Effect of Front Right Toe-out Angles on Fuel Consumption for a Light Vehicle

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Abstract
In this paper, fuel consumption for a TOYOTA ECHO PLUS-2ZZ-GE-02 model light vehicle has been analyzed by changing the front right toe-out angles. A computerized wheel alignment machine (Best-5800) has been used to measure the misalignment of the wheels. Fuel consumptions were then measured for different front right toe-out when the car was travel 6 km. The results show that the fuel consumption was increased linearly for front right toe-out angle 0^{o} to -0.36^{o}, whereas for -1.70^{o} to -2.53^{o}, the fuel consumption was increased nonlinearly. It was found that due to misalignment of front right toe-out angle (from 0.00° to -2.53°), the fuel consumption rate was increased up to 41.21%. The Pearson's correlation coefficient was found as $r_{(\alpha F)abs.}=0.99$, which proves a very strong correlation between fuel consumption and front right toe-out angle. Also, a mathematical model proposed in this study can be used to predict the amount of fuel consumption by the different model of vehicles.

Keywords
Wheel alignment, Wheel alignment machine, Fuel consumption, Front right toe-out angles and Light vehicle.

1. Introduction
In today's world, automobiles play an important role in everyday life. At present, with the advancement of automotive technology, the speed of travel of the automobile is increasing, but the impact of travel, safety and stability of automobiles is gradually diminishing. Among the different factors of stability and safety of the vehicle, wheel angles directly play an important role in the maintenance of the stability and safety of the vehicle (Salve and Sarodi, 2017; Kalita, 2016; Vijaya kumar and Ganesh, 2013). Nevertheless, most road accidents occur because of erroneous wheel adjustment and incorrect steering position (Pundir et al., 2019).The misalignment of the vehicle also reduces fuel consumption and increases tire wear. Figure 1 shows the effect on tire wear due to wheel misalignment. There are several factors associated with wheel misalignment, some factors are as follow-

- Impact on road conditions
- Improper design of vehicle body shape
- Improper height of vehicle body
- Improper construction of the suspension system
- Environmental conditions, e.g. corrosion, temperature
- High speed lead to overheat the wheel hub, bearing etc.
- King bolt/rivet failure
- Impact loading and bumping
- Excess weight of the vehicle body
- Premature failure by wrong bearing
- Improper brake function
- Improper steering wheel turning
- Impact on tire wear
- Change of straight-line stability
- Improper corner entry handling or turning
- Straight-ahead position change of the wheel
- Axle position change
- Wear of the steering knuckle

In this regard, car manufacturers have introduced several wheel alignment techniques to enhance the tire life and reduced the tire wear of the vehicle. Barhe and Gawalwad, 2016, proposed a wheel alignment active safety system that deals with IR sensors to accurately measure the caster, camber and toe angle settings. A computerized wheel alignment machine has been widely used to measure the correct wheel alignment of heavy and light vehicles (Barhe and Gawalwad, 2016; Patil and Kadlag, 2016). The system uses a simple circuit designed with high resolution and reliable to work which is available at low cost (Balakrishnan et al., 2016; Chatur, 2015). Another study shows that the wireless process used a simple data transfer system with better results than conventional systems (Chatur, 2015). In recent studies, a number of researchers have widely used the machine vision process to find out the wheel characteristic angles for easy and proper way (Furferi et al., 2013; Korhonen, 2020). The machine vision system inspection mechanism generally used four wheel centers; therefore, it cannot be applied to the wheel alignment inspection of the suspension modules. Kim and Lee, 2020, have introduced a novel and efficient way to inspect vehicle wheel alignment for suspension module.

It should be noted that driver satisfaction is directly related to tire stability, safety, tire quality, tire material and proper tire size (Young et al., 2017). Prabhu et al., 2014, demonstrates the dynamic alignment control using infrared light, depth imagery to enable automated wheel loading for the final automotive assembly line and the alignment features that provides real time data simultaneously and the improvement of the steerability and handling of the vehicle by avoiding the steering pull and the study of wheel wandering problems. Mascioa et al., 2012, shows the positive caster angle, negative caster angle, steering axis inclination (SAI), toe in angle, toe out angle and negative scrub radius have stabilizing effect on vehicle handling. It is noted that the tire wear and wheel misalignment is greatly influenced by the road surface condition. The tire tread wear and its performance depends on tire characteristics such as blocks, grooves, voids, sipes and channel design with grip on the road conditions (Sreeraj et al., 2016).

Though several techniques were available to adjust the misalignment of the wheels (Salve and Sarodi 2017; Kalita 2016; Barhe and Gawalwad, 2016; Patil and Kadlag, 2016), however, it needs to be investigated the fuel efficiency with the causes of wheel misalignment. It is obvious that the fuel economy of an automotive vehicle could not defined by a single factor, however, to a certain extent by several factors that includes engine performance, tire size, tire pressure, tire wear, suspension conditions, load conditions, road conditions, speed, braking application, temperature, humidity, wheel angles, etc. (Riton et al., 2018a). A great deal of research has been done to reduce tire wear, fuel consumption and incidental costs, reduce carbon emission to save the environment and make travel safer, and reduce transportation costs (Riton et al., 2018b). Also, a number of studies have been undertaken to improve fuel performance and tire life of an automotive vehicle (Riton et al., 2020a; Riton et al., 2020b; Riton et al., 2020c; Riton et al., 2021). Oduro et al., 2013, investigate the relationship between tire pressure and fuel consumption of vehicles. They suggest an experimental and a mathematical model for determining and prediction of the amount fuel consumption by different model vehicles. Riton et al., 2018c, experimentally demonstrates that the light vehicle becomes misalignment 4000-5000km after travelling, but regular examination and proper alignment can increase tire life.

In the present study, A TOYOTA ECHO PLUS-2ZZ-GE-02 model light vehicle was used to analyze the fuel consumption rate based on the front right toe-out angles.

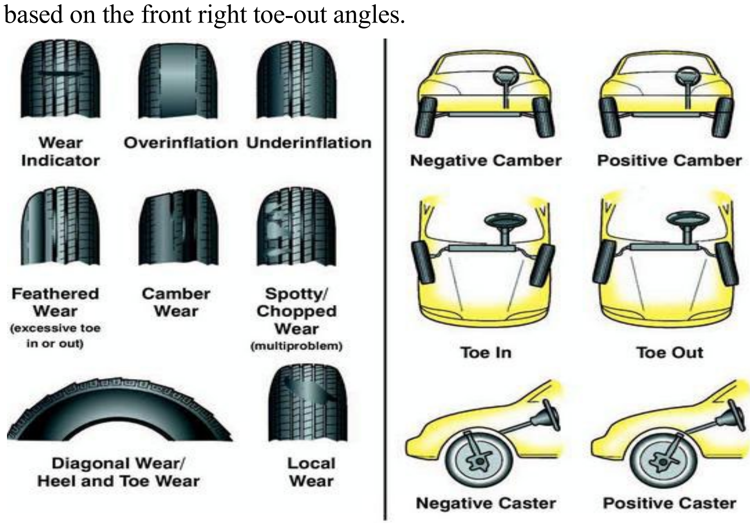


Figure 1: Effect of various alignment angles on tire (Chatur, 2015).

2. Experimental Procedure

The characteristic angles of the wheel are related to the alignment of the wheel and it is perpendicular to the surface and parallel to others. Wheel alignment functions are related to the caster, camber, toe and kingpin inclination, steering system, respectively. The experimental setup has been carefully carried out in such a way that the vehicle is on a level surface and must not have any slack or damage to the steering and suspension systems. Figure 2 shows the experimental setup for the wheel alignment system. An E-Modern (Best-5800) computerized wheel alignment machine was used to measure the front right toe angle. In this setup, the open end wrench was used to adjust the tie rod and pushrod function for the adjustment of the front right toe angle and the measured data was stored in computer memory drive. The correct measurement of the wheel alignment was carried out in accordance with a specific conditions such as: vehicle particulars, suspension condition, engine cylinder performance, and other alignment conditions as given below.

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

Suspension Conditions
LH FRONT Suspension Weight: 1.49kN
Adherence: 57%,
RH FRONT Suspension Weight: 1.76kN
Adherence: 60%,
LH REAR Suspension Weight: 1.1kN
Adherence: 45%,
RH REAR Suspension Weight: 1.12kN
Adherence: 51%,

Engine Cylinder Performance Conditions
Cylinder-1 = 80.63%
Cylinder-2 = 80.10%
Cylinder-3 = 80.63%
Cylinder-4 = 80.10%

Alignment Conditions
Caster angle (Left) = 0.12°
Caster angle (Right) = 0.10°
Camber angle (Left) = 0.17°
Camber angle (Right) = -0.25°
Tire pressure (Front and Rear) = 32 psi
Speed = 30 km/hr, Travelling distance = 6km
Driver and one passenger weight = 125kg

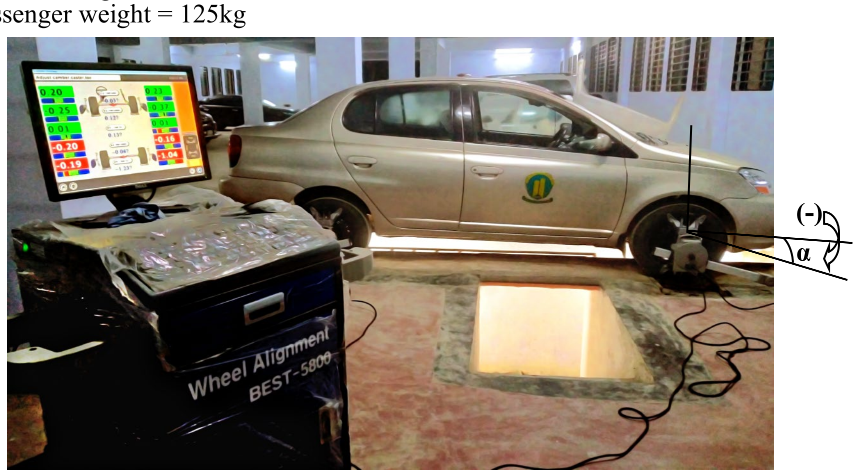


Figure 2: Experimental setup of wheel alignment system with wheel alignment machine (Best-5800).

For wheels alignment, at first, the light car is put in the alignment pit and the alignment turntable locks are opened, then the sensor connection boards are attached to the four wheels and connected the cables to the wheel alignment machine, and loading the car data into the wheel alignment machine and the brake pedal lever is attached. Then the steering wheel is turned and set the adjusting position of the wheel and attaching the steering handle holder. Finally, the wheel alignment condition of the car is checked and images were taken by adjusting the front right toe-out angle.

3. Mathematical Model

The vehicle experimental data (as shown in Table 1) have been used to develop a mathematical model by the least square method, the equation of the model is given by $F=B_0+B_1\alpha+B_2\alpha^2$, where F represent the fuel consumption and α is the front right toe-out angle, B_0, B_1 and B_2 are constants for the polynomial which must be derived from the experimental data. The above parabola equation can be written into three equations as:

$$\sum_{i=1}^{n} F_i = B_0\text{n} + B_1 \sum_{i=1}^{n} \alpha_i + B_2 \sum_{i=1}^{n} {\alpha_i}^2 \qquad (1)$$
$$\sum_{i=1}^{n} \alpha_i F_i = B_0 \sum_{i=1}^{n} \alpha_i + B_1 \sum_{i=1}^{n} {\alpha_i}^2 + B_2 \sum_{i=1}^{n} {\alpha_i}^3 \qquad (2)$$
$$\sum_{i=1}^{n} {\alpha_i}^2 F_i = B_0 \sum_{i=1}^{n} {\alpha_i}^2 + B_1 \sum_{i=1}^{n} {\alpha_i}^3 + B_2 \sum_{i=1}^{n} {\alpha_i}^4 \qquad (3)$$

By putting the various values from the Table 1 into the Equations (1), (2) and (3), we can get,

$$8304=20B_0+26.08B_1+47.31B_2 \qquad (4)$$
$$11534.37=26.08B_0+47.31B_1+95.59B_2 \qquad (5)$$
$$21468.96=47.31B_0+95.59B_1+204.28B_2 \qquad (6)$$

Solving above equation simultaneous gives B_0=4.383, B_1=41.896, and B_2 = 350.20. Now substituting the constant values to the model equation $F = 4.3838\alpha^2 +41.896\alpha+ 350.20$ as the model for predicting the vehicle fuel consumption.

4. Results and Discussion

Table-1 shows the experimental test result of fuel performance at different front right toe-out angles for the light vehicle of TOYOTA ECHO PLUS-2ZZ-GE-02 model. The results of this experimental study showed that the fuel consumption was increased as the misalignment (front right toe-out) of the car increases as shown in Figure 3(a). From this graph it was also seen that front right toe-out angle 0^o to -0.36^o, the fuel consumption was increased linearly, whereas for -1.70^o to -2.53^o, the fuel consumption was increased nonlinearly.

From Figure 3(b), it has been observed that when the front right toe-out angle of the car is 0^o, the car can travels about 17.291 km per liter (km/L), however, the travel distance was decreased to 12.244 km/L with the increase of misalignment (front right toe-out angle) of -2.53^o. This means that due to misalignment of the front right toe-out angle (from 0.00^o to -2.53^o), the car travel was approximately 5 km less for the same amount of fuel.

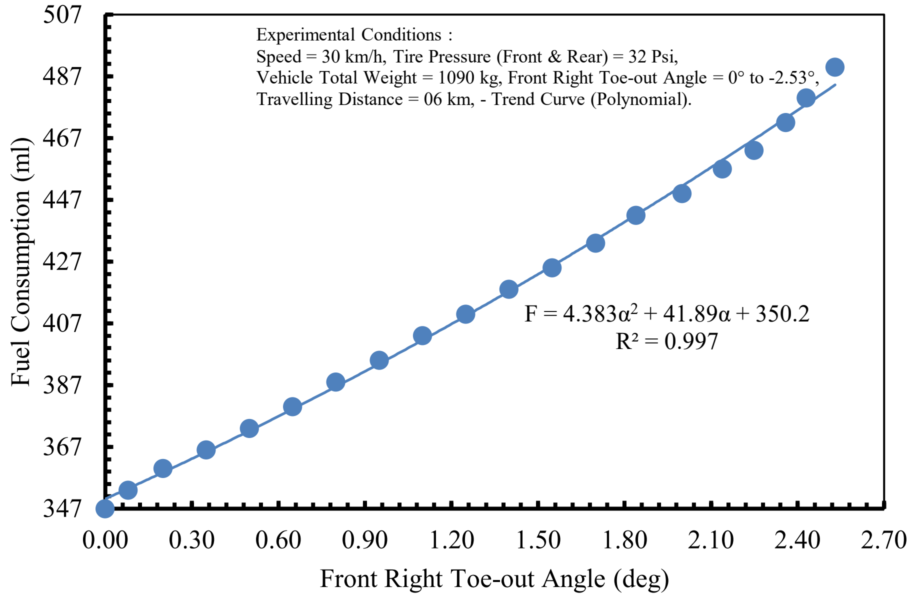
Figure 3(c) shows the changes in fuel consumption rate with the misalignment of the front right toe-out angle. It was seen that the changes in the fuel consumption rate for front right toe-out angle from 0^o to -1.56^o shows a linear increment whereas; for angle -1.72^o to -2.53^o, its shows nonlinearly. Based on the results, it was observed that the fuel consumption rate changed up to 41.21% with the changes in the front right toe-out angle from 0^o to -2.53^o. The experimental result has been verified by the Pearson's correlation coefficient,$r_{\alpha F}$

$$r_{\alpha F} = \frac{\sum_{i=1}^{n}(\alpha_i - \bar{\alpha})\left(F_j - \bar{F}\right)}{\sqrt{\sum_{i=1}^{n}(\alpha_i - \bar{\alpha})^2 \sum_{i=1}^{n}\left(F_j - \bar{F}\right)^2}}$$

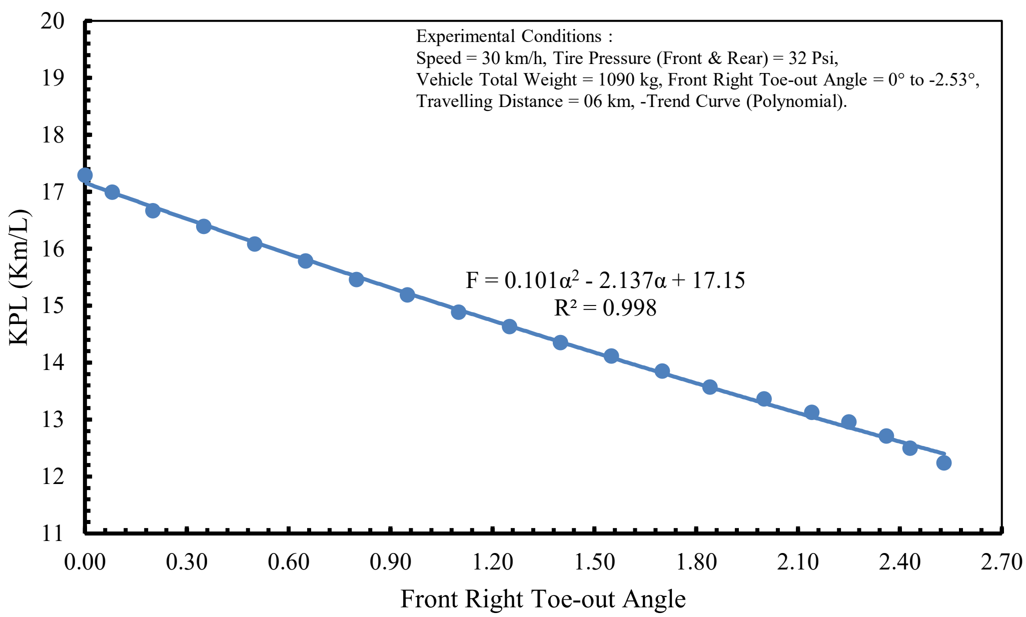
The correlation coefficient $(r_{\alpha F})_{\text{abs.}}$ was found 0.99 (as shown in Table-1), which is within the range $-0.75<r_{\alpha F}>-1$. It proved a very strong correlation between front right toe-out angle and fuel consumption of the light vehicle (Schober et al., 2018). In the above experimental study, it was observed that the fuel consumption of the light vehicle increases with the increase of front right toe-out angle. It is worth noting that fuel consumption has increased due to higher misalignment, as it requires a lot of force to propel the vehicle.

Table 1: Experimental data of wheel alignment (front right toe-out angles) and fuel performance of a TOYOTA ECHO PLUS-2ZZ-GE-02 Light vehicle (Condition: Weather temperature: 17.93°c to 31.47°c, Engine outer temperature: 79.43°c to 82.63°c, Humidity: 30.67% to 68.00% and no. of test run, n = 20)

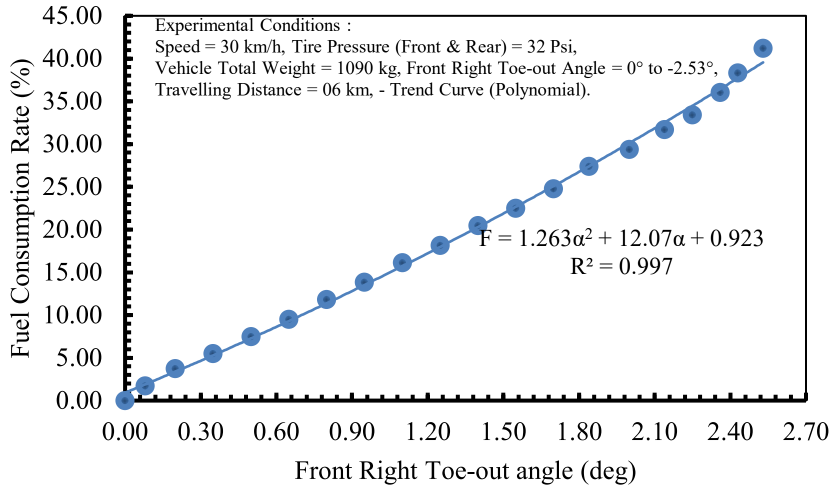
Front right toe-out angle, (deg), α	$\bar{\alpha}$	Fuel Consumption (ml),F	$\bar{F}$	KPL (km/L)	Fuel Consumption Rate (%) $\frac{F - Fmin}{Fmin} \times 100$	Correlation Coefficient $(r_{\alpha F})_{abs.}$
0.00	-1.30	347	415.20	17.291	0.00	0.99
-0.08		353		16.997	1.73	
-0.20		360		16.666	3.75	
-0.35		366		16.393	5.48	
-0.50		373		16.085	7.49	
-0.65		380		15.789	9.51	
-0.80		388		15.463	11.82	
-0.95		395		15.189	13.83	
-1.10		403		14.888	16.14	
-1.25		410		14.634	18.16	
-1.40		418		14.354	20.46	
-1.55		425		14.117	22.48	
-1.70		433		13.856	24.78	
-1.84		442		13.574	27.38	
-2.00		449		13.363	29.39	
-2.14		457		13.129	31.70	
-2.25		463		12.958	33.43	
-2.36		472		12.711	36.02	
-2.43		480		12.5	38.33	
-2.53		490		12.244	41.21	


Experimental Conditions :
Speed = 30 km/h, Tire Pressure (Front & Rear) = 32 Psi,
Vehicle Total Weight = 1090 kg, Front Right Toe-out Angle = 0° to -2.53°,
Travelling Distance = 06 km, - Trend Curve (Polynomial).
F = 4.383α² + 41.89α + 350.2
R² = 0.997
Fuel Consumption (ml)
507
487
467
447
427
407
387
367
347
0.00
0.30
0.60
0.90
1.20
1.50
1.80
2.10
2.40
2.70
Front Right Toe-out Angle (deg)

(a)


Experimental Conditions :
Speed = 30 km/h, Tire Pressure (Front & Rear) = 32 Psi,
Vehicle Total Weight = 1090 kg, Front Right Toe-out Angle = 0° to -2.53°,
Travelling Distance = 06 km, -Trend Curve (Polynomial).
F = 0.101α² - 2.137α + 17.15
R² = 0.998
KPL (Km/L)
20
19
18
17
16
15
14
13
12
11
0.00
0.30
0.60
0.90
1.20
1.50
1.80
2.10
2.40
2.70
Front Right Toe-out Angle

(b)



(c)

Figure 3: Variation of (a) fuel consumption, (b) travelling distance (Km/L),
And (c) fuel consumption rate with respect to front right toe-out angle.

5. Conclusion

The following conclusion can be drawn from the experimental results of a light vehicle (TOYOTA ECHO-PLUS-2ZZ-GE-02) and computerized wheel alignment machine (Best 5800) based on wheel alignment (front right toe-out angle) and corresponding to the fuel performance states:

- It was found that due to misalignment of the front right toe-out angle (from 0.00^o to -2.53^o), the car was travelling approximately 5km less for the same amount of fuel.
- It was also found that for front right toe-out angle 0^o to -0.36^o, the changes in fuel consumption rate were linearly increased, whereas for angle -1.70^o to -2.53^o, it was increased nonlinearly and fuel consumption rate was changed up to 41.21%. Finally, it was observed that the rate of change of fuel depends on misalignment (front right toe-out angle variation) of the car.
- The Pearson's correlation coefficient $(r_{\alpha F})_{abs}$ was found to be 0.99 (in the range $-0.75< r_{\alpha F}>-1$) which exhibits a very strong correlation between front right toe-out angle and fuel consumption.

Finally, it has been recommended to maintain the standard toe angle at all times for better fuel economy.

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Nomenclature

α_i = Values of the front right toe-out angle (deg.)
$\overline{\alpha}$ = Mean of the values of the front right toe-out angle (deg.)
F = Values of the fuel consumption (ml)
$\overline{F}$ = Mean of the values of the Fuel consumption (ml)
$r_{\alpha F}$ = Correlation coefficient (dimensionless)
$(r_{\alpha F})_{abs.}$ = Correlation coefficient(dimensionless) for absolute value
α = Front right toe-out angle (deg.)
B = Constant

Biographies

Riton Kumer Das is a PhD candidate at the Chittagong University of Engineering and Technology (CUET), Chattogram, Bangladesh. He is now pursuing PhD in Mechanical Engineering with focus on Wheel alignment system for light vehicle. As a growing researcher, he has published in MAT journals, international and national conferences in the areas of Engineering Economy, Machining Science and Automobile.

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