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ORIGINAL RESEARCH

More efficiency in fuel consumption using gearbox optimization based on Taguchi method

Masoud Goharimanesh · Aliakbar Akbari · Alireza Akbarzadeh Tootoonchi

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Abstract Automotive emission is becoming a critical threat to today's human health. Many researchers are studying engine designs leading to less fuel consumption. Gearbox selection plays a key role in an engine design. In this study, Taguchi quality engineering method is employed, and optimum gear ratios in a five speed gear box is obtained. A table of various gear ratios is suggested by design of experiment techniques. Fuel consumption is calculated through simulating the corresponding combustion dynamics model. Using a 95 % confidence level, optimal parameter combinations are determined using the Taguchi method. The level of importance of the parameters on the fuel efficiency is resolved using the analysis of signal-to-noise ratio as well as analysis of variance.

Keywords Fuel consumption · Driving cycle · Design of experiment optimization · Taguchi · ANOVA

Introduction

Efficiency of fuel consumption depends on several design factors. To optimize the fuel consumption and minimize the exhaust products, the parameters which can be effective in this matter must be found and discussed. Grugett et al. (1981) worked on the effect of under-inflated tire pressure in fuel consumption. Moreover, they admitted that the decreasing of 5 psi could increase fuel consumption to 3 % for a proper tire. Taguchi et al. (1995) examined the vehicle operating patterns to study fuel consumption behavior. Bradley and Delaval (2013) had shown that tire-rolling resistance as an effective parameter can be influential in fuel consumption. In addition, diagnosis and prediction for fuel consumption is common in the DOE literature. Kilagiz et al. (2005) used fuzzy logic to minimize the emission products. Wu and Liu (2012) presented a model based on artificial network to forecast the fuel consumption in an engine. Due to different motion and road types, there are some standard driving cycles. An example of this case is on study of Ergeneman et al. (1997) when they progressed a driving cycle to predict the emission products. Many scientists have worked on for the megacities to derive a driving cycle generally. Tzeng and Chen (1998) developed a driving cycle for Taipei. Furthermore, Tong et al. (2011) built a driving cycle for Hongkong city. Optimizing the fuel consumption is not straightforward. Common optimization algorithms such as genetic algorithm, pattern search, etc., cannot be efficient because the current engine model is not an absolutely clear mathematics model. It means that it is necessary to use a practical approach for this especial problem. Fuzzy logics, neural networks, artificial neural fuzzy, reinforcement learning and designing of experiments look like new methods to solve this optimization problem. Among these methods, designing of experiments based on Taguchi can be efficient for its minimum solution. This method is so famous in the industry (Taguchi and Yokoyama 1994; Taguchi et al. 1989; Taguchi 1986).

According to fuel consumption minimizing, Win et al. (2005) considered six main parameters in engine with

M. Goharimanesh (✉) · A. Akbari · A. Akbarzadeh Tootoonchi
Department of Mechanical Engineering, Faculty of Engineering, Ferdowsi University of Mashhad (FUM) campus, Azadi Sq., P.O. Box: 9177948974, Mashhad, Khorasan Razavi, Iran
e-mail: ma.goharimanesh@stu.um.ac.ir

A. Akbari
e-mail: akbari@um.ac.ir

A. Akbarzadeh Tootoonchi
e-mail: ali_akbarzadeh@um.ac.ir

two levels. They investigated the change of parameters using signal-to-noise ratio as a powerful statistical criterion. Although the designing of experiments decrease the number of experiments intensely, all proposed experiments are not possible. That is why a powerful simulator is needed to calculate the fuel consumption. This computer toolbox is able to define a specified vehicle to assess fuel consumption, exhaust products and useful performance characteristics (Wang et al. 2012; (ADVISOR) AVS 2002; Markel et al. 2002; Omidvar et al. 2012).

One of the major factors in Powertrain systems which are able to influence on fuel consumption is the gearbox. In this paper, an investigation on gear ratio effects and optimizing is presented so that a minimizing of fuel consumption can be achieved. The rest of the paper is organized as follows. Driving cycles and proposed car specification, respectively, are discussed in sections "Driving cycles" and "Car specification". The design of experiments and simulation of each one in ADVISOR is presented in section "Designing experiments based on Taguchi method" and finally, conclusion is shown in section "Conclusion".

Driving cycle

To have an obvious study on estimating fuel consumption it is needed to test every vehicle based on an international standard. These tests have the standard in every country. The protocol is named driving cycle. Driving cycle is a series of data, which shows the speed of vehicle versus time. They are different all over the world. Some of them such as European models are smooth. In Fig. 1, European driving cycles are shown.

In Fig. 2, FTP75 (federal test procedure), one of the most famous driving cycles is demonstrated. In Table 1, some characteristics for some driving cycles are presented.

Car specifications

Upon obtaining a gearbox model that relates gear ratio input with capacitance output, we can proceed to optimize the fuel consumption. Fuel consumption in automobile can be defined regarding to a certain driving cycle. Furthermore, to develop a reliable study, two internal combustion engines with 50 and 150 horsepower are assumed respectively (Figs. 3, 4)

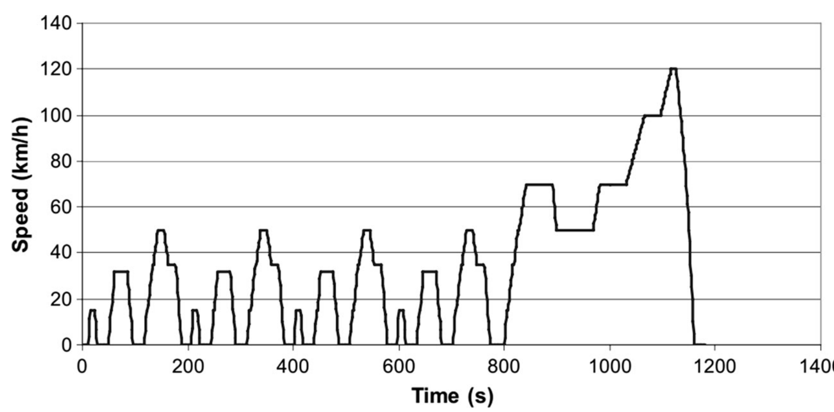

Fig. 1 European driving cycle (Barlow et al. 2009)

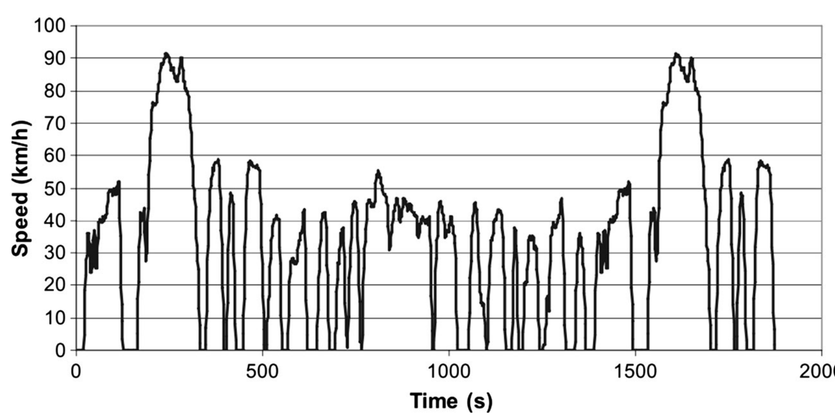

Fig. 2 FTP driving cycle (Barlow et al. 2009)

Table 1 Driving cycles' characteristics (Barlow et al. 2009)

Driving cycle	Average speed (trip) (Km/h)	Average positive acceleration (m/s^2)
HWFET (highway fuel economy test)	77.7	0.157
FTP-72 (federal test procedure)	31.6	0.429
LA92 (California dynamometer driving schedule)	39.6	0.502
NYCC (New York city cycle)	11.5	0.466
US06 supplemental FTP	77.9	0.541

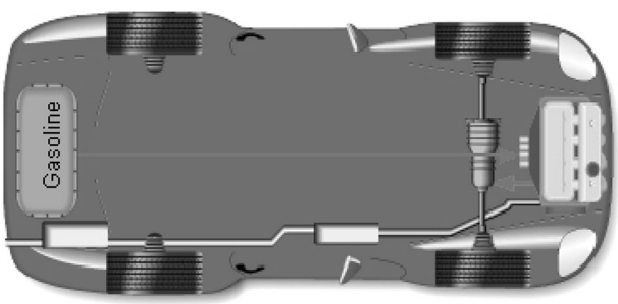

Fig. 3 Conventional automobile ((ADVISOR) AVS (2002); Markel et al. 2002)

Other specification for this automobile is listed in Table 2.

Designing experiments based on Taguchi method

Taguchi method is a powerful tool characterization, design and performance optimization. The Taguchi experimental design method offers a wide range of its applications, simple concept and the use of the method as well as variation reduction. Additionally, Taguchi method reduces the cost of experiments by reducing the number of necessary experiments. The Taguchi process combines mathematical and statistical techniques that are used in experimental studies. By using this method, optimal conditions with minimum experiments can be determined. The method treats variation as a factor of signal-to-noise (S/N) ratio. Then, experimental conditions having maximum S/N ratio are viewed as optimal conditions. To investigate the effects of parameters on fuel consumption and to identify the performance characteristics under the efficient consumption, Taguchi quality engineering method (TQEM) is used. By using this method, optimal parameters resulting in maximum sensitivity are 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,

Fig. 4 Fuel efficiency map ((ADVISOR) AVS (2002)

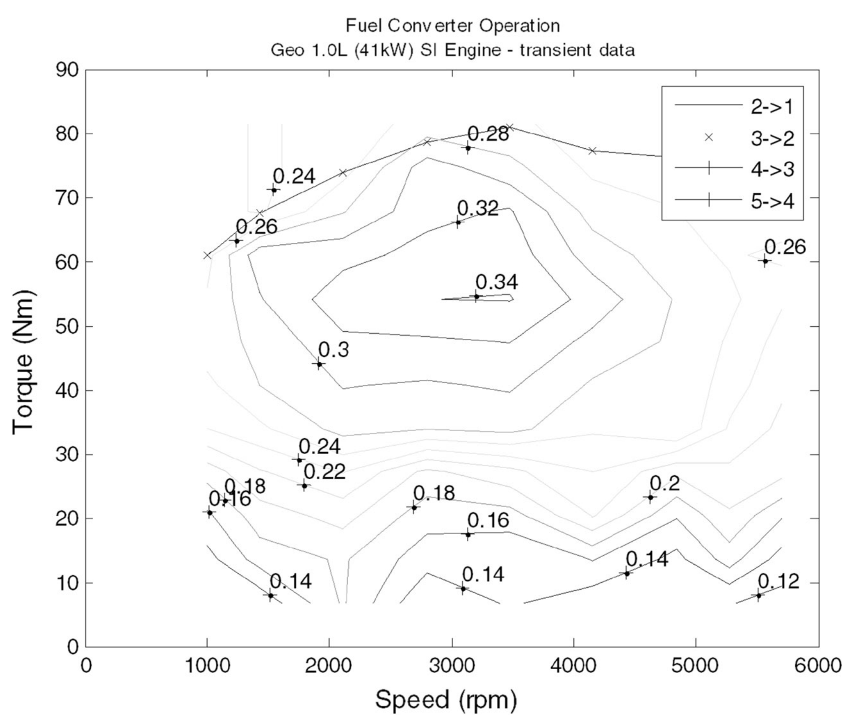

Table 2 Car specifications for a conventional automobile ((ADVISOR) AVS (2002)

Parameter	Nominal value
Maximum power: low performance	50 hp
Maximum power: high performance	150 hp
Mass: low performance	848 kg
Mass: high performance	1,187 kg
Gearbox	Manual
Nominal gear ratios	
Gear 1*Gear_diff	13.45
Gear 2*Gear_diff	7.57
Gear 3*Gear_diff	5.01
Gear 4*Gear_diff	3.77
Gear 5*Gear_diff	2.83

Table 3 Input factors and their levels used in the experiments

Parameter	Symbol	Level 1	Level 2	Level 3	Level 4	Level 5
Gear 1	A	3.19	3.45	3.71	3.97	4.23
Gear 2	B	1.83	2.00	2.17	2.34	2.52
Gear 3	C	1.25	1.35	1.46	1.56	1.67
Gear 4	D	0.89	0.97	1.06	1.15	1.24
Gear 5	E	0.69	0.76	0.84	0.92	1
Gear diff	F	3.23	3.55	3.88	4.20	4.53

according to Taguchi method, are those 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.

This technique has seven steps: determination of function that needs to be optimized, determination of controllable factors and their levels, selection of a suitable orthogonal array, performing the experiments and measuring outputs, calculation of S/N ratio and selecting the parameters corresponding to optimal conditions, analyzing the data and prediction of output in optimum case and the last step which is conducting the confirmation experiment.

In the present study, six parameters are used as control factors. All parameters designed to have five levels are presented in Table 3. To use a proper range for each level, a hundred populations of gearboxes are considered.

Optimization results based on Taguchi method

Utilizing the Taguchi Method, the L_{25} orthogonal arrays table with 25 rows is constructed for the controllable factors (Table 4). Each row corresponds to the number of experiments that needs to be performed. As stated before, the level settings for the input factors are chosen to represent typical fuel consumption.

Optimization and analysis of experimental results

In Taguchi method, a loss function is used to put the cost of deviation from target into perspective. The loss function is further transformed into a signal-to-noise (S/N) ratio. It provides a measure of the impact of noise factors on performance. The larger the S/N, the more robust the product has against noise. Several S/N ratios depend on the experimental objective. For example one may choose, lower is better (LB), nominal is better (NB) or larger is better (LB). In this paper, the lower fuel consumption is the indication of better performance. Therefore, to obtain optimum performance characteristics, "LB" for the fuel consumption is selected. Using LB, the definition of the loss function (L) for fuel consumption output, Y_i, of n repeated experiments using different levels of noise factors is shown in Eq. 1.

$$L_{\mathrm{LB}} = \frac{1}{n}\sum_{i=1}^{n} y_i^2 \tag{1}$$

The S/N ratio η_{ij} can be expressed as

$$\eta_{ij} = -10\log(L_{ij}) \tag{2}$$

where i and j indices represent ith performance characteristic and jth experiment, respectively.

The optimal level of the parameters and better performance is indicated by greater values of η. The S/N ratio for each experiment of L_{25} (Table 4) is calculated and shown in Tables 5 and 6 for 50 and 150 hp, respectively. As shown in Table 5, the efficient performance for the fuel consumption is obtained at the third level of gear 1 (4.23), second level of gear 2 (2), the fifth level of gear 3 (1.67) second level of gear 4 (0.97), the first level of gear 5 (0.65) and finally, the first level of differential gear (3.23). This behavior is similar to the engine with 150 hp. But as, Table 6 shows, the first gear is ranked as the fourth effective gear ratio.

Figures 5 and 6 show the effect of parameters on the fuel consumption for 50 and 150 horsepower engines, respectively. For getting this conclusion, the relative importance of the input parameters with respect to the fuel consumption is going to bet using the analysis of variance (ANOVA). By using this method, the optimum combinations of the input parameters are more accurately determined. It also provides the percent contribution of the input parameters on the sensitivity. The results of ANOVA analysis, at 95 % confidence level, are presented for the fuel consumption in Tables 7 and 8. Data were submitted to analyses of variance using the general linear model. The main effect terms are denoted by the number of gears in table (1st gear, 2nd gear, 3rd gear, 4th gear, 5th gear and differential gear assumes as a covariate). In ANOVA,

Table 4 Taguchi orthogonal table

No.	Parameters						Results			
	Gear1	Gear2	Gear3	Gear4	Gear5	Gear differential	Power 50 (hp)		Power 150 (hp)	
							Fuel consumption	SNR	Fuel consumption	SNR
1	1	1	1	1	1	1	5.7	−15.1175	9.8	−19.8245
2	1	2	2	2	2	2	5.7	−15.1175	9.9	−19.9127
3	1	3	3	3	3	3	5.9	−15.417	10.5	−20.4238
4	1	4	4	4	4	4	6.1	−15.7066	10.8	−20.6685
5	1	5	5	5	5	5	6.3	−15.9868	11.2	−20.9844
6	2	1	2	3	4	5	6.2	−15.8478	11	−20.8279
7	2	2	3	4	5	1	5.9	−15.417	10.4	−20.3407
8	2	3	4	5	1	2	5.7	−15.1175	9.9	−19.9127
9	2	4	5	1	2	3	5.8	−15.2686	10.1	−20.0864
10	2	5	1	2	3	4	6	−15.563	10.7	−20.5877
11	3	1	3	5	2	4	5.9	−15.417	10.3	−20.2567
12	3	2	4	1	3	5	6.1	−15.7066	10.8	−20.6685
13	3	3	5	2	4	1	5.8	−15.2686	10.2	−20.1720
14	3	4	1	3	5	2	6	−15.563	10.7	−20.5877
15	3	5	2	4	1	3	5.8	−15.2686	9.9	−19.9127
16	4	1	4	2	5	3	6.1	−15.7066	10.8	−20.6685
17	4	2	5	3	1	4	5.8	−15.2686	10	−20.0000
18	4	3	1	4	2	5	6	−15.563	10.5	−20.4238
19	4	4	2	5	3	1	5.8	−15.2686	9.9	−19.9127
20	4	5	3	1	4	2	5.9	−15.417	10.4	−20.3407
21	5	1	5	4	3	2	5.8	−15.2686	10.1	−20.0864
22	5	2	1	5	4	3	6	−15.563	10.7	−20.5877
23	5	3	2	1	5	4	6.2	−15.8478	11	−20.8279
24	5	4	3	2	1	5	5.9	−15.417	10.2	−20.1720
25	5	5	4	3	2	1	5.8	−15.2686	9.8	−19.8245

Table 5 Signal-to-noise values for fuel consumption for power 50 hp

Parameters	Level 1	Level 2	Level 3	Level 4	Level 5	Delta	Rank
Gear 1	−15.47	−15.44	−15.44	−15.44	−15.47	0.03	6
Gear 2	−15.47	−15.41	−15.44	−15.44	−15.50	0.09	4
Gear 3	−15.47	−15.47	−15.42	−15.50	−15.41	0.09	3
Gear 4	−15.47	−15.41	−15.47	−15.44	−15.47	0.06	5
Gear 5	−15.24	−15.33	−15.44	−15.56	−15.70	0.47	1
Gear diff	−15.27	−15.30	−15.44	−15.56	−15.70	0.44	2

Table 6 Signal-to-noise values for fuel consumption for power 150 hp

Parameters	Level 1	Level 2	Level 3	Level 4	Level 5	Delta	Rank
Gear 1	−20.36	−20.35	−20.32	−20.27	−20.30	0.09	4
Gear 2	−20.33	−20.30	−20.35	−20.29	−20.33	0.07	5
Gear 3	−20.40	−20.28	−20.31	−20.35	−20.27	0.14	3
Gear 4	−20.35	−20.30	−20.33	−20.29	−20.33	0.06	6
Gear 5	−19.96	−20.10	−20.34	−20.52	−20.68	0.72	1
Gear diff	−20.01	−20.17	−20.34	−20.47	−20.62	0.6	2

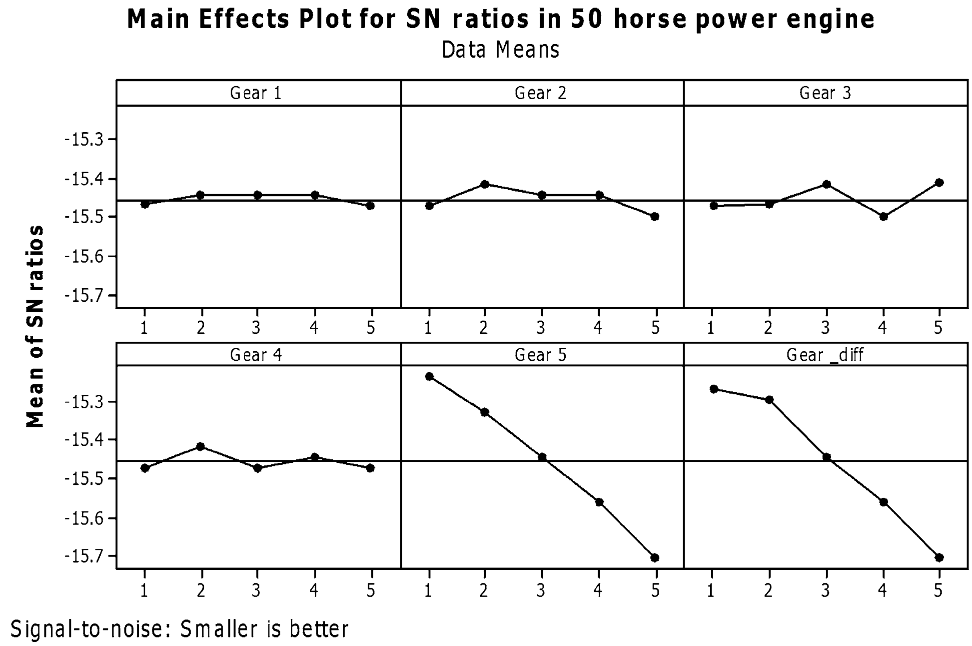

Fig. 5 The effect of parameters on fuel consumption in 50 hp engine

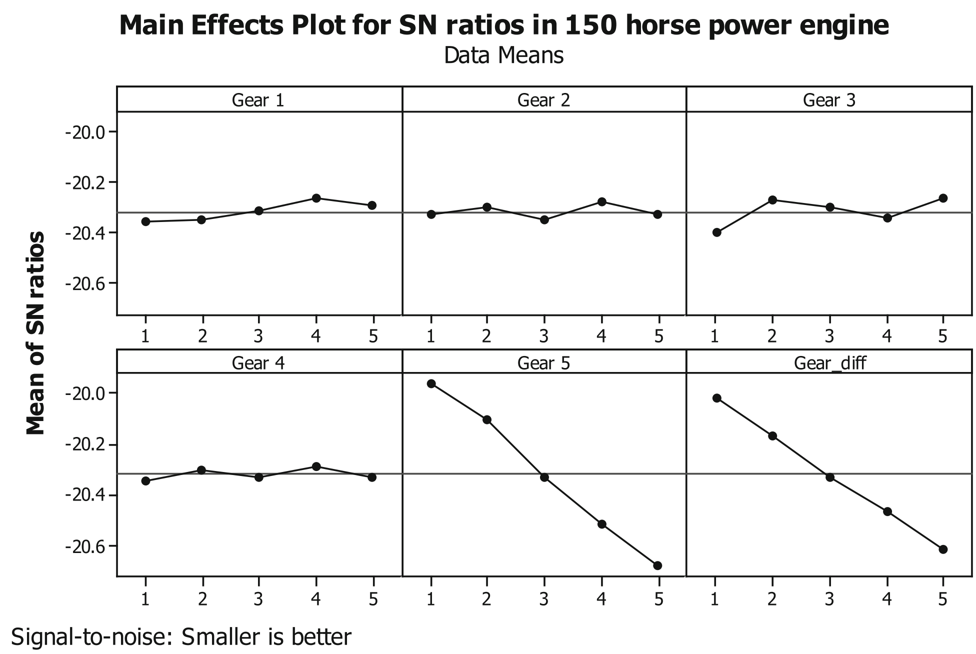

Fig. 6 The effect of parameters on fuel consumption in 150 hp engine

F test, by means of *F* value, can be used to test if the estimates are significantly different using a desirable confidence level. The degree of significance of the computed *F* value can be determined by looking up *F* tables. The greater *F* value shows that the variation of the parameter has a larger impact on the fuel consumption (Taguchi 1986; Taguchi et al. 1989; Taguchi Gi and Yokoyama 1994).

Referring to Tables 7 and 8 for 50 and 150 hp engine, respectively, controllable factors can be ranked as gear 5, gear diff, gear 3, gear 2, gear 4, and gear 1 for 50 hp engine and gear 5, gear diff, gear 3, gear 1, gear 4, and gear 2 for 150 hp engine. The most significant factors affecting the fuel consumption are gear 5, the second ranking factor is differential gear and a third ranking factor is gear 3. According to the *F* value, the remaining factors, gear 1, 2 and 4 are not significant. They are sensitive a little for an engine with a low engine power.

This pattern has changed for 150 hp engine in three first gear ratios. Table 9 describes the general linear model coefficients for two engines. The ranking of the parameters can be evaluated by their *P* values in the each row.

Table 7 Analysis of variance for fuel consumption of 50 hp engine

Source	*df*	Sum of square	Mean of square	*F*	*P*
1st Gear	4	0.002400	0.000600	0.18	0.932
2nd Gear	4	0.010400	0.002600	0.80	0.598
3rd Gear	4	0.014400	0.003600	1.10	0.487
4th Gear	4	0.006400	0.001600	0.49	0.749
5th Gear	4	0.322400	0.080600	24.73	0.012
Differential gear	1	0.304624	0.304624	93.48	0.002
Error	3	0.009776	0.003259		
Total	24				

Table 8 Analysis of variance for fuel consumption of 150 hp engine

Source	*df*	Sum of square	Mean of square	*F*	*P*
1st Gear	4	0.04560	0.01140	24.01	0.013
2nd Gear	4	0.02160	0.00540	11.37	0.037
3rd Gear	4	0.08560	0.02140	45.07	0.005
4th Gear	4	0.02160	0.00540	11.37	0.037
5th Gear	4	2.47760	0.61940	1304.48	0.000
differential gear	1	1.62018	1.62018	3412.16	0.000
Error	3	0.00142	0.00047		
Total	24				

Table 9 General linear model coefficients with their *P* values

	50 hp engine		150 hp engine	
	Coefficient value	*P* value	Coefficient value	*P* value
Constant	4.99665	0.000	8.23610	0.000
1st Gear coef.	0.01200	0.636	0.056000	0.008
2nd Gear coef.	0.01200	0.636	0.016000	0.164
3rd Gear coef.	0.01200	0.636	0.096000	0.002
4th Gear coef.	0.01200	0.636	0.036000	0.026
5th Gear coef.	−0.14800	0.007	−0.424000	0.000
Differential gear coef.	0.24016	0.002	0.553868	0.000

Prediction

The last step on the Taguchi experimental design is the optimum prediction. A new experiment is performed using the optimum conditions provided by the earlier Taguchi analysis. The response under these conditions is also predicted. Using the optimal levels of the parameters, the predicted S/N ratio $\hat{\eta}$ can be defined as the following formula:

$$\hat{\eta} = \eta_m + \sum_{i=1}^{p} (\bar{\eta}_i - \eta_m) \tag{3}$$

where $\bar{\eta}_{\mathrm{i}}$ is the mean of S/N ratio at the optimum control factor settings; η_m is the total mean of S/N ratio, and p represents the number of main parameters that significantly affect the performance. Table 10 shows the predicted value of the fuel consumption and signal-to-noise ratio using the optimal parameters and the experimental values simulated by ADVISOR.

Conclusion

About 100 common automobiles, classes A–E, currently on the road were considered. Ranges of gear ratios for the six gears were determined. For each of the six gears, its ratio range is divided into five levels. Taguchi experimental method is used, and an L_{25} orthogonal arrays table is constructed. Combustion dynamics model for each of the combination for the gearbox was simulated using ADVISOR software and FTP driving cycle. Efficient performance for the fuel consumption is obtained for the various levels of each gear ratio. Analysis of variances reveals that the significant factor effecting the fuel consumption is gear 5, followed by the differential gear and gear 3. According to the *F* values, the remaining factors, gear 1, 2 and 4 are not significant. The conclusions drawn during the analysis is validated with confirmation experiment using two different automobiles with power, 50 and 150 hp. Results obtained in this study demonstrate that the Taguchi experimental techniques can effectively predict the

Table 10 Results of the confirmation experiment for fuel consumption

Level	Engine 50 horsepower			Engine 150 horsepower		
	Starting parameters A1B1C1D1E1F1	Optimal parameters Prediction A5B2C2D4E1F1	Optimal parameters calculation with ADVISOR	Starting parameters A1B1C1D1E1F1	Optimal parameters Prediction A4B4C5D4E1F1	Optimal parameters calculation with ADVISOR
Fuel consumption (L/100 km)	5.7	5.64	5.7	9.8	9.48	9.8
S/N ratio for fuel consumption (dB)	−15.11	−15.03		−19.82	−19.56	

optimum gear ratio arrangements and facilitate the engine design process leading to improved fuel consumption.

References

(ADVISOR) AVS (2002) National Renewable Energy Laboratory

Barlow T, Latham S, McCrae I, Boulter P (2009) A reference book of driving cycles for use in the measurement of road vehicle emissions, vol 1. Department for transport cleaner fuels and vehicles

Bradley CR, Delaval A (2013) On-road fuel consumption testing to determine the sensitivity coefficient relating changes in fuel consumption to changes in tire rolling resistance. Tire Sci Technol 41(1):2–20

Ergeneman M, Sorusbay C, Goktan A (1997) Development of a driving cycle for the prediction of pollutant emissions and fuel consumption. Int J Veh Des 18(3/4):391–399

Grugett BC, Reineman ME, Thompson GD (1981) Effects of tire inflation pressure on passenger-car fuel consumption. Paper presented at the Society of Automotive Engineers international engineering congress and exposition, 23 Feb 1981

Kilagiz Y, Baran A, Yildiz Z, Çetin M (2005) A fuzzy diagnosis and advice system for optimization of emissions and fuel consumption. Expert Syst Appl 28(2):305–311. doi:10.1016/j.eswa.2004.10.016

Markel T, Brooker A, Hendricks T, Johnson V, Kelly K, Kramer B, O'Keefe M, Sprik S, Wipke K (2002) ADVISOR: a systems analysis tool for advanced vehicle modeling. J Power Sources 110(2):255–266

Omidvar H, Azari KK, Taheri AM, Saghafi AA (2012) Impact and ballistic behavior optimization of Kevlar-Epoxy composites by Taguchi method. Arab J Sci Eng 38:1–7. doi:10.1007/s13369-012-0381-4

Taguchi G (1986) Introduction to quality engineering: designing quality into products and processes. The Organization, Tokyo

Taguchi G, Yokoyama Y (1994) Taguchi methods: On-line production, vol 2. American Supplier Institute

Taguchi G, Elsayed EA, Hsiang TC (1989) Quality engineering in production systems. McGraw-Hill College, New York

Taguchi T, Taniguchi M, Yamaguchi T, Koga M, Okamoto S (1995) Analysis of fuel consumption structure based on vehicle operating patterns. JSAE Rev 16(3):310. doi:10.1016/0389-4304(95)95005-F

Tong HY, Tung HD, Hung WT, Nguyen HV (2011) Development of driving cycles for motorcycles and light-duty vehicles in Vietnam. Atmos Environ 45(29):5191–5199. doi:10.1016/j.atmosenv.2011.06.023

Tzeng G-H, Chen J–J (1998) Developing a Taipei motorcycle driving cycle for emissions and fuel economy. Transp Res Part D Transp Environ 3(1):19–27

Wang X, Qin DC, Zhu J (2012) Simulation research on dynamic performance of electric vehicle based on ADVISOR. Adv Mater Res 588:355–358

Win Z, Gakkhar RP, Jain S, Bhattacharya M (2005) Investigation of diesel engine operating and injection system parameters for low noise, emissions, and fuel consumption using Taguchi methods. Proc Inst Mech Eng D J Automobile Eng 219(10):1237–1251

Wu J-D, Liu J-C (2012) A forecasting system for car fuel consumption using a radial basis function neural network. Expert Syst Appl 39(2):1883–1888. doi:10.1016/j.eswa.2011.07.139