2018 3rd International Conference on Intelligent Transportation Engineering

Effect of Engine Operating Altitude Towards Traction Force on Wheels

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Abstract—Many modern day compact cars running on downsized engines with direct drive transmissions are having trouble meeting the practical demands of vehicle usage especially under the varying ambient conditions. The vehicle cannot launch from stationary on inclined roads at high altitudes due to inadequate traction force on wheels. This is due to reduced air density which directly reduces the apparent volumetric efficiency of a normally aspirated spark ignition engine hence reducing the torque output of the engine. The significant reduction in torque output compared to that obtained on the engine dynamometer based on ideal volumetric efficiency simply means the first gear ratio selected initially is no longer adequate to provide the necessary traction force on wheels. This paper details the necessary compensation required for first gear ratio selection to prevent this problem from occurring. It is found that traction force on wheels can drop by as much as 38.2% at high altitudes (1500 m) above sea level.

Keywords - traction; high altitude; gradeability; torque; gear ratio

I. INTRODUCTION

Quite often automotive manufacturers do not conduct sufficient testing and development at high altitudes. Even if they do, it is usually at the tail end of the development cycle so hardware changes are uncommon due to timing constraints. This creates performance and drivability issues since gear ratio selection is done based on the ideal torque curve from the engine dynamometer. This will ultimately affect modern day vehicles built focused toward fuel economy. These modern day vehicles run on downsized normally aspirated engines coupled to direct drive transmissions such as Direct Shift Gearbox (DSG), Dual Clutch Transmission (DCT) and Continuously Variable Transmission (CVT) without a torque converter. For the same gross weight, the absence of a torque converter means the vehicle only has half the amount of launching torque available. This creates a problem at high altitudes where the vehicle struggles to launch from stationary on inclined roads especially when fully loaded. This is because the apparent volumetric efficiency of the engine relative to the air density at sea level reduces as air density drops at increased altitudes.

Efforts have been made by various researchers to study the impact of altitude towards the torque output of an internal combustion engine [1-3]. However to the knowledge of the authors, little evidence can be found regarding the impact of altitude towards the traction force on wheels.

Hence the objective of this paper is to determine the effect of engine operating altitude towards traction force on wheels so that necessary compensation can be made to gear ratio selection during vehicle development. This is to ensure adequate traction force on wheels even at high altitude.

II. EXPERIMENT SETUP

A test car based on the specifications in Table 1 was used for this experiment. Basically a fully laden test car was parked with tyres straight on a slope with 14° gradient angle of inclination at sea level and subjected to a hill start test. A slope with 14° (25%) angle of inclination is used due to it being the maximum gradient permitted for public roads in Malaysia [4].

The fully laden weight of the test car as per market requirements (in kg) is defined as:

$$W=KW+DW+PW+LW \tag{1}$$

Where;
KW = Kerb weight of the vehicle (kg)
DW = Driver weight (kg)
PW = Maximum passenger weight (kg)
LW = Maximum luggage weight (kg)

The hill start test was conducted by flooring the accelerator pedal 100% so that the engine will rev up to 4000 RPM. At this point, the maximum torque of the engine is produced and the CVT will attempt to close the clutch to move the car forward. All auxiliary loads such as air-conditioning, lights and radio were turned off during the test. Additionally, there was no turning of the electric power assisted steering wheel made during the test. This was to prevent any additional torque loss at the air-conditioning compressor and alternator. Efforts were made to ensure the intake air temperature was maintained at 25°C to prevent fluctuation of engine plenum temperatures from influencing the engine torque output. The test was performed based on the stipulated laden weight in (1).

In order to determine the maximum available traction force on wheels at sea level, the laden weight of the test car was deliberately adjusted as per (2) where passenger and luggage weight on the test car was incrementally increased until the test car was no longer able to launch from stationary. This helps determine the maximum amount of engine torque supplied to the gearbox at sea level.

The adjustable laden weight of the test car (in kg) is defined as:

$$W_{adj}=KW+DW+PW_{adj}+LW_{adj} \quad (2)$$

Where;
PW_{adj} = *Adjustable passenger weight (kg)*
LW_{adj} = *Adjustable luggage weight (kg)*

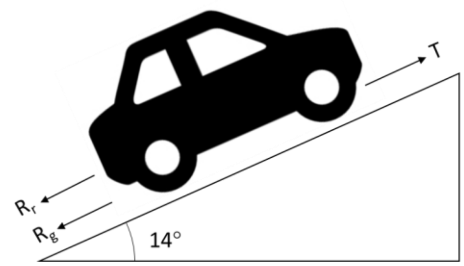
The test was repeated on a slope with 14° gradient angle of inclination at high altitude (500 m, 1000 m and 1500 m) above sea level. When the test car would not move, the laden weight of the test car was adjusted by correspondingly reducing passenger weight and luggage weight as per (2) until the test car was successfully able to launch from stationary.

The reduced laden weigh at which the test car was able to launch from stationary at high altitude will show reduction of traction force available at high altitude. This also helps determine the percentage reduction of engine torque supplied to the gearbox at high altitude.

TABLE I. TEST CAR SPECIFICATIONS

Engine Displacement	1.3 L
Max Torque	122 Nm @ 4000 RPM
Gearbox Type	CVT
Transmission efficiency, ρ_t [5]	82%
1st Gear Ratio	2.416
Final Gear Ratio	5.76
Total Gear Ratio, *G*	13.916
Tyre Size	175/65/R 14
Wheel Rolling Radius, W_{rr}	0.292 m
KW	1169 kg
DW	75 kg x 1 pax = 75 kg
PW	75 kg x 4 pax = 300 kg
LW	7 kg x 5 pax = 35 kg
W	1579 kg

Fig. 1 shows how the traction force generated on the wheels has to be higher than the combined rolling and gradient resistances in order for the vehicle to be able to launch from stationary on a gradient.



T = *Traction force on wheels* (in N)
R_r = *Rolling resistance* (in N)
R_g = *Gradient resistance (in N)*

Figure 1. Required traction force generated on wheels

The maximum traction force on wheels, T_{max} is calculated using the following formula [6]:

$$T_{max}=\frac{T_e\rho_t G}{W_{rr}} \quad (3)$$

Where;
T_e: *Maximum torque of the engine (N)*
ρ_t: *Transmission efficiency*
G: Total gear ratio
W_{rr}: *Wheel rolling radius (m)*

Rolling resistance, R_r is calculated using the following formula:

$$R_r=kW\cos\theta \quad (4)$$

Where;
k : coefficient of rolling resistance
θ : gradient angle of inclination in degrees

Note: The coefficient of rolling resistance is taken as 0.013 [7].

Gradient resistance, R_g is calculated using the following formula:

$$R_g=W\sin\theta \quad (5)$$

Where;
θ : gradient angle of inclination in degrees

The road load of a vehicle is calculated using the following formula:

$$R_L= R_r+ R_g \quad (6)$$

In order for the fully laden vehicle to be able to succesfully perform a hillstart from stationary, the maximum traction force on wheels, T_{max} must exceed the road load R_L at all times.

III. Results and Discussions

Engine torque is influenced by internal and external factors. External factors are variables such as air temperature, density and humidity whilst internal factors are mainly the unseen parameters such as fuel quality, knock control protection calibration and ancillary load friction. In the case where gear ratio, rolling radius and transmission efficiency remain constant, the fluctuating engine torque results in varying traction force on wheels that could significantly impact the hill start capability of the vehicle. For the purpose of this paper, we will only be looking at external factors namely air density which plays a pivotal role in influencing engine torque. The atmospheric pressure decreases according to altitude based on the following formula [8]:

$$P = 100 \times \left(\frac{44331.514 - Z}{11880.516}\right)^{1/0.1902632} \tag{7}$$

Where;
P = Air pressure (Pa)
Z =Altitude (m)

From the ideal gas law we know that lower air pressure directly results in lower air density. Based on (7) above, Figure 2 depicts the relationship between air pressure as altitude increases. It can be seen that from sea level to 500 m elevation the air pressure drops by 5.8% and deteriorates by 11.3% at 1000 m elevation before finally dropping down by 16.5% at 1400 m elevation. This directly effects the oxygen supply to the engine. A typical normally aspirated internal combustion engine only achieves 100% volumetric efficiency around 4000 RPM where it produces its peak torque so the reduced air density at high altitude further deteriorates the peak torque output of the engine.

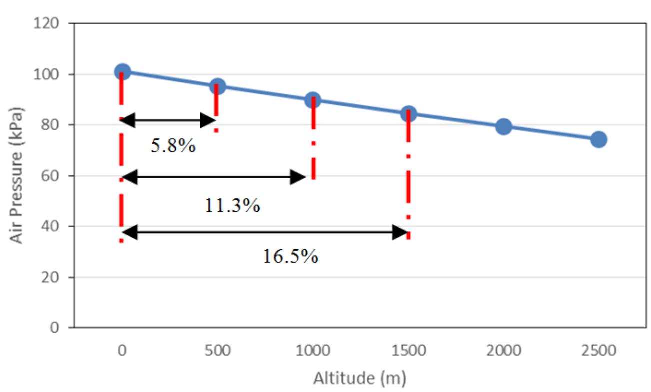


Figure 2. Air pressure vs altitude

Fig. 3 shows us the torque output of the engine drops by 13.1% as the test car is driven at 500 m above sea level.

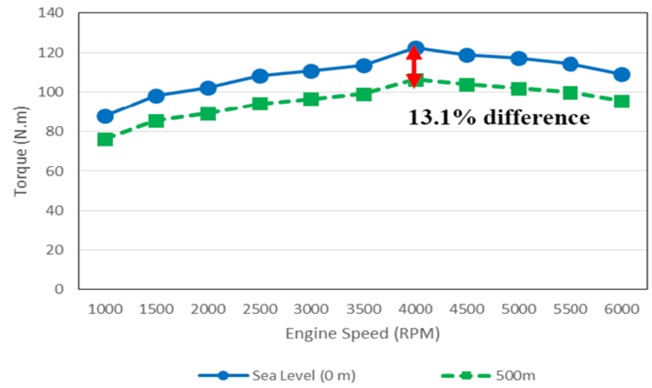


Figure 3. Comparison of engine torque at sea level (0 m) and high altitude (500 m)

Based on (3), we know that the maximum traction force on wheels is directly proportional to the maximum engine torque being supplied since gear ratio, transmission efficiency and rolling radius would remain constant based on initial test car setup. This directly translates to a 13.1% drop in traction force on wheels as can be seen in Figure 4 but there is still sufficient traction force on wheels for the test car to perform a fully laden hill start on a slope with 14° gradient of inclination at 500 m above sea level. R_L denotes the road load for the test car to perform a fully laden hill start on a slope with 14° gradient of inclination.

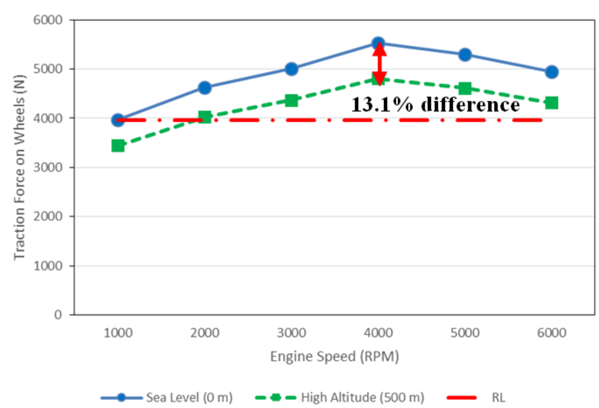


Figure 4.Comparison of traction force on wheels at sea level (0 m) and high altitude (500 m)

Fig. 5 shows us the torque output of the engine drops by 26.5% as the test car is driven at 1000 m above sea level.

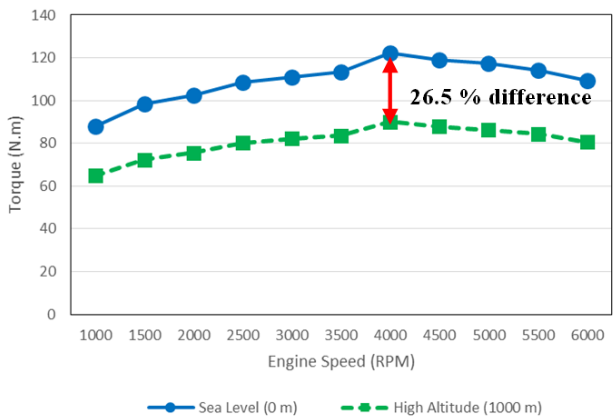


Figure 5. Comparison of engine torque at sea level (0 m) and high altitude (1000 m)

This directly translates to a 26.5% drop in traction force on wheels as can be seen in Figure 6. The test car struggles to perform a fully laden hill start at 1000 m above sea level as there is barely enough traction force on wheels to overcome R_L.

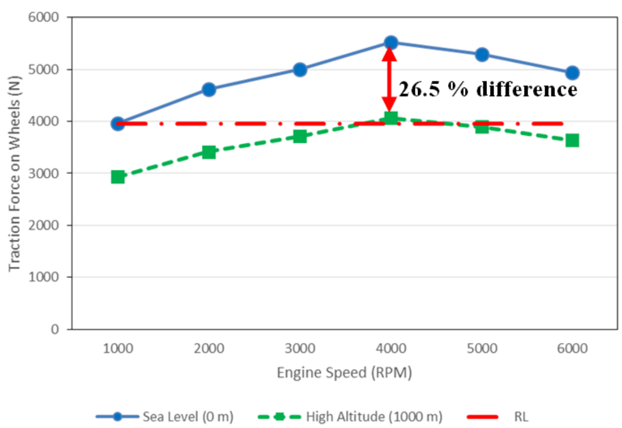


Figure 6. Comparison of traction force on wheels at sea level (0 m) and high altitude (1000 m)

Fig. 7 shows us the torque output of the engine drops by 38.2% as the test car is driven at 1500 m above sea level.

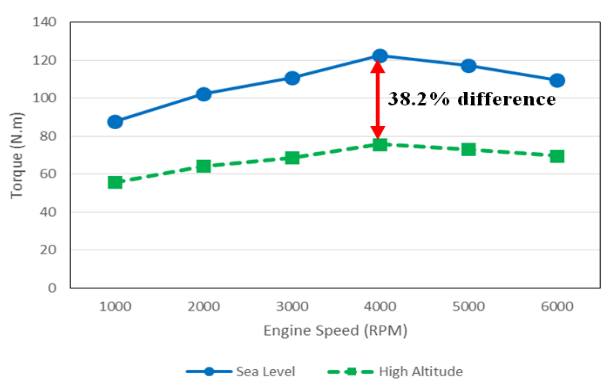


Figure 7. Comparison of engine torque at sea level (0 m) and high altitude (1500 m)

This directly translates to a 38.2% drop in traction force on wheels as can be seen in Figure 8. The test car is unable to move when attempting to perform a fully laden hill start on a slope with 14° gradient of inclination at 1500 m above sea level as there is insufficient traction force on wheels to overcome R_L.

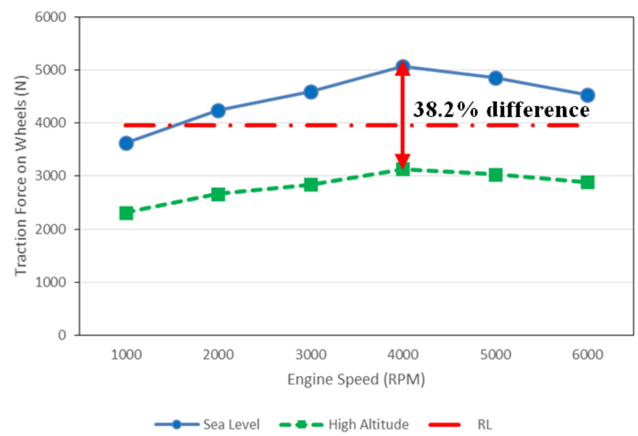


Figure 8. Comparison of traction force on wheels at sea level (0 m) and high altitude (1500 m)

From here we can see that although the original gear ratio selected for the test car is able to generate sufficient traction force to overcome the road load for a fully laden hill start on a slope with 14° gradient of incline, this is only applicable at sea level when the test car engine torque output is similar to the engine torque output obtained on the engine dynamometer. As the test car is driven at higher altitudes, the reduced air density has less oxygen which effects the torque output of the engine thereby resulting in a direct reduction of traction force on wheels but the test car gear ratio and road load remains constant. By the time the vehicle is operated at 1000 m above sea level, the traction force on wheels is barely enough to launch the fully laden car from stationary on a slope with 14° gradient of incline. When the test car is driven at 1500 m above sea level, the engine torque drop is too significant until there is insufficient traction force on wheels to overcome the road load for a slope with 14° gradient of incline and this is what prevents the vehicle from being able to launch from stationary at high altitudes although it is perfectly all right at sea level. This major limitation makes the vehicle unfit for being released into the market. This calls for last minute gear ratio changes which is usually done by adjusting the final drive due to time constraints thereby jeopardizing fuel economy in the process.

IV. CONCLUSION

Engine operating altitude has a significant impact towards the traction force on wheels for a vehicle with a direct drive transmission powered by a normally aspirated internal combustion engine. Experiments conducted on actual test vehicle at high altitudes (500 m, 1000 m and 1500 m) above sea level shows that the traction force on wheels drops by up to 38.2% at 1500 m above sea level hence we recommend the total ratio for first gear to be about 40% higher than the original ratio selected based on the torque curve from the engine dynamometer which is measured at sea level. If the region where the vehicle will be sold has topographical landscapes with altitudes above 1500 m, first gear ratio needs to be further increased. This will ensure the gear ratio can sufficiently compensate for the lower torque at high altitudes so that the vehicle can still perform fully laden hill starts at high altitude without any problem.

ACKNOWLEDGMENT

Special thanks is given to the R&D division of Perusahaan Otomobil Nasional Sdn. Bhd for the use of their vehicles and equipment for this study.

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