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EFFECT OF WHEEL ALIGNMENT, SPEED AND ROAD CONDITION ON FUEL EFFICIENCY OF A LIGHT-DUTY VEHICLE

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ABSTRACT

The fuel efficiency of a TOYOTA ECHO PLUS-2ZZ-GE-02 model light-duty vehicle was investigated experimentally based on the wheel alignment system. The light vehicle has been analyzed with the variation of vehicle speed under three different road pavement conditions. A computerized wheel alignment machine (Best-5800) was used to measure the wheel alignment condition of the light vehicle. The experimental results show that the fuel efficiency of the vehicle depends on the state of the road and the alignment of the wheels. The result also noted that proper wheel alignment and good road pavement conditions with a recommended speed limit can significantly enhance the safety of suspension system component life, reduce tire wear, and boosts vehicle mileage and driver satisfaction. The Pearson's correlation coefficients (r_{zy}) suggest that vehicle speed and fuel consumption are strongly correlated for fair and poor pavement conditions, however, a moderate correlation was observed in very poor pavement conditions.

Keywords: *Wheel alignment, Computerized machine vision, Fuel efficiency, Road pavement condition*

NOMENCLATURE

x	= Values of the speed (km/h)
$\bar{x}$	= Mean of the values of the speed (km/h)
y	= Values of the fuel consumption (ml)
$\bar{y}$	= Mean of the values of the Fuel consumption (ml)
r_{xy}	= Correlation coefficient(dimensionless)

1. INTRODUCTION

The wheel alignment measurement system is one of the most important features of the vehicle maintenance schedule. The advancement of automotive technology and the speed of travel of an automobile are greatly increased, however, at the same time the demands of automotive stability and travel safety are also increasing more rapidly. The alignment system analyzes the wheel functions which are an important component of the vehicle stability and safety system. Recent research shows that most road accidents are caused by improper wheel adjustment and that the steering function is not in a turning position. The condition becomes even more critical in the case of underdeveloped countries due to the lack of adequate planning and maintenance programs for wheel alignment. Numerous researches have conducted on active systems, however, a few studies have focused on wheel alignment systems [1-8]. It is worth noting that the misalignment of the wheel can have a significant impact on vehicle performance, e.g. fuel consumption increased considerably with an increase in misalignment. Moreover, the wheels wear out rapidly [6].

Nowadays, modern passenger vehicles have introduced different wheel alignment techniques for security reasons. The main purpose of the wheel alignment is to ensure the vehicle running in a straight and the right position without pulling to one side or other sided [1,2]. The functions of the vehicle wheel alignment system are the caster, camber, toe, and steering axis inclination (SAI) alignment, which can be easily measured by using IR sensors [3]. In this technique, a computerized wheel alignment machine is used to measure wheel

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alignment for heavy and light vehicles [3-6]. The process has low-cost benefits, a simple electronic circuit, high resolution with better working reliability, and the process used to facilitate system data transfer which is better than the traditional system [2-4]. In recent years, the machine vision process is extensively used for an easy and proper way to know the characteristic angles [5]. The process is used to measure the active function of the vehicle safety system as well as to adjust the characteristic wheel angles [7]. S. Chatur [4] experimentally studied the misalignment functions of vehicles using a computerized wireless system and an accelerometer to measure the data. A. Padegaonkar et al. [8] conducted wheel characteristic angles in vehicles for manufacturer specifications with the use of a machine vision system instead of the conventional process. Salave and Sarode [6] experimentally investigated that tire life and vehicle fuel efficiency are significantly improved when vehicle wheel alignment is checked regularly.

The road surface condition/roughness is another important factor that directly affects the lifespan of the tires and the fuel efficiency of the vehicle. Pavement surface roughness is normally measured using irregularities in the pavement surface through the International Roughness Index (IRI). It should be noted that the lifetime of the tires is inferred when the tread is worn to a minimum depth or has uneven wear [9,10]. Patrick [9] investigated that about 75.4% of the tires assessed had uneven wear profiles due to incorrect tire-road contact effects. It is well known that incorrect tire-road contact is associated with irregularities in the pavement surface. The researchers also showed that tire safety and road vehicle stability as well as driver and passenger satisfaction are related to the quality of tire, tire material, and appropriate tire size [11]. In the present study, a computerized wheel alignment measurement system based on machine vision was used to analyze the fuel efficiency of an ECHO PLUS-2ZZ-GE-02 model light-duty vehicle with three different road pavement conditions at different vehicle speed.

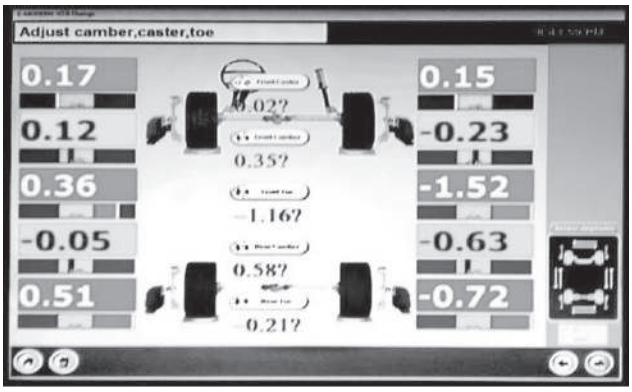
2. EXPERIMENTAL PROCEDURE

Wheel alignment is the adjustment of wheel angles so that they are perpendicular to the ground and parallel to one another. Wheel alignment functions are related to the caster, camber, toe-in and toe-out, kingpin inclination, turning radius, etc. The experimental analysis involves a preliminary check of wheel alignment through a manual check of all parts associated with wheel alignment. The vehicle is then aligned through a computer-assisted wheel alignment machine (Best-5800) as shown in Fig. 1. The computer vision-based commercial software for the wheel alignment system was used to measure the caster, camber and toe angles and these angles were adjusted by loosen and tightening the tie rod and push rod function with the steering system. For data capture, the four sensors were attached to four-wheel discs on the front and rear axle. Then, the system was used to utilize the images captured by a video camera, and the images were then processed using a built-in algorithm to obtain the main wheel angles as shown in Fig. 2 and measured data are presented in Table 1. The measurement of the wheel alignment was carried out in specific vehicle particulars given below.

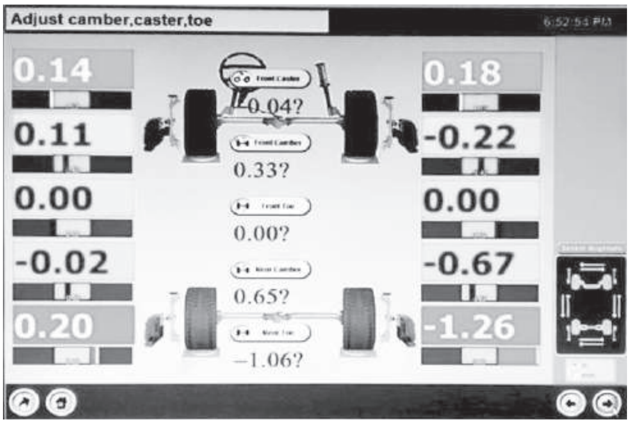
Vehicle Particulars

Vehicle Model: TOYOTA ECHO PLUS-2ZZ-GE-02
Engine displacement: 1300 cc
Tire Size: 175/70R14
Vehicle weight with load: 1305Kg
Air condition system: Non air condition
Gear position: Auto transmission
Type of fuel: Octane
Tire Pressure (Front) = 32 psi
Tire Pressure (Rear) = 30 psi
One driver and two passenger weight = 197 Kg
Average weather temperature (T_{av}) = 20.6°c
Average weather humidity (av) = 72.6%
Tire outer diameter (Front left) = 596 mm
Tire outer diameter (Front right) = 596 mm
Tire outer diameter (Rear left) = 595.5 mm
Tire outer diameter (Rear right) = 595.5 mm

Fig. 1 Experimental setup for wheel alignment system.



(a) Before alignment



(b) After alignment.

Fig. 2 Display before alignment and after alignment.

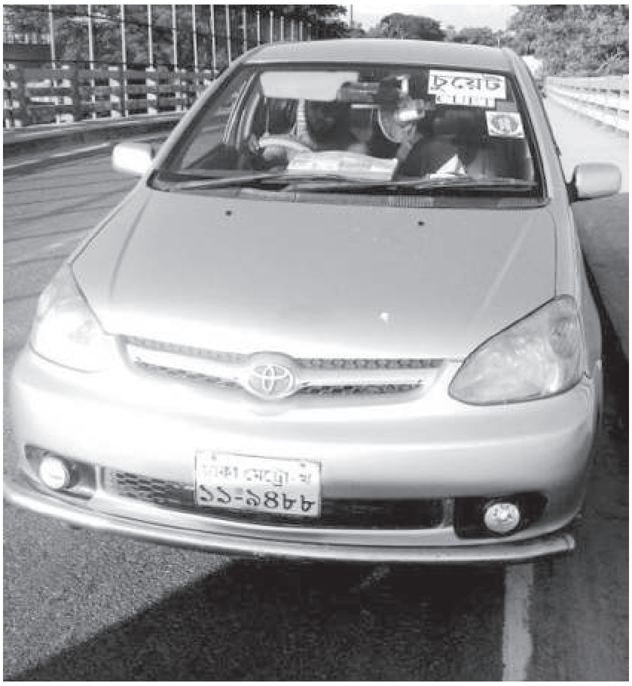
Table 1 Wheel Alignment data for ECHOPLUS-2ZZ-GE-02, 1300cc light vehicle

Condition	Position	Toe	Camber
Before alignment	L	0.36°	0.12°
	R	-1.52°	-0.23°
After alignment	L	0.00°	0.11°
	R	0.00°	-0.22°

* L = Left; R = Right

In this study, an ECHO PLUS-2ZZ-GE-02 vehicle was considered for analysis of the fuel efficiency as a function of wheel alignment and three different road pavement conditions with the variation of vehicle speed. For the analysis, three road pavement conditions such as fair road pavement, poor road pavement, and very poor road pavement were considered as shown in Fig. 3. Road pavement roughness is generally measured by the International Roughness Index (IRI). The Bangladesh Roads and Highways Department (RHD) conducts regular nationwide surveys to obtain IRI data [12]. Their statistical data showed that the IRI values for fair, poor, and very poor road pavement are 1.8, 3 and 5.5 respectively. The Pavement Condition Rating (PCR) is also a well-known methodology for assessing the service life of flexible pavement conditions. The IRI data of several road conditions were then converted to PCR values. For classifying conditions as “Very Poor”, “Poor”, “Fair”, “Good” or “Very Good” a range of PCR of 0-50, 51-70, 71-80, 81-90 and 91-100 were used respectively [12].

a) Fair road pavement condition.



b) Poor road pavement condition

c) Very poor road pavement condition
Fig. 3 Road pavement condition for vehicle testing.

3. ANALYSIS RESULTS

3.1 Wheel alignment

There are a number of factors that can cause vehicle wheels to be misaligned. The vehicle traveling distance with the road pavement condition is one of the key factors that lead to the misalignment of the wheel. For the analysis, three different types of road pavement conditions with a fixed traveling distance of 8 km were considered. The light-duty vehicle was tested at ten different speeds of 10 km/h, 20 km/h, 30 km/h, 40 km/h, 50 km/h, 60 km/h, 70 km/h, 80 km/h, 90 km/h, 100 km/h and, respectively, after each test, the wheel alignment and fuel consumption data were recorded as shown in Tables 1-4, respectively. The statistical data analysis at Rahimafrooz Auto Center, Bangladesh found that the vehicle wheel alignment became misaligned when the running distance range was assumed to be 3000 km (approx.) for very poor road pavement conditions, 4000 km (approx.) for poor road pavement conditions, and 5000 km (approx.) for the fair pavement conditions. The analysis results observed that the fuel consumption rate was greatly increased with wheel misalignment. However, the analysis results also suggest that regularly checking and adjusting the wheel alignment may have greatly improved the overall performance of the vehicle and reduced fuel consumption.

3.2 Fuel consumption

The fuel consumption rate based on three different road pavement conditions with various vehicle speeds is shown in Tables 2-4 and graphically illustrated in Figs. 4-6 shows fuel consumption and KPL rates based on vehicle speed under three different road pavement conditions. The analysis result showed that the fuel consumption shows a significant variation depending on the vehicle speeds and road pavement conditions with wheel alignment. Fuel consumption increased with the speed of the vehicle and became the maximum value at approximately 50 km/h of the vehicle speed. Fuel consumption was further reduced by increasing the speed of the vehicle. It was also found that the fuel consumption rate was much higher in very poor road pavement conditions. However, fuel consumption improved considerably as the wheel alignment was adjusted. It is well understood that speed plays an important role in deciding vehicle handling and fuel efficiency. Furthermore, an incorrect speed may increase the risk of wheel misalignment and thus increase the fuel consumption rate. It is interesting to note that the fuel efficiency changed when the vehicle speed was varied.

Comparison of the fuel efficiency in Fig. 4 to Fig. 6 shows that the proper wheel alignment can save the fuel consumption at about 4.95% for fair road pavement, 5.64% for poor road pavement and 6.59% for very poor road pavement, respectively when the vehicle was running at 10 km/hr. It is interesting to note that the rate of the fuel consumption history (Figs. 4(a), 5(a) and 6(a)) shows some dependency on the vehicle speed, while the rate of the KPL history (Figs. 4(b), 5(b) and 6(b)) is nearly independent of the vehicle speed. The dependency is very likely caused by the different road conditions.

The experimental result has been verified by the Pearson's correlation coefficient, r_{xy} can be expressed as

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

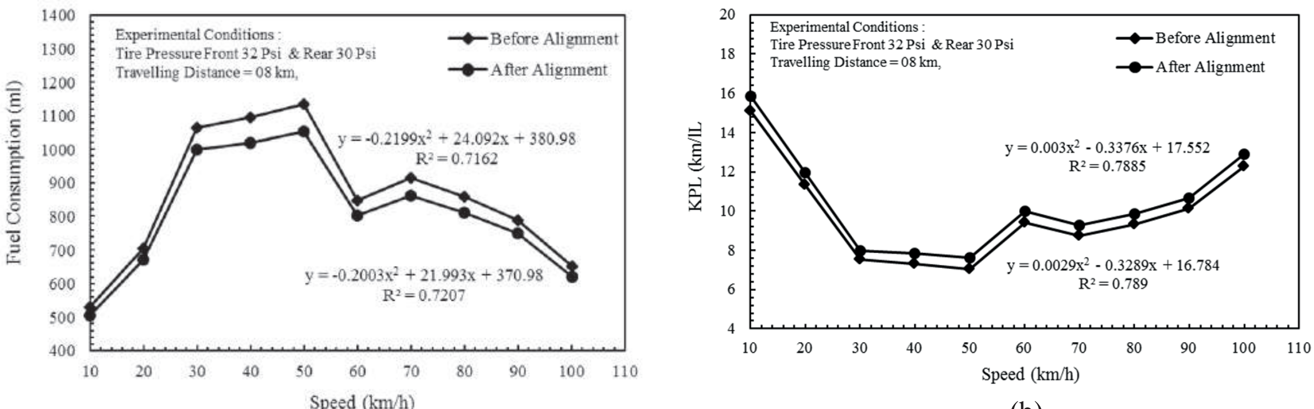
The Pearson's correlation coefficient (r_{xy}) were found 0.71 (in the range $1<r_{xy}> 0.70$) before alignment and 0.72 (in the range $1<r_{xy}> 0.70$) after alignment, and PCC values for very poor pavement were found to be 0.59 before and after alignment, respectively [13]. The PCC values suggest that the very poor pavement condition shows a moderate correlation among the three road conditions.In the above experimental study, it was observed that the fuel consumption of the light vehicle increases with the variation of speed, road and alignment conditions. As shown in Figs. 7(a) and (b), there was a little variation in fuel consumption on both fair and poor road pavement; however, the percentage of fuel losses became much higher in very poor road pavement conditions. Likewise, the maximum fuel loss readings were observed at a vehicle speed of 50 km/h. The percentage of fuel loss is further reduced by varying the speed and proper alignment with a proper road pavement of the vehicle. It turns out that the fuel consumption rate was significantly higher in very poor road pavement conditions. This is because of the higher rolling resistance associated with the roughness of the road.

It is worth noting that the fuel efficiency or fuel consumption rate does not depend on one factor, but rather on several factors. The fuel consumption may also vary according to engine performance, tire pressure, tire wear, suspension conditions, load condition, temperature, humidity, wheel angles, etc. [14-16].

From the above discussion, it was concluded that proper wheel alignment and good road surface conditions with a recommended speed limit can significantly enhance the safety of suspension system component life, reduce tire wear, and boosts vehicle mileage and driver satisfaction.

Table 2 Fuel consumption and KPL data of the ECHOPLUS-2ZZ-GE- 02 light vehicle for fair road pavement

Speed (x)	Before Alignment		After Alignment		% of fuel loss for misalignment and speed
	Fuel Consumption (ml)(y)	KPL(km/L)	Fuel Consumption (ml)(y)	KPL(km/L)	
10	530	15.094	505	15.841	4.95%
20	705	11.347	670	11.940	5.22%
30	1065	7.511	1000	8	6.50%
40	1095	7.305	1020	7.843	7.35%
50	1134	7.054	1052	7.604	7.79%
60	849	9.422	802	9.975	5.86%
70	915	8.743	863	9.269	6.02%
80	860	9.302	812	9.852	5.91%
90	790	10.126	749	10.680	5.47%
100	652	12.269	620	12.903	5.16%

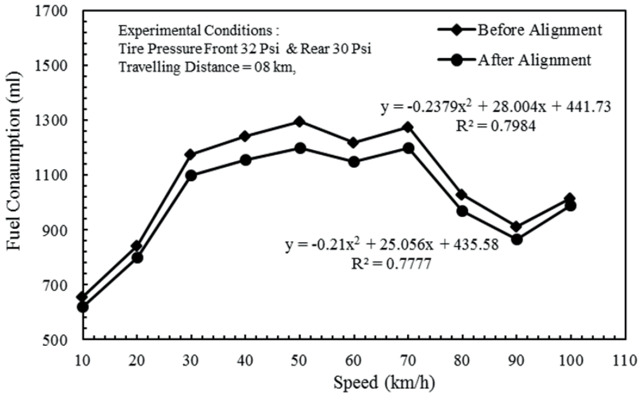


(a) (b)

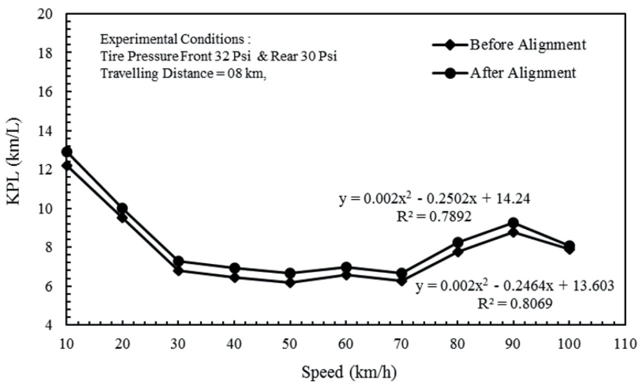
Fig. 4: (a) Variation of fuel consumption before and after alignment with respect to speed and (b) travelling distance (Km/L) before and after alignment with respect to speed for fair road pavement.

Table 3 Fuel consumption and KPL data of the ECHOPLUS-2ZZ-GE-02 light vehicle for poor road pavement

Speed (x)	Before Alignment		After Alignment		% of fuel loss for misalignment and speed
	Fuel Consumption (ml)(y)	KPL(km/L)	Fuel Consumption (ml)(y)	KPL(km/L)	
10	655	12.213	620	12.903	5.64%
20	842	9.501	800	10	5.25%
30	1175	6.808	1100	7.272	6.82%
40	1243	6.436	1155	6.926	7.62%
50	1295	6.177	1200	6.666	7.91%
60	1218	6.568	1150	6.956	5.91%
70	1276	6.269	1200	6.666	6.33%
80	1028	7.782	970	8.247	5.97%
90	914	8.752	865	9.248	5.66%
100	1015	7.881	990	8.080	5.85%



(a)

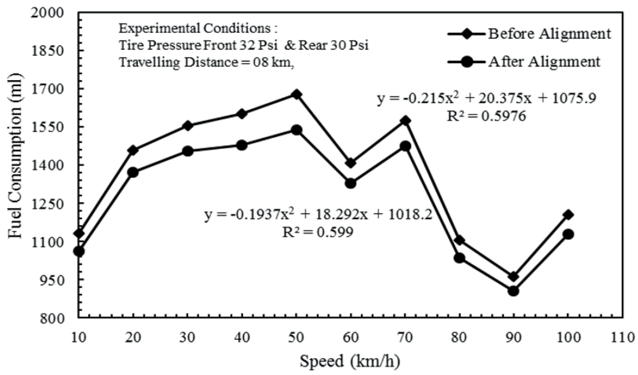


(b)

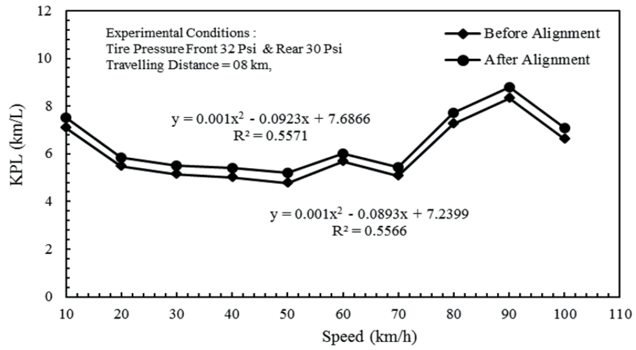
Fig. 5 (a) Variation of fuel consumption before and after alignment with respect to speed and (b) travelling distance (Km/L) before and after alignment with respect to speed for poor road pavement.

Table 4 Fuel consumption and KPL data of the ECHOPLUS-2ZZ-GE- 02 light vehicle for very poor road pavement

Speed (x)	BeforeAlignment		AfterAlignment		% of fuel loss for misalignment and speed
	Fuel Consumption (ml)(y)	KPL(km/L)	Fuel Consumption (ml)(y)	KPL(km/L)	
10	1132	7.067	1062	7.532	6.59%
20	1458	5.486	1373	5.826	6.19%
30	1557	5.138	1455	5.498	7.01%
40	1602	4.993	1480	5.405	8.24%
50	1680	4.761	1540	5.194	9.09%
60	1408	5.681	1328	6.024	6.02%
70	1577	5.072	1475	5.423	6.91%
80	1105	7.239	1035	7.729	6.76%
90	963	8.307	908	8.810	6.05%
100	1207	6.628	1130	7.079	6.37%

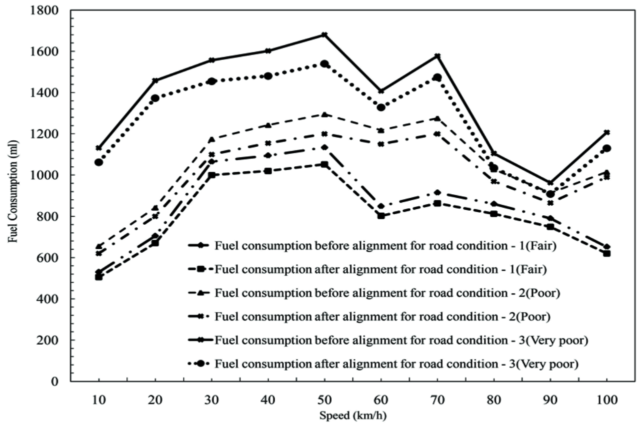


(a)

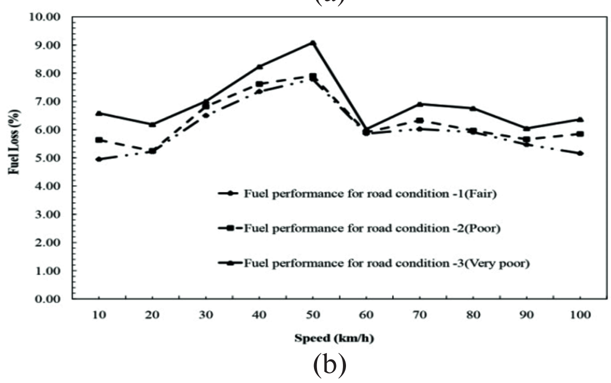


(b)

Fig. 6 (a) Variation of fuel consumption before and after alignment with respect to speed and (b) travelling distance (Km/L) before and after alignment with respect to speed for very poor road pavement.



(a)



(b)

Fig. 7: (a) Comparison of fuel consumption before and after alignment with respect to speed and road condition and (b) fuel loss with respect to speed and road condition.

4. CONCLUSION

The following conclusion can be drawn from the experimental results of a light-duty vehicle (TOYOTA ECHO-PLUS-2ZZ- GE-02) analyzed according to speed and road conditions with before and after wheel alignment:

・ It was observed that the fuel consumption rate was greatly increased with wheel misalignment. However, the analysis results also suggest that regularly checking and adjusting the wheel alignment may have greatly improved the overall performance of the vehicle and reduced fuel consumption.

・ The analysis result showed that the fuel consumption shows a significant variation depending on the vehicle speeds and road pavement conditions. The fuel consumption rate was even much higher in very poor road pavement conditions.

・ The Pearson's correlation coefficients (r_{xy}) indicate that vehicle speed and fuel consumption are strongly correlated for fair and poor pavement conditions, however, a moderate correlation was observed in very poor pavement condition.

According to the observations and experimental results obtained from the wheel alignment system, the right time and consideration of road conditions can have a major influence on the life of the tires, reduce tire wear, and increase vehicle mileage.

5. ACKNOWLEDGMENTS

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