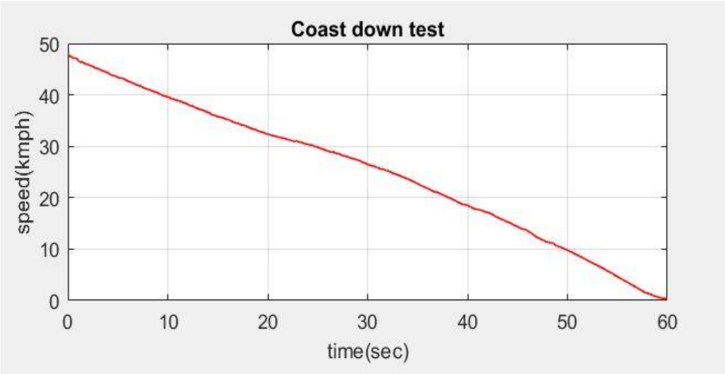

Fig. 3. *Coast down test results.*

3.2 Inertial Forces (F_I)

Inertial forces arises from variation in speed of vehicle; like, during acceleration or deceleration of the vehicle. Many computational models approximate the rotational inertia by using a rotational inertia compensation factor to increase the vehicle's apparent mass in the F_I term by 3% to 4%. Inertial forces arise from the resistance offered by the inertia of the rotating components which needs to get adjusted to the variation of speed of the vehicle. The inertial force is given by the Eq. (5) [5].

$$F_I = (M_v \times \gamma_m + M_p) \times a \tag{5}$$

3.3 Gradient Forces (F_G)

When negotiating a slope, a component of weight acts against the direction of motion which is proportional to the angle of inclination of the road surface. This force of gravity imposes an additional energy demand equal to the potential energy being invested in the vehicle due to the change in elevation. The gradient of the road is typically described in terms of its inclination from the horizontal in degrees or radians (θ). Instantaneous gradient is found using lateral and longitudinal velocities at that instant which are recorded by the VBOX.

The weight of the vehicle is determined by using the mass of the vehicle and the gravitational constant. The component of the weight that acts in the direction of the instantaneous gradient is given in Eq. (6).

$$F_G = (M_v + M_P) \times g \times cos\theta \tag{6}$$

3.4 Tractive Torque and Power

Total tractive torque required at the wheel to overcome the road load is given by Eq. (7).

$$T_{tot} = (F_{rr} + F_{AD} + F_I)R_W \tag{7}$$

Power is energy per unit time. Since energy is force multiplied by distance and velocity is distance per unit time, it can be shown that power is force multiplied by velocity. It is given by Eq. (8).

$$P = \int (F_{rr} + F_{AD} + F_I)V\, dt \tag{8}$$

The power we obtain from this equation is the instantaneous power required to overcome all the resistances encountered by the vehicle in driving mode.

4. Power Requirement Calculations

Table 2. *Vehicle design parameters used in simulation.*

Sl No	Parameter	Value
1	Mass of the vehicle	350 kg
2	Mass of passenger	350 kg
3	Radius of the wheel	0.2365 m
4	Acceleration due to gravity	9.81 m/s^2
5	Coefficient of rolling resistance	0.0109
6	Density of air	1.2 kg/m^3
7	Aerodynamic drag coefficient	0.4792
8	Frontal area	2.09 m^2
9	Wind velocity	2 m/s
10	Rotational inertia compensation factor	1.04

The drive cycle shown in Fig. 1 was used to mathematically simulate the model created in MATLAB. Instantaneous gradient value for each and every data point on the drive cycle was calculated using a separate channel in Vbox Test Suite. This enabled us to have a more realistic simulation of driving on a road than having a constant gradient value over the duration of the driving cycle. The remaining parameters like air density, wind velocity, Aerodynamic drag coefficient are assumed to be constant. With these parameters we have calculated the instantaneous power that needs to be delivered in order to overcome the resistances.

From the Fig. 4, it is clear that the power requirement varies with varying velocity. The vehicle needs to increase power when accelerating, constant power when cruising, and no power when decelerating. This makes simple averaging insufficient for estimation of optimum power rating of the electric motor. Hence, the RMS value of this instantaneous power requirement is taken as the optimum value for the power rating for our electric motor [5]. From the calculations given in Section 3, RMS power is calculated to be 4.1 kW. The chosen electric motor should be of comparable power rating.

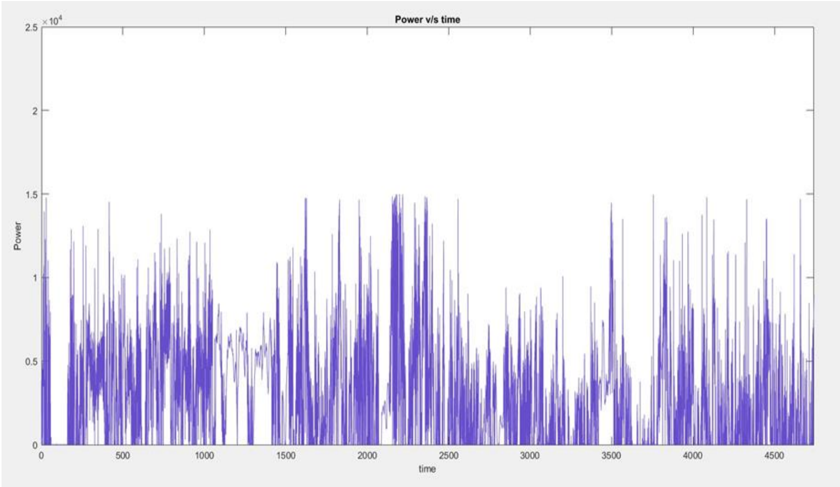

Fig. 4. *Instantaneous power requirement curve.*

5. Dyno Testing

Dyno testing simulates the driving condition experienced by the vehicle on open roads in a controlled environment. In this study Dyno testing is done to understand the torque characteristics of the vehicle at different RPM and for different gears. The vehicle under study is subjected to this test in order to assess the on road torque performance of it. The vehicle is mounted on a dynamometer and the torque and power variation are recorded with the help of a telemetry system.

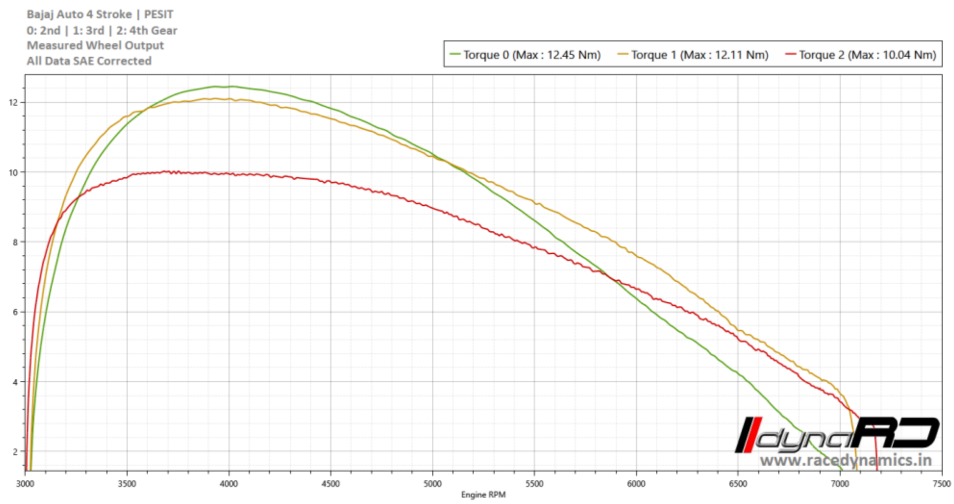

Fig. 5. *Dyno testing results.*

Fig. 5 shows maximum torque delivery around 12-13 Nm for all the tested gear ratios. The official Figures for Bajaj RE 4S CNG show the maximum torque delivered to be 14.1 Nm. The chosen electric motor must therefore be able to deliver comparable torque Figures [6].

6. Motor Selection and Torque Comparison

As per Section 4, the chosen electric motor should have a power rating of around 4 kW. Various types of motors were compared in order to choose the right kind of motor to retrofit the IC engine based power train. Considering the efficiency of energy conversion and the economical factor, BLDC motors are seen as the optimum fit. There is a need to maximize the range of the vehicle over a single charge which shows the energy conversion efficiency. 'Volcano Electric VOL-BL400C48' is taken into study as it satisfies the power demand set by our previous simulations and that it is a BLDC motor. The torque delivery of the electric motor is studied so that it satisfies the torque demand set by Dyno testing [7].

The specification sheet shows a maximum torque of 14.8 Nm for 'Volcano Electric VOL-BL400C48' for a 48 V power supply. Since there in no gap in torque demand and torque delivery, the motor can be used directly without the use of additional drive unit to bridge the gap. If there is a torque delivery gap, we can use a two speed drive system which helps deliver higher torque at lower RPM. With this, we can see that 'Volcano Electric VOL-BL400C48' delivers the required power as well as required torque. This motor coupled with an optimum power source can thus be used to retrofit the conventional IC engine based powertrain system.

7. Conclusion and Result

In this paper a methodology for retrofitting electric power train in place of conventional power train in three wheeler Autorickshaw was presented. A three wheeler driving cycle for Bengaluru city was developed which simulated various traffic conditions and gradient variation which were experienced by the vehicle during a work shift. Aerodynamic drag coefficient of the vehicle and rolling resistance coefficient of the tires were estimated using Coast down test. The longitudinal dynamics of the Vehicle was simulated using MATLAB. The optimal power rating of the motor to be retrofitted was calculated considering all the resistive forces. The vehicle was also subjected to a Dyno test in order to understand the on road Torque characteristics for different engine RPM and at different gears. The results from dyno testing and the torque delivery from the chosen electric motor was in agreement with each other. Hence the 'Volcano Electric VOL-BL400C48' was chosen as the suitable motor to retrofit the IC engine for the Autorickshaw under study.

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