

Analytical Study on the Performance Analysis of Power Train System of an Electric Vehicle

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Abstract

An analytical simulation algorithm is developed to estimate driving performance of power train system of an electric vehicle that is propelled by the electric energy stored in a rechargeable battery. The principal theory is conservation of energy and several analytical and experimental data such as rolling resistance, aerodynamic drag, mechanical efficiency of power transmission etc are incorporated to have the simulation algorithm for the general driving performance of an electric vehicle designed. From the analytical calculation results, running resistance of a designed vehicle is obtained with the change of operating condition of a model vehicle such as inclined angle of road and vehicle speed. Tractive performance of a model vehicle with a given power train system is also calculated at each gear ratio of transmission. Through analysis of the two calculation results: running resistance and tractive performance, the driving performance of a designed electric vehicle is obtained and it will be used to evaluate feasibility of the designed power train system on the model vehicle designed.

Keywords: *EV (Electric Vehicle, CVT (Continuously Variable Transmission), PEV (Pure Electric Vehicle), HEV (Hybrid Electric Vehicle, MMS (Motor Management System)*

1 Introduction

Air pollution especially in the urban area is a serious issue all through the world. As well known, the main reason of the pollution is due to the urban transportation such as public buses, taxis and private vehicles that uses conventional gasoline and diesel engines. Because not only for pollution problem but for the shortage of oil people has been studied on the alternative fuels for the transportation industry. One of the promising alternative energy sources that have been studied for the last two decades is an electric energy that is known as zero emission source of energy. Since 1990s, several major automobile manufacturers in the world have been studied to develop lower emission power train system and it is now released to the market

known as a hybrid engine that is operated with conventional gasoline or diesel engine in half and electric motor with the battery on the other half and the hybrid engine still consumes hydro-carbon (HC) fuel and produces the pollution.

Global warming problem mainly due to carbon dioxide became another serious issue asking engineers to develop zero-emission vehicle that uses only electricity for energy source and electricity is known as clean and renewable energy generated from solar, wind, hydro-power, geothermal energy.

In this study, analytical algorithm is developed to find out the optimum size of the power train of an electric vehicle designed. The principal theorem of the algorithm is on the conservation of energy in a control volume. All of the sink or source terms of the energy in the governing equation were evaluated numerically and experimentally.

2 Theoretical Background of an Analytical Algorithm

2.1 Running resistance of a designed vehicle

When a vehicle runs on a road, it experiences resistance force from outside of the vehicle. It is called running resistance of the vehicle on road. If a driver wants to keep its speed constant, he needs to have equivalent engine power to the running resistance but needs more power for acceleration to overcome the inertia resistance. In the case of deceleration of a vehicle, inertia energy of the vehicle can be restored by an inertia energy recovery system of a vehicle.

The engine power required for driving changes at all the time due to the variation of moving condition on a road.

In here, mathematical equations of the resistance terms are introduced to make the governing equation of the power train system of a vehicle. In general, the running resistance terms on a moving vehicle consist of:

- (1) Rolling resistance (R_R)
- (2) Aerodynamic resistance (R_A)
- (3) Gradient resistance (R_G)
- (4) Acceleration/Deceleration resistance (R_I)
- (5) Traction resistance (R_T)

A general form of total running resistance force of a vehicle can be expressed as a summation of above terms as given below:

$$R_{\text{tot}} = R_R + R_A + R_G + R_I + R_T \quad (1)$$

With the change of driving condition, the general equation Eq. (1) should be modified. If a vehicle moves at a constant speed on a level road, the terms; R_I and R_G , are ignored. For the deceleration of the vehicle, R_I should be negative signed.

2.1.1 Rolling resistance

The friction resistance between road and tire surface is defined as rolling resistance of a vehicle. It is clearly affected by the surface roughness of road and the vehicle speed as well. From principle of physics, the rolling resistance of a running vehicle can be obtained from the equation given below.

$$R_R = \mu_R \times (W_{\text{car}} + W_x) \quad (2)$$

Where W_{car} is gross weight of a vehicle and W_x is aerodynamic lift or down force on a running vehicle

The rolling resistance coefficient (μ_R) depends on surface condition of road, material and tread pattern of tires and its charged air pressure and vehicle speed etc. Thus the multiple factors affecting rolling resistance cannot be taken into account at a time. In here, the most commonly used coefficient varied with the road surface condition is incorporated in this study.

Table 1: Variation of rolling resistance coefficient with road surface condition [2]

Road surface condition	μ_R
Asphalt paved road	approx. 0.010
Concrete paved road	approx. 0.011
Stone block paved road	approx. 0.020
Well-maintained unpaved road	approx. 0.04
Unpaved road	approx. 0.08
Pebble-stone road	approx. 0.12
Sand and pebble-stone road	approx. 0.16
Sand road	approx. 0.2 -0.3

2.1.2 Aerodynamic resistance

As a vehicle runs on a road, the relative air movement occurs opposite to the driving direction of the vehicle even with no wind in air. Because of this air flow, the vehicle experiences aerodynamic force such as drag and lift on the body. The aerodynamic drag force generated on the frontal and rear side of the body acts on the vehicle as a driving resistance.

From the analytical equation given below, the aerodynamic drag force can be estimated [3].

$$R_A = C_D \frac{1}{2} \rho (V_{\text{car}} - V_{\text{wind}})^2 A \cos \theta \quad (3)$$

Where C_D is drag coefficient of a model vehicle, A is a projected frontal area of the vehicle and θ is the angle between wind and driving direction.

The projected frontal area (A) of a vehicle is normally obtained with the empirical equation given below [7]:

$$A = 0.83 \times b \times h \quad (4)$$

Where b and h is the maximum width and height of a model vehicle respectively.

Drag coefficient of a vehicle is obtained from the wind-tunnel test results and in general it is in the range of 0.35 ~ 0.55 for small sedans.

Air density is very sensitive to the atmospheric pressure and temperature, therefore an air density equation that is a function of atmospheric pressure and temperature is given below;

$$\rho(P, T) = \frac{348.7 \times P \text{ (bar)}}{273.15 + t(^{\circ}\text{C})} \text{ (kg/m}^3\text{)} \quad (5)$$

2.1.3 Gradient resistance (R_G)

When a vehicle goes up or down a hill, it experiences gravitational resistance due to its weight and it is called the gradient resistance of the vehicle.

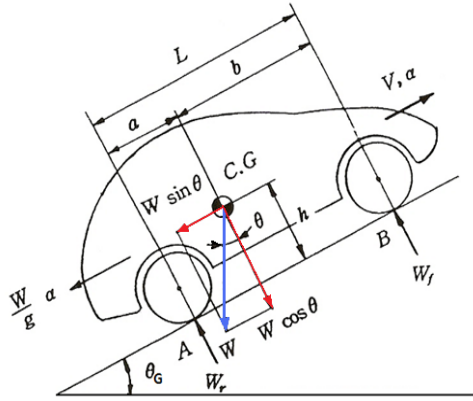


Figure1: Gradient resistant of a model vehicle

The gradient resistant is calculated with Eq. (6) given below:

$$R_G = \pm W_{\text{car}} \times \sin \theta_G \quad (6)$$

Where θ_G is gradient angle of road.

When a car goes down a hill, the gradient resistance is negative value and the total resistance power required is reduced and instead the inertia energy can be restored with the energy recovery system.

2.1.4 Acceleration resistance (R_I)

When a vehicle accelerates or decelerates on a road with the change of traffic condition, it will experience positive or negative inertia resistance. The inertia resistance of a running vehicle consists of two different parts: an angular inertia

of the rotating parts of power train system and a linear inertia of the running vehicle body.

The inertia resistance is calculated by the equation given below [1]:

$$R_I = \frac{W + W_r}{g} \alpha = w \left(1 + \frac{W_r}{W}\right) \frac{\alpha}{g} \quad (7)$$

Where W is the gross weight of a vehicle, W_r is the equivalent mass of all rotating components of the power train and α is acceleration speed of a vehicle.

Table 2: Variation of (W/W_r) with the gear ratio of power transmission [6]

	Small Car	Large Car
Low gear	1.4	-
1-gear	0.5	0.3
2-gear	0.2	0.14
3-gear	0.11	0.09

For the decision of acceleration resistance of a designed car, the detailed acceleration performance schedule of a designed vehicle should be decided therefore, a steady state driving condition has only been considered in this study.

2.1.5 Towing resistance (R_T)

When a vehicle tows a trailer at the rear, the vehicle experiences the pulling resistance and it is called towing resistance of the vehicle. The size of the coupled resistance can be estimated with the same analytical equations; rolling resistance, aerodynamic resistance, gradient resistance given above but it is not considered in this study.

2.1.6 Tractive force (F_{trac})

Engine power is transmitted to the tires through power transmission unit, driveshaft and axle in a vehicle. The force required to overcome the total running resistance at a given driving condition on tires is called the tractive force of a vehicle.

The size of tractive force on tire is proportional to the torque generated at the engine crank shaft. The crank shaft torque is:

$$\tau_{\text{engine}} = F \times l \quad (8)$$

Where F is the torsional force (N) and l is radius (m) of engine crank shaft.

The tractive force of a vehicle is obtained from the Newton's 2nd Law (NSL):

$$F_{\text{trac}} = F_{\text{engine}} - (F_{\text{IE}} + F_{\text{IT}} + F_{\text{ID}} + F_{\text{IWA}}) \quad (9)$$

Where F_{IE} , F_{IT} , F_{ID} and F_{IWA} are the resistance of inertia force of engine, transmission, driveshaft and wheel & axles shaft respectively

The total resistance of angular inertia force of rotating parts of power train system can simply be expressed with the concept of the equivalent mass as given in Eq. (10).

$$F_{IE} + F_{IT} + F_{ID} + F_{IWA} = w \left(\frac{W_r}{W} \right) \frac{a}{g} \quad (10)$$

For steady state driving condition of a vehicle, the acceleration resistance of the rotating parts of power train system is ignored and then the tractive of the power train is calculated by Eq. (11) given below.

$$F_{trac} = \frac{\tau_{engine} \times \eta_{tm} \times i_{tm}}{R_{tr}} \quad (11)$$

Where τ_{engine} is the brake torque of engine, η_{tm} is the combined mechanical efficiency of transmission and final drive, i_{tm} is the combined gear ratio of transmission and final drive and R_{tr} is the radius of a tire.

3 Performance Analysis of the Designed Power Train System of a Vehicle

An analytical algorithm to estimate the general driving performance of a designed power train system can be made with the theoretical background given above. The tractive force versus to vehicle speed curve can be obtained with the algorithm and the maximum speed of the vehicle, the maximum climbing capacity can be estimated with the performance curve. The maximum curve distance of a vehicle with the given battery size can also be estimated as well.

3.1 Input conditions of the analytical algorithm

For the calculation of the driving performance of a designed power train system of a vehicle, the initial condition of the vehicle should be decided:

- (1) Specification of vehicle
 - Dry weight of a vehicle (kg)
 - Vehicle size in width (m) and height (m)
 - No. of passenger and payload capacity (kg)
- (2) Specification of power transmission

- Mechanical efficiency of transmission (η_{tm})
 - Gear ratio of total speed change of transmission
- (3) Driving characteristics
 - Acceleration performance (α)
 - Aerodynamic drag coefficient (C_D)
 - Rolling resistance coefficient (μ_R)
 - (W/W_r) of vehicle
 - (4) Atmospheric condition
 - Atmospheric pressure and temperature
 - (5) Performance curve of electric power motor
 - (torque-rpm) curve in operating range

3.2 Analytical Algorithm of Calculation

The total resistance force of a designed vehicle is varied with the road condition and the effective parameters are weight of vehicle and its speed, aerodynamic drag coefficient and gradient angle of road. The calculated total resistance force of a vehicle is energy sink term that is needed by the vehicle on its driving condition.

The power generated from a designed power train system is calculated with the technical information of a proposed power train system, such as a performance curve of engine (rpm-torque curve) and specification of power transmission. This is energy source term that is generated by the proposed power train system.

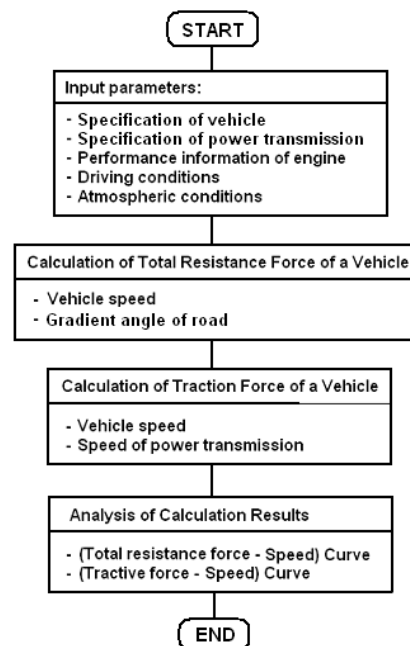


Figure 2: Flow chart of analytical calculation algorithm

The energy source generated by the power train system should keep its balance to the energy required by a designed vehicle to have its stable driving condition on a road.

3.3 Analytical simulation of an example model vehicle

A case study is conducted to estimate the driving performance of a vehicle installed with the designed power train system with the analytical simulation algorithm developed in this study. One of the small-size hatchback type vehicles was selected for this case study and its specification is given below.

(1) Specification of model vehicle [4]

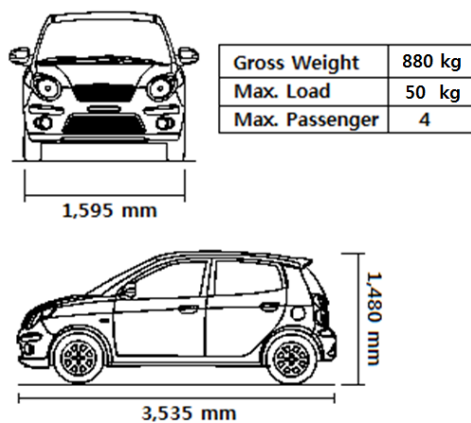


Figure 3: Configuration of a model vehicle

(2) Driving conditions:

- Steady state driving ($\alpha = 0$)
- Aerodynamic drag coefficient ($C_D=0.4$)
- Rolling resistance coefficient ($\mu_R=0.02$)

(3) Atmospheric conditions

25°C at 1 atm

(4) Performance curve of electric power motor [5]

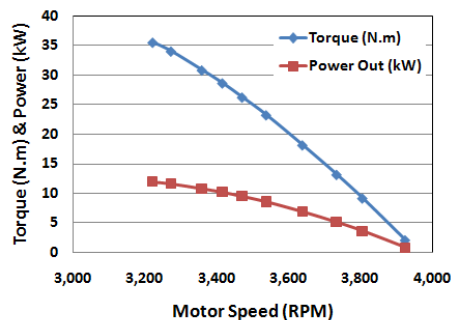


Figure 4: Performance curve of an electric power motor chosen for this study

(5) Specification of a designed power transmission

Table3: Gear ratio of a designed transmission system

	1-gear	2-gear	3-gear	4-gear
Gear Ratio	2.3	1.68	1.06	0.44
Reduction Gear Ratio	8	8	8	8
Final Speed Change Ratio	18.4	13.4	8.48	3.52
Mechanical Efficiency(η_{tm})	96.6	96.7	97.2	97.3

4 Results and Discussion

The driving performance of a designed power train system of a model vehicle was calculated with the analytical simulation algorithm developed in this study. This driving performance curve of a designed system offers very important information to vehicle designers to get an optimum size of the power train system of a designed vehicle.

In this study, two cases: the first case with the original rotational speed of electric power motor and the second case with double of the original rotational speed of the power motor, are calculated and compared the results to understand the effect of rotational speed of the electric power motor on the driving performance of a designed vehicle.

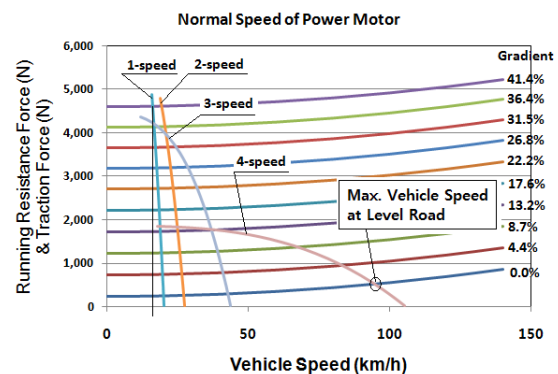


Figure 5: Performance curve of the designed power train system of a model vehicle at its original rotational speed of the electric power motor with the designed gear ratio of transmission

Fig. 5 shows the driving performance of a model vehicle with the designed power train system on its operating range.

As shown in Fig. 4, the maximum vehicle speed is about 94km/h at a level road. The vehicle can go up the hills with 41.4% of gradient at 1-speed gear ratio.

Maximum gradient that the vehicle can go up is about 26.8% on the constant speed of 37 km/h at 1-speed gear ratio

Fig. 6 shows the driving performance of a model vehicle at the double of its original rotational speed of the electric power motor with the designed gear ratio of transmission on its operating range. To increase the maximum driving speed of the vehicle, the rotational speed of the power motor has been increased twice. In this case, the highest vehicle speed reached at a level road is about 125 km/h and increased about 33% in speed.

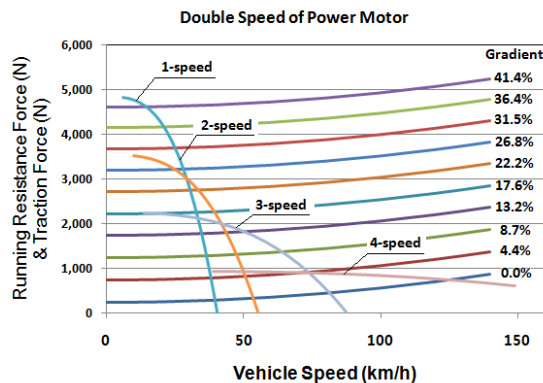


Figure 6: Performance curve of the designed power train system of a model vehicle at the double of original rotational speed of the electric power motor with the designed gear ratio of transmission

5 Conclusion

In this study, an analytical simulation algorithm was developed to estimate the driving performance of a designed power train system of a model vehicle.

The simulation result obtainable from the analytical algorithm must be very important information for the vehicle design engineers on the process of power train design of a vehicle because it offers enormous time savings for an optimum design of the new power train system.

With the simulation outputs of the analytical algorithm, the following results are estimated for an optimum design of a new power train system of a vehicle.

- Maximum driving speed of a designed vehicle at each gradient angle of a road
- Climbing ability of a designed vehicle
- Maximum driving distance with one charge of a designed electric battery
- Optimum gear ratio of a designed transmission to meet the required driving performance of a vehicle

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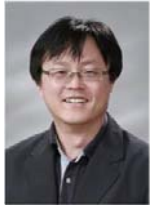
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