# Vehicle Fuel Optimization Based on the Dynamic Parameters via TAGUCHI Method

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**Abstract.** Nowadays many researchers in the whole of the world are attempting to optimize the vehicle engines because of shortages in fuel sources as well as pollution issues. There are many factors depend on fuel consumption and emission products. Rolling resistance, type of engine, coefficient of drag and other vehicle dynamic parameters can be considered to demonstrate the effect of them. In this paper, the effectiveness of fuel consumption for an internal combustion using the Taguchi quality engineering method is designated. A design of experiment is continued and finally, the effects of vehicle dynamics parameters on fuel consumption and harmful gas products are prioritized using the analysis of signal-to-noise ratio.

**Keywords:** *fuel consumption, driving cycle, design of experiment, optimization, Taguchi*

## 1. Introduction

Efficiency of fuel consumption has been influenced by type of vehicle designing factors [1]. In producing vehicle, the most challenging factor is engine structure. Kilagiz et al. [2] using fuzzy logic, exhibited how the faults in engine parts like ignition systems or intake valve can influence on fuel consumption. Moreover, parameters like rolling resistance, coefficient of drag, total mass, change of vehicle gravity and level shifting delay can be effective on fuel consumption and cause to produce harmful exhaust gases [3-6]. To have an equal comparison in fuel consumption, a series of standards for driving cycle is considered. A novel information source for comparison of emissions for different driving cycles is pointed out by Kumar et al. [7]. Ergeneman et al. [8] developed a driving cycle by experimental data from traffic loads for the prediction of pollutant emissions and fuel consumption. Frey and Zheng [9]worked on driving cycle in face of emission factors. Their paper showed perfect discrimination of Selected driving cycles and demonstrated that excellent comparison can be achieved by exploiting the probabilistic analysis. Tong et al. [10] Esteves-Booth et al. [11] and Tzeng et al. [12] examined various ways to derive a generic driving cycle for Hong Kong, Edinburgh and Taipei respectively. Armas et al. [13] deals with a particularly successful approach based on new European driving cycle and presents fuel performance and pollutant emissions. In recent years, driving cycles are developed more and used for a various of hybrid usages instead of conventional Powertrain. Ji et al. [14] worked on the hybrid hydrogen gasoline engine under the New European Driving Cycle(NEDC).

Design of experiments(DOE) is a technique to gather all of useful experiments for analyzing. Taguchi as a non-full factorial method of DOE, can decrease the number of experiments extremely. In this method, the criterion of signal to noise ratio is used to evaluate the magnitude of changes in system output where the input variables change moderately [15-19]. Although this method is not a new technique, but the combining of this process with other techniques like fuzzy and neural network can develop this procedure more [20]. Win et al. [21] studied on the engine operation system to decrease the noise, emissions and fuel consumption. They designed an experiment for five engine parameters and examined various levels to derive confidence measures for exploring emissions of hydrocarbons, oxides of nitrogen, and carbon monoxide. To study embody the notion of engine and estimate the fuel consumption and other products, advanced vehicle simulator, ADVISOR, as a validated simulator is used to evaluate the fuel consumption and also emission products in the vehicle engine. There are so many papers in literature related to this software package[22-25].

Indeed, observing the vehicle dynamic factors can be useful for fuel consumption prediction. an earlier work is by Wu and Liu using an artificial network to predict the fuel consumption. They applied engine style, weight of car, vehicle type and transmission system as input information.

But considering the priority of vehicle dynamic parameters and applying the Taguchi method, this forecasting for fuel consumption and other products can be progressive [26, 27].

The rest of the paper is organized as follows. In the next section, the vehicle dynamic effects on fuel consumption are examined. The pressure of the tire as a significant factor in rolling resistance and fuel consumption is discussed in this part. Section 3, presents the design of the experiment on vehicle dynamics parameters to investigate the fuel consumption. Taguchi method and fuel consumption calculation are described in section 4 and 5 respectively. In section 5, SNR as a powerful statistical criterion is employed to define the effects of each experiment factor on output results. Finally, a comprehensive discussion of the present study is presented.

## 2. Vehicle Dynamics Effects on fuel consumption

It is clearly that hybrid engine, mass, coefficient of drag, rolling resistance, gear shifting and other vehicle dynamic parameters can touch the fuel consumption affectedly. Among of these listed factors, rolling resistance is more discussed in the literature [5, 23, 28]. Changing of this parameter, rolling resistance, depends on tire and road properties. Among these, tire inflation pressure is so eye- catching. In this section an investigation of the consequence of pressure in fuel consumption is achievable. To study more, a population of around 500 vehicles was set. The vehicles are the taxis were selected from a major city with a population of over two million people. Tire pressure in the cooling state was experienced to obtain the minimum error in the data mining. Results on each tire individually recorded and their distribution is obtained. Statistical study shows deviation of 5 psi for this population for each tire. Grugett et al.[29] showed the effect of pressure on fuel consumption. They found that the decrease of 5 psi pressure in a proper tire i.e. 32 psi could increase the fuel consumption by 3%. *Fig. 1* showed the comparison of four tires of about 500 passenger vehicles. As statistical parameter shows, standard deviation is 5 psi. Also, the distribution of tire pressure follows a normal curve. This means that a middle of this population are all doomed and cause to increase the fuel consumption.

## 3. DOE on vehicle dynamics parameters

Six factors are employed to get in experiments. They are listed in *table 1* and contain Hybrid type, rolling resistance, coefficient of drag, height, mass and gear shift delay. To minimize the fuel consumption and harmful emissions, the effects of six parameters should be investigated. Three levels for each one are used to study a wide variety of tests. In this case, approximately

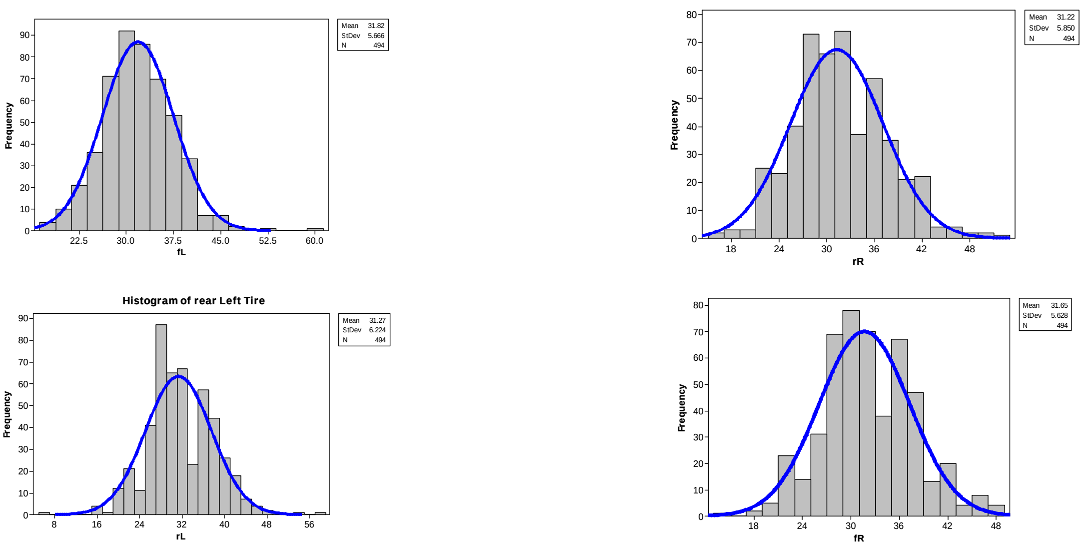


***Figure1.*** *The Histogram of inflation pressure for passenger vehicle tires*

200 experiments must be conducted to find the optimum quantities of different parameters.

***Table 1.*** *Input Factors and their levels used in the experiments*

| Level | Hybrid type | Rolling resistance | Coefficient of Drag | Height (m) | Mass (Kg) | Gear shift delays (second) |
|---|---|---|---|---|---|---|
| 1 | Parallel | 0.001 | 0.3 | 0.4 | 800 | 0 |
| 2 | Parallel SA | 0.005 | 0.4 | 0.45 | 1200 | 0.5 |
| 3 | Conventional | 0.01 | 0.5 | 0.5 | 1600 | 1 |

Another challenge is to study the influence of each parameter in fuel consumption and exhaust products. Taguchi method as an approach to design the experiments  is a powerful tool characterization  to optimize the design and performance. Furthermore, Taguchi method decreases cost of experiments by reducing the number of required experiments (200 reduced to 27). The method treats variation as a factor of signal to noise (S/N) ratio. Then, experimental circumstances having a maximum S/N ratio are regarded as optimal settings [30]. ADVISOR as a powerful software is used to determine the fuel consumption and exhaust products. With this software, vehicle parameters are changeable. In this paper, three types of engine including two types of parallel hybrid engine and one conventional type are considered. Two schematic engine types are depicted in *Fig. 2*. The parallel vehicle apparatuses contain an engine, batteries, and a motor.  It is named parallel because both the motor and the engine can apply torque to move the vehicle. The parallel starter/alternator vehicle components include an engine, batteries, and a motor. It is named parallel starter/alternator because the motor behaves like the starter and the alternator of a conventional vehicle [22].


***a.*** *Parallel Hybrid Engine* ***b.*** *Conventional Engine*

***Figure2.*** *Schematic of different engine and their position in passenger vehicles [22]*

To have an obvious study in estimating fuel consumption, every experiment should be designed at same road and traffic conditions. For having this condition, a driving cycle is employed to test every vehicle for that.  *Fig. 3* displays the new European driving cycle(NEDC), one of the most famous driving cycles [7, 10]. *Fig. 3* represents the vehicle’s speed as a function of time in the NEDC. As it demonstrates, the driving cycle total time is 1200 Sec.

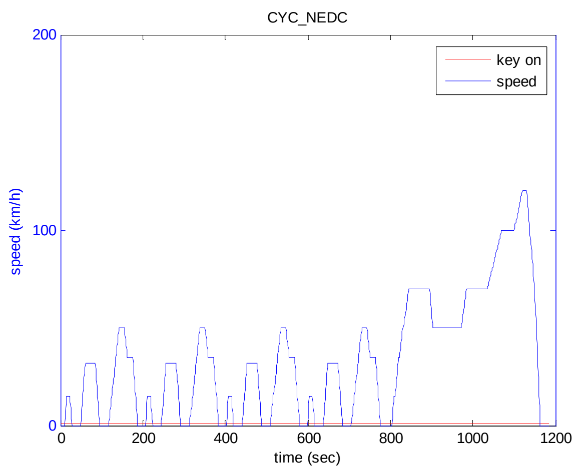


***Figure 3.*** *NEDC driving cycle [22]*

In addition, the max speed that vehicle experiences during this cycle is 120 km/h at 1750 Sec. The vehicle undergoes fourteen local maxima speed points as shown in this driving cycle. NEDC is one of the plenty of standard driving cycles which exist for testing the vehicles. *Table 2* represents 5 more driving cycles and some of their characteristics. The values for average Speed and max acceleration for any of these cycles are shown in this *table*.

***Table2.*** *Driving Cycle Characteristics*

| Driving Cycle | Average speed (Km/h) | Acceleration_ Max (m/s2) |
|---|---|---|
| HFEDS | 77.6 | 1.5 |
| FTP72 | 31.4 | 1.5 |
| LA92 | 39.7 | 4.0 |
| NYCC | 11.4 | 2.7 |
| US06 | 77.2 | 3.8 |

## 4. TAGUCHI METHOD

To examine the effects of parameters on fuel consumption and to identify the performance characteristics under the efficient consumption, Taguchi method is used.

***Table3.*** *Table of experiments*

| No | Hybrid type | Rolling resistance | Coefficient of Drag | Height | Mass | Gear shifts delay |
|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 1 | 1 | 1 | 2 | 2 |
| 3 | 1 | 1 | 1 | 1 | 3 | 3 |
| 4 | 1 | 2 | 2 | 2 | 1 | 1 |
| 5 | 1 | 2 | 2 | 2 | 2 | 2 |
| 6 | 1 | 2 | 2 | 2 | 3 | 3 |
| 7 | 1 | 3 | 3 | 3 | 1 | 1 |
| 8 | 1 | 3 | 3 | 3 | 2 | 2 |
| 9 | 1 | 3 | 3 | 3 | 3 | 3 |
| 10 | 2 | 1 | 2 | 3 | 1 | 2 |
| 11 | 2 | 1 | 2 | 3 | 2 | 3 |
| 12 | 2 | 1 | 2 | 3 | 3 | 1 |
| 13 | 2 | 2 | 3 | 1 | 1 | 2 |
| 14 | 2 | 2 | 3 | 1 | 2 | 3 |
| 15 | 2 | 2 | 3 | 1 | 3 | 1 |
| 16 | 2 | 3 | 1 | 2 | 1 | 2 |
| 17 | 2 | 3 | 1 | 2 | 2 | 3 |
| 18 | 2 | 3 | 1 | 2 | 3 | 1 |
| 19 | 3 | 1 | 3 | 2 | 1 | 3 |
| 20 | 3 | 1 | 3 | 2 | 2 | 1 |
| 21 | 3 | 1 | 3 | 2 | 3 | 2 |
| 22 | 3 | 2 | 1 | 3 | 1 | 3 |
| 23 | 3 | 2 | 1 | 3 | 2 | 1 |
| 24 | 3 | 2 | 1 | 3 | 3 | 2 |
| 25 | 3 | 3 | 2 | 1 | 1 | 3 |
| 26 | 3 | 3 | 2 | 1 | 2 | 1 |
| 27 | 3 | 3 | 2 | 1 | 3 | 2 |

Using this method, optimal parameters resulting in maximum sensitivity is identified. Taguchi method divides input parameters into two branches; control factors and noise factors. The control factors are used to find the optimal sensitivity in the design process. Noise factors, according to Taguchi method, are factors that influence the response of a process, but cannot be economically controlled. The Taguchi method allows inclusion of the noise factors in the experimental array [31]. Experiments details are demonstrated in *table 3*. Each parameter is examined at every level and fuel consumption is recorded.

*__Table4.__ Results of Fuel Consumption and exhaust products*

| No | Fuel (Lt/100Km) | HC | CO | $NO_x$ |
|---|---|---|---|---|
| 1 | 4.4 | 0.305 | 1.372 | 0.139 |
| 2 | 4.9 | 0.324 | 1.769 | 0.165 |
| 3 | 5.4 | 0.334 | 2.143 | 0.177 |
| 4 | 5 | 0.316 | 1.51 | 0.158 |
| 5 | 5.6 | 0.336 | 2.034 | 0.182 |
| 6 | 6.1 | 0.349 | 2.256 | 0.202 |
| 7 | 5.8 | 0.328 | 1.628 | 0.174 |
| 8 | 6.6 | 0.35 | 2.183 | 0.216 |
| 9 | 7.3 | 0.368 | 2.427 | 0.243 |
| 10 | 4.9 | 0.319 | 1.482 | 0.158 |
| 11 | 5.4 | 0.332 | 1.902 | 0.18 |
| 12 | 5.9 | 0.345 | 1.845 | 0.194 |
| 13 | 5.5 | 0.33 | 1.672 | 0.173 |
| 14 | 6.2 | 0.343 | 2.085 | 0.201 |
| 15 | 7 | 0.361 | 2.002 | 0.233 |
| 16 | 5.4 | 0.329 | 1.603 | 0.177 |
| 17 | 6.3 | 0.346 | 2.103 | 0.206 |
| 18 | 6.9 | 0.365 | 1.965 | 0.247 |
| 19 | 5.9 | 0.391 | 1.622 | 0.215 |
| 20 | 6.3 | 0.404 | 1.542 | 0.246 |
| 21 | 7.2 | 0.399 | 2.656 | 0.252 |
| 22 | 5.4 | 0.383 | 1.452 | 0.206 |
| 23 | 5.9 | 0.401 | 1.378 | 0.243 |
| 24 | 6.9 | 0.398 | 2.748 | 0.243 |
| 25 | 6 | 0.396 | 1.63 | 0.233 |
| 26 | 6.7 | 0.418 | 1.521 | 0.285 |
| 27 | 8.1 | 0.418 | 3.156 | 0.267 |

In Taguchi Method, there are seven steps for finishing experiments as follows.

- Purposing of function that needs to be optimized (maximized or minimized)
- Purposing of experimental factors and their levels
- The choosing of a suitable orthogonal array (some software like MINITAB, has a database)
- Performing the experiments and measuring outputs (In this paper, Fuel consumption& exhaust products)
- Calculation of S/N ratio and selecting the parameters corresponding to optimal conditions
- Analyzing the data and predicting of output in optimum case
- Conducting the confirmation experiment.

In the present study, six parameters are used as control factors. All parameters are designed to have three levels as located in *table 1*.

## 5. CALCULATION AND ANALYSIS

In Taguchi Analysis, there is an important factor named signal to noise ratio. This ratio is introduced in Formula

$$S / N = -10 \log_{10}(MSD) \qquad (1)$$

MSD is also, introduced in three categories, when goal is to minimize something, it is defined as "Smaller is Better". When an optimization function is maximized, "Larger is Better" is planned. Each of two formulas is in relations 2 to 3 respectively.

$$\mathrm{MSD} = \frac{1}{\mathrm{n}} \sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{y_i} - y_0)^2 \qquad (2)$$

$$MSD = \frac{1}{n} \sum_{i=1}^{n} y_i^{\,2} \qquad (3)$$

In this paper, SNR is illustrated in figures for fuel consumption, HC, CO and $No_x$, separately. For analyzing, the "Smaller is Better" criterion is selected to minimize fuel consumption and exhaust gasses. For each parameter, the level has the highest SNR is the optimum one. It is obvious in *figure 4-7*. Each figure, contains six parameters with their considering levels. An increase trend to signal to noise ratio for a parameter, causes to minimize the fuel consumption or emission products. The levels were described in *table 1*.

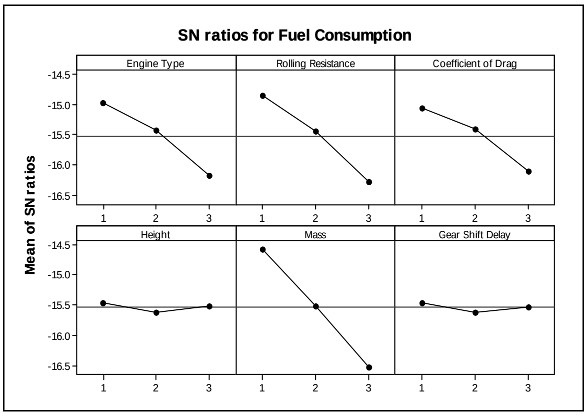


***Figure 4.*** *The effect of parameters on fuel consumption*

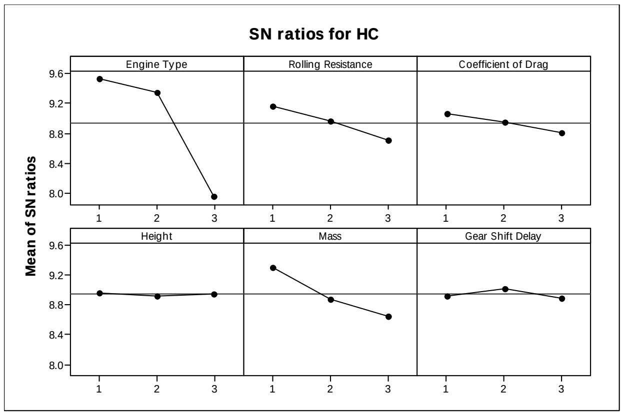


***Figure 5.*** *The effect of parameters on HC (one of exhaust products*

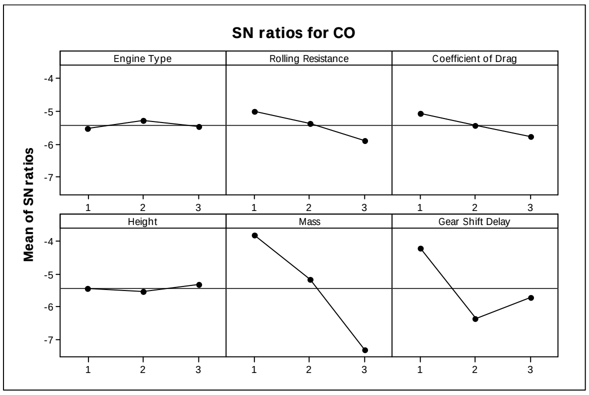


***Figure 6.*** *The effect of parameters on CO (one of exhaust products)*

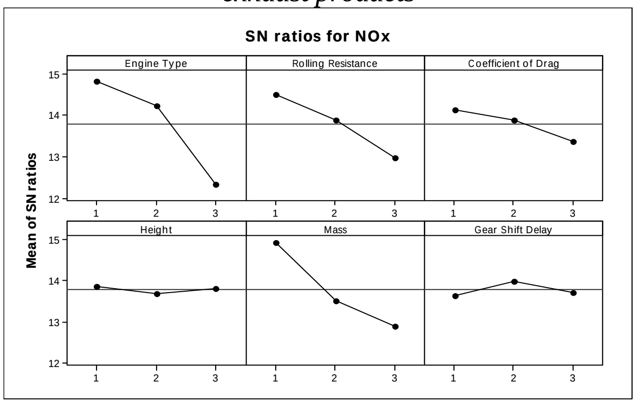


***Figure 7.*** *The effect of parameters on NOx (one of exhaust products)*

## 6. Discussion

As shown in *figures 4-7*, the mass and type of engine are efficient parameters that influence on outputs. SNR shows that hybrid engines are the most important parameter and at the first level can be effectual i.e. parallel hybrid engine. According to *figures 4-7*, parallel SA engines consume much fuel and produce much emissions in a comparison to the Parallel engines. Finally, conventional engines are the worst kind of engines that can be chosen among these three kinds of engines due to their high fuel consumption and emission production. Although, as shown in *Fig. 6*, engine type has no a significant effect on CO production. Additionally, as shown in SNR plots, the vehicle’s mass reduction has a significant positive impact on all of the outputs, decreasing the vehicle’s fuel consumption and exhaust gasses. After mass and engine, rolling resistance and coefficient of drag can be seen powerful parameters in touch the outputs. By decreasing both, the drag of the coefficient and rolling resistance, the fuel consumption and exhaust gasses decrease. Whereas, increasing of vehicle heights and level shifting delay doesn't effect on fuel consumption severely. But, the latter has a tiny effect in CO and $NO_x$ as two harmful exhaust products. A comparison *table 5* presents a rank position for each parameter in face of minimizing each product. The mass of the vehicle and rolling resistance are the priority. As this *table* shows, considering the engine type in reducing HC and NOx is proposed. Also in this case, the results show that gear shift delays is not a significant parameter. Coefficient of drag in all cases is not an imperative factor nor the height of the vehicle.

*Table5. Priority level for experiment parameters in difference outputs*

| Level | Hybrid type | Rolling resistance | Coefficient of Drag | Height (m) | Mass (Kg) | Gear shift delays (second) |
|---|---|---|---|---|---|---|
| Fuel consumption | 3 | 2 | 4 | 5 | 1 | 6 |
| HC | 1 | 3 | 4 | 6 | 2 | 5 |
| CO | 5 | 3 | 4 | 6 | 1 | 2 |
| $NO_x$ | 1 | 3 | 4 | 6 | 2 | 5 |

## 7. CONCLUSION

A statistical analysis based on Taguchi method and signal to noise ratio is employed to investigate the vehicle dynamic parameters effect on fuel consumption and emission products. Six parameters such engine type, rolling resistance, mass, height, drag coefficient and level shifting delay in three levels are analyzed using designing of experiments based on Taguchi method. All experiments were done on NEDC as a famous driving cycle. Statistics works are shown how each parameter can be effective on fuel consumptions and exhaust products.

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