Drag Optimization on Rear Box of a Simplified Car Model by Robust Parameter Design

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ABSTRACT

Reducing fuel consumption of cars is one of the main targets of the automotive manufacturers. Optimum design of car from the aerodynamic viewpoint to reduce drag coefficient is one of the efficient methods toward this aim. In this paper, optimum geometrical parameters of rear box in a simplified car model are obtained to minimize aerodynamic drag. For this purpose, the powerful method of robust parameter design (RPD) along with computational fluid dynamics is used. Optimum values of the parameters obtained by the RPD method is compared with the results of numerical simulations. The comparisons show good agreement between the results.

Keywords: **Vehicle Aerodynamic, Drag Coefficient, Robust Parameter Design, CFD**

1. INTRODUCTION

Different models are used in the literature to study aerodynamics of vehicles [1]. One of the standard models to study air flow over the vehicle rear end is the Ahmed model [2], which is used in many experimental [3-7] and numerical [8-13] investigations. In sedan cars, besides the slant angle considered in the standard Ahmed model, there are other geometric parameters like rear box length, rear box angle, and boat tail angle, which have considerable effect on the aerodynamic drag coefficient of the vehicle [14].

Conventional methods fail in finding optimal values of aerodynamic parameters of the vehicle rear end due to large number of parameters and time-consumption and expense of conducting experimental and numerical procedures for different levels of parameters. Therefore, Taguchi and response surface methods of design of experiments approach are used in these studies. These methods are applied not only in experimental and industrial works [15-18] but also in expensive and time-consuming numerical studies such as CFD and crash simulations [19-24].

In this paper, a simplified vehicle model with four parameters, namely slant angle, rear box length, rear box angle, and tail boat angle is studied. Each of the parameters are considered in five levels. For reducing computational cost, Taguchi method based on the robust parameter design is used in the study and the optimal levels of parameters for drag reduction are determined. The process of optimization using Taguchi method is shown in Fig. (1).

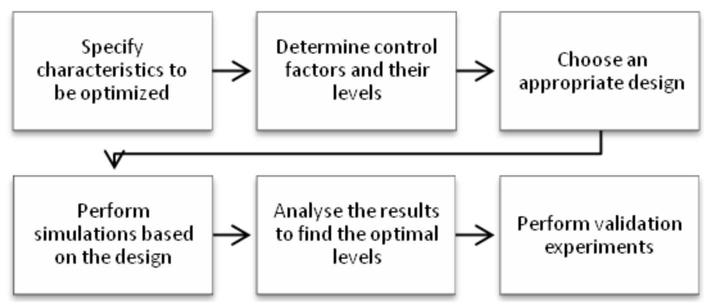

Fig. (1) Aerodynamic optimization using Taguchi method

2. VEHICLE MODEL

The vehicle model used in this research is an extended version of Ahmed model [2] which is proposed for studying drag coefficient variation due to slant angle.

In sedan cars, geometric parameters of rear box has considerable effect on the aerodynamics of the vehicle. These parameters are rear box length, rear box angle, and boat tail angle. In this study, as well as slant angle (φ) which was considered by Ahmed, rear box angle α, boat tail angle β, and rear box length l, which are effective parameters on drag coefficient [14] are considered. The parameters and dimensions of the model are shown in Fig. (2).

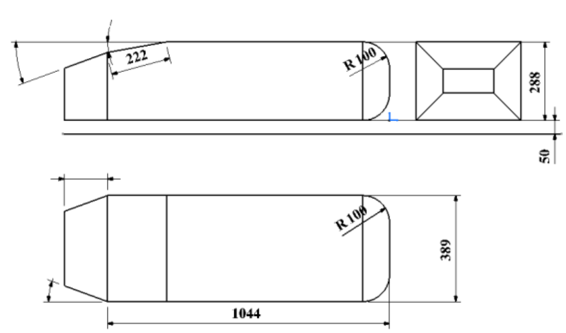

Fig. (2) Extended Ahmed model (dimensions are in mm)

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The range of parameter values are assumed to be $5 \leq \varphi \leq 25$ for slant angle, $0 \leq \alpha \leq 20$ for rear box angle, $0 \leq \beta \leq 20$ for boat tail angle, and $80 \leq L \leq 400$ for rear box length

3. TAGUCHI METHOD

Robust parameter design (RPD) is an approach to obtain the levels of controllable parameters in a process to set the output mean at a desired target and to minimize the variability around this target value. Taguchi formulated the general RPD problem and proposed an approach to solving it based on designed experiments. He also presented some novel methods for analysis of the results [25].

Taguchi's methodology provides some rules, which simplify and standardize design of experiments. The key tool in Taguchi's method of parameter design is designed experiments by statistical methods. The experiments are designed using a set of orthogonal arrays and conducted in-parallel. Utilizing orthogonal arrays in design of experiments, considerably decreases the number of required experiments.

I n Taguchi's method, results of experiments are analyzed for:

Determining Optimal operation conditions

Investigating the influence of each of the factors on the response

Estimating the response in optimal conditions

The tool used in Taguchi's method for analyzing results of experiments is signal to noise ratio (SN). SN is the ratio of signal variables to noise variables, which are uncontrollable. The aim of SN analysis is determining the best combination of variables to obtain optimal response. SN parameter is obtained by minimization of loss function, which is defined as

$$SN = -10 \log MSD \qquad (1)$$

MSD stands for Mean Squared Deviations. Definition of MSD depends on the desired conditions, i.e.,

When smaller is more desirable

$$MSD = \frac{\sum_{i=1}^{r} Y_i^2}{r} \qquad (2)$$

When bigger is more desirable

$$MSD = \frac{\sum_{i=1}^{r} \left(\frac{1}{Y_i^2} \right)}{r} \qquad (3)$$

When closer is more desirable

$$MSD = \frac{\sum_{i=1}^{r} (Y_i - M)^2}{r} \qquad (4)$$

Where Yi is response value, M is mean value, and r is number of repetition of each experiment. Using this method ensures that the effects of noise variables are less than the signal variables, i.e., the final response has the minimum sensitivity with respect to noise variables. The attractiveness of Taguchi method is that instead of controlling noise variables, by reducing their effects minimizes deviation in the quality characteristic. This is cost effective since controlling noise variables in the production process is very expensive.

In this study, since the target is to obtain minimum drag coefficient, the SN definition in (1) is used with MSD in the case of smaller is more desirable, i.e. (2). Considering the number of parameters and levels assumed for each parameter, L25 design is used in this study, which reduces number of simulations from 625 cases to 25 cases.

Table (1) Parameter values at each level

Parameter levels	φ (°)	L(mm)	α(°)	β(°)
1	5	80	0	0
2	10	160	5	5
3	15	240	10	10
4	20	320	15	15
5	25	400	20	20

The studied parameters and their levels are given in Table (1). The configuration of Taguchi L25 design for the problem with 4 variables, each of which are in 5 levels, are shown in Table (2). After performing 25 simulations of the designs given in Table (2), equations (1) and (2) are used to calculate signal to noise ratio. It should be noted that since the number of repetition of each experiment is 1, the value of r is set to 1 in (2). Therefore,

$$SN = -10 \log (Y^2) \qquad (5)$$

Table (2) Taguchi L25 design for aerodynamic optimization problem with 4 variables and 5 levels

Simulation No.	φ (°)	**L(mm)**	α(°)	β(°)
1	1	1	1	1

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2	1	2	2	2
3	1	3	3	3
4	1	4	4	4
5	1	5	5	5
6	2	1	2	3
7	2	2	3	4
8	2	3	4	5
9	2	4	5	1
10	2	5	1	2
11	3	1	3	5
12	3	2	4	1
13	3	3	5	2
14	3	4	1	3
15	3	5	2	4
16	4	1	4	2
17	4	2	5	3
18	4	3	1	4
19	4	4	2	5
20	4	5	3	1
21	5	1	5	4
22	5	2	1	5
23	5	3	2	1
24	5	4	3	2
25	5	5	4	3

4. RESULTS AND DISCUSSION

4.1. Taguchi Results Analysis

After performing 25 simulations based on the Taguchi L25 design and using orthogonal arrays algorithm, the response can be predicted in the other levels of variables. The simulation results for each design are shown in Table (3). Using equation (5), the signal to noise ratio is computed for each drag coefficient obtained by simulations.

Taguchi analysis results are given in Figs. (3) and (4) as signal to noise ratios and mean value of drag coefficient for different levels of parameters, respectively. The mean value of drag coefficient reported for each level of parameters is summation of drag coefficients at that level divided by 5, e.g., The mean value of drag coefficient at the first level of the parameter β is the average of drag coefficients in the simulation number 1, 9, 12, 20, and 23.

Considering the signal to noise ratio graphs for different levels of parameters, the optimum value of parameters are obtained. Reminding the definition of signal to noise ratio in (5), it is obvious that maxima of these graphs are the optimal levels of parameters for minimum drag coefficient.

Table (3) Simulation results and signal to noise ratios

Simulation No.	$\varphi\,(^\circ)$	L**(mm)**	$\alpha\,(^\circ)$	$\beta\,(^\circ)$	**Drag Coef.**	**SN ratio**
1	5	80	0	0	0.253	11.948
2	5	160	5	5	0.207	13.666
3	5	240	10	10	0.169	15.422
4	5	320	15	15	0.138	17.188
5	5	400	20	20	0.130	17.688
6	10	80	5	10	0.203	13.830
7	10	160	10	15	0.176	15.077
8	10	240	15	20	0.146	16.701
9	10	320	20	0	0.231	12.728
10	10	400	0	5	0.207	13.696
11	15	80	10	20	0.196	14.158
12	15	160	15	0	0.232	12.687
13	15	240	20	5	0.188	14.530
14	15	320	0	10	0.206	13.710
15	15	400	5	15	0.149	16.527
16	20	80	15	5	0.222	13.058
17	20	160	20	10	0.187	14.569
18	20	240	0	15	0.195	14.195
19	20	320	5	20	0.166	15.592

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20	20	400	10	0	0.207	13.686
21	25	80	5	15	0.213	13.435
22	25	160	0	20	0.208	13.656
23	25	240	5	0	0.234	12.616
24	25	320	10	5	0.189	14.479
25	25	400	15	10	0.167	15.566

As can be seen in Fig. (3), slant angle $\varphi = 5°$, length $L = 400mm$, rear box angle $\alpha = 15°$, and boat tail angle $\beta = 20°$ are the optimum values of parameters, which are verified by mean value of drag coefficient graphs in Fig. (4).

Fig. (4) shows that increasing slant angle has direct effect while increasing the rear box length and boat tail angle has inverse effect on increasing drag. Increasing rear box angle up to $\alpha = 15°$ decreases the drag coefficient and beyond this value increases the drag coefficient.

The parameter range is defined as

$$R_p = \max(SNR_L | L = 1,2,3,4,5) - \min(SNR_L | L = 1,2,3,4,5) \quad (6)$$

Where p can be replaced by φ, L, α , and β. The contribution ratio of parameters to drag coefficient is estimated by

$$c = \frac{R_p}{R} \quad (7)$$

Where R is

$$R = \sum R_p \quad (8)$$

The pie chart obtained by equation (13) is shown in Fig. (5). It is observed that contribution of parameters to drag coefficient reduction is in the order of boat tail angle, rear box length, and slant angle.

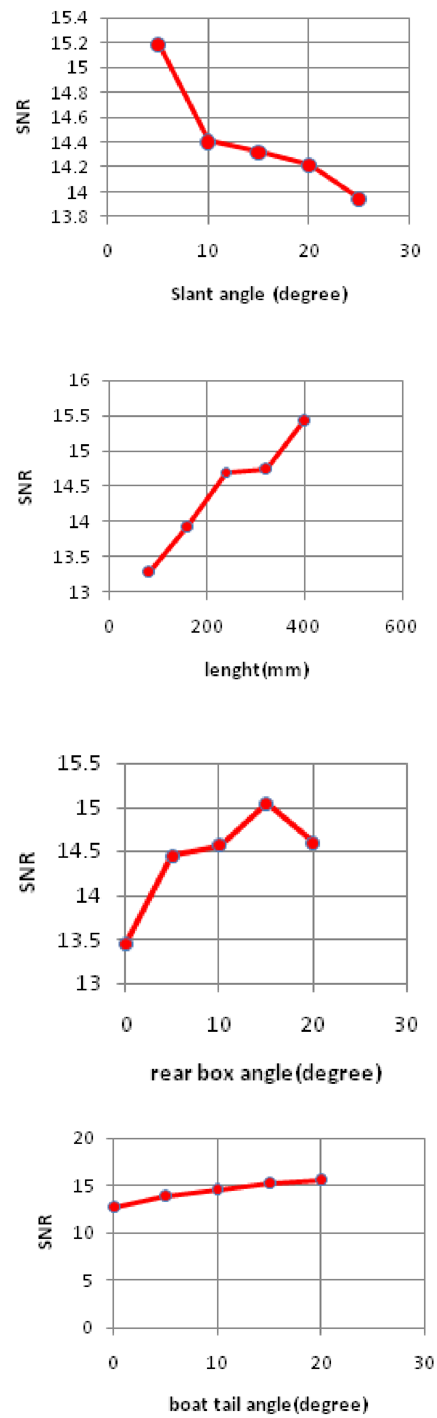

Fig. (3) Signal to noise ratios for different levels of parameters

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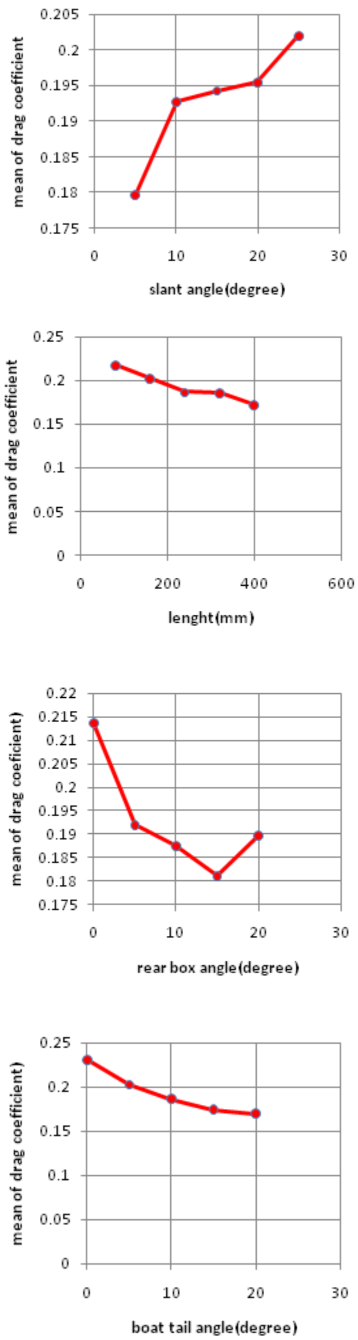

Fig. (4) Mean value of drag coefficient for different levels of parameters

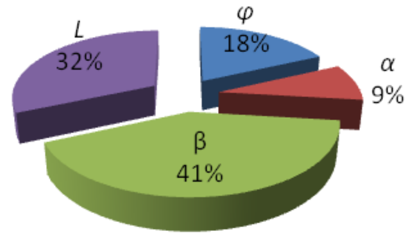

Fig. (5) Contribution ratios of parameters to drag coefficient

4.2. Validation of Taguchi Results

In the previous section, the optimum values of parameters for obtaining minimum drag coefficient is computed by Taguchi method. The optimal drag coefficient predicted by Taguchi method is $CD = 0.124$. Now Taguchi prediction is validated by simulation.

Table (4) Optimum values of parameters and drag coefficient

Parameter	Optimum Value
Slant angle (degree)	5
Rear box length(mm)	400
Rear box angle (degree)	15
Boat tail angle (degree)	20
Drag coefficient by Taguchi	0.124
Drag coefficient by simulation	0.132
Difference between Taguchi & simulation	6%

As can be seen in Table (4), Taguchi results are in good agreement with the simulation results. Therefore, the parameter values obtained by Taguchi method can be accepted as optimum values.

4.3. Investigation of Flow Around Optimal Model

Figures (6) and (7) show that similar to the Ahmed model, 2 D and 3 D vortices are formed at the rear end of the optimal model.

In contrast to the Ahmed model, due to the configuration of optimal model, the size of vortices is decreased considerably and the existence of rear box makes delay in separation of flow. Despite this fact, formation of four 3 D vortices on side edges of the rear box slipping downward is clearly observed. The other important issue to be noted is formation of vortices due to

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boat tail angle comparable to vortices on rear box due to slant angle and rear box angle.

As can be seen in Fig. (8), the variation of pressure coefficient distribution on the optimal model is reduced. The friction drag is increased due to generation of boundary layer on the rear box. Therefore, the contribution of the pressure drag is reduced and the contribution of the friction drag is increased to overall drag.

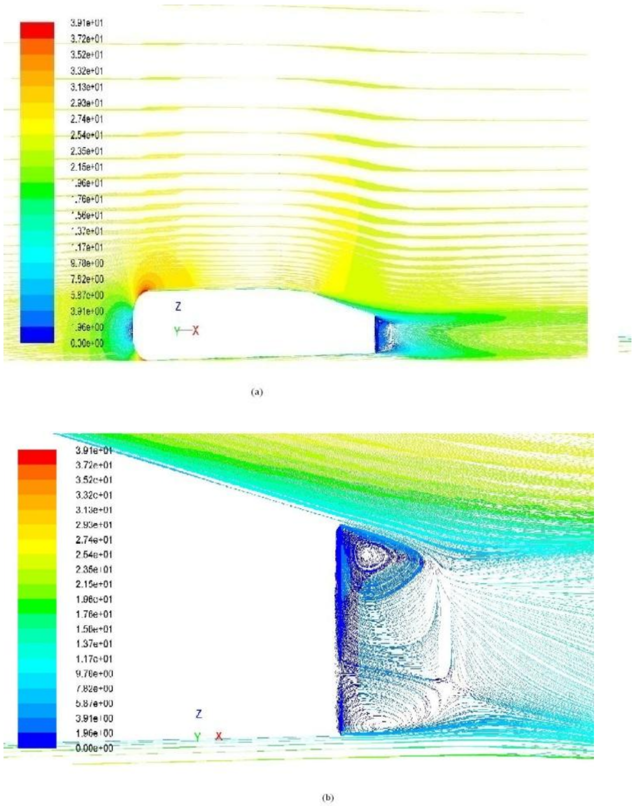

Fig. (6) (a) Streamlines based on velocity field on symmetry plane, (b) 2 D vortices formed at the rear end of the optimal model

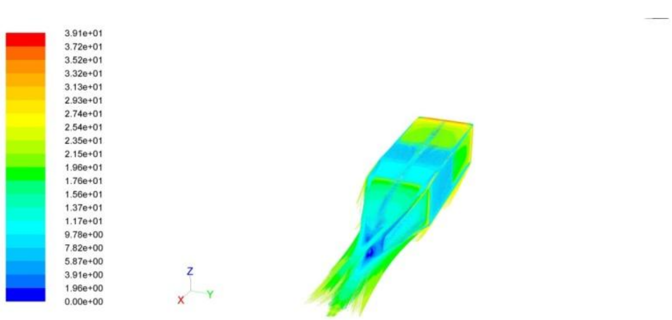

Fig. (7) Formation of 3 D vortices at rear end of the optimal model

In optimal model 51% and 49% of overall drag is due to friction drag and pressure drag, respectively. In contrary to Ahmed model with 80% and 20% of overall drag is due to pressure drag and friction drag, respectively. This discrepancy between the optimal and Ahmed models can be justified by streamlining of the optimal model.

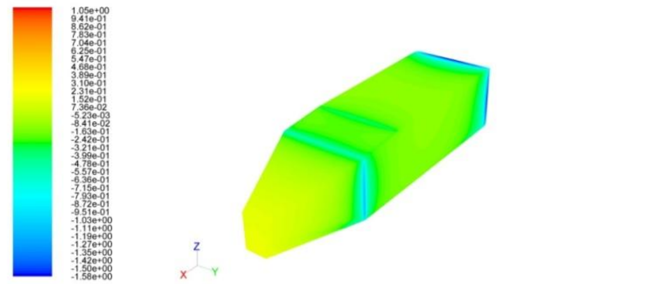

Fig. (8) Pressure coefficient distribution on the optimal model

5. CONCLUSION

In this paper, Taguchi method is used for optimal aerodynamic design of a simple vehicle model. The optimum values of parameters are obtained and the contribution of parameters to aerodynamic drag are determined. Using Taguchi method has considerable effect on reducing computational cost of the CFD simulations in design process. Comparing simulation results of optimal model with the Ahmed model reveals that the contribution of friction drag increases and the contribution of pressure drag decreases to overall drag.

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