ICMIEE22-184

An Experimental Study of the Front Left Toe-in angle on Fuel Consumption and Traveling Cost for a Light Vehicle

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ABSTACT

The wheel toe angle is an important factor affecting the rolling resistance and energy consumption of automotive vehicles. The increase in rolling resistance and energy consumption led to an increase in the fuel consumption rate and traveling cost for the light vehicle. In this study, the fuel performance of a light vehicle (model: TOYOTA ECHO PLUS-2ZZ-GE-02) is analyzed in terms of the wheel front left toe-in angle of the car. The test results suggest that wheel front left toe-in angle is strongly correlated with rolling resistance, energy consumption, fuel consumption and traveling cost of the vehicle. It is found that when the vehicle front wheel toe-in angle is misaligned from 0.00° to 2.53°, the car had traveled approximately 4.76 km less for the same fuel quantity, and the fuel consumption increment with respect to without misalignment condition is up to 38.22%. The rate of increase in rolling resistance is found to be about 75.29% as the wheel front left toe-in angle increased (from 0.00° to 2.53°). It is also found that the traveling cost per kilometer is increased \$0.0645 to \$0.0891 when the front left toe-in angle is out of alignment. The Pearson correlation coefficient measured in this study is 0.99; showing a very strong positive correlation between fuel consumption and the front left toe-in angle. Finally, it is suggested that proper wheel alignment should be maintained for improved vehicle fuel performance.

Keywords: Light vehicle, Wheel alignment (front left toe-in angle), Rolling resistance, Fuel consumption, Traveling cost

1. Introduction

The wheel is an important component of an automobile that has a direct relationship to vehicle stability and travel safety. With the increased demand for safe travel, the alignment of the wheels has to be maintained. The wheel alignment active safety system is proportional to the steering functions in an automobile [1,2]. Research has shown that most vehicle accidents may occur due to wheel misalignment. It should be noted that the misalignment of the wheel resulted in increased fuel consumption, reduced tire life, and decreased passenger comfort. In this respect, numerous wheel alignment techniques have been developed to ensure that the vehicle's wheels are properly running straight and in the right direction. One of the wheel alignment techniques is the computerized wheel alignment machine that is used to measure the proper wheel alignment of heavy and light vehicles. The vehicle's wheel alignment functions such as caster, camber, toe, and steering axle inclination (SAI) can be much more easily measured by using an IR sensor. In IR sensors, the system uses a simple circuit that has low cost and gets high resolution, and its works with high reliability.

In recent decades, researchers [3–6] have focused on tire wear reduction for enhanced tire life and increased the fuel performance of the vehicle. Research has demonstrated that tire life is inferred when the tread is worn to a minimum depth or is irregular. It is worth noting that tire safety and stability and also driver satisfaction is related to the quality of the tire, tire materials, and appropriate tire size [6]. R.K. Das et al. [7–10] experimentally investigated that the fuel consumption of the vehicle does not depend on one factor, but rather on several factors such as wheel characteristics angle, tire pressure, suspension conditions, road conditions, load conditions, speed, etc. In their study, a computerized wheel alignment machine (Best-5800) was used to estimate the wheel alignment function. Their result found that due to misaligned of the front right toe-out angle, the fuel consumption rate rose by up to 41.21%. Furthermore, they proposed a mathematical model which can be utilized to predict the quantity of fuel consumed by the different models of vehicles [11].

It is well known that the slip/toe angle has a negative effect on rolling resistance. Different studies have found that a 10% reduction in tire rolling resistance could have saved fuel by about 1-3% [12-14]. Yurko [15] reported that small changes in toe-in angle (0° to 0.5°) should cause only a very small increase in rolling resistance. However, more changes in toe angle led to rapid increases in rolling resistance and fuel consumption, which are not recommended. Therefore, the impact of the misalignment of wheels on rolling resistance should be investigated.

This study aims to investigate the effect of wheel front left toe-in angle on fuel consumption and traveling cost of a light vehicle. The test will also be performed to examine the relationship between the

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wheel front left toe-in angle and the rolling resistance of the light vehicle.

2. Experimental analysis

2.1 The wheel alignment procedure

Wheel alignment is the adjustment of wheel characteristic angles to make them perpendicular to the ground and parallel to each other. The experimental setup was carefully performed to ensure that the vehicle was on a level surface. In this experimental setup, a computerized wheel alignment machine E-Modern (Best-5800) was used. The wheel front left toe-in angle of the wheel was properly aligned by adjustment of the tie rod and push rod function with the help of open-end wrenches as shown in Fig. 1. For measurement, the Toyota Echo Plus-2ZZ-GE-02 car was first placed in the alignment pit and the alignment turntable locks are open. Afterward, the sensor connection boards were fixed to the four wheels and the cables were connected to the wheel alignment machine. Then the steering wheel was rotated to adjust the wheel position and fixed the steering handle holder. At last, wheel alignments were checked and images are taken by adjusting the front toe angle. The measured data were subsequently stored in a memory drive.

During the test operation the following test conditions were maintained:

Experimental test conditions:

Weather temperature = (20.06 °C to 37.63°C)
humidity = (29.00% to 85.67%)
Engine outer temperature = (77.97°C to 82.73°C)
Number of test runs, n = 20,
Road condition = Fair pavement
International Roughness Index (IRI) value = 1.8
Pavement Condition Rating (PCR) value = 72.32% [16]

Vehicle Particulars:

Vehicle Model: TOYOTA ECHO PLUS-2ZZ-GE-02
Engine type: VVT
Engine size: 1300 cc
Tire size: 175/70R14
Vehicle weight: 965 kg
Air conditioning system: Non air conditioning
Gear position: Auto transmission
Type of fuel: Octane

Suspension Conditions:

Front left suspension weight: 1.49 kN
Front right suspension weight: 1.76 kN
The adherence of the front left and right is 57% and 60%, respectively.
Rear left suspension weight: 1.1 kN
Rear right suspension weight: 1.12 kN
The adherence of the rear left and right is 45%and 651%, respectively.

Cylinder Performance:

The performance of cylinder-1, 2, 3, and 4 is 80.63%, 80.10%, 80.63%, and 80.10%, respectively.

Alignment Conditions:

Front left toe-in angle = α
The left and right Caster angle is 0.20° and 0.23°
The left and right Camber angle is -0.25° and -0.37°
Pressure in all four tire is 32 psi
Vehicle speed = 30 km/hr.
Distance travel per test = 6 km
Driver and one passenger weight = 125 kg

Fig. 1 Experimental setup.

2.2 Determination of the rolling resistance

Rolling resistance is defined as the resistance force due to the deformation of the tire in contact with the pavement surface. The rolling resistance force (F_R) can be determined by a simple equation such as.

$$F_R = \mu_{RRC} \times V_W \quad (1)$$

Where, μ_{RRC} is the rolling resistance coefficient and V_W is the vehicle weight.

In this paper, the coefficient of rolling resistance (μ_{RRC}) was used with respect to the slip/toe angle graphically presented by Clark [17]. Using the graph, a general polynomial equation of 2nd order ($y = ax^2 + bx + c$) was considered. Let x be the toe angle (α) and y be the rolling resistance coefficient (μ_{RRC}), so the equation may be written like in Eqn. (2).

$$\mu_{RRC} = a\alpha^2 + b\alpha + c \quad (2)$$

Now, in equation (2), putting the values of the wheel front left toe-in angle (α) and using the second-order polynomial regression, the rolling resistance coefficient can be written as in Eqn. (3).

$$\mu_{RRC} = 0.0015\alpha^2 + 0.000143\alpha + 0.021 \quad (3)$$

Subsequently, the rates of angle, engine speed, rolling resistance force, energy consumption, and their rates were calculated from the test data which are presented in Table1.

3. Results and discussion

The experimental test results for engine rpm, rolling resistance force, rolling resistance coefficient, energy consumption, fuel consumption, KPL, and travel costs for a light vehicle as a function of the front left toe-in angle are shown in Table 1 and graphically illustrated in Figs. 2(a)-(g). Figures 2(a)-(e) showed that the engine rpm, rolling resistance force, rolling resistance coefficient, energy consumption, fuel consumption, and traveling cost rate increased as the wheel front left toe-in angle increased. Figure 2(f) shows that the KPL decreased considerably with an increase in the front left toe-in angle. When the wheel front left toe-in angle was 0.00°, the car's KPL (Kilometers Per Liter) was about 17.24 (km/L), and the fuel consumption increment with respect to without misalignment condition and KPL rate was considered to be 0%. It was found that while the front left toe-in angle was increased to 2.53°, the car's KPL was reduced to approximately 12.47 km/L and the KPL reduction rate was about 27.65%. It also shows that fuel consumption increased by up to 38.22%. The experimental results also reveal that due to the misalignment of the wheel's front left toe-in angle (from 0.00° to 2.53°), the car had traveled approximately 4.76 km less for the same fuel quantity. In Fig. 2(g), the calculated traveling cost per kilometer was increased from \$0.0645 to \$0.0891 when the front toe-in angle is out of alignment (from 0.00° to 2.53°).

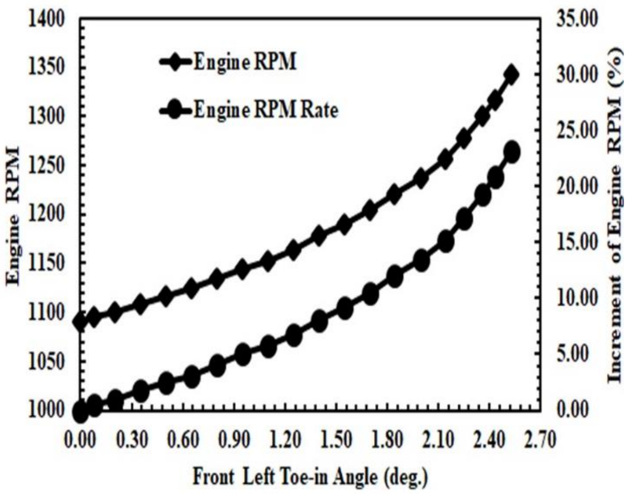
The experimental result was further verified using Pearson's correlation. The correlation coefficient r_{xy} can be written as

$$\boldsymbol{r_{xy}} = \frac{\sum_{i=1}^{n}(\boldsymbol{x_i} - \bar{\boldsymbol{x}})\left(\boldsymbol{y_j} - \bar{\boldsymbol{y}}\right)}{\sqrt{\sum_{i=1}^{n}(\boldsymbol{x_i} - \bar{\boldsymbol{x}})^2 \sum_{i=1}^{n}\left(\boldsymbol{y_j} - \bar{\boldsymbol{y}}\right)^2}}$$

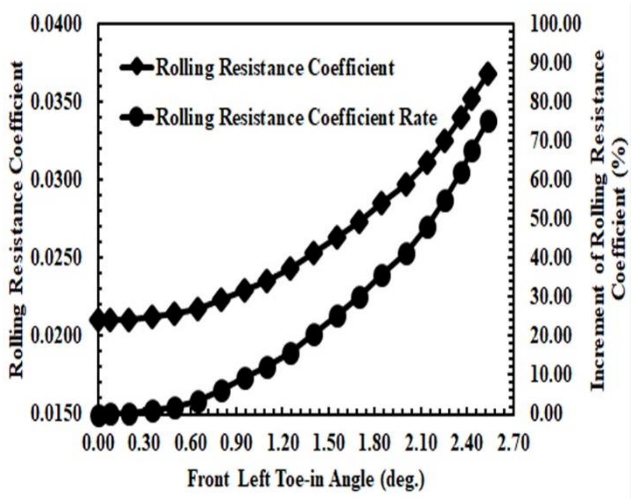
The correlation coefficient (r_{xy}) is found to be 0.99 for the front left toe-in angle and fuel consumption, which is within the range of $0.75 < r_{xy} < 1$. It shows a very strong positive correlation between the front left toe-in angle and fuel consumption of light vehicles [18]. From the above discussion, it was concluded that the fuel consumption of the vehicle increased as the wheel front left toe-in angle increased.

Table 1 Experimental data for 20 test runs for different front left toe-in angle.

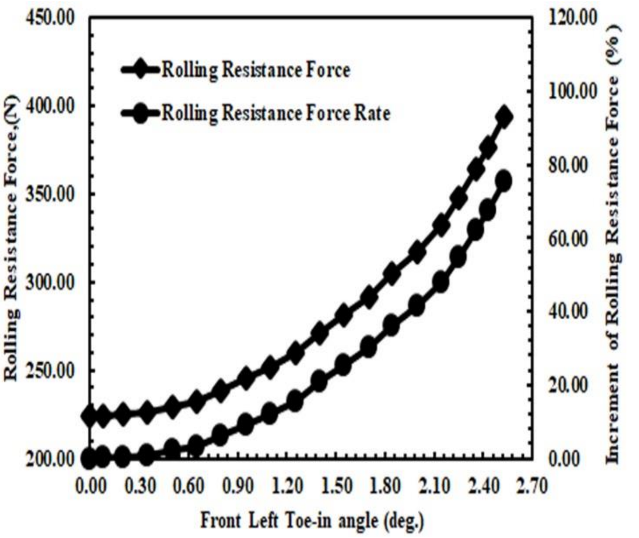
Front Left Toe-in Angle (deg.)	Angle Rate, $Ar = \frac{\alpha_t \times V_s}{T_d}$ (°/s) [19]	Engine RPM	Rolling Resistance Coefficient $\mu_{RRC} = \frac{F_R}{V_W}$ (dimensionless)	Rolling Resistance Force $(F_R) = \mu_{RRC} \times V_W$, (N)	Energy Consumption $(\boldsymbol{E_c}) = (\boldsymbol{F_R} \times \boldsymbol{T_d})$, **KJ**	Fuel Consumption (ml)	% of Fuel Consumption Increment w.r.t.no Misalignment Consumption	KPL (km/L)	KPL Reduction Rate (%)	Traveling Cost Per Kilometer in USD (For octane) $(\boldsymbol{T_c}/\boldsymbol{k_m}) = (\boldsymbol{F_c} \times \boldsymbol{F_r})$	Traveling Cost Rate Per Kilometer in USD (For octane), %
0.00	0.00	1090	0.0210	224.4223	1346.5340	348 ±2	0.00	17.241	0.00	0.0645	0.00
0.08	0.01	1095	0.0210	224.4480	1346.6878	352±2	1.15	17.045	1.14	0.0652	1.15
0.20	0.03	1100	0.0210	224.8698	1349.2189	356±2	2.30	16.854	2.25	0.0660	2.30
0.35	0.05	1109	0.0212	226.5410	1359.2459	363±1	4.31	16.529	4.13	0.0673	4.31
0.50	0.07	1117	0.0214	228.8943	1373.3656	369±1	6.03	16.260	5.69	0.0684	6.03
0.65	0.09	1124	0.0217	232.0718	1392.4306	375±2	7.76	16.000	7.20	0.0695	7.76
0.80	0.11	1135	0.0223	238.3282	1429.9689	384±1	10.34	15.625	9.37	0.0712	10.34
0.95	0.13	1145	0.0229	245.3272	1471.9633	392±1	12.64	15.306	11.22	0.0726	12.64
1.10	0.15	1153	0.0235	251.4241	1508.5444	398±2	14.37	15.075	12.56	0.0737	14.37
1.25	0.17	1164	0.0243	259.4138	1556.4828	405±1	16.38	14.815	14.07	0.0750	16.38
1.40	0.19	1178	0.0253	271.0025	1626.0152	414±2	18.97	14.493	15.94	0.0767	18.97
1.55	0.21	1190	0.0263	280.9800	1685.8803	421±2	20.98	14.252	17.34	0.0780	20.98
1.70	0.23	1204	0.0273	291.7472	1750.4832	428±1	22.99	14.019	18.69	0.0793	22.99
1.84	0.25	1221	0.0285	304.9542	1829.7255	436±2	25.29	13.761	20.18	0.0808	25.29
2.00	0.28	1237	0.0297	317.2408	1903.4447	443±3	27.30	13.544	21.44	0.0821	27.30
2.14	0.30	1256	0.0311	332.0451	1992.2703	451±1	29.60	13.304	22.84	0.0836	29.60
2.25	0.31	1277	0.0325	347.5835	2085.5007	459±2	31.90	13.072	24.18	0.0851	31.90
2.36	0.33	1300	0.0340	363.7709	2182.6257	467±2	34.20	12.848	25.48	0.0865	34.20
2.43	0.34	1317	0.0352	376.2850	2257.7100	473±3	35.92	12.685	26.43	0.0877	35.92
2.53	0.35	1342	0.0368	393.3964	2360.3786	481±2	38.22	12.474	27.65	0.0891	38.22


Engine RPM
Engine RPM Rate
Engine RPM
Increment of Engine RPM (%)
Front Left Toe-in Angle (deg.)

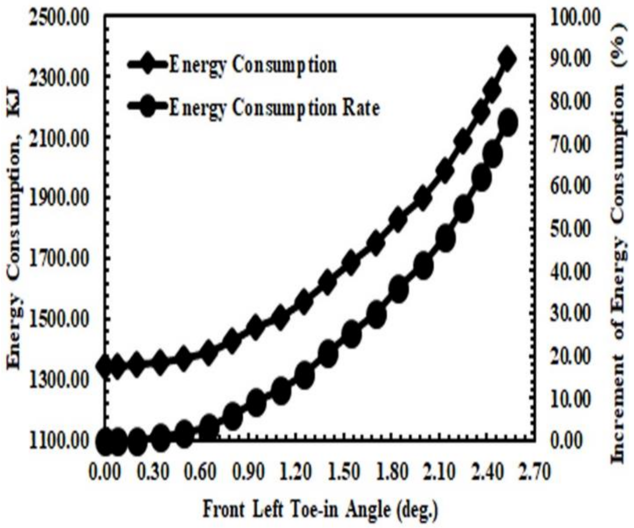
(a)


Rolling Resistance Coefficient
Rolling Resistance Coefficient Rate
Rolling Resistance Coefficient
Increment of Rolling Resistance Coefficient (%)
Front Left Toe-in Angle (deg.)

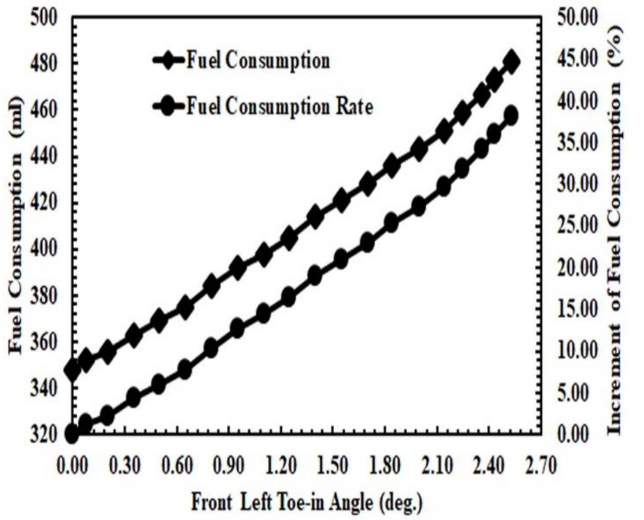
(b)


Rolling Resistance Force
Rolling Resistance Force Rate
Rolling Resistance Force,(N)
Increment of Rolling Resistance Force (%)
Front Left Toe-in angle (deg.)

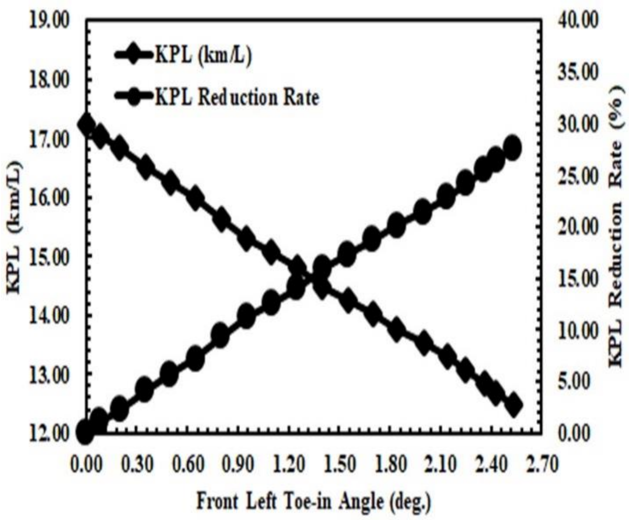
(c)


Energy Consumption
Energy Consumption Rate
Energy Consumption, KJ
Increment of Energy Consumption (%)
Front Left Toe-in Angle (deg.)

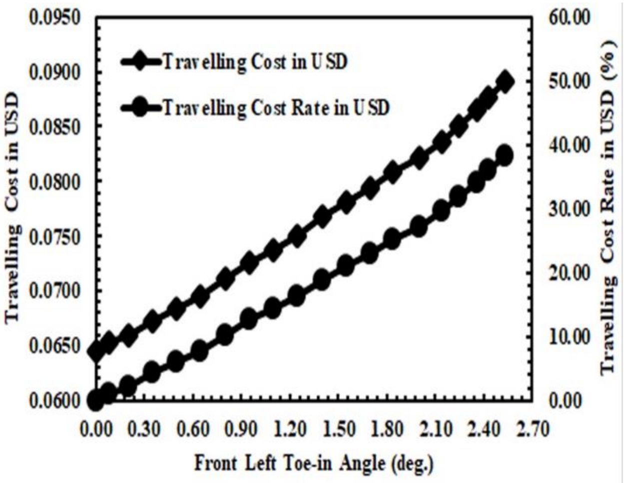
(d)


Fuel Consumption
Fuel Consumption Rate
Fuel Consumption (ml)
Increment of Fuel Consumption (%)
Front Left Toe-in Angle (deg.)

(e)


KPL (km/L)
KPL Reduction Rate
KPL (km/L)
KPL Reduction Rate (%)
Front Left Toe-in Angle (deg.)

(f)



(g)

Fig. 2: Variation of (a) engine RPM and rate(%), (b) rolling resistance coefficient and rate(%), (c) rolling resistance force (N) and rate(%), (d) energy consumption (KJ) and rate(%), (e) fuel consumption and rate(%), (f) KPL (km/L) and rate(%), and (g) traveling cost in USD and rate(%) with respect to front left toe-in angle(deg.)

4. Conclusion

The following conclusions are drawn from the experimental results of the light vehicle:

- It is found that when the wheel's front left toe-in angle is misaligned from 0.00° to 2.53°, the car traveled approximately 4.76 km less for the same fuel quantity with respect to without misalignment condition.
- It was also found that the rate of engine rpm, rolling resistance force, fuel consumption, and traveling cost per kilometer in USD were increased by up to 23.12%, 75.29%, 38.22%, and 38.22%, respectively, and the KPL reduction rate was 27.65% when the wheel front left toe-in angle was 0^{o} to 2.53^{o}.
- The results have shown that the wheel front left toe-in angle was strongly correlated with rolling resistance, energy consumption, fuel consumption, and travel cost of the light vehicle.
- The Pearson correlation coefficient measured in this study is 0.99, which claimed a very strong positive correlation between the front left toe-in angle and fuel consumption.

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NOMENCLATURE

x_i : Values of the front left toe-in angle (deg.)

$\bar{x}$: Mean of the values of the front left toe-in angle (deg.)

y_j : Values of the fuel consumption(ml)

$\bar{y}$: Mean of the values of the Fuel consumption (ml)

r_{xy} : Pearson's Correlation Coefficient for the front left toe-in angle and fuel consumption

A_r : Angle rate (%)

V_s : Vehicle speed (km/hr.)

μ_{RRC} : Rolling resistance coefficient (dimensionless)

F_R : Rolling resistance Force (N)

V_W : Vehicle Weight (N)

T_d : Travelling distance (km) .

T_p : Tire pressure (psi)

α : Front left toe-in angle (deg.)

E_c : Energy consumption (KJ)

α_t : Slip/toe angle (deg.)

RPM : rev/min

F_c : Fuel consumption (ml)

F_r : Fuel rate (USD)

$T_{c/km}$: Travelling cost per kilometer (USD)

KPL : km/L

IRI : International Roughness Index

PCR : Pavement Condition Rating