Highway Gradient Effects on Hybrid Electric Vehicle Performance

Mohammad Waseem, A. F. Sherwani and Mohd Suhaib

Abstract In the current era, the public is receiving much devotion to hybrid electric vehicles as the subsequent technology pattern in the road transport sector. Three-wheeler 'battery' vehicles are extensively used for intracity transport facility in Indian cities. These vehicles are known as smart e-vehicle and have the potential to mitigate the carbon emissions of conventional vehicles. The driving range of three-wheeler e-vehicle is greatly affected by the gradient of terrain/highway. The projected research emphasis the highway gradient effects on a three-wheeler e-vehicle performance. Next, to examine the effects of road gradient on the three-wheeler e-vehicle, the dynamics motion equations are modelled and derived. Appropriate three-wheeler e-vehicle design parameters and constants are taken from the literature survey. Finally, simulations of the dynamic vehicle model are performed in the MATLAB® simulation tool to compute road gradient effect of zero degrees, three degrees, six degrees, nine degrees, twelve degrees and fifteen degrees, respectively.

Keywords Vehicle dynamics · MATLAB® · Three-wheeler electric vehicle · Road gradient · Hybrid vehicles

1 Introduction

The transportation sector is contributing to several environmental issues such as water, land and air pollutions [1]. Globally, conventional fuel-powered vehicles are the major source of pollution issues and climate change [2–5]. According to the international energy agency report, the road transport sector is responsible to increase global CO_2 emission by 71% during 1990–2014 [6]. In India, 18% of CO_2 emissions are produced by road transportation itself [7, 8]. The most widely used

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technology in the existing transportation system is the internal combustion engine (ICE). The combustion of fossil fuel in ICE results in harmful gases to the environment. Emissions of carbon contain product from ICE vehicles which are dominating environmental and pollution issues [9, 10].

The automobile industry is undergoing a revolution in designing new electrical platforms for vehicles to counter the sophistication involved with engine and carbon emission issues. Therefore, the alternate engine technology is needed to revamp the ICE vehicles. Electric vehicles are the alternate in place of ICE technology. Electric propulsion system not only diminishes the pollution issue but also conveys precision accuracy of power and easy vehicle handling. Hybrid electric vehicles are investigated by the automobile zone to lessen the application of ignition engine with integrating of electric motor/machine system, i.e. electric propulsion system. The proposed technology by the automobile sector has lessened carbon emissions in the transportation sector as compared to the conventional engine [11, 12].

Bäckryd et al. proposed multidisciplinary optimization technique to improve the design of vehicle structure [13]. Abdullah et al. propose a model updating approach to improve the dynamic properties of go-kart chassis structure [14]. Janarthanan develops a simulation model of a heavy tracked vehicle to demonstrate the transient analysis of longitudinal dynamics [15]. Vibration effect and analysis for passenger electric vehicle with four-wheel drive structure is proposed in [16–18]. Wang et al. propose a particle swarm optimization strategy to design a four-wheeled independently actuated vehicle [19]. Various aspects of parallel, series hybrid architecture e-vehicles are developed in the current literature, but no one has reported highway/road gradient effects on the three-wheeler e-vehicle performance [20, 21]. Work presented above suggests that hybrid electric vehicles are perceived as 'the vehicles of future'. In this research, highway/road gradient effects on the three-wheeler e-vehicle performance are analysed.

2 Three-Wheeler e-Vehicle Active Model

To examine the forces at work of the three-wheeler electric vehicle, the autonomy of the vehicle model is presented as follows: X-direction as the longitudinal, Y-direction as the side, Z-direction as vertical, rolling around the X-direction, pitching around the Y-direction, yawing around the Z-direction. Each wheel of the electric vehicle is a sub-module and has the freedom to turn around the wheel axle [22]. Figure 1 demonstrates the model of the proposed three-wheeler e-vehicle dynamic.

Figure 2 shows the stress acting on each wheel in the *X-direction*, *Y-direction* and Z-direction, respectively. The stress acting on each wheel is assumed by manifestation F_U (V, W), where the subscript U is X, Y and Z, which represents the force acting in the X-direction, Y-direction and Z-direction, respectively. $V = 1$ means front wheel of the vehicle; $V = 2$ means rear wheel of the vehicle; $W = 1$ means the wheel on left side of vehicle; $W = 2$ means the wheel on right side of vehicle; a is the distance from the vehicle centre of gravity to the front wheel axle;

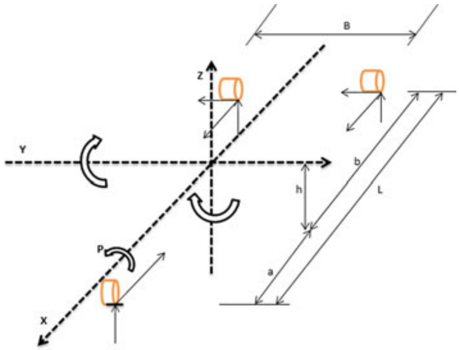

Fig. 1 A dynamic layout diagram of the three-wheeler e-vehicle

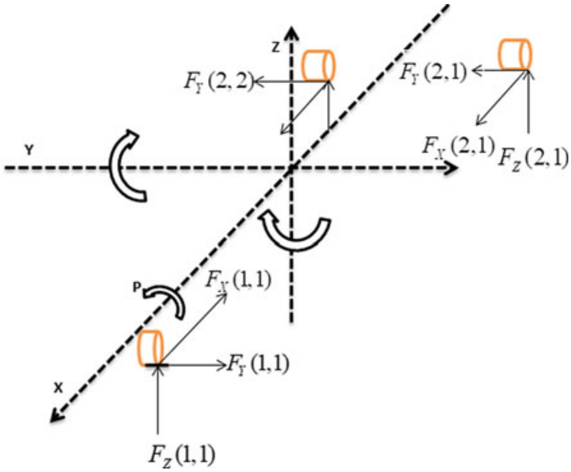

Fig. 2 Forces acting on all wheels of the three-wheeler e-vehicle

b is the distance from the vehicle centre of gravity to the rear axle; h is the height between the vehicle centre of gravity and ground level; B is the gap between back wheels centres of the three-wheeler hybrid e-vehicle; and L is the wheelbase.

3 Longitudinal Motion of the Three-Wheeler e-Vehicle

Considering the motion of the three-wheeled vehicle in the longitudinal direction, the stress acts on each wheel in X-direction only. The movement deployment of the three-wheeler e-vehicle in a moving way is estimated by the sum of all forces acting in that specific course [23]. According to the Newton laws, the dynamic movement of the three-wheeled vehicle in the longitudinal direction is governed by Eq. (1).

$$\lambda M\dot{V}_X = \sum_{W=1}^{1} F_X(1, W) + \sum_{W=1}^{2} F_X(2, W) - \sum F_{\text{Resistive}} \quad (1)$$

$$\lambda M\dot{V}_X = F_X(1, 1) + F_X(2, 1) + F_X(2, 2) - \sum F_{\text{Resistive}} \quad (2)$$

where M is the estimated mass of the e-vehicle, λ is a factor of rotating mass, V_X is velocity in X-direction and $F_{\text{Resistive}}$ is the sum of all resistance force acting the three-wheeled vehicle.

Figure 3 shows all the forces and moments that act on the three-wheeler e-vehicle in the longitudinal direction of the highway with a positive gradient (α). The external resistive agents on the three-wheeler e-vehicle in the longitudinal direction are as follows: the drag force due to air (F_{drag}), the rolling resistance force (F_{roll}) and resistance to the gradient (F_{grad}). F_{TF} is the tractive effort that acts on the front wheel and equal to the stress (F_X (1,1)). Similarly, F_{TR} is the tractive effort that acts on the rear 'left' and 'right' wheels and equivalent to the summation of tensions (F_X (2,1) + (F_X (2,2)). The electrical actuating system provides the necessary total tractive effort (F_{Tractive}). Hence, Eq. (2) of three-wheeled vehicle movement can be expressed as Eq. (3).

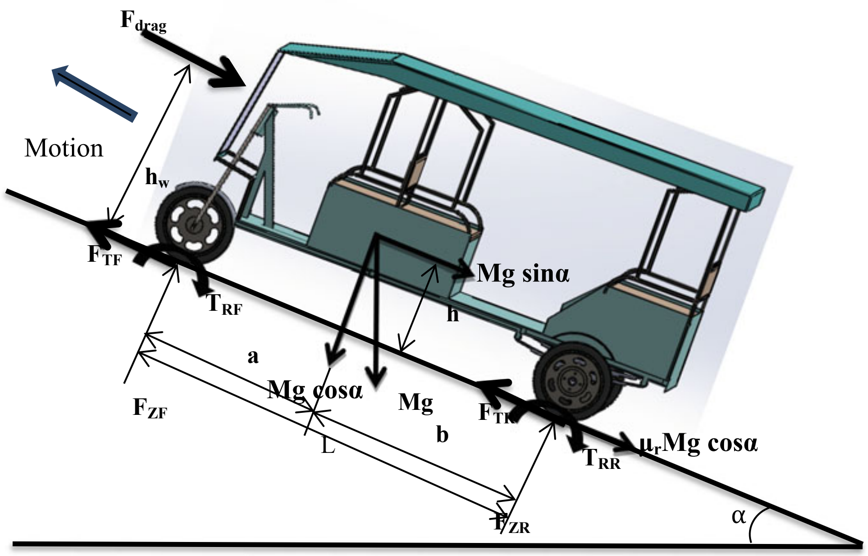

Fig. 3 Free body diagram of three-wheeler e-vehicle on a gradient

$$\lambda M \frac{\mathrm{d}V_X}{\mathrm{d}t} = (F_{\mathrm{TF}} + F_{\mathrm{TR}}) - \sum F_{\mathrm{Resistive}} \tag{3}$$

$$\lambda M \frac{\mathrm{d}V_X}{\mathrm{d}t} = F_{\mathrm{Tractive}} - \sum F_{\mathrm{Resistive}} \tag{4}$$

$$F_{\mathrm{Tractive}} = \lambda M \frac{\mathrm{d}V_X}{\mathrm{d}t} + \sum F_{\mathrm{Resistive}} \tag{5}$$

The tractive effort and active opposing pull that act on the three-wheeler e-vehicle in the longitudinal direction is governed by Eq. (6) (please see Eq. (5)).

$$F_{\mathrm{Tractive}} = \lambda M \frac{\mathrm{d}V_X}{\mathrm{d}t} + Mg \sin\alpha + Mg\mu_{\mathrm{r}} \cos\alpha + \frac{1}{2}\rho A_{\mathrm{f}} C_{\mathrm{D}} V_X^2 \tag{6}$$

where g is gravitation acceleration, α is highway/road gradient, μ_{r} is coefficient of friction, ρ is the air density, A_{f} is the front area of the vehicle, C_{D} is drag coefficient and V_X is the speed of the vehicle.

The vertical normal load acting on the front and rear wheel locations are governed from the Eqs. (7) and (8).

$$F_{\mathrm{ZF}} = \frac{Mgb\cos\alpha}{L} - \frac{h}{L}\left(F_{\mathrm{Tractive}} - \mu_{\mathrm{r}} Mg\cos\alpha\left(1 - \frac{r_{\mathrm{w}}}{h}\right)\right) \tag{7}$$

$$F_{\mathrm{ZR}} = \frac{Mga\cos\alpha}{L} + \frac{h}{L}\left(F_{\mathrm{Tractive}} - \mu_{\mathrm{r}} Mg\cos\alpha\left(1 - \frac{r_{\mathrm{w}}}{h}\right)\right) \tag{8}$$

4 Selection of Parameters for Three-Wheeler e-Vehicle

Design and development of e-vehicle depend on the mechanical parameters and coefficients associated with the aesthetic and technical look of the vehicle. Hence, parameters determine the overall technical and aesthetic behaviour of a vehicle. Therefore, design parameters associated with the tractive effort (F_{Tractive}), the normal loads (F_{ZF}, F_{ZR}) and applied torque (T_{tractive}), etc. have been taken from literature and connected work (Table 1).

5 Simulation Result

Three-wheeler hybrid e-vehicle model dynamics performance is simulated and estimated for six different road gradient conditions. To examine the active performance of the e-vehicle model, simulation has been performed in the MATLAB® tool for each highway/road gradient. Thereafter, effort, active load and the applied

Table 1 Three-wheeler hybrid e-vehicle mechanical parameters and coefficient

Name of parameters	Modelling value	SI unit
Friction coefficient (μ_r) [24, 25]	0.80	
Drag coefficient (C_D) [26]	0.30	
Mass factor (λ) [27, 28]	1.05	
Air density (ρ) [27]	1.20	kg/m^3
The front area (A_f)	1.65	m^2
Vehicle speed (V_X)	24.000	km/h
vehicle weight (M)	725.0	kg
Wheel diameter (d_w)	0.508	m
Wheelbase (L)	2.100	m
Vehicle C.G. height (h)	0.275	m

torque of three-wheeler e-vehicle model are computed for zero degrees, three degrees, six degrees, nine degrees, twelve degrees and fifteen degrees gradient of highway/road. Figure 4 shows the variation in the computed torque for the highway gradient of six degrees.

Simulated results are further post-processed by estimating the average value of the applied torque, the active load on the front and rear wheels supporting point, to forecast the road gradient effects on three-wheeler e-vehicle the active performance accurately. Mean values of applied torque on the rear wheels are 108.3317, 173.5099, 238.4582, 302.9987, 366.9543 and 430.1498 (Nm) for highway with gradient order zero degrees, three degrees, six degrees, nine degrees, twelve degrees and fifteen degrees, respectively, to attain 25 km/h of vehicle speed as shown in Fig. 5.

The mean estimated evaluates of dynamic load that acts on the front wheel support are 2.6188, 2.5802, 2.5343, 2.4814, 2.4215 and 2.3548 kN for highway with gradient order of zero degrees, three degrees, six degrees, nine degrees, twelve

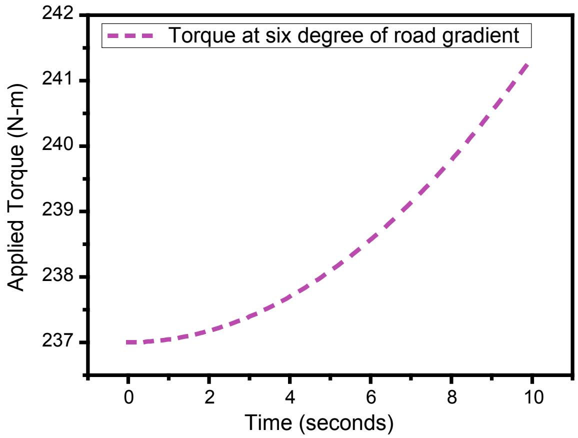

Fig. 4 Torque applied to the wheel of three-wheeler e-vehicle

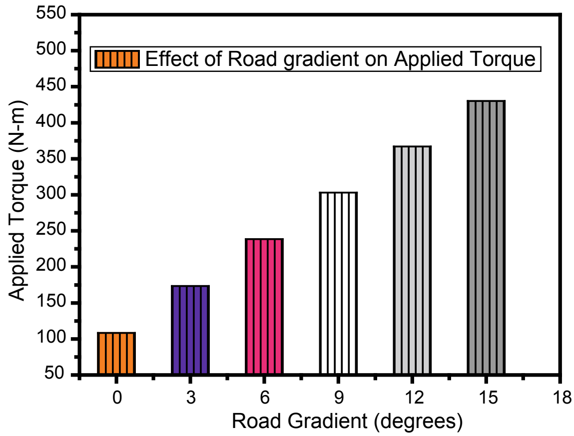

Fig. 5 Effect of gradient on applied torque

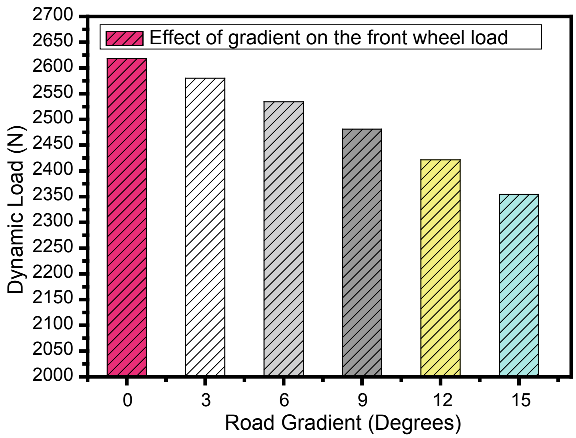

Fig. 6 Effect of the gradient of dynamic load on the front wheel of a three-wheeler e-vehicle

degrees and fifteen degrees, respectively, to reach 25 km/h of vehicle speed as shown in Fig. 6. Mean computed evaluates of the dynamic load that acts on the rear wheel support are 2.2862, 2.3181, 2.3438, 2.3632, 2.3763 and 2.3830 kN for highway with gradient order of zero degrees, three degrees, six degrees, nine degrees, twelve degrees and fifteen degrees to reach 25 km/h of vehicle speed.

6 Discussion and Limitation

The mathematical dynamic modelling of the three-wheeler e-vehicle is presented. After that, the dynamics motion equations of the tractive effort, the torque applied the rear axle, the load that acts on the front and rear wheel are simulated in MATLAB® tool. Thereafter, the appropriate mechanical designing constraints and constants from the literature investigation are determined and assigned in the coded equations. Thereafter, simulations of the dynamic e-vehicle have been performed for 10 s in the MATLAB® programming tool for highway with gradient order of zero degrees, three degrees, six degrees, nine degrees, twelve degrees and fifteen degrees, respectively. Next, for each road gradient condition, simulation output values of applied torque, normal active load that acts on the front and rear wheels support are computed and recorded. Finally, highway/road gradient effects on the three-wheeler e-vehicle active performance are analysed. Time to refuel is the most crucial factor for slow penetration of three-wheeler e-vehicles as slow charging takes 7–8 h. Public awareness is also one of the important factors to adopt e-vehicle in the developing country India. The government of India should start new policy and rules towards sustainable development goals.

7 Conclusion

Active dynamics model of three-wheeler e-vehicle with six degrees of freedom is presented. The active performance of the three-wheeler e-vehicle is simulated for the highway/road gradient order of zero degrees, three degrees, six degrees, nine degrees, twelve degrees and fifteen degrees in MATLAB® tool. Simulation results show that higher torque is required to form the electric propulsion system for the inclined road as compared to the flat road. The simulated results signify that the applied torque on the three-wheeler e-vehicle is 430 Nm for the road gradient of fifteen degrees, while the estimated torque on the e-vehicle is 108 Nm for the gradient of zero degrees. Hence, the power required from the electric motor is more times more for fifteen degrees inclined road as compared to the plane surface road. The percentage increment in the numerical magnitude of the load that acts on the e-vehicle is 4.2% for road gradient of fifteen degrees as compared to zero degrees gradient of the road. Hence, the gradient of the road is a significant factor that affects the dynamic performance of the three-wheeler hybrid vehicle.

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