Hindawi
Journal of Engineering
Volume 2024, Article ID 5723254, 15 pages
https://doi.org/10.1155/2024/5723254

Research Article

Effects of Front Total Toe-In Angle on Tire Wear and Emissions for a Light-Duty Vehicle

Riton Kumer Das,[1] **Md. Abu Mowazzem Hossain**,[1] **Md. Tazul Islam**,[1] **Sajal Chandra Banik**,[1] **and Md. Golam Hafez**[2]

[1]*Department of Mechanical Engineering, Chittagong University of Engineering and Technology, Chattogram 4349, Bangladesh*
[2]*Department of Mathematics, Chittagong University of Engineering and Technology, Chattogram 4349, Bangladesh*

Correspondence should be addressed to Md. Abu Mowazzem Hossain; mowazzem@cuet.ac.bd

Received 14 November 2023; Revised 22 February 2024; Accepted 1 March 2024; Published 18 March 2024

Academic Editor: Amiya K. Jana

An experimental investigation is carried out in this study to investigate the effect of wheel alignment, particularly the front total toe-in angle, on tire wear and emissions for a light-duty vehicle. Such investigations reveal that there is a substantial correlation among rolling resistance, energy consumption, tire wear, tire travel life, and the total toe-in angle of the front wheel. It is observed that the rate of loss in tire travel life with regard to a condition without misalignment is up to 98.33% when the front total toe-in angle is out of alignment (ranging from 0.00° to 4.20°). It is found that rolling resistance increases by about 128.86%, while CO_2, CO, and NO_x emissions rise by nearly 36.67%, 26.83%, and 31.25%, respectively, as the front total toe-in angle increases from 0.00° to 4.20°. The experimental results also reveal that tire circumferential groove wear is observed at 0.04 mm after the vehicle's travelling distance of 500 km, where the front total toe-in angle is 0.00°, and the tire travelling life is 92250 km. In addition, the tire circumferential groove wear is investigated as 2.40 mm after the vehicle's travelling distance and tire travel life are recorded to be 3,500 km and 1537.50 km, respectively, due to the occurrence of misalignment (the front total toe-in angle is 4.20°). Finally, a regression model is proposed using the test data. Such a model would be useful to explain the relationship between the related factors and determine the rate of tire wear and emissions. It is noteworthy that the wheels should always remain aligned in accordance with the manufacturer's specifications in order to ensure optimal performance and longevity of the tires

1. Introduction

Motor vehicles are essential modes of transport in daily life. With the advancement of automotive technology, the travelling speed of an automobile has significantly increased; however, the vehicle's safety and stability are continually discussed today. Automobile safety and stability depend on a variety of factors, tires being one of them. Tires are a key subsystem of vehicles responsible for comfort, fuel consumption, and traffic safety. It is a primary component that directly interacts with the road surface. Its main job is to guide the wheel on the road and support the associated forces. Despite the pavement's roughness and the vehicle's dynamic motion, the tire bears a combined force, encompassing longitudinal, lateral, and vertical forces. The tire becomes worn out rapidly due to the combined effects of pitch, roll, or yaw. In the past, researchers [1–3] have focused on tire wear reduction for enhanced tire life and increased vehicle fuel efficiency. Xu et al. [4] demonstrated that tire life is inferred when the tread is worn to a minimum depth or becomes irregular. Patrick [5] has investigated and found that about 75.4% of the tires assessed had uneven wear profiles due to incorrect tire-road contact effects. It is also confirmed that incorrect tire-road contact is associated with irregularities in the pavement surface. The researchers in [6, 7] have also shown that tire safety and road vehicle stability, as well as driver and passenger satisfaction, are related to tire quality, tire material, appropriate tire size, and inadequate tire characteristics. According to previous research [3, 8–12], most researchers measured tire wear using

various approaches, such as the finite element method (FEM) and the analytical method, with most case model-based analyses supporting the experimentally measured data. The quantity of tire wear is predicted numerically for use in tire design [11]. The tire dynamic rolling analysis of a 3D-patterned tire model computes the tire frictional energy rates produced in each driving mode. Based on laboratory testing of rubber abrasion, a power function wear model has been presented in [3, 13, 14] to test uneven tire wear. It involves applying a single layer of reflective paint to the tread surface by spraying and measuring the intensity of light reflected from a matrix of blocks on the unworn tire. Li et al. [15] analyzed tire wear based on various factors such as speed, ambient temperatures, tire pressure, and sprung mass. Pan et al. [16] suggested a new multiaxle steering vehicle (MSV) kinematics model to achieve more than 30% reduction in tire wear on multiaxle heavy commercial vehicles. Based on route data and a vehicle model, Lepine et al. [17] introduced a novel empirical tire-wear model that can be employed to estimate tire wear for multiaxle vehicles. Gohane et al. [18] suggested several approaches for reducing tire wear, including the use of fuzzy logic, alignment techniques, and tire sensing. They also showed that by using an automated tire monitoring and inflation system, proper tire pressure can be maintained better to meet the safety and stability of the vehicle. Among the various models, the elasto-kinematic axle is a relatively good match with the experimental results.

Uneven tire wear, on the other hand, has a more significant impact on vehicle safety. The typical source of this issue is commonly attributed to wheel misalignment and imbalanced tire pressure, either being underinflated or overinflated. Further, improperly aligned wheels can potentially damage vehicles' axles, springs, and shock absorbers and lead to faster tire wear. Many modern passenger vehicles are equipped with different wheel alignment techniques for security reasons [19–21]. The primary purpose of the wheel alignment is to ensure the vehicle runs in a straight line and in the correct position without pulling to one side or the other [20]. The different characteristic angles of different types of tires can be determined by adjusting their angle of rotation, which can greatly increase fuel performance, tire longevity, and driving satisfaction. Young et al. [21] have found that an appropriate adjustment of wheel characteristic angles can considerably improve the vehicle's fuel efficiency and tire wear resistance. Das et al. [6, 22–25] have developed a relationship between various factors and the alignment of the wheels. They have experimentally investigated how the fuel consumption of an automotive vehicle depends on several factors. It is noted that improper alignments, such as toe-in and toe-out, camber, and caster, offered tire wear. However, toe-in and toe-out angles had significantly more tire wear than others. This misalignment occurs as a result of the sudden shock that appears due to the abrupt application of the brakes when the vehicle drives on the road surface. In [26], the authors have shown that wheel slip angle (toe angle) has a negative effect on rolling resistance. With a few degrees of slip, the rolling resistance coefficient can almost double, which leads to rapid tire wear that is not anticipated. Interestingly, many people are not concerned about wheel misalignment in their daily driving and are not focused on tire wear until and unless it has ruptured or worn out. The truth is that they are ignorant of how lousy wheel alignment affects a vehicle's performance and its relationship to fuel economy. Also, there is a dearth of statistical information in the open literature about tire wear caused by wheel toe-angles. Thus, the research work in this study explores the effect of wheel alignment, especially the front total toe-in angle, on tire wear and tire travel life for a light-duty vehicle. The test will also be performed to examine the relationship between wheel alignments (front total toe-in angle), rolling resistance, and CO_2, CO, and NO_x emissions for light-duty vehicles.

2. Experimental Setup and Test Condition

2.1. Wheel Alignment. Wheel alignment is the process of adjusting the angles of the wheels, so they are perpendicular to the ground and parallel to each other. Wheel alignment functions are related to the caster, camber, toe-in and toe-out, kingpin inclination, turning radius, etc. In this study, only the front total toe-in angle (as shown in Figure 1) is considered to examine tire wear and emissions (CO_2, CO, and NO_x) for light-duty vehicles. It is important to note that the toe angle is the key factor responsible for vehicle stability, performance, and tire life, despite other wheel alignment functions. The initial step of the experimental analysis involves a manual inspection of all components related to the alignment of the wheel's toe angle. The vehicle is then aligned through a computer-assisted wheel alignment machine, the E-Modern (Best-5800), as shown in Figure 1. Due to the proper arrangement of the experimental setup in the above procedure, the vehicle is on a level surface. The wheel alignment machine's cables are connected, and once the alignment turntable locks are unlocked, the car is positioned in the alignment pit. The sensor connection boards are connected to each of the four wheels. After that, the steering wheel is turned to adjust the wheel's position and attach the steering handle holder. Finally, the wheel alignment is thoroughly checked by precisely adjusting the front toe-in angle and capturing detailed images. In this setup, the open-end wrench is used to adjust the tie rod and push rod functions to adjust the front toe-in angle, and the measured data are stored on a computer drive. As mentioned below, the vehicle's characteristics, the suspension's condition, the engine's cylinder performance, and other alignment parameters are considered while measuring the correct front total toe-in angle.

2.1.1. Experimental Test Conditions

Weather temperature: 20.06°C to 37.63°C

Humidity: 29.0% to 85.67%

Engine outer temperature: 77.97°C to 82.73°C

Number of test runs, $n = 5$

Road condition: Fair pavement

International Roughness Index (IRI) value: 1.8

Pavement Condition Rating (PCR) value: 72.32% [27]

Figure 1: Experimental setup of vehicle wheel alignment system with wheel alignment machine (Best-5800).

2.1.2. Tire Particulars

Tire size: 165/80R13

Brand: Maxxis, DOT, 20E9, EEC, 2721, SNI (83T), (E4), 027277, S2WR2, 0285667

Tubeless Radial, Max. Load: −487 kg (1074 lb); Max. Pressure: −44 psi (300 kip), MA-P3-04

Tread: 1 Polyester + 2 Steel + 1 Nylon Sidewall: 1 Polyester, Made in Thailand

2.1.3. Vehicle Particulars

Vehicle Model: TOYOTA COROLLA-2E-86

Engine displacement: 1300 cc; Vehicle weight: 830 kg

Air conditioning system: Non-air conditioning

Gear condition: Manual transmission

Tire pressure (front and rear wheels): 40 psi

Vehicle speed: 40 km/hr

The driver and one passenger weight = 125 kg

2.1.4. Engine Cylinder Performance Conditions. The performance of cylinders 1, 2, 3, and 4 is 78.84%, 79.37%, 79.37%, and 77.78%, respectively.

2.1.5. Suspension Conditions

Front left and right suspension weights: 1.43 kN and 1.53 kN, respectively.

The adherences of the front left and right are 50% and 45%, respectively.

Rear left and right suspension weights: 1.24 kN and 1.34 kN, respectively.

The adherences of the rear left and right are 42% and 19%, respectively.

2.1.6. Alignment Conditions

Front total toe-in angle $(\alpha) = \alpha_1 + \alpha_2$

Where α_1 = Front left toe-in angle (°), α_2 = Front right toe-in angle (°)

The left and right Caster angles are 0.12° and 0.10°, respectively

The left and right Camber angles are 0.17° and −0.25°, respectively

2.2. Determination of the Rolling Resistance and Energy Consumption. Rolling resistance refers to the force that opposes the motion of a tire as it rolls on a road surface due to the deformation of the tire [28]. The following equation is used to calculate the rolling resistance (R_R):

$$R_R = \mu_{\mathrm{RRC}} \times W_v, \tag{1}$$

where μ_{RRC} is the rolling resistance coefficient and W_v is the vehicle weight.

Developing a formula that takes into account all variables affecting rolling resistance is a highly complex task due to the numerous factors involved. Researchers have developed several equations over the years to estimate rolling resistance. The study considers the slip/toe angle graph by Clark et al. [29] as a reference and utilizes the rolling resistance coefficient (μ_{RRC}) in conjunction with it. Using the graph, a general polynomial equation of 2nd order ($y = ax^2 + bx + c$) is considered, where x is the toe-in angle (α) and y is the rolling resistance coefficient (μ_{RRC}). As a result, equation (2) is converted to

$$\mu_{\mathrm{RRC}} = a\alpha^2 + b\alpha + c. \tag{2}$$

The absolute values of the front total toe-in angle (α) and rolling resistance coefficient from Clark et al. [29] can now be used to estimate a, b, and c by solving the above second-order polynomial equation through the least square method. Then, the equation can be written as

$$\mu_{\mathrm{RRC}} = 0.0015\alpha^2 + 0.000143\alpha + 0.021. \tag{3}$$

The values of the front total toe-in angle of 0.00°, 0.40°, 1.00°, 1.60°, and 4.20° are now entered into equation (3). The rolling resistance coefficient is then found to be 0.021, 0.021, 0.023, 0.025, and 0.048, and the rolling resistance is found to be 196.74 N, 199.52 N, 212.13 N, 234.86 N, and 450.26 N, respectively.

The amounts of energy consumption listed in Table 1 can also be calculated using a simplified equation as

$$E_c = (R_R \times T_d). \tag{4}$$

In the current study, a light-duty Toyota Corolla-2E-86 vehicle is taken into consideration to examine the impact of wheel front total toe-in angle on tire wear and emissions (CO_2, CO, and NO_x). In the experiment, the rolling resistance and other parameters (listed in Table 1) are calculated using equations (3) and (4) based on the total toe-in angle of the front wheels

2.3. Exhaust Emission Measurement. Exhaust gas emission measurement can be done through laboratory or field testing using different methods. However, laboratory

Table 1: Experimental data for different parameters based on the front total toe-in angle.

Front total toe-in angle (°)	Angle rate, $A_r = \alpha_t \times V_s/T_d$ (°/S)	Engine RPM	Increment of engine RPM (%)	Rolling resistance coefficient, $\mu_{RRC} = R_R/W_v$	Increment of rolling resistance coefficient (%)	Rolling resistance, $R_R = \mu_{RRC} \times W_v$ (N)	Increment of rolling resistance (%)	Energy consumption, $E_c = (R_R \times T_d)$ (KJ)	Increment of energy consumption (%)	CO_2 emissions (PPM/%) for octane	Increment of CO_2 emissions (%)	CO emission PPM/(%)	Increment of CO emissions (%)	NO_x PPM	Increment of NO_x (%)
0.00	0.00	1310	0.00	0.021	0.00	196.74	0.00	1180.44	0.00	30000/(3%)	0.00	30300/ (3.03%)	0.00	32	0.00
0.40	0.06	1415	8.02	0.021	1.42	199.52	1.42	1197.14	1.42	33000/ (3.3%)	10.00	32700/ (3.27%)	7.92	36	12.50
1.00	0.14	1455	11.07	0.023	7.82	212.13	7.82	1272.80	7.82	34000/ (3.4%)	13.33	34400/ (3.44%)	13.53	38	18.75
1.60	0.22	1485	13.36	0.025	19.38	234.86	19.38	1409.15	19.38	35000/ (3.5%)	16.67	36100/ (3.61%)	19.14	39	21.87
4.20	0.58	1710	30.53	0.048	128.86	450.26	128.86	2701.55	128.86	41000/ (4.1%)	36.67	38300/ (3.83%)	26.83	42	31.25

testing methods are more complex and repeatable as they utilize precise and sophisticated equipment. On the other hand, field testing is more straightforward. This experimental analysis used a portable emission measurement system (PEMS) to measure exhaust emissions [30, 31]. During the emissions' test, the front toe-in angle was first adjusted to 0.00° and the engine RPM was recorded while the vehicle was driving at 40 km/h, as shown in Table 1. The exhaust gas emissions, namely, CO_2, CO, and NO_x,were then measured using a portable K-Kane AUTOPlus Gas Analyzer (manufactured by Distek) at that particular engine speed. The Gas Analyzer was calibrated prior to the experiment. Similarly, the exhaust emissions were measured at the front toe-in angles of 0.40°, 1.00°, 1.60°, and 4.20°, respectively, as a function of the engine speed during the experiments.

2.4. Tire Wear Estimation. This analysis uses the Maxxis brand tire (165/80R13), which features two types of grooves in its tread: lateral grooves and circumferential grooves. After each set of test runs, the tire wear is measured using a digital depth gauge (manufactured by Insize), as shown in Figure 2. Three sets of repeated data are measured for each test over a period of time to determine an average and reduce the amount of error in the results. The tire wear is measured based on the wheel front total toe-in angle (as shown in Table 1) with a tire pressure of 40 psi and vehicle speed maintained at 40 km/hr. For the analysis, we use the fair road pavement condition with an International Roughness Index (IRI) value of 1.8. The tests are carried out at midnight on a quiet, car-free road without significant braking or acceleration.

During the tests, other parameters such as weather temperature (ranging from 20.06°C to 37.63°C), humidity (29.0% to 85.67%), and engine outer temperature (77.97°C to 82.73°C) are also measured. In the first case, the depth of the lateral and circumferential grooves is measured using an electronic digital tire tread depth gauge after a travel distance of 500 km with one driver and one passenger at a 0° front total toe-in angle. The depth of the grooves is then measured by the change in the front total toe-in angle of 0.40°, 1.00°, 1.60°, and 4.20°, respectively, with a travel distance of 1000 km, 1500 km, 2000 km, and 2500 km. These measurements are shown in Table 2. Initially, two new tires were mounted on the front wheels before the experiment started, and the toe angle of the front wheel was set to 0.00°. Then, tire wear is measured after 500 kilometers of driving in this setting. Likewise, replace the old front wheel tires with new ones before each test. Hence, throughout the experiment, a total of 10 new tires were utilized. A light-duty vehicle weighing 955 kg, including the driver and one passenger, is used for all tests. It is important to note that a number of factors, such as wheel alignment, road conditions, load, vehicle speed, braking, operating conditions, tire material, etc., affect tire wear. Since the tests are carried out in relatively controlled conditions, other factors that might affect tire wear are assumed to be minimal.

3. Results and Discussion

The experiment is carried out under steady-state test conditions (i.e., constant load, speed, and tire pressure), with the only variation in slip angle taken into account being the wheels' front total toe-in angle, which is thought to be the most critical factor that affects the tire wear of the vehicle. As a function of the front total toe-in (left and right) angle, the tests have recorded engine RPM (measured using a tachometer) and emissions (measured using a K-Kane AUTO plus Gas Analyzer). Rolling resistance and energy consumption are calculated for each experiment, as shown in Table 1 and graphically illustrated in Figures 3 and 4. The experimental investigations show that the engine RPM, rolling resistance, rolling resistance coefficient, energy consumption, tire wear, and emissions' rate increased with an increased front total toe-in angle. Figure 5 shows that the engine RPM increased as the vehicle's front total toe-in angle increased. It is well known that an increase in the toe-in angle causes the rolling resistance to increase more rapidly, as shown in Figures 3 and 6. This is likely due to the lateral acceleration over the curve and the surface's local stiffness.

It should be noted that the variation in tire vertical load also influences the stiffness or lateral force of the tire during cornering [32]. However, the rolling resistance generated is also dependent on a variety of factors, such as vehicle type, tire properties, tire materials, operating conditions, etc. It is noted that increasing the toe-in angle of the wheels results in greater rolling resistance, which requires an increase in engine speed to maintain a consistent vehicle speed. Hence, energy consumption would be higher as more fuel was burned (Figure 4). As a consequence, the rate of emissions increases. When the front total toe-in angle is set to 0.00° (Figures 7–9), the emissions for octane are 3% (30,000 ppm) CO_2, 3.03% (30,300 ppm) CO, and 32 PPM NO_x. When the front total toe-in angle is raised to 4.20°, the emissions rise to 4.1% (41,000 ppm), 3.83% (38,300 ppm), and 42 PPM, respectively. It is worth noting that low-rolling resistance tires may help reduce CO_2 and NO emissions, as well as local pollutants like CO emissions from gasoline engines. It is also pointed out that reducing energy consumption is a national goal for a number of reasons, including improvements in air quality and reductions in greenhouse gas emissions. A survey report at the University of British Columbia in Canada has shown that a 10% variation in the coefficient of rolling resistance of a tire will result in 1.5–2% lower CO_2 emissions per ton of carbon dioxide (CO_2) [14, 33]. Due to the misalignment of the front total toe-in angle from 0.00° to 4.20°, there has been a significant increase in engine RPM, rolling resistance, CO_2, CO, and NO_x emission by 30.53%, 128.86%, 36.67%, 26.83%, and 31.25%, respectively, as shown in Table 1.

The results in Figures 3–6 suggest that the front total toe-in angle strongly correlates with rolling resistance. It is also observed that tire rolling resistance significantly impacts vehicle tire life and emissions. Uneven tire wear, especially on the outside edges of the tires, can result from toe-in misalignment. This is due to the fact that the inside edges of the tires are actually travelling a shorter distance than the

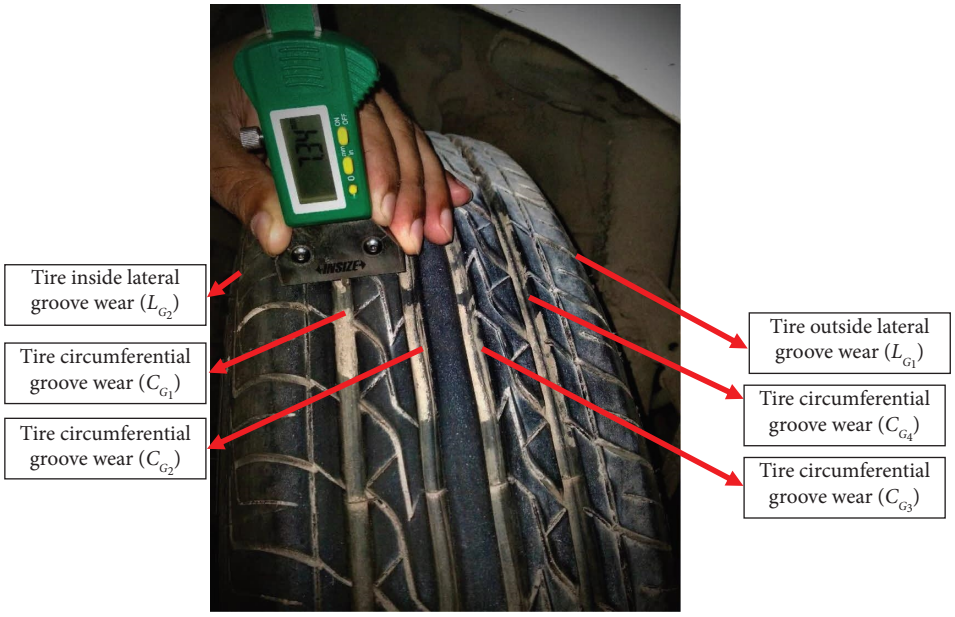

Figure 2: Tire marked for wear measurement.

outside edges, which causes more friction and heat to be produced there. Furthermore, excessive toe-in can cause a car's tires to rub or drag on the pavement. This can have a detrimental effect on handling and fuel efficiency, as well as increase tire wear. However, it should be noted that a positive toe angle (toe-in) benefits vehicle stability when driving straight. Whereas, Yurko [34] has been reported to say that a bit of change in toe-in angle (0° to 0.5°) should cause only a minimal increase in rolling resistance. Thus, it can be concluded that little changes in toe angle can be allowed; however, more changes in the toe angle lead to rapid increases in tire wear and emissions, which are not recommended.

This study looks at how changes in the vehicle's front total toe-in angle affect uneven tire wear. To do this, tests and estimates of tire groove wear are done under five different test conditions, which are listed in Table 2 and shown graphically in Figures 10 and 11. It should be noted that tire wear depends largely on the cornering forces, which are mainly developed by the effect of suspension and steering geometry on the slip angles of the two front wheels [35]. In Figure 10, the tire circumferential grooves' wear increases as the wheel front total toe-in angle increases. The trial findings revealed that the tire circumferential groove wear is observed to be 0.04 mm after the vehicle's travel distance of 500 km when the front total toe-in angle is at 0.00° (Table 2). In that case, the tire travelling life is found to be 92250 km, where the tire wear increment rate and tire travelling life reduction rate at total toe-in angle at 0° are considered to be 0%.

On the other hand, while the front total toe-in angle reaches 4.20°, the tire circumferential groove wear is observed to be 2.40 mm after the vehicle's travelling distance of 3,500 km, and the tire's travel life is reduced to approximately 1537.50 km (Figure 12). Thereby, it is observed that due to misalignment of the front total toe-in angle (from 0.00° to 4.20°), the tire travel life is approximately 90712.5 km less for the same tire size. The tire life reduction rate is about 98.33% (Figure 12), which increases the cost by about 3.7 TK (BDT) per kilometer of travel. It is also seen that the tire wear increment rate is minimal up to the front total toe-in angle of 1.6°; however, further increases in the front total toe-in angle can cause a much faster increase in tire wear. It is worth mentioning that the toe angle over 1 degree is rarely used on vehicles; however, in the worst-case scenario, the 4.20° toe-in angle has been used in this study. Figures 10 and 11 show that circumferential groove wear is more severe, particularly in L_{G1} and C_{G1}. Figure 13 shows the passenger car tires with asymmetric wear at a different total toe-in angle. The circumferential grooves C_{G1}–C_{G3} (Table 2) showed nearly similar wear patterns. The minimum groove wear is observed at the tire's inside lateral groove (L_{G2}) compared to the outside lateral groove (L_{G1}). In cases of misalignment of the toe-in angle, tire wear primarily began from the outer shoulder to the inner shoulder of the tire. The outside of the tread wears out much faster for a front tire with an excessive toe-in (4.20°) in Figure 13(a). It is also observed that if one's hand rubs through worn-out tread (from inside to outside and vice-versa), he or she will experience smoothness from outside to inside. However, sharp edges on the inside edges of the tread are observed. In either case, the tread wear is the same around the tire, and both tires showed the same type of asymmetrical wear. It can be seen that outside and inside shoulder wear around the tire depends on the wheel's front toe angle. The experimental result is well in agreement with the theoretical wear pattern for the toe-in angle of the wheel [36].

The experimental result is further verified using Pearson's correlation coefficient. The Pearson correlation coefficient (r) is the most often used method for finding a linear correlation. The magnitude and direction of the relationship between two variables are stated as numbers ranging from −1 to 1. Pearson's correlation coefficient can be defined as

Table 2: Experimental data for tire wear as a function of front total toe-in angle.

Front total toe-in angle (°)	Tire outer lateral groove wear (L_{G_1}) (mm)	Tire outer lateral groove wear rate (%)	Tire circumferential groove wear (C_{G_1}) (mm)	Tire circumferential groove wear rate (%)	Tire circumferential groove wear (C_{G_2}) (mm)	Tire circumferential groove wear rate (%)	Tire circumferential groove wear (C_{G_3}) (mm)	Tire circumferential groove wear rate (%)	Tire circumferential groove wear (C_{G_4}) (mm)	Tire circumferential groove wear rate (%)	Tire inner lateral groove wear (L_{G_2}) (mm)	Tire inner lateral groove wear rate (%)	Tire travelling life, $T_{tl} = T_d \times T_{\mathrm{cgd}}/T_w$	Tire travelling life reduction rate (%)
0.00	0.03	0.00	0.04	0	0.04	0	0.04	0	0.04	0	0.03	0.00	92250.00	0.00
0.40	0.05	66.67	0.06	50	0.07	75	0.06	50	0.06	50	0.05	33.33	61500.00	33.33
1.00	0.09	200.00	0.08	100	0.08	100	0.09	125	0.08	100	0.07	133.33	46125.00	50.00
1.60	0.37	1133.33	0.35	775	0.34	750	0.35	775	0.20	400	0.09	200.00	10542.86	88.57
4.20	2.43	8000.00	2.40	5900	2.41	5925	2.40	5900	0.90	2150	0.13	333.33	1537.50	98.33

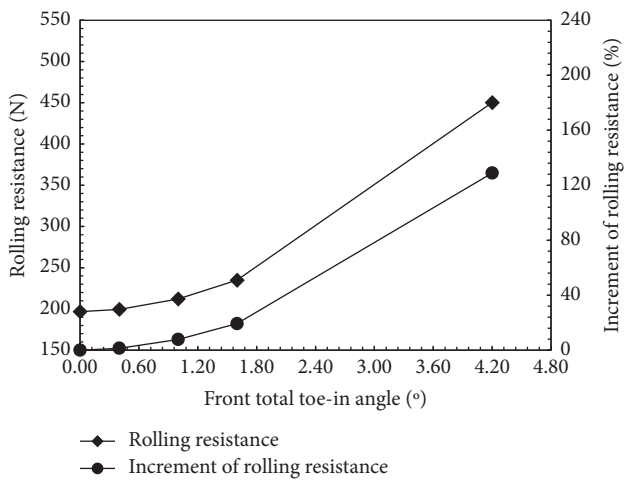

Figure 3: Variation of rolling resistance (N) and rolling resistance rate (%) with respect to front total toe-in angle (°).

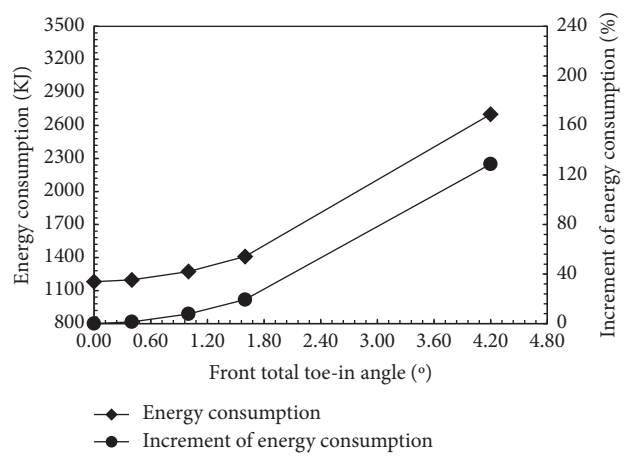

Figure 4: Variation of energy consumption (KJ) and energy consumption rate (%) with respect to front total toe-in angle (°).

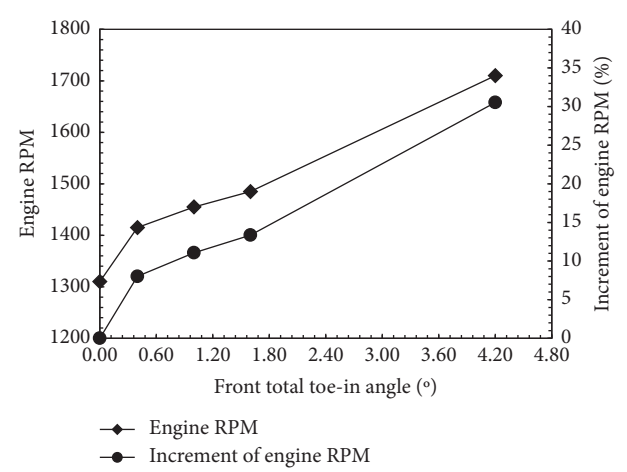

Figure 5: Variation of engine RPM and engine RPM rate (%) with respect to front total toe-in angle (°).

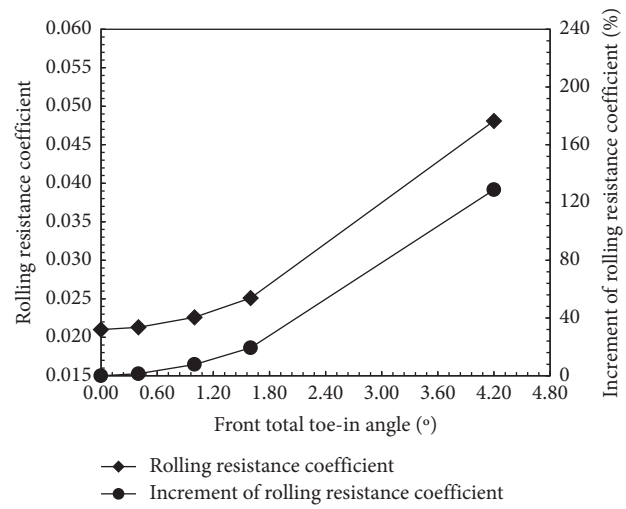

Figure 6: Variation of rolling resistance coefficient and rolling resistance coefficient rate (%) with respect to front total toe-in angle (°).

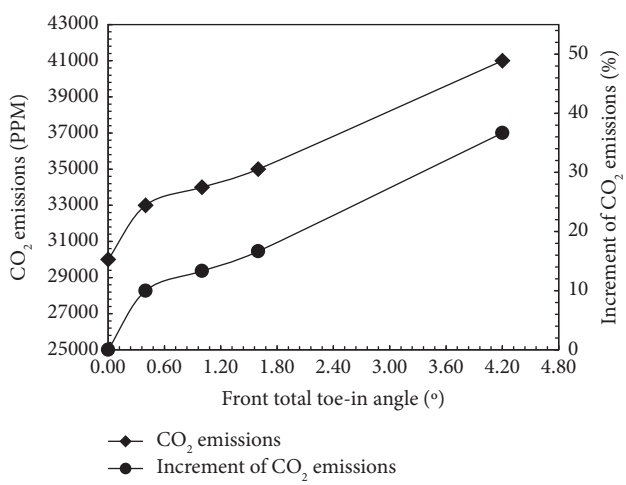

Figure 7: Variation of CO_2 emissions and CO_2 emissions rate (%) with respect to front total toe-in angle (°).

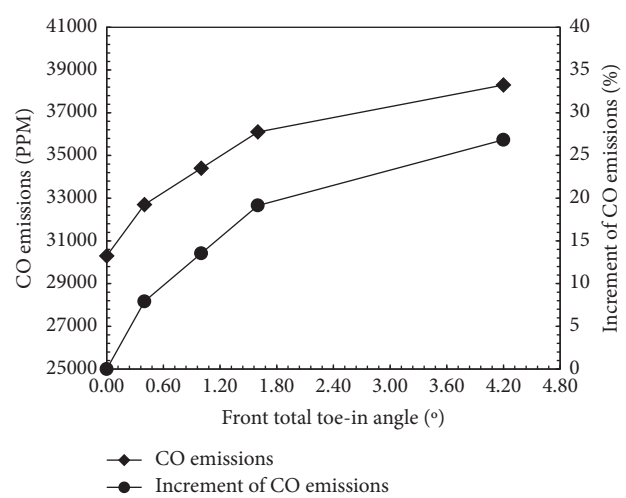

Figure 8: Variation of CO emissions and CO emissions rate (%) with respect to front total toe-in angle (°).

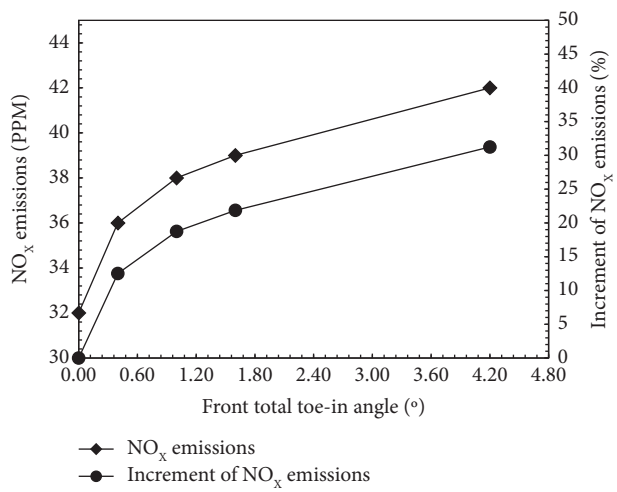

Figure 9: Variation of NO_x emissions and NO_x emissions rate (%) with respect to front total toe-in angle (°).

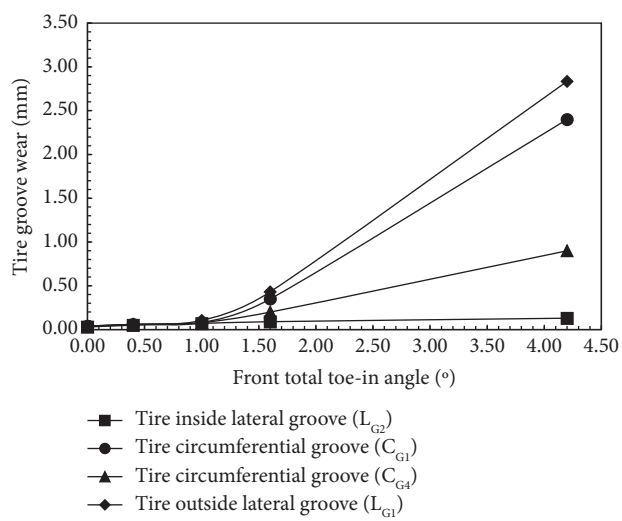

Figure 10: Variation of tire outside lateral groove wear (mm), inside lateral groove wear (mm), and circumferential groove wear (mm) with respect to front total toe-in angle (°).

$$r_{\alpha t_{cg}} = \frac{\sum_{i=1}^{n} (\alpha_i - \overline{\alpha})(t_{cg} - \overline{t}_{cg})}{\sqrt{\sum_{i=1}^{n} (\alpha_i - \overline{\alpha})^2 \sum_{i=1}^{n} (t_{cg} - \overline{t}_{cg})^2}}. \quad (5)$$

The correlation coefficient ($r_{\alpha t_{cg}}$) is found to be 0.97 for front total toe-in angle and tire circumferential groove wear, and the correlation coefficients ($r_{\alpha E_{CO_2}}$), ($r_{\alpha E_{CO}}$), and ($r_{\alpha E_{NO_X}}$) are found to be 0.98, 0.91, and 0.88 for front total toe-in angle and CO_2, CO, and NO_x emissions, which is within the range of $1 < r_{\alpha t_{cg}} > 0.75$ [37]. It demonstrates a strong positive correlation among front total toe-in angle, tire wear, and emissions (CO_2, CO, and NO_x) for light-duty vehicles.

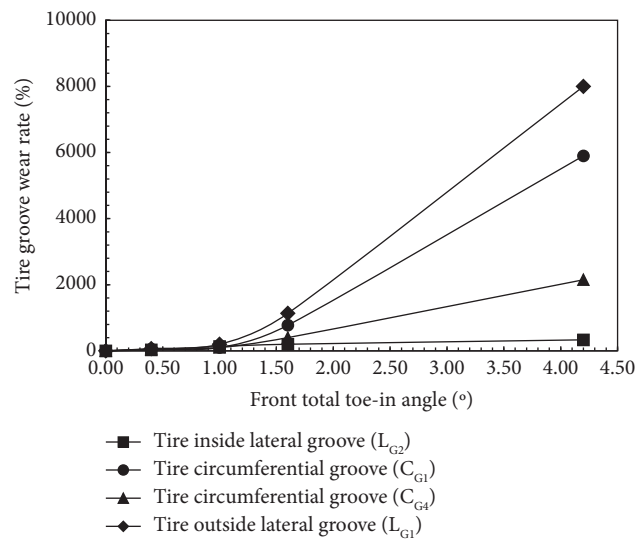

Figure 11: Variation of tire outside lateral groove wear rate (%), inside lateral groove wear rate (%), and circumferential groove wear rate (%) with respect to front total toe-in angle (°).

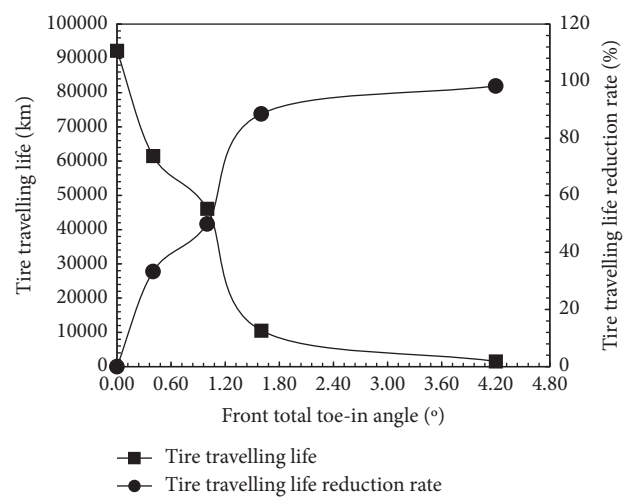

Figure 12: Variation of tire travelling life (km) and tire travelling life reduction rate (%) with respect to front total toe-in angle (°).

4. Data Analysis and Correlation Development

4.1. Regression Analysis. It is found in the literature [8, 11] that most researchers have discussed their research outcomes using various models where the experimental results support the case model-based analyses. Apart from various models, a regression analysis is one of the most powerful statistical methods for examining the relationship between two or more variables of interest. The most frequently employed method by sociologists is the linear equation. As a result, the multiple linear regressions can be written in the following form:

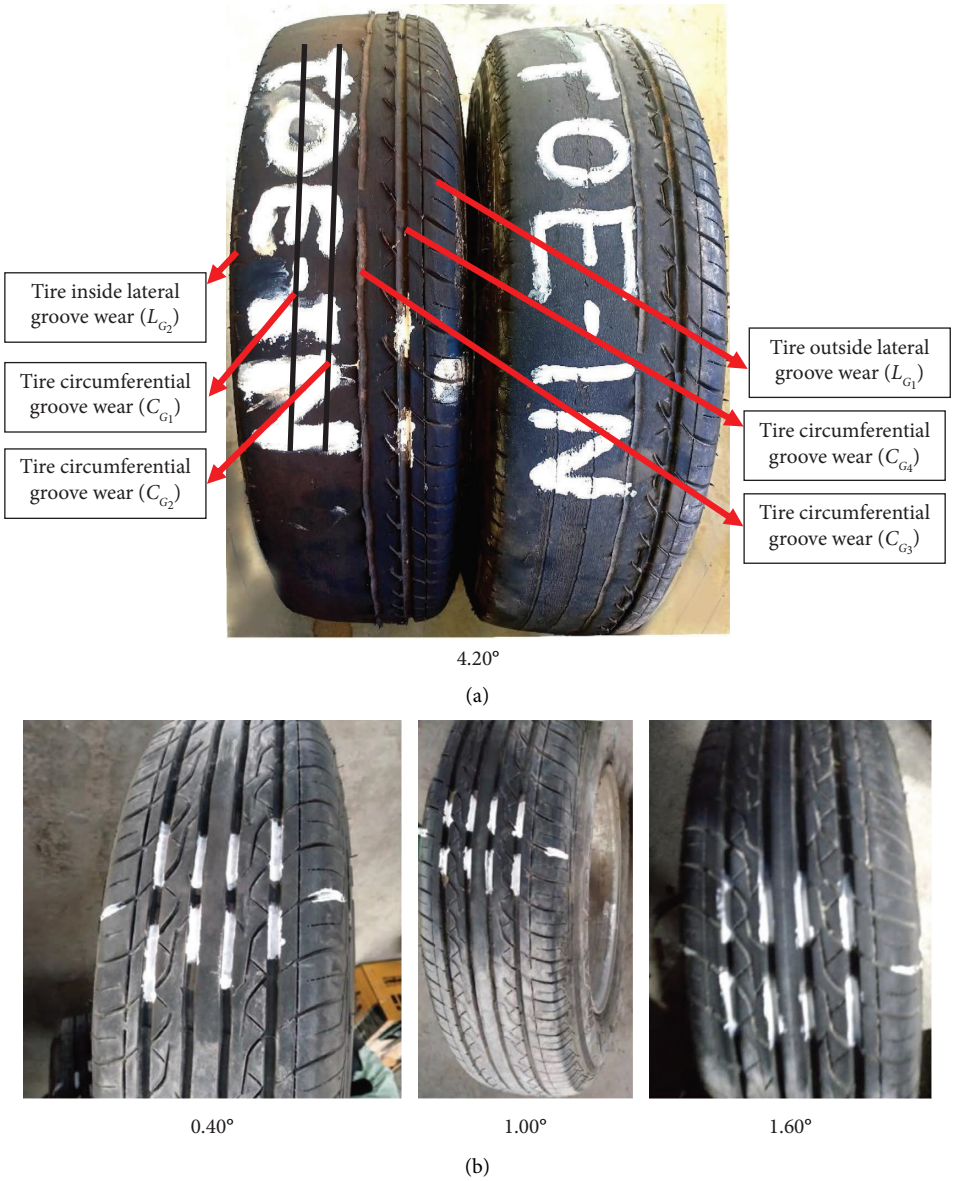

Figure 13: A photographic view of tire wear at different front total toe-in angles (a) at 4.20° and (b) at 0.40°, 1.00°, and 1.60°.

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 + \cdots\cdots\cdots\cdots + b_kX_k, \quad (6)$$

where Y is the dependent variable to be determined; X_1, X_2, X_3,. . ., X_k are the known variables on which the predictions are to be made, and a, b_1, b_2, b_3,. . ., b_k are the coefficients to be determined through the least squares method.

In this study, the analysis of variance (ANOVA) is employed to determine the level of significance of the effect of wheel front total toe-in angle on tire wear and CO_2 emissions. Tables 3 and 4 present sample ANOVAs for tire wear and CO_2 emissions with respect to the total toe-in angle of the front wheel. The mean effects of wheel front total toe-in angle on tire wear and CO_2 emissions are highly significant at the 0.01 probability level.

The experimental method was developed based on the concepts of Singh and Taheri [38] and Kim and Lee [39], which focused on the regression model and the wheel alignment inspection process. Regression analysis is carried out to determine the best prediction equation describing tire wear and CO_2 emissions in relation to the wheel front total toe-in angle. Regression models are chosen according to their best R square and their level of statistical significance. It was found that the proposed regression model maintained a good correlation with the experimental data for the dependent variables (tire wear and CO_2 emissions) and the independent variables (front total toe-in angle, engine RPM, rolling resistance, rolling resistance coefficient, and energy consumption). The following correlation models in terms of different factors, such as front total toe-in angle, engine

Table 3: (a) ANOVA for tire wear in terms of wheel front total toe-in angle. (b) Regression analysis for the effect of wheel front total toe-in angle on tire wear.

	df	SS	MS	*F* value	Significance *F*
(a)					
Regression	1	3.8731	3.8731	33.39	0.0044
Residual	4	0.3040	0.1013		
Total	5	4.1771			

Model no.	Form of equation	Equation constants m_1	k_1	Multiple *R*	*R* square	Adjusted *R* square	Stand. error	*p* value
(b)								
1	$(T_w)_{1,1} = m_{1\alpha} + k_1$	0.593	−0.268	0.961	0.927	0.903	0.318	0.008
2	$(T_w)_{2,1} = m_1 R/M + k_1$	0.006	−8.884	0.924	0.854	0.805	0.451	0.025
3	$(T_w)_{3,1} = m_1 \mu_{\mathrm{RRC}} + k_1$	88.312	−1.853	0.999	0.998	0.998	0.047	$2.705E-05$
4	$(T_w)_{4,1} = m_1 R_R + k_1$	0.009	−1.857	0.999	0.998	0.997	0.049	$2.999E-05$
5	$(T_w)_{5,1} = m_1 E_c + k_1$	0.002	−1.857	0.999	0.998	0.997	0.049	$2.999E-05$
6	$(T_w)_{6,1} = m_{1\alpha} + m_1^* R/M + k_1$	1.004; −0.005*	6.079	0.971	0.942	0.885	0.346	0.542
7	$(T_w)_{7,1} = m_{1\alpha} + m_1^* \mu_{\mathrm{RRC}} + k_1$	−0.077; 99.073*	−2.039	0.999	0.999	0.999	0.038	0.005
8	$(T_w)_{8,1} = m_{1\alpha} + m_1^* R_{\mathrm{R}} + k_1$	−0.076; 0.011*	−2.041	0.999	0.999	0.998	0.041	0.006
9	$(T_w)_{9,1} = m_{1\alpha} + m_1^* E_{\mathrm{c}} + k_1$	−0.076; 0.002*	−2.041	0.999	0.999	0.998	0.041	0.006

Note. $(T_w)_{i,j} = T_w$ means tire wear; i = model number and j = effect of wheel front total toe-in angle on tire wear.

Table 4: (a) ANOVA for CO_2 emissions in terms of wheel front total toe-in angle. (b) Regression analysis for the effect of wheel front total toe-in angle on CO_2 emissions.

	df	SS	MS	*F* value	Significance *F*
(a)					
Regression	1	62831004.37	62831004.37	79.57	0.0030
Residual	3	2368995.63	789665.21		
Total	4	65200000			

Model no.	Form of equation	Equation constants m_2	k_2	Multiple *R*	*R* square	Adjusted *R* square	Stand. error	*p* value
(b)								
1	$(E_{CO_2})_{1,2} = m_{2\alpha} + k_2$	2390.83	31157.21	0.986	0.964	0.951	888.63	0.003
2	$(E_{CO_2})_{2,2} = m_2 R/M + k_2$	27.44	−5875.16	0.999	0.999	0.999	96.84	$3.805E-06$
3	$(E_{CO_2})_{3,2} = m_2 \mu_{\mathrm{RRC}} + k_2$	324713.70	25631.41	0.930	0.865	0.820	1714.32	0.022
4	$(E_{CO_2})_{4,2} = m_2 R_R + k_2$	34.72	25617.10	0.930	0.865	0.820	1713.41	0.022
5	$(E_{CO_2})_{5,2} = m_2 E_c + k_2$	5.78	25617.10	0.930	0.865	0.820	1713.41	0.022
6	$(E_{CO_2})_{6,2} = m_{2\alpha} + m_2^* R/M + k_2$	−97.58; 28.52	−7329.44	0.999	0.999	0.999	111.02	0.005
7	$(E_{CO_2})_{7,2} = m_{2\alpha} + m_2^* \mu_{\mathrm{RRC}} + k_2$	3345.21; −140933.28*	33675.48	0.986	0.973	0.946	937.98	0.493
8	$(E_{CO_2})_{8,2} = m_{2\alpha} + m_2^* R_R + k_2$	3341.08; −15.01*	33670.52	0.986	0.973	0.946	939.31	0.495
9	$(E_{CO_2})_{9,2} = m_{2\alpha} + m_2^* E_c + k_2$	3341.08; −2.50*	33670.51	0.986	0.973	0.946	939.31	0.495

Note. $(E_{CO_2})_{i,j} = E_{CO_2}$ means CO_2 emissions; i = model number and j = effect of wheel front total toe-in angle on CO_2 emissions.

RPM, rolling resistance, rolling resistance coefficient, energy consumption, tire wear, and CO_2 emissions, are developed by defining their relationships.

4.1.1. Effect of Wheel Front Total Toe-In Angle on Tire Wear. Based on experimental data, nine different correlation models are developed using the regression method, which are (i) Model 1: correlation between front total-in angle and tire wear; (ii) Model 2: correlation between engine RPM and tire wear; (iii) Model 3: correlation between rolling resistance coefficient and tire wear; (iv) Model 4: correlation between rolling resistance and tire wear; (v) Model 5: correlation between energy consumption and tire wear; (vi) Model 6: correlation among the front total-in angle, engine RPM, and tire wear; (vii) Model 7: correlation among the front total-in angle, rolling resistance coefficient, and tire wear; (viii) Model 8: correlation among the front total-in angle, rolling resistance, and tire wear; (ix) Model 9: correlation among the front total-in angle, energy consumption, and tire wear.

Each regression model is subjected to a total of five tests. The R square, adjusted R square, and p values of the corresponding regression model are shown in Table 3. This value is found to be 0.9272 in model 1. It can be said that the front total toe-in angle explains 92.72% of the variation in the tire wear rate. It is observed that the values of R^2 and adjusted R^2 are 0.9272 and 0.9029, respectively. These values are very close, and the p values are less than 0.05, indicating a perfect relationship between front total toe-in angle and tire wear. Based on the statistical analysis, it has been determined that making changes to the front total toe-in angle from 0.00° to 4.20° shows a substantial correlation with the change in tire wear rate. The correlation coefficient value between these two variables is approximately 92.72%, indicating that there is a strong relationship between them. This finding suggests that changes in the front total toe-in angle can significantly impact the tires' longevity and performance.

Similarly, models 2 to 9 show a true relationship between the dependent and independent variables that predict the tire wear rate. The correlation R square values of 85.41%, 99.84%, 99.82%, 99.82%, 94.24%, 99.93%, 99.91%, and 99.91% for models 2, 3, 4, 5, 6, 7, 8, and 9, respectively, were tending towards 1. Hence, the developed regression model can be used to explain the variation in tire wear.

4.1.2. Effect of Wheel Front Total Toe-In Angle on CO_2 Emissions. Likewise, nine different correlation models are developed using the regression method in terms of the impact of wheel front total toe-in angle on CO_2 emissions, which are (i) Model 1: correlation between front total toe-in angle and CO_2 emissions; (ii) Model 2: correlation between engine RPM and CO_2 emissions; (iii) Model 3: correlation between rolling resistance coefficient and CO_2 emissions; (iv) Model 4: correlation between rolling resistance and CO_2 emissions; (v) Model 5: correlation between energy consumption and CO_2 emissions; (vi) Model 6: correlation among the front total toe-in angle, engine RPM, and CO_2 emissions; (vii) Model 7: correlation among the front total toe-in angle, rolling resistance coefficient, and CO_2 emissions; (viii) Model 8: correlation among the front total toe-in angle, rolling resistance, and CO_2 emissions; (ix) Model 9: correlation among the front total toe-in angle, energy consumption, and CO_2 emissions.

The corresponding R square, adjusted R square, and p values of the regression model are shown in Table 4. In Table 4, the value is found to be 0.9640. Thus, it can be said that the front total toe-in angle explains 96.40% of the variation in the CO_2 emissions rate. It is also seen that the values of R^2 and adjusted R^2 are 0.9640 and 0.9510, respectively; these values are very close, and the p values are less than 0.05, by which it can be claimed that the relationship between the front total toe-in angle and CO_2 emissions is acceptable. Similar results are obtained for models 2 through 9, respectively. The correlation R square values of 99.90%, 86.50%, 86.50%, 86.50%, 99.90%, 97.30%, 97.30%, and 97.30% for models 2, 3, 4, 5, 6, 7, 8, and 9, respectively, are approaching to the value of 1. Therefore, the developed regression model can explain the variance of CO_2 emissions.

5. Conclusions

The presented research work has analyzed the effect of wheel alignment (front total toe-in angle) on tire wear, tire travel life, and emissions (CO_2, CO, and NO_x) for light-duty vehicles. Based on the analytical and experimental findings, the outcomes are summarized as

(i) The angle rate, engine RPM, rolling resistance, energy consumption, and emissions rate increased as the vehicle's front total toe-in angle increased.

(ii) The experimental results show that the front total toe-in angle strongly correlates with rolling resistance. Tire rolling resistance has been observed to impact vehicle tire life and emissions considerably. The results show that the rate of increase in rolling resistance is found to be about 128.86%, and the rate of CO_2, CO, and NO_x emissions is increased by nearly 36.67%, 26.83%, and 31.25% for the car as the front total toe-in angle increases to 4.20°.

(iii) In cases of misalignment of the toe-in angle, it has been found that tire wear primarily began from the outer shoulder to the inner shoulder of the tire. The outside of the tread wears out much faster on a front tire with an excessive toe-in (4.20°).

(iv) It has been observed that due to misalignment of the front total toe-in angle (from 0.00° to 4.20°), the tire travel life is approximately 90712.5 km less for the same size of tire and the tire travel life reduction rate is about 98.33%.

(v) It has been found that the proposed regression models have maintained a good correlation between a dependent variable and an independent variable with the experimental data. The correlation R square

values for the models are tending towards 1. Hence, the variance in tire wear and emissions can be explained by the developed regression model.

According to the observations, a proper wheel alignment, especially the manufacturer's standard toe-in angle, can significantly improve the tire's travel life, reduce the total emissions for the light-duty vehicle, and make passengers safer and more comfortable. Therefore, it is recommended to maintain the standard front total toe-in angle at all times for better tire life and lower exhaust emissions.

Nomenclature

α:	Values of the front total toe-in angle (°)
$\overline{\alpha}$:	Mean of the values of the front total toe-in angle (°)
$\overline{t}_{cg}$:	Mean of the values of the tire circumferential groove
$r_{\alpha t_{cg}}$:	Pearson's correlation coefficient for front total toe-in angle and tire circumferential groove
μ_{RRC}:	Rolling resistance coefficient (dimensionless)
t_{cg}:	Tire circumferential groove (mm)
V_s:	Vehicle speed (km/hr.)
R_R:	Rolling resistance (N)
W_v:	Vehicle weight (N)
T_d:	Traveling distance (km)
T_p:	Tire pressure (psi)
E_c:	Energy consumption (KJ)
α_t:	Slip/toe angle (°)
RPM:	rev/min
L_{G1}:	Tire outside lateral groove (mm)
L_{G2}:	Tire inside lateral groove (mm)
C_{G1}, C_{G2}, C_{G3}, C_{G4}:	Tire circumferential groove (mm)
T_{tl}:	Tire travelling life (km)
T_{cgd}:	Tire circumferential groove depth (mm)
T_w:	Tire wear (mm)
IRI:	International roughness index
PCR:	Pavement condition rating.

Data Availability

The data used to support the findings of this study can be obtained from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors would like to acknowledge the Directorate of Research and Extension (DRE) section of Chittagong University of Engineering & Technology for their financial support to continue the project. The authors would also like to thank the Department of Mechanical Engineering for their support and providing lab facilities.

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