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Optimizing Gear Ratios for Vehicle Performance Enhancement Using Taguchi Method

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Abstract

Gear ratio is a term used to describe the relationship between the number of teeth on two interlocking gears. It determines the speed and torque of a mechanical system, with higher gear ratios providing more torque but lower speed, while lower ratios offer higher speed but less torque. The study aims to design and develop a 1D vehicle physics model for powertrain matching and fuel economy prediction with the car's performance. For this study, the vehicle is modeled in GT-Suite to predict vehicle performance and fuel economy. The baseline results are compared with the actual testing data with the correlation of each parameter, performance, and fuel economy, which resulted in less than a 3% tolerance difference. The Taguchi method determines the optimal selection of gear ratios, while each gear ratio's significance toward the complete transmission set is calculated using ANOVA. The test subject for this research study is the Proton Saga 1.3L VVT, equipped with a 4-speed automatic transmission. The simulation results show an improvement of 3.36% for standing start acceleration and 3.18% for MDC fuel economy compared to the baseline model. Combining a 1D simulation cycle and statistical analysis approaches is a promising solution for optimizing system performance and fuel economy.

1. Introduction

An automobile's performance and fuel economy are contingent on many design elements. In order to maximize the performance of a vehicle while simultaneously reducing its fuel consumption, it is necessary to identify influential parameters, such as the utilization of a cold-start turbocharged gasoline direct injection engine [1][2]. According to a previous study, the method could control the combustion characteristics of the engine, resulting in reduced emissions and enhanced vehicle performance. Additionally, gearbox gear ratios impact a vehicle's performance and emissions. Although research indicates that the final drive ratio has a more significant influence on carbon emissions than progression, a variety of ratios still produce acceptable levels of carbon emissions.
Furthermore, previous research studies have implemented the Taguchi Method to optimize gearboxes, demonstrating that Taguchi experimental techniques can accurately forecast the optimal gear ratio configurations that enhance fuel economy [3]. Meanwhile, a group of researchers [4] proposed the computationally efficient analytical method with the gear shift indicator technology approach, capable of reducing 7.5% in brake-specific

fuel consumption and 6.75% in nitrogen oxide emissions. An investigation conducted in 2018 examines the impact of vehicle gap adjustments on fuel economy and emission performance [3]. The findings suggest that by refining the control strategy for the ACC system, stability, and fuel economy can be enhanced. Due to a shortage of facilities and expertise, sophisticated optimization techniques such as numerical simulations, gear shift technology, and the designation of coupled thermal management systems are ineffective [5-7]. Additionally, converting conventional petrol is inefficient due to drawbacks such as engine redesigning requirements and increased emissions. Therefore, the most effective approach to resolving an optimization problem is to utilize a designated experiment or adhere to stringent vehicle emission standards. Numerous engineers and scientists used the design of experiments (DOE) to increase the speed and efficiency of their experiments. DOE is a technique utilized to examine the testing of industrial processes on a massive scale and to guide the selection of experiments to be conducted in the most efficient manner possible [8]. The Taguchi method is among the DOE's methods. The Taguchi method systematically assesses and integrates enhancements into facilities, equipment, products, processes, and materials. Existing in numerous industries, the Taguchi method appears to be the most labor-intensive, cost-effective, and time-efficient approach. Figure 1 shows the standard procedure process for optimizing [9].

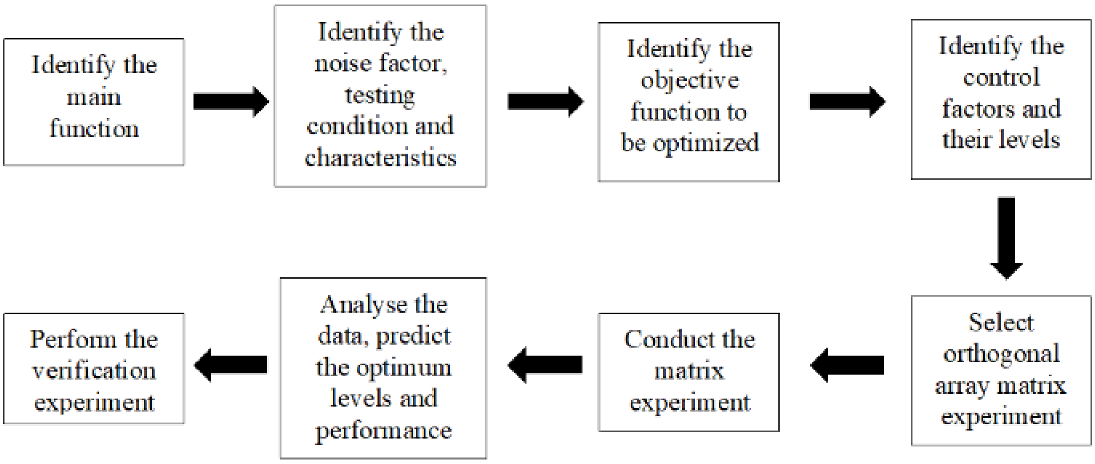

Fig. 1 *Taguchi method procedure* [9]

The current emphasis on vehicle development with reduced emissions is inadequate, particularly in light of cost and time challenges. This research aims to devise and construct a one-dimensional vehicle physics model that facilitates fuel economy and powertrain matching. Additionally, it seeks to assess and optimize gearbox gear ratios to enhance vehicle performance and fuel economy and suggest the most fuel-efficient engine-transmission configuration for standard operation. The comprehensive vehicle model is developed utilizing the 1D GT-Suite simulation application. The object of simulation is a Proton Saga 1.3L passenger vehicle from Segment A. Integrating a 4-speed automatic gearbox (4AT) with the vehicle model is in the works. The Taguchi method will optimize the ratios to attain the fuel consumption target that aligns with the research objective.

2. Method of Research

The model was constructed utilizing GT-Suite, a vehicle modeling software, and subsequently assessed by GT-Drive following a case study. The GT-Suite modeling system was used to determine and optimize 4AT gear ratios to enhance the fuel economy and performance of the Proton Saga 1.3L. In order to verify the integrity of the results, the Taguchi method and analysis of variance (ANOVA) are utilized to validate them statistically. The research process is depicted in Figure 2.

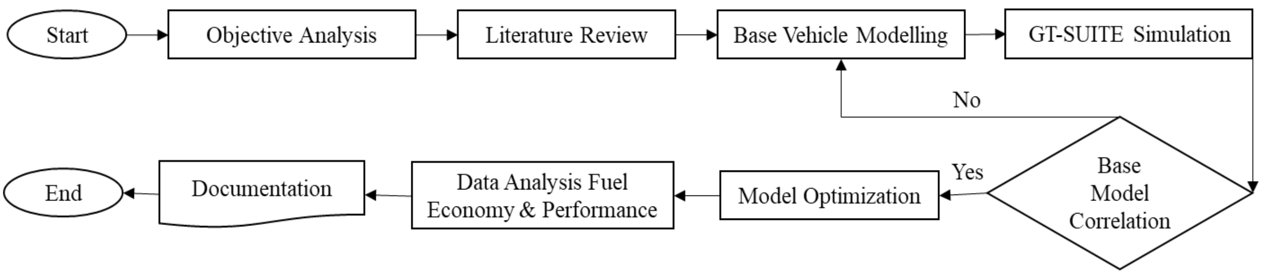

Fig. 2 *Flow of the research*

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2.1 Driving Cycle

In order to ascertain fuel consumption with precision, the experiments are carried out following an internationally recognized standard. The examination is standardized in numerous nations, Malaysia included. The driving cycle comprises and displays a sequence of data that depicts the velocity of a vehicle over time. The Malaysian Driving Cycle (MDC) was utilized for this research. The initial Malaysian urban drive cycle comprises 17 representative sequences with a total cycle time of 1138 s, a distance of 5.86 km, and an average driving speed of 21.01 km/h [10]. The lower average driving speed in the Malaysian urban drive cycle is believed to be influenced by the higher number of stops, higher percentage of stationary, and lower sequence speed [10]. The initial Malaysian urban drive cycle has a higher rate of stops per distance.

Table 1 *MDC parameter [13]*

Distance (km)	Duration (s)	Average Speed (km/h)	Maximum Acceleration (m/s^2)
15.21	1477	37.2	14.3

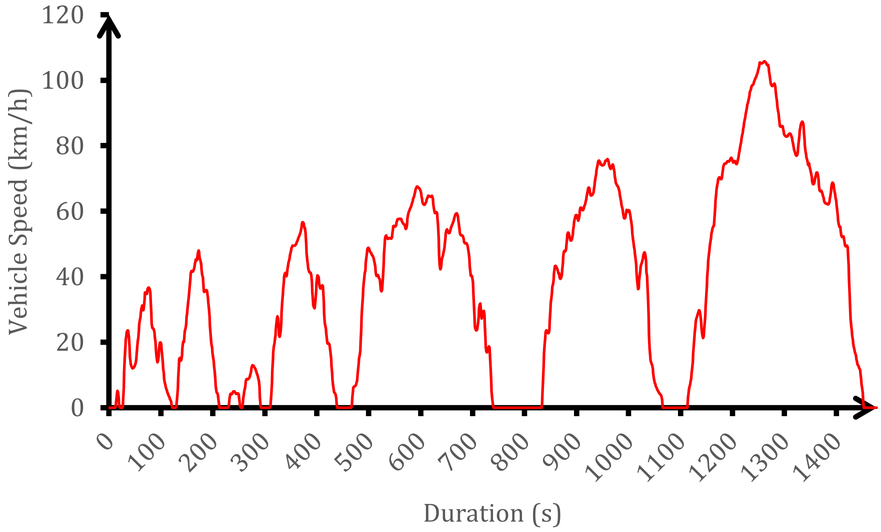

Fig. 3 *Velocity profile of MDC[13]*

2.2 Vehicle Parameter

A comprehensive vehicle is engineered to function across various driving cycles to ascertain a known vehicle's fuel consumption and performance attributes. The vehicle model utilized in this study is detailed in Table 2. Correlated is a Proton Saga with a 1.3L FWD inline 4-cylinder naturally aspirated engine. The process of vehicle modeling in GT-SUITE entails inputting specific information or values for every vehicle component. The Proton engineering team furnished a substantial amount of the data necessary for numerous components, including crucial details regarding the transmission, torque converter, and brakes. The required inputs and templates for the modeling process are briefly described.

Table 2 *Vehicle specification of Proton Saga [10]*

Parameter	Description
Engine Displacement	1332 cc
Maximum Torque	120 Nm @ 4000 rpm
Maximum Power	70 Kw @ 5750 rpm
Gearbox	Automatic Transmission
Engine Type	Gasoline
Length (mm)	4331
Width (mm)	1689
Height (mm)	1491
Wheelbase (mm)	2465
Curb Weight	1075

Tire Size	175/70 R13
Tire Rolling Radius	284
Rolling Resistance Factor	10.3%
Drag coefficient	0.33

2.3 Base Model Correlation

A base model has been developed and correlated with the actual test data. Both test results from the simulation and actual testing have been compared and analyzed in order to ensure the developed model could mimic actual testing. This analysis compares the 0-100 km/h simulation result obtained from the New European Driving Cycle (NEDC) with that of the actual model. To ensure the simulated model replicates the behavior of the exact model when other parameters are reacted to, the tolerance for percentage differences among results must be 4% or less [14]. The comparison results of the baseline model for the actual and simulated models are presented in Table 3. The 0-100 km/h and fuel consumption outcomes of the simulated model are within the acceptable range for the actual model.

Table 3 *Comparison between simulation results and the actual model [11]*

	Actual Model	Simulated Model
NEDC Fuel Consumption (L/100 km)	6.60	6.62
0 – 100 km/h time (s)	13.2	13.4

2.4 Design of Experiment on Taguchi Method

The Taguchi method, which combines mathematical and statistical techniques, optimizes engineering experimentation processes and enhances the quality of the design of experiments. Additionally, the Taguchi method eliminates unnecessary experiment numbers, reducing real-world experiment costs. One can determine the optimal condition by examining the signal-to-noise (S/N) ratio as it varies. This approach is utilized to determine the optimal parameters following the intended sensitivity. The Taguchi method comprises two parameters, namely the noise factor and the control factor. The various levels of gearbox configuration are detailed in Table 4. The standard gear set utilized in the Proton Saga 1.3L is a Level 3 configuration.

Table 4 *Transmission setup*

	Level 1	Level 2	Level 3	Level 4	Level 5
Gear 1	2.627	2.773	2.919	3.065	3.211
Gear 2	1.396	1.473	1.551	1.629	1.706
Gear 3	0.900	0.950	1.00	1.050	1.100
Gear 4	0.642	0.677	0.713	0.749	0.784

3. Result and Discussion

An orthogonal array with 25 rows is constructed for the controllable parameters using the Taguchi method. Each cell in the table denotes the result of an experiment yet conducted. The Taguchi method employs a loss function to provide context for the number of deviations from the objective. Subsequently, the loss function is transformed into the signal-to-noise ratio (S/N). The output is utilized as a metric to assess the noise factor that affects the performance. The S/N ratio is highly dependent on the experiment's objective. A lower fuel consumption is indicative of superior efficacy in this study. Utilize the lower is preferable (LB) S/N ratio as the indicator for this experiment. Equation 1 illustrates the definition of the loss function (L) for the fuel consumption output, Y_i, obtained through repetitive experiments employing various levels of noise factors.

$$L_{LB} = \frac{1}{N}\sum_{i=1}^{n} Y^2 i \quad (1)$$

The S/N ratios n_{ij} can be expressed as

$$n_{ij} = -10 \log L_{ij} \quad (2)$$

Where the i and $_j$ indices represent performance characteristics and experiment, respectively. Table 5 shows the number of experiments created by the Taguchi method. Each number represents the gear number for each

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level. Each experiment is simulated to analyze the result of MDC and 0 - 402 m, respectively, for each of the gear sets given.

Table 5 *Orthogonal array from Taguchi design*

Gear 1	Gear 2	Gear 3	Gear 4	MDC (L/100 km)	402 m (s)
2.627	1.396	0.900	0.642	5.98	23.69
2.627	1.473	0.950	0.677	6.04	23.35
2.627	1.551	1.000	0.713	6.12	23.03
2.627	1.628	1.050	0.749	6.19	22.77
2.627	1.706	1.100	0.784	6.26	22.47
2.773	1.396	0.950	0.713	6.09	23.21
2.773	1.473	1.000	0.749	6.16	22.90
2.773	1.551	1.050	0.784	6.25	22.59
2.773	1.628	1.100	0.642	6.16	22.86
2.773	1.706	0.900	0.677	6.09	23.20
2.919	1.396	1.000	0.784	6.21	22.76
2.919	1.473	1.050	0.642	6.13	22.99
2.919	1.551	1.100	0.677	6.20	22.71
2.919	1.628	0.900	0.713	6.13	23.06
2.919	1.706	0.950	0.749	6.20	22.72
3.065	1.396	1.050	0.677	6.16	22.85
3.065	1.473	1.100	0.713	6.24	22.56
3.065	1.551	0.900	0.749	6.18	22.94
3.065	1.628	0.950	0.784	6.24	22.60
3.065	1.706	1.000	0.642	6.16	22.82
3.211	1.396	1.100	0.749	6.28	22.43
3.211	1.473	0.900	0.784	6.22	22.85
3.211	1.551	0.950	0.642	6.13	23.01
3.211	1.628	1.000	0.677	6.19	22.70
3.211	1.706	1.050	0.713	6.27	22.39

3.1 Optimization Based on Fuel Consumption

Table 6 shows that the first level of each gear, 1(2.627), 2(1.396), 3(0.900), and 4(0.642), is the most suitable gear ratio toward MDC. Figure 4 represents the plot of the S/N ratio towards the MDC experiment. The plot graph of the S/N ratio helps the user to review all the data quickly.

Table 6 *Response table for signal to noise (S/N) ratio for fuel consumption*

Level	Gear 1	Gear 2	Gear 3	Gear 4
1	-15.73	-15.77	-15.73	-15.72
2	-15.78	-15.79	-15.76	-15.76
3	-15.81	-15.81	-15.80	-15.81
4	-15.84	-15.82	-15.85	-15.85
5	-15.87	-15.84	-15.89	-15.90
Delta	0.14	0.07	0.15	0.17
Rank	3	4	2	1

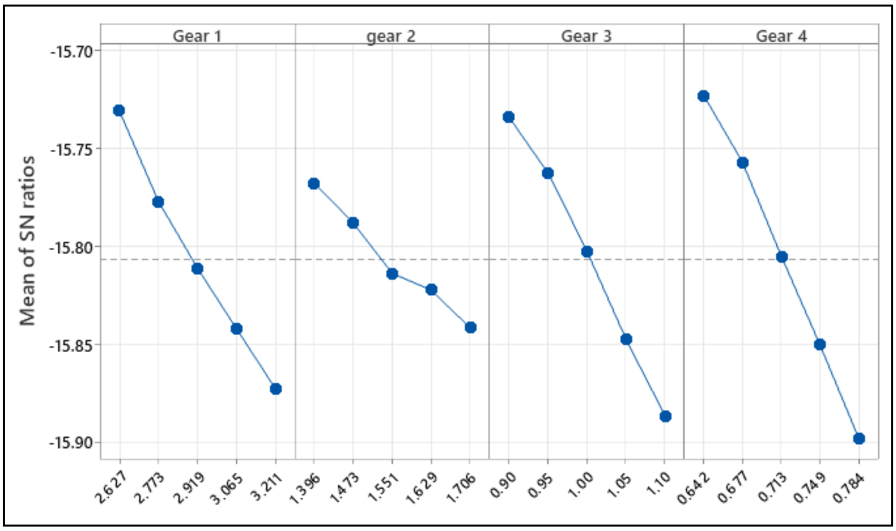

Fig. 4 *Main effect plot for S/N ratios*

To properly investigate the impact of each mechanism on the experiment, analysis of variance (ANOVA) is employed to obtain results. The purpose of using ANOVA is to determine which factor has a statistically significant effect on the response because it provides the percent of the contribution of each gear towards the respective response, which, in this case, is fuel consumption. The ANOVA analysis at a 99.93% confidence level using the general linear model is shown in Tables 7 and 8. For Table 7, the value of F represents the significant effect of each gear. Additionally, Table 8 shows the probability that each gear affects fuel consumption. The most significant gear for this test is gear 4 (1128.79), followed by gear 3 (875.45), gear 1 (700.87), and gear 2 (193.77). Furthermore, the value of P with the lowest number is the highest probability, which can affect the test.

Table 7 *Analysis of variance for S/N ratios for fuel consumption*

Source	DF	Seq SS	Adj MS	F - Value	P -Value
Gear 1	4	0.061139	0.061139	0.015285	0
Gear 2	4	0.016903	0.016903	0.004226	0
Gear 3	4	0.076368	0.076368	0.019092	0
Gear 4	4	0.098468	0.098468	0.024617	0
Residual Error	8	0.000174	0.000174	0.000022	
Total	24	0.253054			

Table 8 *Coefficient for S/N ratios for fuel consumption*

Term	Coef	SE Coef	T - Value	P - Value	VIF
Constant	-15.8068	0.000934	-16924	0	1
Gear 1	-0.0044	0.001868	-2.341	0.047	1
Gear 2	-0.0071	0.001868	-3.789	0.005	1
Gear 3	0.004	0.001868	2.158	0.063	1
Gear 4	-0.0436	0.001868	-23.359	0.393	10

Using the data from the S/N ratio response with the analysis of variance (ANOVA), the prediction was determined using both to optimize the gear set based on fuel consumption. According to the prediction of the gear set, it is used in the simulation to obtain the simulated result. The simulation stated that the value of the MDC test is 5.98L/100km, and the different value after the optimization is 3.18% for fuel consumption.

Table 9 *Prediction of fuel consumption*

Prediction	Configuration			
MDC	Gear 1	Gear 2	Gear 3	Gear 4
5.98	2.627	1.396	0.900	0.642

3.2 Optimization Based on Performance

Table 10 shows that the fifth level of gear 1(3.211), gear 2(1.706), gear 3(1.100), and gear 4(0.784) are the most suitable gear ratio toward performance. Figure 5 represents the plot of the S/N ratio towards the 0 – 402m experiment. The plot graph of the S/N ratio helps the user to review all the data quickly.

Table 10 *Signal to noise (S/N) ratio performance*

Level	Gear 1	Gear 2	Gear 3	Gear 4
1	-27.25	-27.23	-27.29	-27.26
2	-27.22	-27.21	-27.23	-27.22
3	-27.18	-27.18	-27.17	-27.18
4	-27.14	-27.16	-27.12	-27.14
5	-27.11	-27.13	-27.08	-27.10
Delta	0.14	0.1	0.21	0.16
Rank	3	4	1	2

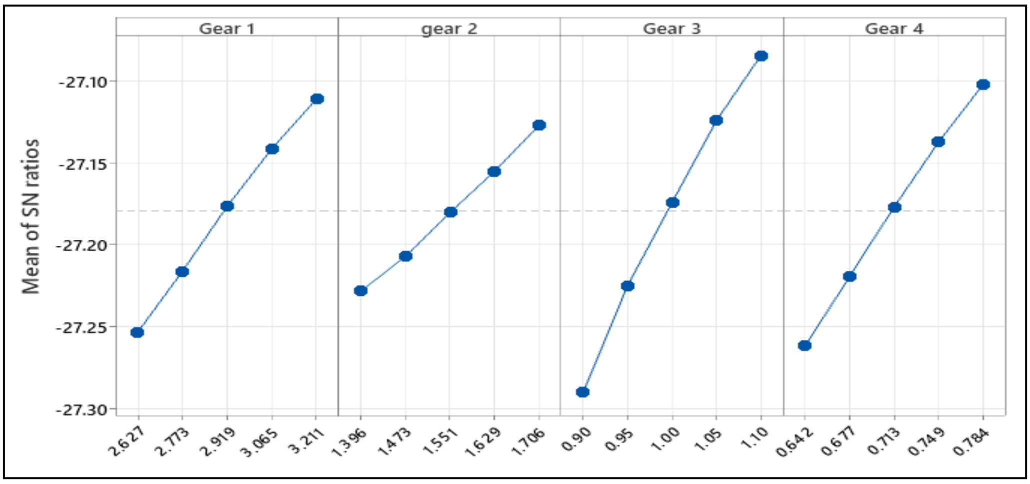

Fig. 5 *Graph of S/N ratio response*

The general linear model ANOVA analysis results with a confidence level of 99.94% are presented in Tables 11 and 12. The value of F in Table 11 signifies the proportional impact of each gear. Aside from that, the probability that each ratio affects fuel consumption is detailed in Table 12. Gear 3 (1083.01) is the most significant gear for this exercise, followed by gear 4 (660.75), gear 1 (7531.82), and gear 2 (265.38). Moreover, the result may be influenced by the value of P with the smallest number, which corresponds to the highest probability.

Table 11 *Analysis of variance for S/N ratios for performance*

Source	DF	Seq SS	Adj MS	F - Value	P -Value
Gear 1	4	0.064585	0.016146	531.82	0
Gear 2	4	0.032228	0.008057	265.38	0
Gear 3	4	0.131522	0.032881	1083.01	0
Gear 4	4	0.80242	0.020061	660.75	0
Residual Error	8	0.000243	0.00003		
Total	24	0.30882			

Table 12 *Coefficients for S/N ratios for performance*

Term	Coef	SE Coef	T - Value	P - Value	VIF
Constant	-27.1798	0.001102	-24664	0	1
Gear 1	0.0031	0.002204	1.41	0.196	1
Gear 2	-0.007	0.002204	-0.324	0.754	1
Gear 3	0.0053	0.002204	2.392	0.044	1
Gear 4	0.0026	0.002204	19.101	0.27	10

Through the utilization of analysis of variance (ANOVA) and the S/N ratio response data, it was possible to ascertain the prediction for optimizing the gear set following performance by employing both variables. The simulation utilizes the gear set following its predicted value to generate the simulated outcome. According to the simulation, the 0 – 402m test value is 22.08 s, whereas the optimized value for performance is 3.36%.

Table 13 *Prediction of car performance*

Prediction	Configuration			
0 – 402m	Gear 1	Gear 2	Gear 3	Gear 4
22.08	3.211	1.706	1.100	0.784

3.3 Multi-Response Prediction

Table 14 shows that the fifth level of each gear, 1(3.211), 2(1.706), 3(1.100), and 4(0.784), is the most suitable gear ratio toward multi-response prediction. Figure 6 represents the plot of the S/N ratio towards multi-response prediction. The plot graph of the S/N ratio helps the user to review all the data quickly.

Table 14 *Signal to noise (S/N) ratio for multi-response*

Level	Gear 1	Gear 2	Gear 3	Gear 4
1	-24.54	-24.52	-24.57	-24.55
2	-24.51	-24.50	-24.51	-24.51
3	-24.47	-24.48	-24.47	-24.47
4	-24.44	-24.45	-24.44	-24.44
5	-24.42	-24.43	-24.39	-24.41
Delta	0.21	0.09	0.18	0.14
Rank	3	4	1	2

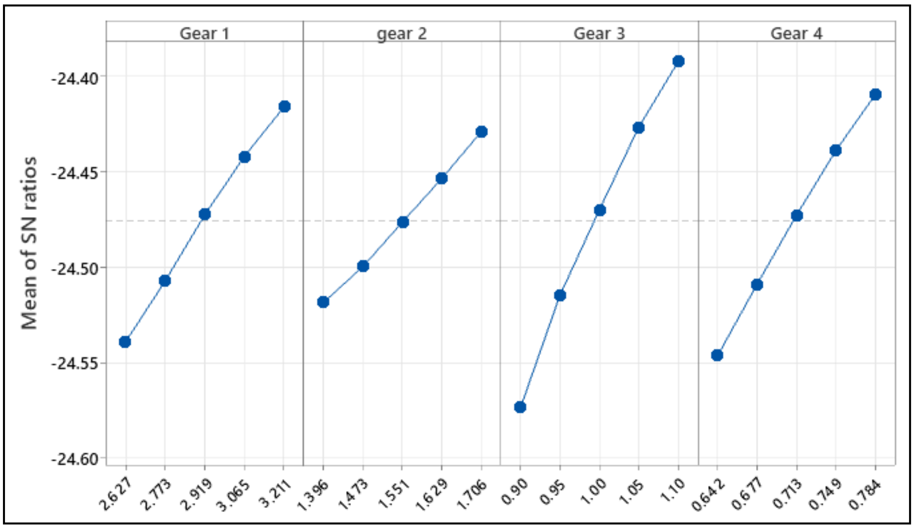

Fig. 6 *Graph of S/N ratio for multi-response prediction*

The ANOVA analysis at a 99.92% confidence level using the general linear model is shown in Tables 15 and 16. For Table 15, the value of F represents the significant effect of each gear. Also, Table 16 shows the probability that each gear affects fuel consumption. The most significant gear for this test is gear 3 (1088.56), followed by gear 4 (629.15), gear 1 (518.88), and gear 2 (269.5). Furthermore, the P value with the lowest number has the highest probability of affecting the test.

Table 15 *Analysis of variance for S/N ratios for multi-response*

Source	DF	Seq SS	Adj MS	F - Value	P -Value
Gear 1	4	0.048807	0.012202	518.88	0
Gear 2	4	0.025350	0.06337	269.5	0
Gear 3	4	0.102392	0.025598	1088.56	0
Gear 4	4	0.059179	0.014795	629.15	0

Residual Error	8	0.000188	0.000024
Total	24	0.235916	

Table 16 *Coefficients for S/N ratios for multi-response*

Term	Coef	SE Coef	T - Value	P - Value	VIF
Constant	-27.1798	0.001102	-24664	0	1
Gear 1	0.0031	0.002204	1.41	0.196	1
Gear 2	-0.007	0.002204	-0.324	0.754	1
Gear 3	0.0053	0.002204	2.392	0.044	1
Gear 4	0.0026	0.002204	19.101	0.27	10

The analysis of variance (ANOVA) and the S/N ratio response data made it possible to ascertain the prediction for optimizing the gear set following car performance fuel consumption by employing both variables. The simulation utilizes the gear set per its predicted value to generate the simulated outcome. According to the simulation, the 0 – 402m test value is 22.08 s, while the MDC experiment value is 6.36L/100km, and the optimized value for performance is 2.99% and 3.35%, respectively.

Table 17 *Comparison of each response with the base model*

Response		Base Model	GT- SUITE Prediction	Improvement over based
Fuel Consumption		6.17	5.98	3.18%
Car Performance		22.82	22.08	3.36%
Multi-Response	MDC	6.17	5.99	2.99%
	0-402m	22.82	22.08	3.36%

Table 17 summarizes the optimization based on fuel consumption (MDC), car performance (0-402m), and multi-response prediction. It obtained all the data and results according to simulation by an overview of the alternatives to fulfill the research objective. The comparison between the simulation (GT-SUITE) and the actual model shows a significant result of 3.18% and 3.36% for fuel consumption and car performance, respectively.

4. Conclusion

The analysis of variances indicates that the final gear ratio substantially impacts fuel consumption, whereas gear 3 is responsible for vehicle performance and multi-response. A simulation was conducted through GT-SUITE software using the gear set configuration obtained from the Taguchi method. The comparison between the simulation (GT-SUITE) and the actual model shows a significant result of 3.18% and 3.36% for fuel consumption and car performance, respectively. The study results demonstrate that the Taguchi method optimizes engineering experimentation processes and reduces the number of experiments required, thereby reducing the cost of real-world experiments. The optimization of the gear ratios in the automatic gearbox resulted in enhanced performance as well as improved fuel economy.

Regarding future research, it is suggested that the project's scope be expanded by conducting a comparative analysis with another subject utilizing a different engine capacity. By comparing this data with engine output variations, it is possible to determine whether or not the study is significant. The subject selection process for this research should be significantly distinct from the subject matter employed to facilitate easy observation of the analyzed data.

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Conflict of Interest

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

Author Contribution

Shaiful Fadzil Bin Zainal Abidin and Mohamad Helmi Bin Ripin contributed significantly to this study. Rifqi Irzuan bin Abdul Jalal provided technical expertise, and Nurulafiqah binti Aziz contributed to data analysis and interpretation.

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