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Fuel consumption-aware powertrain selection and optimization for a B-class sedan

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ABSTRACT

In the current research, we studied different powertrain options for a given B-class sedan vehicle in terms of fuel consumption target. The considered options include two engines and a base manual gearbox assuming the gear numbers and ratios can be changed. We concentrated on 5 and 6-speed gearboxes and used two parallel techniques to optimize gear ratios of the manual gearbox due to in-cycle fuel consumption which led to approximately the same results. To predict the fuel consumption in the NEDC cycle, a longitudinal dynamic model of the vehicle was developed in a GT-Suite environment. Two approaches by which we optimized the gear ratios were a direct optimizer based on a genetic algorithm and a set of DOE analysis tools provided by GT-Suite software. The best result we got among all configurations was the combination of a 1500 cc turbocharged engine with a 5-speed manual gearbox with optimized gear ratios based on the DOE analysis technique. In this case, we reached to 13.5% reduction in in-cycle fuel consumption.

1) Introduction

The climate change caused by CO2 emission and greenhouse gases as well as fossil fuels limitations, makes many countries all around the world have updated the fuel economy regulations in the transport section. Light-duty vehicles constitute the major part of the transportation fleet in Iran, therefore, developing efficient powertrains for different light-duty vehicle platforms has been one of the main concerns of OEMs during the past two decades. Due to the time-consuming and expensive process of engine and transmission development, powertrain adaption is one of the cost-effective strategies in the automotive industry.

On other hand, different specifications in different vehicle platforms make redesigning or resizing some parts of the powertrain inevitable to achieve the minimum fuel consumption along with acceptable drivability and performance characteristics.

Automotive transmissions which make a vehicle capable to confront largely changing load conditions have a considerable impact on fuel consumption. Out of many types of transmissions, the manual with stepped gear ratios is still widely used [1].

In [2], the gear selection optimization problem framework and the related methodology were presented. In another research, the general form of the objective function and design constraints for the gearbox optimization problem was developed [3]. In [4] a Genetic Algorithm (GA) was used to solve a helical gear optimization problem. The optimized engine operation zone was determined in [5] using a geometric progression for gear ratios of the Roa vehicle.

In another work, the authors presented an analysis of the effects of varying the absolute and relative gear ratios of a given transmission on carbon emissions and performance. They also considered the energy-based methods of selecting absolute gear ratios are considered and examined the effects of alternative engine selections [6]. Such Studies show that many researchers proposed various optimization techniques for gear ratio selection.

In the present work, we investigate the best choice for a given B-class sedan vehicle by considering the existing engine and optimizing the gear ratios and number of manual transmissions. The optimum selection hereinafter means minimum in-cycle fuel consumption.

2) Vehicle Model

In this research, we investigated the best manual transmission for a B-class sedan vehicle in terms of fuel consumption, thus only the longitudinal dynamics are considered in the vehicle model regardless of the handling stability and vertical vibration.

To simulate fuel economy in a driving cycle, the vehicle speed history should be imposed on the model. We used GT-Suite v2016 to develop the vehicle dynamic model. We also implemented the "VehKinemAnalysis" object in GT-Suite to control the engine and gearbox submodels.

To predict vehicle fuel consumption in GT-Suite, we used the backward analysis technique, in which the vehicle speed was imposed on the model by defining a driving cycle. Also, we protected the ability to drive a performance analysis by using the "VehKinemAnalysis" object. One can use the same model, imposing the engine speed and load and calculating the vehicle speed and acceleration as output.

To have comparable fuel consumption predictions, we used the New European Driving Cycle (NEDC), depicted in Figure 1, and also, its shifting schedule as the driving cycle for all simulations.

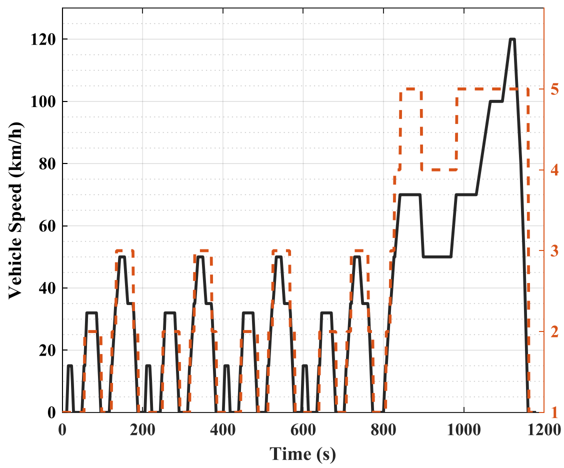

Figure 1: NEDC vehicle and gear history

The base vehicle is a B-class sedan with a 1.6 liter naturally aspirated engine and a 5-speed manual gearbox. According to the emission regulation and also to increase vehicle performance another engine with a 1.5-liter displacement and turbocharged system has been nominated for this vehicle. The vehicle parameters and the base and new engine specifications can be found in Table 1.

Table 1: Vehicle and Engines parameter

Curb Weight	1250 kg	
Frontal Area	2.13 m2	
Drag coefficient	0.32	
	Base Engine	Nominated Engine
Engine Displacement	1650	1499
Engine Max. Power	84 kW@6000 rpm	107 kW @ 5500 rpm
Engine Max Torque	150 N.m@3800-4600	211 N.m@2000-4000
Engine Min. BSFC at full load	234 g/kWh	268 g/kWh

We used equation (1) to determine the vehicle's current targets for maximum speed and gradeability based on the existing design [7].

$$F = m_F g(f_r \cos\alpha_{st} + \sin\alpha_{st}) + \frac{1}{2}\rho_L\, c_W A\, v^2 + m_F \lambda a \qquad (1)$$

The existing gear ratios set and final drive ratio are given in Table 2.

Table 2: Base Gear Ratios

Gear Number	Gear ratio (-)
1	3.58
2	1.97
3	1.37
4	1.03
5	0.767
Final drive ratio	4.053

Due to the first gear ratio, the gradeability target, α in equation (1) was achieved at 30.6° using maximum engine torque and neglecting vehicle speed and acceleration. In the next step, the power-speed characteristics can be plotted as shown in figure 2, using equation (1) and gear ratios. The intersection of the traction demand curve and the fifth gear traction line is about 55 m/s (200 km/h). The value can be considered as the top speed target for the base vehicle.

Furthermore, we investigated the method by which the intermediate gear ratios were selected in the base gearbox. Figure 3 depicted engine speed versus vehicle speed in different gears. It can be seen that the amount of maximum-vehicle-speed (in each gear) difference between two neighboring gears is the same for gears one to four. It shows that the progressive method has been used to determine gear ratios.

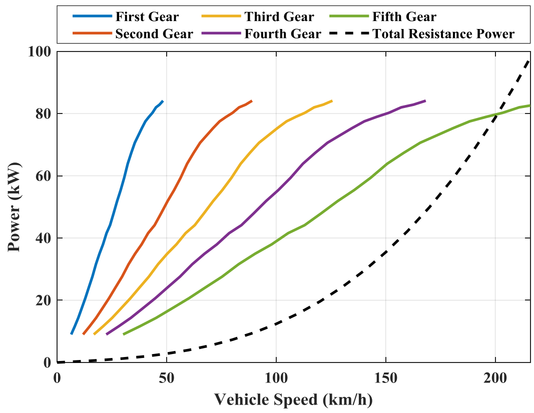

Figure 2: power versus speed for each gear

Also, it can be seen on the gear change line (dashed line) that the engine speed at the shifting point increases, which shows progressive gear ratio selection for gears two to four but in shifting from fourth to fifth gear, engine speed at the shifting point is the same as for third to fourth, which shows an inclination from the progressive method to geometric one in the last gear [7].

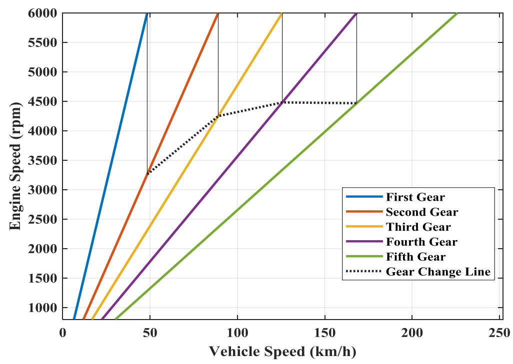

Figure 3: Saw diagram for engine speed versus vehicle speed

3) Gear Ratio Selection

The progressive method has been selected for the preliminary design of gear ratios to optimize the fuel consumption of the vehicle. For the nominated engine, there is a matched gearbox for another vehicle, thus we started designing and modifying the gear ratios of this gearbox. The original gear ratios are listed in Table 3.

We took two approaches to obtain new gear ratios. In the first one, we assumed the existing minimum and maximum gear ratios were fixed to determine intermediate gear ratios. The second approach is based on our calculated requirements for gradeability and maximum speed targets.

Table 3: Gear ratios and final drive ratio

i_1	3.917
i_2	2.208
i_3	1.408
i_4	1.078
i_5	0.813
i_6	0.725
i_{FD}	4.235

The maximum gradeability intended for this design is 30.6 degrees. For the nominated engine, we have maximum available power P_{max} and if the full-load engine power were available over the whole speed range of vehicle v, the so-called "ideal traction hyperbola" $F_{Z,Aid}$ and the effective traction hyperbola $F_{Z,Ae}$ can be calculated as following [7]:

$$F_{Z,Ae} = \frac{P_{max}}{v}\eta_{tot} \text{ or } F_{Z,Aid} = \frac{P_{max}}{v} \quad (2)$$

Based on resistance forces for the vehicle on the level road at different speeds the vehicle obtained from Equation (1) and effective available traction in Equation (2) the maximum reachable vehicle speed can be obtained as depicted in Figure 4. That means, that using the new nominated engine can improve the vehicle target in terms of top speed due to different engine capabilities.

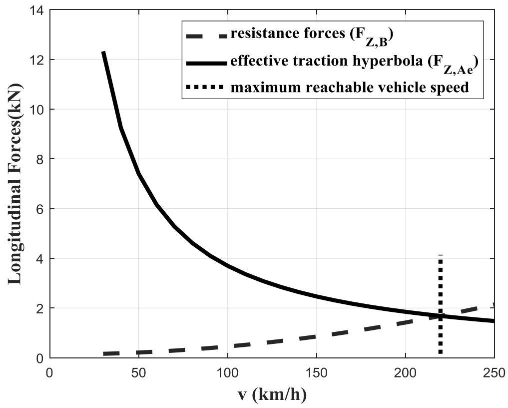

Figure 4: Available traction and resistance forces

4) Selecting the largest powertrain ratio

Two extreme conditions may be considered for the largest ratio (stall torque ratio) $i_{A,max} = i_1 i_{FD}$; the maximum gradient that can be climbed at an acceleration of $a = 0\ m/s^2$ or the maximum acceleration on the level road, in this work the first condition is considered. The stall torque ratio for passenger cars and commercial vehicles designed for maximum gradeability is [7]:

$$i_{A,max} = \frac{r_{dyn} m_F g (f_R \cos\alpha + \sin\alpha)}{T_{M,max}\eta_{tot}} \quad (3)$$

According to Equation (3) and the calculated target for gradeability, the stall torque ratio was obtained.

5) Selecting the smallest powertrain ratio

Assuming there is no slip between wheel and road and that the maximum speed is reached at maximum engine speed, then the smallest powertrain ratio is given by [7]:

$$i_{A,min} = \frac{3.6\frac{\pi}{30} n_{M,max}\left[\frac{1}{\text{min}}\right] r_{dyn}[\text{m}]}{v_{max}\left[\frac{\text{km}}{\text{h}}\right]} \quad (4)$$

6) Selecting the intermediate powertrain ratios

As mentioned before, the selected method for the preliminary design of gear ratio in this work is progressive gear steps that are used for passenger car transmissions. This method reduces the gaps between the effective traction hyperbola and the available traction in the top gears. The relationship for calculating each gear ratio (i_n) is:

$$i_n = i_z \varphi_1^{(z-n)} \varphi_2^{0.5(z-n)(z-n-1)} \quad n = 1, \dots, z-1 \quad (5)$$

Where φ_2 is progression factor and φ_1 is base ratio change. There is a relationship in terms of the number of gears (z), overall gear ratio $(i_{G,tot}) = i_1/i_z$ and φ_2, which is defined as:

$$\varphi_1 = \left[i_{G,tot}\varphi_2^{-0.5(z-1)(z-2)}\right]^{z-1} \quad (6)$$

In addition, considering comfort and noise criteria while shifting, the ratio of two adjacent gears should not be too large, thus generally ratio was chosen from 1.2 to 1.8 [8].

$$1.2 \le \frac{i_{n-1}}{i_n} \le 1.8 \quad (7)$$

We added inequality constraints in the form of Relation (7) for every two adjacent gears. On the other hand, it is noticeable that these fractions in the inequality constraints are functions of φ_2 as can be seen in Equation (8).

$$\frac{i_{n-1}}{i_n} = \varphi_1(\varphi_2)\varphi_2^{(z-n)}, \quad n = 2, \dots, z \quad (8)$$

Therefore, considering all inequality constraints, the allowable range of φ_2 can be obtained. For instance, where 6 gears are considered and the first and last gears are designed according to our requirements, the allowable range for φ_2 is determined according to Figure 5.

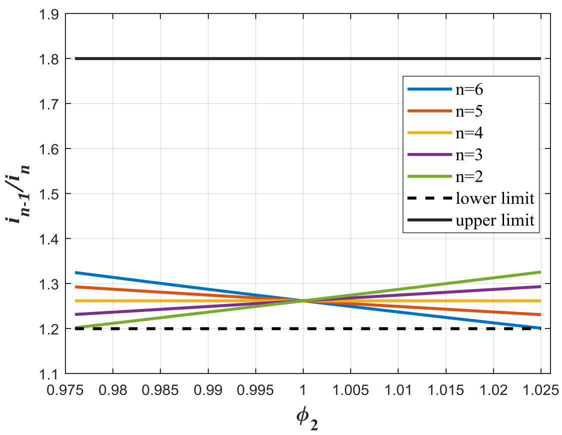

Figure 5: Allowable range for φ_2 based on adjacent gear constraints

Similarly, for other cases the range of φ_2 will be obtained based on their adjacent constraints.

7) Gear ratios optimization

To optimize any model in GT-SUITE, two methods can be used: Direct Optimizer and DOE. Various algorithms of direct Optimizer perform the simulation repeatedly and each time changes the values of the independent variables until the predefined criteria are met. Also, GT-SUITE is capable of performing DOE analysis and post-processing results. DOE-Post, the processing tool of the GT-Suit, is used for DOE analysis and Genetic Algorithm optimization. After performing DOE simulation, the results can be observed in GT-POST, and also, it's possible to use DOE-POST to process, explore and optimize results. DOE-POST creates a model fit from several possible cases with different gear ratios using the vehicle dynamic simulation model. After model post-processing, the optimizer tool which is based on the genetic algorithm is used to determine the gear ratios for minimum fuel consumption. Since the optimizer is only evaluating mathematical models for each iteration, this analysis is very fast [9].

In the current research, firstly we considered 4 cases listed in Table 4, as the preliminary design. Then, by using Direct Optimizer, we optimized φ_2 for each case and obtained optimum intermediate gears. After the preliminary design, the ratios of intermediate gears were considered as optimization variables and another optimization was performed by considering the inequality constraints of adjacent gears mentioned in Equation (7). Afterward, for the best case, these steps have been repeated using DOE-POST. A comparison of these two methods for optimizing the second stage is presented in the next section.

Table 4: Preliminarily design cases

Case	Number of gears	First and last gear design
1	6	Based on vehicle target
2	6	base gearbox
3	5	Based on vehicle target
4	5	base gearbox

8) Results and Discussion

As mentioned in the previous section, in the first step, φ_2 was considered as the decision variable of the fuel consumption minimization. The results for each case described in Table 4, are given in Table (5).

Table 5: Optimum φ_2 for preliminarily design cases

	Optimum φ_2
Case 1	1.025
Case 2	1.080
Case 3	1.075
Case 4	1.140

According to the φ_2 obtained in the first phase of the optimization, we calculated the other gear ratios for all cases using Equation (5) and the values are reported in Table 6. As it can be seen due to our case definition i_1 and i_6 for case 2, and i_1 and i_5 for case 4 remained the same compared to the base gearbox.

As shown in Table 7, the vehicle fuel consumption is improved in all cases except case 2.

Table 6: Optimum gear ratios for preliminarily designed cases

	Case 1	Case 2	Case 3	Case 4	Base
i_1	2.419	3.917	2.419	3.917	3.917
i_2	1.825	2.396	1.623	2.173	2.208
i_3	1.411	1.583	1.170	1.373	1.408
i_4	1.118	1.130	0.907	0.990	1.078
i_5	0.908	0.871	0.756	0.813	0.813
i_6	0.756	0.725	-	-	0.725

Table 7: Achieved target for preliminarily design cases

Case	Fuel consumption [L/100 km]	Reduction
1	7.272	2.6%
2	7.843	- 4.9%
3	6.650	11%
4	7.390	1%
Base	7.472	-

For the second phase of the optimization, we considered the intermediate gear ratios as decision variables and the ratio of two adjacent gear ratios, Relation (7), as the optimization constraints. Based on the selected method for defining first and last gear ratios for each case the upper and lower limit for each gear ratio should be calculated separately. The calculated limit values are given in Table 8.

Table 8: Inequality constraints of adjacent gears for second stage optimization

	Case1	Case2	Case3	Case4
i_2 lower limit	1.3442	2.1761	1.3442	2.1760
i_2 upper limit	2.0163	3.2642	2.0163	3.2642
i_3 lower limit	1.3064	1.2528	1.0886	1.2090
i_3 upper limit	1.6802	2.7201	1.6802	2.6341
i_4 lower limit	1.0886	1.0440	0.9072	0.9756
i_4 upper limit	1.4002	2.2668	1.3608	1.4634
i_5 lower limit	0.9072	0.87	-	-
i_5 upper limit	1.3608	1.3050	-	-

The gear ratios obtained from the second phase of the optimization are presented in Table 9.

Table 9: Optimum gear ratios for second stage optimization

	Case1	Case2	Case3	Case4
i_1	2.419	3.917	2.419	3.917
i_2	1.59	2.18	1.38	2.176
i_3	1.31	1.26	1.1	1.21
i_4	1.09	1.05	0.907	0.976
i_5	0.907	0.87	0.756	0.813
i_6	0.756	0.725	-	-

Also, the predicted fuel consumptions for each case with new optimized gear ratios (Table 9) during the NEDC cycle which were calculated using the GT model, are given in Table 10. Considering the intermediate gear ratios as decision variables resulted in fuel consumption improvement in all cases with the most reduction of 13% for case 3 and the least reduction of less than 1% for case 2.

Table 10: an achieved target for second phase optimization

Case	Fuel consumption [L/100 km]	Reduction
1	7.03	5.9%
2	7.42	0.6%
3	6.47	13.4%
4	7.27	2.7%
Base	7.472	-

The results show that neglecting the first and last gear ratios in the base gearbox and redesigning them based on vehicle functional targets can lead to better outcomes.

Afterward, considering case 3 as the best potential gearbox, we used GT-Suite DOE analysis tools to optimize the gear ratios in case 3. Using alternative optimization techniques may help to verify that obtained results were not local minima or maxima. In direct GA Optimization on the GT model, the maximum number of iterations like as default of GA setting 100 and number of GA population 10 was selected. Optimization continued until the maximum number of iterations, so in direct GA optimization, the GT model was run 1000 times which took over 2 hours. The suggested number of populations for DOE by GT was 35, after creating the DOE population, in DOE-Post a fitted model from the population was created. Then a GA optimization was applied to this created model. The time that took for the three above steps is very smaller than the times when we used direct GA on the GT model. As it can be seen in Table 11, using the DOE method led to almost the same results and additionally decreased simulation time significantly, by achieving optimum solution in 35 iterations compared to the direct optimization method in 1000 iterations. In summary, DOE analysis led to better results in less time. So, the maximum fuel consumption reduction we got was about 13.5% in case 3.

Table 11: Comparison of two methods for optimizing Case3 in the second stage: Direct Optimizer vs DOE-POST

	Case3 Direct Optimizer	Case 3 DOE-POST
i_2	1.38	1.349
i_3	1.1	1.1
i_4	0.9072	0.9072
FC [L/100 km]	6.47	6.458
Number of iterations	1000	35

Figure 6 and Figure 7 show the movement of gear ratios across the constant power lines to the zone of lower BSFS during the optimization process. One can compare the location of the gear ratios of the base gearbox with the best cases in the first phase of this optimization process in Figure 6. The location of the final gear ratios at the end of the second phase is depicted in Figure 7. As it can be seen, the movement of the gear ratio's location is toward the minimum BSFC line on the map which generally leads to lower ratios for each gear within the inequality constraints.

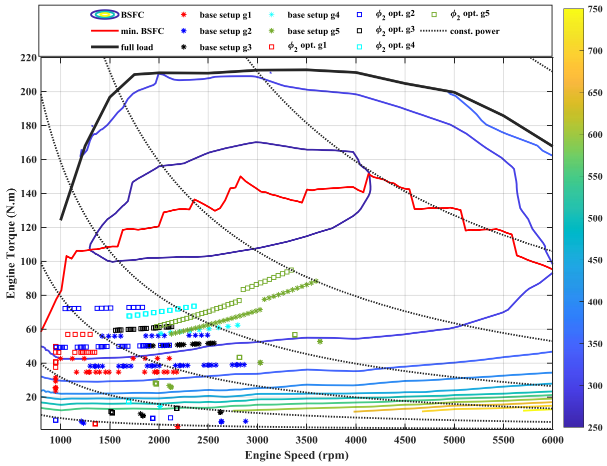

Figure 6: Gear ratio locations in the first phase of the optimization process

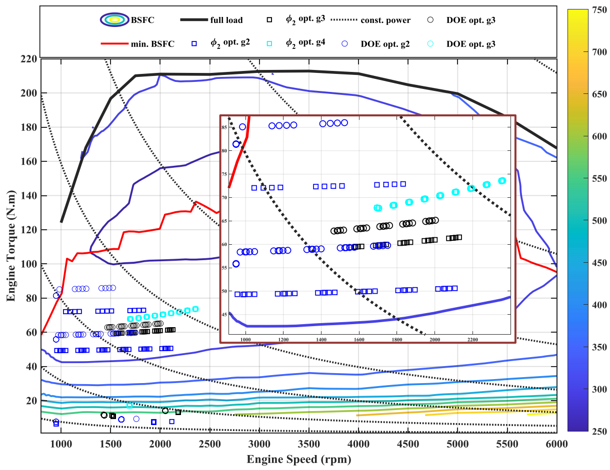

Figure 7: Gear ratio locations in the second phase of the optimization process

8) Conclusions

We studied different choices and approaches to select and optimize a powertrain for a B-class sedan vehicle regarding in-cycle fuel consumption. Results showed that neglecting the first and last gear ratios in the base gearbox and redesigning them based on vehicle functional targets can lead to better outcomes. Two approaches by which we optimized the gear ratios were a direct optimizer based on a genetic algorithm and a set of DOE analysis tools provided by GT-Suite software. Based on current research, DOE analysis led to better results in less time. The best result we got among all configurations was the combination of a 1500 cc turbocharged engine with a 5-speed manual gearbox with optimized gear ratios based on the DOE analysis technique. In this case, we reached to 13.5% reduction in in-cycle fuel consumption.

List of Symbols

m_F	Vehicle mass (kg)
g	The gravity of earth (m/s^2)
f_r	Rolling resistance coefficient
α_{st}	Road Slope
ρ_L	Air density (kg/m^3)
c_W	Drag coefficient
A	Frontal area (m^2)
v	Speed (m/s)
λ	Rotational inertia coefficient
a	Acceleration (m/s^2)
φ_1	Base ratio change
φ_2	Progression factor
z	Number of gears
i_n	nth gear ratio

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انتخاب و بهینه‌سازی قوای محرکه برای یک خودروی سدان ردهٔ ب با توجه به مصرف سوخت

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چکیده

در این پژوهش بررسی و مقایسهٔ گزینه‌هایی برای قوای محرکه خودروی سدان ردهٔ ب از حیث مصرف سوخت ارائه شده است. انتخاب‌ها شامل دو موتور و یک جعبه‌دندهٔ دستی با قابلیت تغییر تعداد نسبت دنده‌ها بوده است. با توجه به نمونه‌های مشابه، بررسی در زمینهٔ تعداد دنده‌ها روی جعبه‌دنده‌های ۵ و ۶ سرعتی محدود شد. بطور موازی از دو روش بهینه‌سازی برای بدست‌آوردن نسبت دنده‌های بهینه برای رسیدن به کمترین مصرفت سوخت در یک چرخهٔ رانندگی استفاده شد که نتایج تقریباً یکسانی حاصل شد. برای پیش‌بینی مصرف سوخت خودرو در چرخهٔ اروپا، یک طرح دینامیک طولی خودرو که در محیط GT-Suite توسعه یافت، استفاده شد. دو رهیافت استفاده‌شده برای بهینه‌سازی نسبت دنده‌ها شامل یک بهینه‌سازی مستقیم بر پایهٔ روش وراثت و همچنین بهینه‌سازی با استفاده از ابزارهای تحلیل DOE موجود در محیط نرم‌افزار GT-Suite بوده‌اند. بهترین نتیجه از بین گزینه‌های موجود برای ترکیب یک موتور ۱٫۵ لیتری پرخوران با یک جعبه دندهٔ ۵ سرعتی دستی با استفاده از بهینه‌سازی با روش DOE بدست آمد. در این حالت بهینه، کاهش مصرف سوخت در چرخهٔ اروپا نسبت به حالت پایه، ۱۳٫۵ درصد کاهش یافت.

اطلاعات مقاله

تاریخچهٔ مقاله:

دریافت: ۱۵ بهمن ۱۴۰۰

پذیرش: ۲۹ اردیبهشت ۱۴۰۱

کلیدواژه‌ها:

بهینه‌سازی

نسبت دنده‌ها

مصرف سوخت چرخه‌ای

تحلیل DOE