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Aerodynamic Design of Buses Inspired by Sperm Whale

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Abstract: In this work, drag forces and drag coefficients of various bus models are investigated in CFD and wind tunnel. Reduced drag forces result in lower fuel consumptions. For new designs of buses, inspiration is taken from nature. Sperm whale shape forms are used in the analysis. The buses are drawn using UNIGRAPHICS program. The drawings are inserted into ANSYS CFD program for meshing. Drag forces and drag coefficients corresponding to the various designs are determined using Fluent (solver) and CFX (result) program. To compare with the experimental results, the experiments are carried out in a wind tunnel. Test data and CFD results are compared. Substantial reduction in drag coefficients is possible for these new geometries which are inspired from whales.

Keywords: Sperm whales, Computational Fluid Dynamics, Aerodynamics

1 Introduction

Biomimetic is a science where technological improvements are achieved by mimicking designs, structures and treatments from nature. A further jump in the current advanced level of technology can be possible by taking examples from nature and applying the concepts for solving our problems [1].

Mimicking forms from nature give rise to improvements in design concepts. Structure of humpback whale fins are investigated and the bumps known as tubercules can reduce drag and increase lift. Similar bumps can lead to more-stable airplane designs, submarines with greater agility, and turbine blades that can capture more energy from the wind and water [2]. Usage of edge tubercles on the wings and stabilizers of a commercial jet airliner could improve safety and reduce weight and fuel cost [3].

In this study, the sperm whales are mimicked to reduce drag forces and coefficients of buses. Different new models were constructed all inspired by the sperm whale geometry. Solid models of the new buses are drawn using Unigraphics program. The models are placed in a control volume in Ansys CFD program. Drag forces and drag coefficients are calculated for these new designs.

For aerodynamic designs of vehicles inspired from creatures, some of the recent work is as follows: A bionic car has been designed by Mercedes-Benz engineers mimicking the form of a boxfish. The drag coefficient of the car reached a very low value of 0.19 [4]. Mohamed et al. [5] studied the drag reduction of buses and found that reductions in aerodynamic drags up to 14% can be reached, which equals to 8.4% reduction in fuel consumption by modifications in the shape. Aerodynamics technology for the shape of Mitsubishi Lancer Evolution IX is changed and Mitsubishi Lancer Evolution X is occurred as a result. The shape of nose is imitated from a shark. As a result, the drag coefficient and lift coefficient values are less than that of the Lancer Evolution IX [6]. Airbus cargo plane is designed inspired by the form of beluga whales named as Airbus Beluga [7].

2 Materials and Methods

New designs of buses are presented in order to reduce drag force and hence fuel consumption. The drag forces and the drag coefficients of the new designs are contrasted with the commercial Neoplan Skyliner bus model which has one of the lowest drag coefficient value of 0.41 as provided by the manufacturer. The Skyliner bus is shown in Figure 1.

Figure 1: Neoplan Skyliner Bus [8]

3D Solid model of the Skyliner bus is drawn using Unigraphics program as shown in Figure 2. The length of the bus is 14 m, the width is 2.55 m, and the height is 4 m.

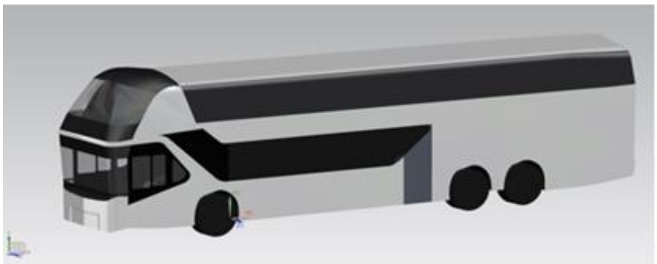
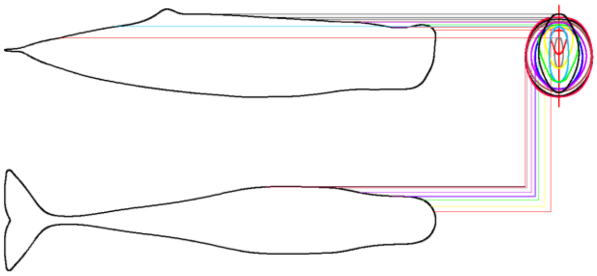


Figure 2: Neoplan Skyliner model drawn by Unigraphics

For new designs of buses, inspiration is taken from nature. Sperm whale shape forms are used in the analysis. Sperm whale grow up to 9-13 m in length and weighs up to 15-20 ton. Since buses need a large volumetric space, the sperm whales with their bulky bodies and excellent streamlined shapes are taken as examples. The shape is drawn in 2D using Autocad program and 3D shape is formed by Unigraphics program. The sperm whale (a), 2D model (b) and 3D model of it (c) is shown in Figure 3.

(a) [9]



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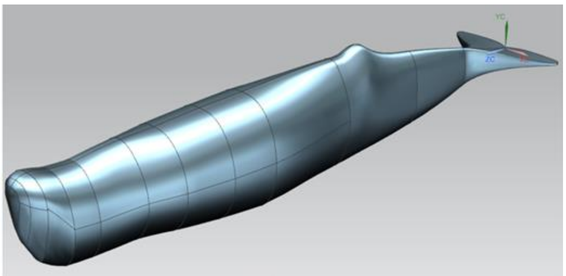

(c)

Figure 3: Sperm Whale and models

The dimensions of the solid model sperm whale are 2.8 m x 2.2 m x 14 m. The width of the tail is 3.2 m. Two dimensional models are drawn with Autocad program and the solid model is drawn with Unigraphics program.

Three different variants of the sperm whale bus models are drawn and specific names are given. The names are SW 1.1, SW 1.2, SW 1.3. The first number indicates to the form of the snout of the bus and the second number indicates to the middle and back part of the bus.

Partly reductions in width and height is observed in SW 1.1 model when viewed from above and sides. The frontal cross sectional area is designed to be larger than the rear cross sectional area.

In SW 1.2 model, the design of frontal part is same with the others but the rear body differs. From front to back, the height and width increase partially and then decrease towards the rear part. Excluding the frontal design, SW 1.3 has an identical body shape with the Skyliner body.

The original Neoplan Skyliner which is named as Skyliner N has a volume of 122.8 m^3. Instead of producing SW models with this volumetric size which will not be suitable in dimensions according to 128^{th} article of Highway Regulations, a reduced model of 100 m^3 volumetric space is selected for both the new designs and Skyliner models. The corresponding Skyliner model with 100 m^3 is called Skyliner.V. So, the bus with original volume is named as Skyliner.N and the bus with a partially reduced volume which has equivalent volume with the new designs is called Skyliner.V. SW 1.1.V, SW 1.2.V, SW 1.3.V. have all equal volumes with Skyliner.V.

The new designs of buses inspired from the sperm whales are shown in Figure 4.

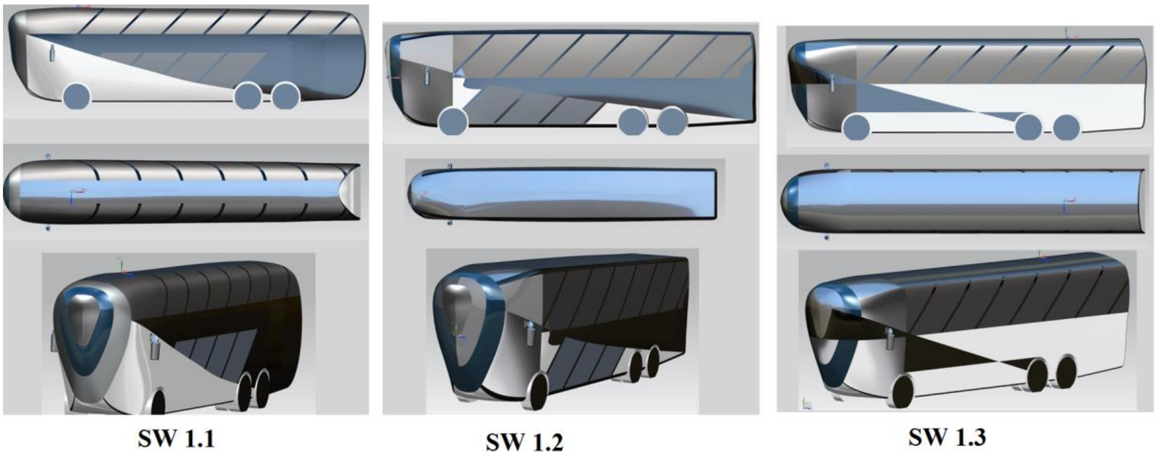

Figure 4: Three Different Sperm Whale Bus Designs

2.1 Numerical Methods

The models are located in a control volume. The control volume dimensions are 12 m, 22.5 m and 98 m in Ansys Workbench. The model is replaced in the control volume with twice the bus length from the inlet, four times bus length from the outlet and 8 times the bus width from sides. Blockage ratio is defined to be the ratio of cross-sectional area of the prototype to the cross-sectional area of the control volume. For reliable results this ratio is kept under 7.5% in this study. Skyliner.N model has the highest blockage with the rate of 3.6%. No reductions in the original dimensions are taken in the initial computations.

2.2.Mesh Converter

The model is placed in two rectangular prism shaped boxes as shown in Figure 5. Maximum skewness is kept under 0.95 in Ansys mesh for quality of mesh.

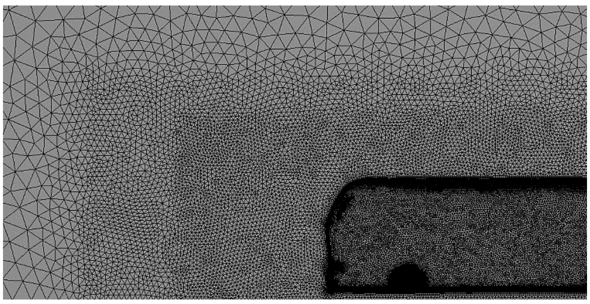
Figure 5: Meshing of Skyliner.N Model

Five different number of total meshes are used to test the mesh-independency with respect to drag coefficient (Figure 6). 8,000,000 number of meshes is observed to be ideal for convergence of the results. Maximum skewness ratio is found to be between 0.8-0.9.

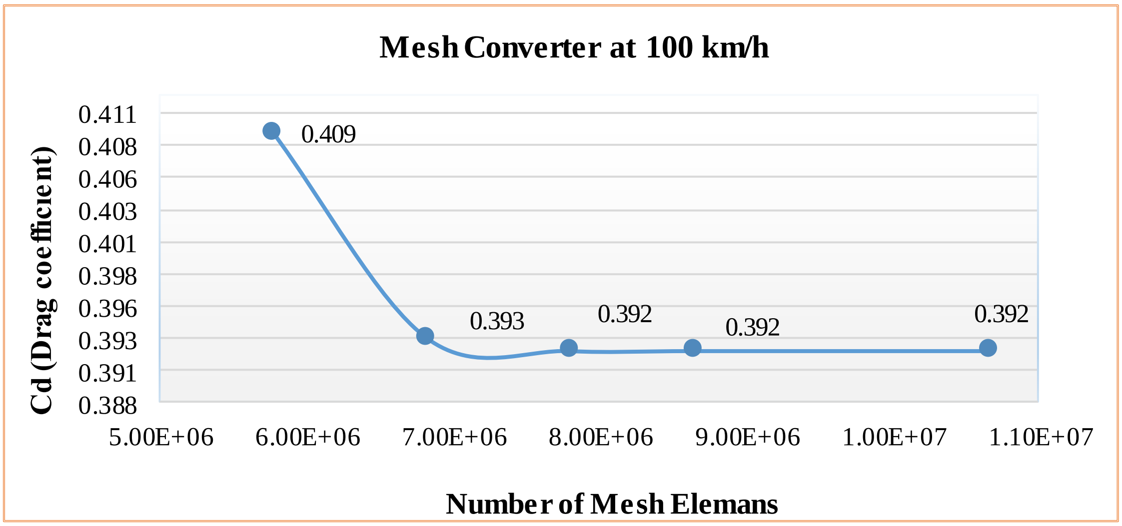

Figure 6: Mesh converter at 27 m/s (100 km/h)

2.3 Boundary Conditions

The boundary conditions are 27.7 m/s (100 km/h) velocity at the inlet surface, zero pressure at outlet, no slip condition at the road and bus, free slip condition at the sides for models. The road is taken as a moving road. The temperature, density of air and dynamic viscosity values used in the analysis are taken as 15.5°C, 1.225 kg/m^3 and 1.79 x 10^{-5} kg/ms, respectively.

The drag force is

$$F_d = 0.5\rho C_d A U^2 \tag{1}$$

where ρ is the fluid density, C_d is the drag coefficient, A is the cross sectional area perpendicular to the air flow direction of the bus and U is the fluid velocity relative to the bus. The cross-sectional areas of Skyliner N., Skyliner V., SW 1.1, SW 1.2, SW 1.3 are taken as 4.906 m^2, 4.285 m^2, 4.532 m^2, 4.388 m^2, 4.356 m^2 respectively.

In the flow analysis an important parameter is the boundary layer thickness. During the CFD stage, a suitable size for the first layer of grid cells (inflation layer) must be selected so that y^+ is in the desired range. The actual flow-field will not be known until one has computed the solution (and indeed it is sometimes unavoidable to have to go back and remesh the model on account of the computed y^+ values). To reduce the risk of re-meshing, one may want to try and predict the cell size by performing a hand calculation at the start [10].

Boundary layer computations should be included in the analysis. The parameters are

$$C_f = 0.058\,\mathrm{Re}^{-0.2} \tag{2}$$

$$\tau_w = 0.5\rho C_f V^2 \tag{3}$$

$$U^* = \sqrt{\frac{\tau_w}{\rho}} \tag{4}$$

$$y = \frac{y^+ \mu}{U^* \rho} \tag{5}$$

where C_f is the skin friction, τ_ω is the wall shear stress, U^* is the friction velocity. In the aerodynamic analysis, the reference displacement should be $y^+ \leq 1$ [10]. In this paper, $y^+=1$ is used and the turbulence model is selected as k-ω SST model which is recommended for external flow. First boundary layer thickness y is found by taking $y^+=1$.

2.4 Experimental Methods

In the experiments, 1:40 scale model of Skyliner.V are produced as a prototype. The test model is demonstrated with a suffix P. To be able to make comparisons, results of the 1:40 experimental models are also contrasted with the ANSYS solutions of the conventional dimension buses.

The boundary conditions of the domain of the 1:40 scale volumes are: 25.2, 28, 35 m/s velocities at the inlet surface, zero pressure-gradient at the outlet, the surfaces of the bus and road are defined to have no slip conditions. The road is taken to be stationary to comply with the experiments. The physical parameters during experimentation is given in Table 1.

Table 1: The physical parameters during wind tunnel experiments

Models	**T ^{o}C**	**ρ (kg/m^3)**	**μ (kg/ms)**
Skyliner.P	30.00	1.16	1.87E-05

The experiments are conducted in the wind tunnel which is located in Experimental Sciences Center (DEFAM) of Celal Bayar University (Figure 7). The maximum velocity of flow in the wind tunnel is 70 m/s, the section of test room is 300 x 300 mm^2, the length of test room is 1000 mm, the total length of the tunnel is approximately 6400 mm, the total weight is approximately 400 kg and contraction ratio is 11.1.

Figure 7: Wind tunnel in DEFAM

The inlet section of the tunnel is 1000x1000 mm. The diffuser spread angle is not higher than 7°. The power of the electrical motor is 15 kW, the fan with 0.8 diameter can produce 30000 m^3/h flow rate under 800 Pascal pressure.

3 Results

First the computational results with real dimensions are given and then the results of the experimentation are contrasted with the computational results of the reduced order models.

3.1.CFD Results

CFD results of the Neoplan Skyliner and whale models are given in this part. First, to confirm our computations, the drag coefficient of the commercial Skyliner N is calculated using ANSYS. The company procure a drag value of 0.41. Our calculations find out a number of 0.392. Our slightly lower value may be due to the smoothness of our model whereas the real bus definitely has some minor irregularities influencing the smoothness. Next, the SW models and the Skyliner model of 100 m^3 volumetric space which are indicated by the suffix V are compared with each other. The first boundary layer thicknesses, the Reynolds numbers, the drag coefficients and the total drag forces are given in Table 2 using the k-ω SST turbulence model for the inlet fluid velocities of 27.7 m/s, y^+=1.

Table 2: The drag forces and the coefficients at 27.7 m/s inlet velocity

Models	***y (m)***	**Re**	C_d	F_d **(N)**
Skyliner.N	2.57E-05	2.65E+07	0.392	1807.74
Skyliner.V	2.55E-05	2.48E+07	0.394	1589.30
SW 1.1.V	2.56E-05	2.59E+07	0.386	1644.27
SW 1.2.V	2.56E-05	2.54E+07	0.343	1414.77
SW 1.3.V	2.55E-05	2.52E+07	0.412	1686.98

The drag coefficients are not influenced from the small reduction in size of the Skyliner models. However, due to the reduction in the cross sectional area, the drag forces of V models are smaller than the N model. The drag force of Skyliner.N is 1807.74 N whereas that of Skyliner.V is 1589.30 N. Comparing the drag forces and the drag coefficients of all sperm whale models with that of Skyliner.V which has the same volumetric space, one can conclude that drag reductions may be achieved by mimicking sperm whale models. SW 1.2 performs the best compared to others. The total drag forces and the drag coefficients of the buses in Table 2 are given in Figures 8 and 9 also.

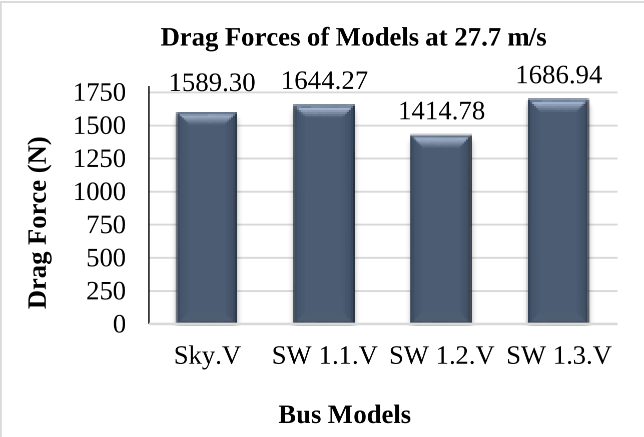

Figure 8: Drag forces of models at 27.7 m/s

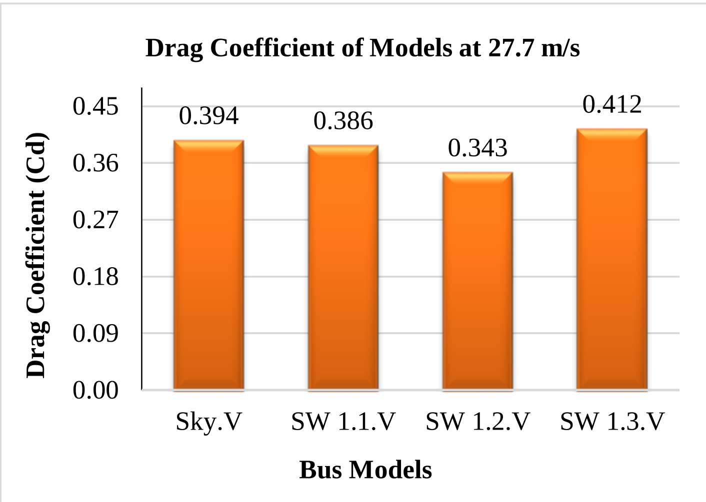

Figure 9: Drag coefficient of models at 27.7 m/s

Among the three variants of the whale models, the best is the SW 1.2.V with the lowest drag coefficient of 0.343. The drag coefficient of the SW 1.3.V (only the frontal part mimicked from Sperm Whale, the rest same with the Skyliner model) is highest compared to the new designs with a value of 0.412. This suggests that a merely frontal desing modification without designing the middle and rear parts of the bus is of no use.

Streamlines for the models are shown in Figure 10. Eddies are observed at the rear of all models.

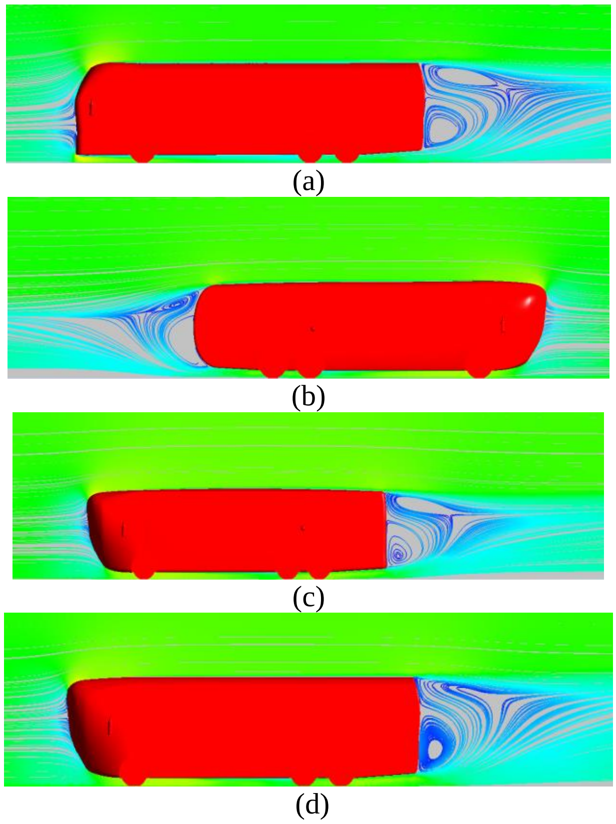

Figure 10: Streamlines of buses (a) Skyliner.V, (b) SW 1.1.V, (c) SW 1.2.V, (d) SW 1.3.V

The eddy formation at the rear is associated with the body design. The smallest eddies are formed for SW 1.2 model. This may be due to the curved design at the rear of the bus.

3.2.Experimental Results

For experimental studies, 1:40 scale prototypes of the skyliner is produced and named as Skyliner.P. The prototype model is shown in Figure 11.

Figure 11: Skyliner prototype model

The experimental results conducted in the wind tunnel are given in Table 3. The Reynolds numbers, the drag coefficients and the total drag forces are given for the three inlet fluid velocities of 25.2, 28, 35 m/s.

Table 3. Experimental drag forces and the coefficients

Models	**V (m/s)**	**Re**	C_d	F_d **(N)**
	25.2	5.10E+05	0.470	0.930
Skyliner.P	28	5.69E+05	0.494	1.210
	35	7.10E+05	0.493	1.880

To make accurate comparisons with the computational data, the same reduced dimensions of scale 1:40 are also taken in the CFD analysis and the results are compared.

Figure 12 shows the comparisons of experimental and CFD results for drag coefficient of the Skyliner.P model. The match is almost perfect. At the lowest velocity, while the discrepancy is 6.4%, the match becomes perfect for higher velocities.

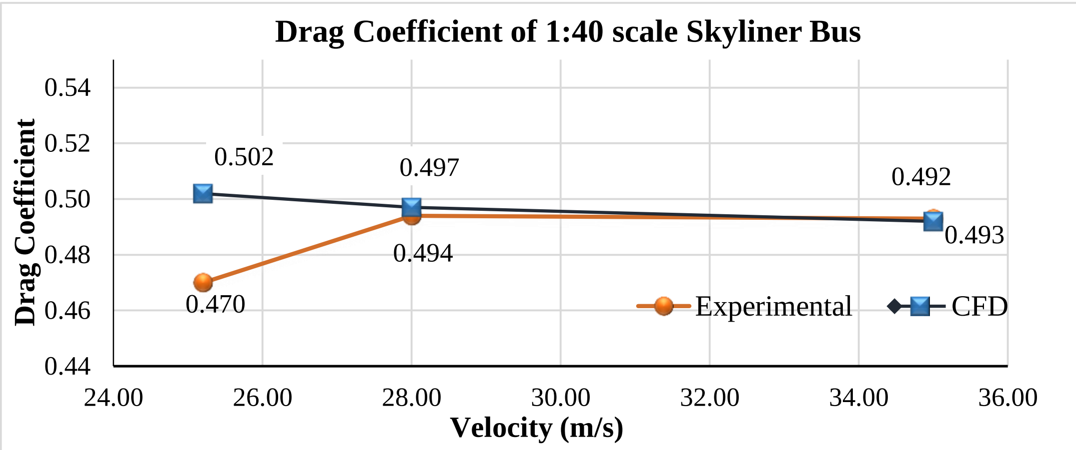

Figure 102: Comparisons of the experimental and the CFD analysis for the drag coefficients of Skyliner.P

The drag coefficients of Skyliner.P versus the Reynolds numbers are given in Figure 13. The drag coefficient decrease as the Reynolds number increases.

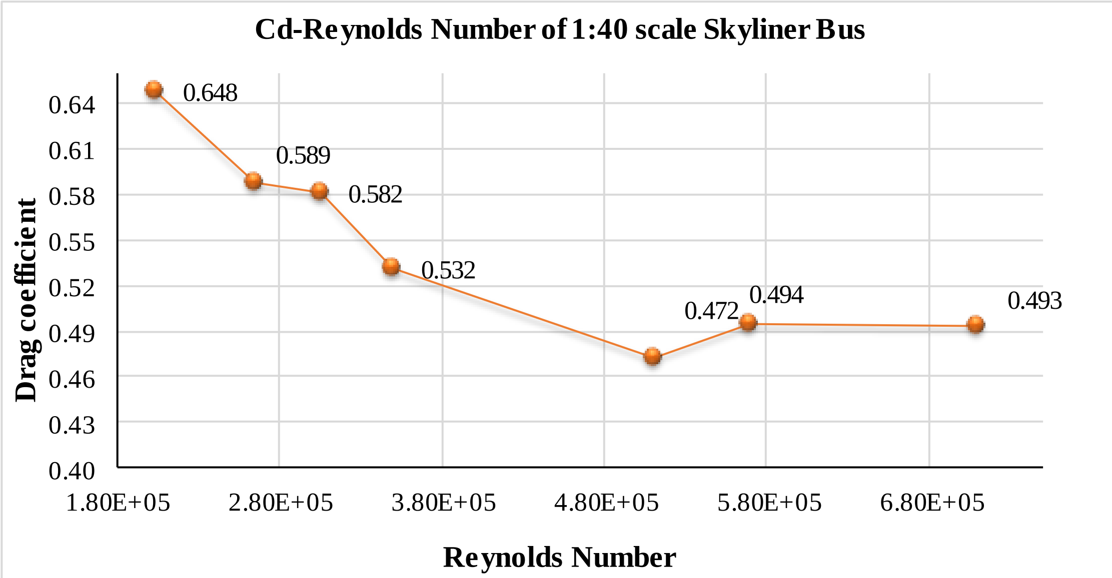

Figure 13: The Reynolds number and the drag coefficients

The experimental and computational results have a reasonable agreement in general.

4 Conclusion and Future Work

Inspired by sperm whales, three variants of the whale bus designs are compared to the comercial Neoplan Skyliner model which has one of the lowest drag coefficients among the conventional bus designs. In equal volumes of buses (named as .V models), the drag coefficients can be reduced to lower values of 0.343 as compared to some common designs of drag values as high as 0.394. In all variants of the models, the best is SW 1.2.V model with a drag coefficient reduction of 12.94 %.

The drag coefficient of the conventional prototype Skyliner.P model is calculated to be 0.470 (experimental) and 0.502 (CFD) at low velocity. The computational and experimental analysis indicate that there is 6.4% discrepancy between the results at low velocities. At higher velocities, the so called differences reduce to about 0.2 %.

Analysis shows that drag coefficients can be lowered by mimicking the perfect streamlined shapes of creatures. This in turn would result in lower fuel consumptions. Other fishes may be mimicked to design new buses in the future. The fuel consumption reduction is approximately 0.6 times the drag coefficient reduction [11] and hence a fuel consumption reduction of 7.77 % is expected in the new design.

Acknowledgments

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