

The Influence of Fluid Dynamics on the Design of Different Vehicle Structures

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Abstract. It is of great significance to understand the airflow disturbance above the vehicle for the design of the vehicle model. However, the traditional method is wind tunnel test, which is inconvenient and time wasted. In this article the team simulated the curves of different shapes above cars, such as Beetle, modern sedan car, jeep, and wedge-shaped cars. Besides, calculated the small disturbance equation in the form of python code. This paper analysed the full potential equation to find the small disturbance equation. Then studied and analyzed the disturbance of subsonic airflow above cars. Finally, this paper analysed the functional image and did a conclusion. The results shows that different shape of cars has different flow above the car in the subsonic flow and the wedge car has almost the best shape. The experiment result shows that it has an exelent accuracy compared to the literature, besides it has a low cost and a shorter time waste.

Keywords: Airflow disturbance, vehicle model, wind tunnel test, small disturbance equation.

1. Introduction

With the development of the technology and science. The modes of transportation have been fast promoted and changing itself quickly [1]. And one very important technical support for these developments is fluid dynamic. The flow of liquid is so normal that they cannot be reminded, not only the flow of the liquid, but also the flow of the air. The flow of air over objects is basic topic to the design of the shape of the vehicle and the design of aircraft in space engineers. The different shape of this transportation can greatly affect the air resistance when they are working [2].

Our paper will focus on a problem, which is closer to our daily life: the application of the fluid dynamics in autos. When the vehicle first came out [3]. People was fascinated by its convenience and the principle how it works. But at that time, cars were only a represent of the status and the wealth of a person, because the cars at that time couldn't move much faster than the traditional horse-drawn carriage, and its price were also not friendly to the normal workers' class [4]. And most of these were on account of the lack of the appropriate technology and the poor manufacturing capability. And our paper will mainly discuss how the fluid dynamics improve our cars to make it from a luxurious toy to a most commonly used daily transportation. Our paper will from three aspects to discuss this problem: first, this paper will study the history of some car shape evolution, and how cars become better with the change of shape. Then, this article will use python code to build the shape patterns of modern and old cars to simulate the movement of air above the vehicle surface. After that, this paper will compare the current and past cars, and use the chart obtained from python code to find out more clearly why fluid dynamics is so important in car design. But obviously, this article cannot only focus on the past and the present. Future developments should also be considered. At the end of this paper, we will propose some possible methods to further improve the automobile in the future.

2. Methods

2.1. Physical model

When building the model, this study will use specific intervals of different functions to simulate the surface contours of cars with four kinds of structures, namely: Beetle, Hyundai sedan, Jeep, and wedge-shaped sports car. In order to ensure the universality of the model, this study investigated the data of 40 cars and found that the overall length is about 2500 mm-5500 mm, while the length is concentrated at about 4000 mm [5-6]. The height of the car is between 1200 mm and 1700 mm, most of which are concentrated at 1400 mm. In this paper, the car length is unified into 2 unit lengths to avoid the extreme data impact of some cars. Each car is also divided into three parts, which are the front (0-0.5), the body (0.5-1.5), and the rear (1.5-2). Besides, it is more convenient to plug the model into the simulation system and analyze airflow streamlines. In this study, the height is an important factor, so different bump sizes were adapted in the functions [7].

The first model is a Beetle. It has a smooth operation and good safety performance. However, its power doesn't perform well. Beetle cars' starting capacity is slow. They also consume much fuel. Their tires' grip ability is poor [8]. In this study, three functions were used to simulate beetle car's structure. In Figure 1, the red sine function representing the front of the car, the blue sine function representing the body, which has a smaller bump size than the front, and the green linear function represents the rear of the car [9].

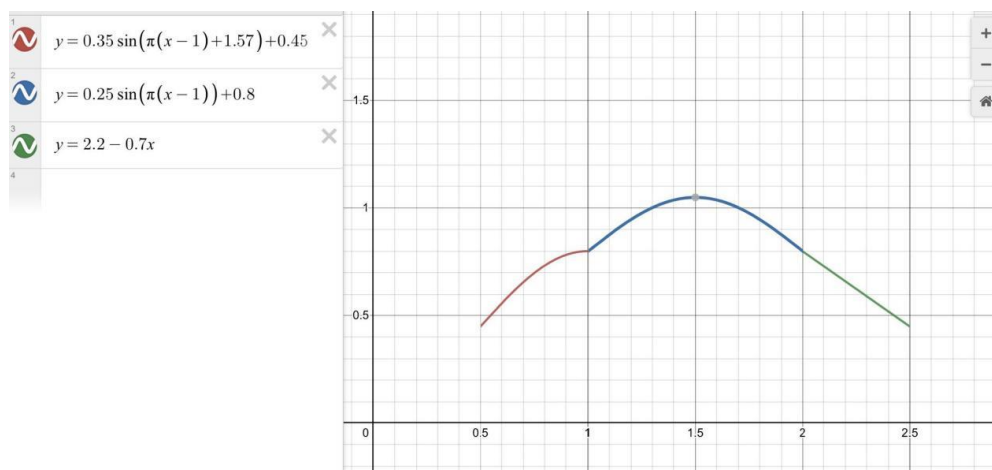


Figure 1. The model of a beetle car

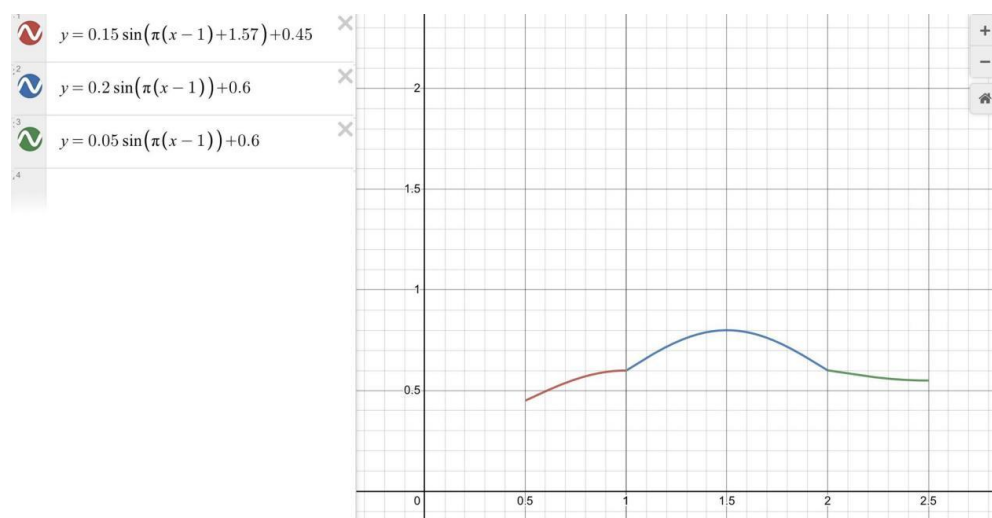


Figure 2. The model of a sedan car

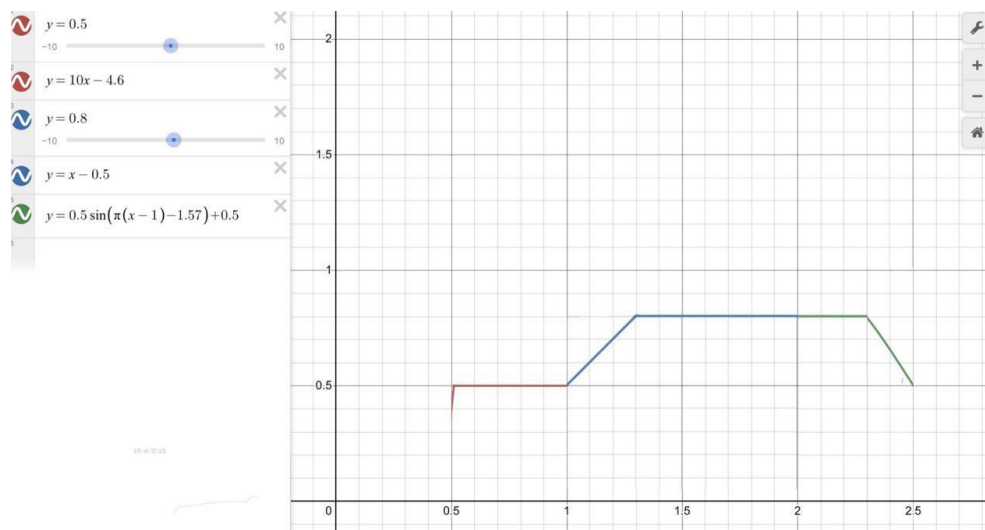


Figure 3. The model of a jeep

The second model is a modern sedan car. The shape of this car is between wedge-shaped and streamlined. The car is balanced in every aspect to meet the different needs of modern people. The car ensures the space, operate feeling, comfort, and speed at the same time. The sedan car uses a more smooth streamlined structure than the beetle. In the study, the three functions that are shown in Figure 2 were established. All three functions are sine functions. The bump sizes of the functions are not the same [10].

The third model simulates a jeep. Compared with other cars, jeeps are more applied on mountains or off-road. Strong stability and safety should be guaranteed to a jeep. Because of this requirement, jeeps abandon some speed ability. Jeeps also retain more space to carry passengers. This paper shows the functions in Figure 3 to display the model. Three sets of piecewise function were decided to show the edges of the car.

Finally, the last model is used to simulate wedge-shaped cars. This design is widely used in sports cars. The model shows a strong streamlined structure. The front of the car inclined down to increase the downward pressure. The design of wedge shape reduces air drag. But the car has very little space and is not suitable for heavy traffic on city streets. In order to show the most streamlined application of wedge-shaped cars, only two functions were established in the study. In Figure 4, the front part is a linear function with positive slope. The body and the rear share a sine function with a small bump size.

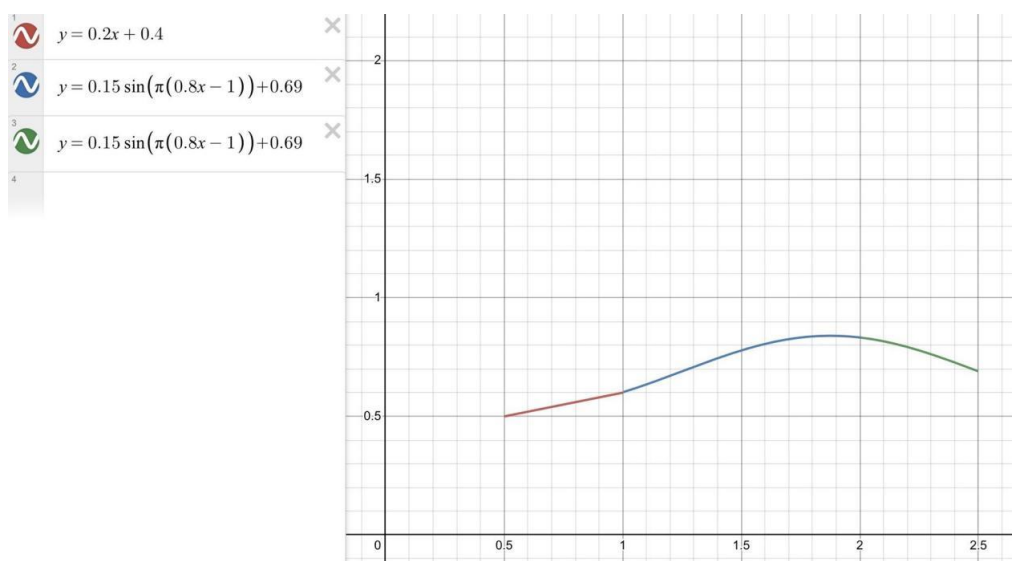


Figure 4. The model of a wedge-shaped car

2.2. Mathematical model

This paper used very simplified model and the model captured a very important physical phenomena. Start with the adjacency equation, and then described what it is, and how to solve it. Our first step advancing equation was going to be linear equation. Then this paper will discuss an equation called burgers equation, which is a nonlinear equation and has been transported by truck. One of the features of the flow is that shocks can develop. So the burgers equation, which is three one-dimensional equation in space and time, and in one time dimension can end meet shocks. Starting with a simple linear equation, there can be no influence. Then, by making the equation nonlinear, we increase the complexity slightly. As a result of this, solutions could admit shocks. The convection equation:

$$\frac{\partial u}{\partial t} + a \frac{\partial u}{\partial x} = 0 \quad (1)$$

Suppose time 0 is the shape given by the function.

Considered the problem $t > 0$, and x in the whole space. Let the initial condition be $a(x)$. Then the solution for all times was $g(x - at)$.

Noted that this was a moving wave whose shape was $g(x)$ and its speed was a (in the positive direction).

In this paper, numerical solutions will be developed to solve this equation, preparing for more complex problems involving vector valued function u . It will start with a physically meaningful solution.

The waves come from the left, so this paper will shift the scheme to the left.

The solution propagates along lines, called characteristics. See the analysis below.

When the slope 'a' was constant, as shown in the Figure 5:

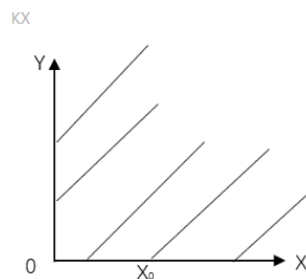


Figure 5. The limit and derivative form of function

Let $z(t)$ satisfy $\frac{\partial z}{\partial t} = a$, $z(0) = X_0$, and $z(t)$ was a point moving at speed. $u(t, z(t)) = u(0, z(0))$ u was const along these lines called characteristics:

$$\frac{\partial}{\partial t} u(t, z(t)) = \frac{\partial u}{\partial t} + \frac{\partial u}{\partial x} \times \frac{\partial z}{\partial t} = \frac{\partial u}{\partial t} + a \frac{\partial u}{\partial x} = 0 \quad (2)$$

And now the slope 'a' was not constant, as shown in the Figure 6, which could depend on time.

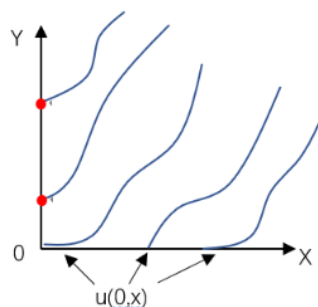


Figure 6. The limit and derivative form of function

The initial condition $u(0, x) = f(x)$ needed to specify.

But solution also propagate along these lines from red points in figure. These were boundary condition $u(t, 0) = h(t)$. and to solve the problem we needed $g(x)$ and $h(t)$.

But what if $a < 0$, as shown in the Figure 7.

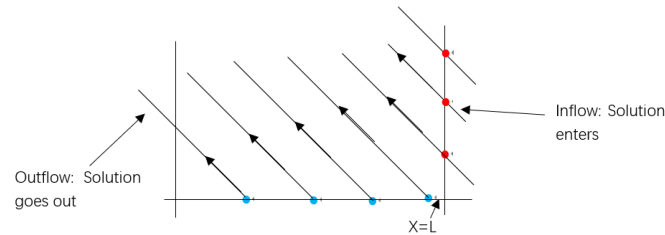


Figure 7. The limit and derivative form of function

Solution propagates from right to left. No boundary condition was needed at $x=0$. But it needed boundary condition at $x=L$. Based on $U \cdot N$. U : velocity vector. N : outward normal.

- $U \cdot N < 0$ inflow
- $U \cdot N > 0$ outflow
- $U \cdot N = 0$ wall

If the problem was in the whole space in X , no need to specify boundary condition. What if characteristic did not cover the whole space? There was a region in which there was ambiguity of the solution, as shown in the figure 8.

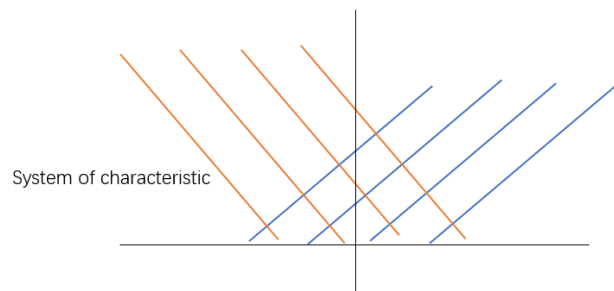


Figure 8. The limit and derivative form of function

Burger Equation. Here the speed of the wave depended on the solution as it evolves over time. This model allowed us to understand Important properties of the 1D Euler equations, as shown in the Figure 9.

$$\frac{\partial u}{\partial t} + \frac{\partial}{\partial x} \left(\frac{u^2}{2} \right) = 0 \quad (3)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} = 0 \quad (4)$$

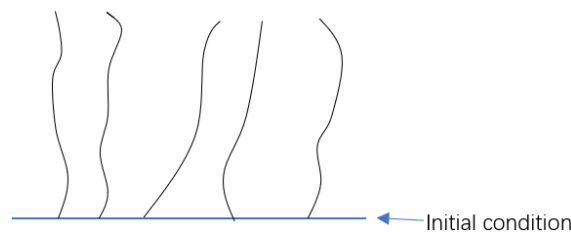


Figure 9. The limit and derivative form of function

And now, how could we determine the shock? As shown in the Figure 10, the middle part is shock.

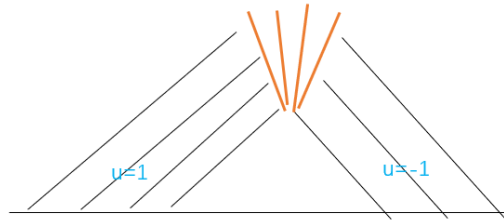


Figure 10. The limit and derivative form of function

Calculation of the shock speed was done by integrating the equation across a shock on an infinitesimal region containing it. The equation must be in conservation form in this analysis. We considered a general 1D scalar conservation law. u was the unknown function $f(u)$ was called the flux. It integrated the equation in x , in an infinitesimal region around the shock. See figure below.

Shock condition:

$$\frac{\partial u}{\partial t} + (f(u))_x = 0 \quad (5)$$

$$\int_a^b \left[\frac{\partial u}{\partial t} + (f(u))_x \right] dx = 0 \quad (6)$$

$$\frac{\partial}{\partial t} \int_a^b u dx + \int_a^b (f(u))_x dx = 0 \quad (7)$$

$$\frac{\partial}{\partial t} \int_a^b u dx + f(u(b)) - f(u(a)) = 0 \quad (8)$$

$$\int_a^b u dx = \int_a^{x_s(t)} u dx + \int_{x_s(t)}^b u dx \quad (9)$$

Let $[z]$ denotes the jump in quantity z across the shock.

The jump condition for general scalar equation was shown to satisfy:

$$c[u] = [f(u)]$$

Where c was the shock speed, $[u]$ is the jump in u , and $[f(u)]$ is the jump in $f(u)$. Note that for Burgers get $c = (u_1 + u_2)/2$.

Noted that the analysis of shocks was done in conservation Form of the equations. In the following Figure 11 it shown the limit and derivative form of function.

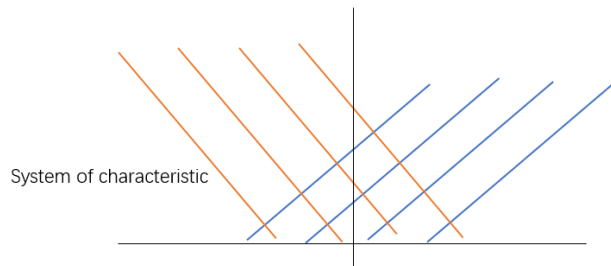


Figure 11. The limit and derivative form of function

A simplification of the full potential equation was done in the case of thin obstacles, such as thin airfoils. This paper would restrict the discussion to 2D.

Since the obstacle was 'small', its effect on the flow was small and it considered perturbation to uniform flow with velocity of magnitude in the x -direction. The potential had a representation

$$\phi = U_\infty(x + \Phi) \quad (10)$$

Where velocities were recovered from the potential using the formulas

$$u = U_\infty(1 + \Phi_x) \quad (11)$$

$$v = U_\infty \Phi_y \quad (12)$$

The equation became with the Mach number:

$$(1 - M_x^2)\Phi_{xx} + \Phi_{yy} = 0 \quad (13)$$

Which could be simplified further to

$$(1 - M_\infty^2)\Phi_{xx} + \Phi_{yy} = 0 \quad (14)$$

The wall BC became where $f(x)$ is the shape of the airfoil.

Then it comes to the full potential equation. Scientists usually speak about subsonic flow and supersonic flow, transforming law. So there are different regimes of law supersonic flow is faster than the speed of sound, and the speed of subsonic flow is slower than the speed of sound. It's a flow which is relatively slow. It means not very but it's still a car. So it's fast but not as fast as the speed of sound. This paper is talking about problems, like, what does it means to simulate an error foil.

The first equation which need to understand for subsonic flow is the Poisson equation.

$$\Delta\phi = \text{div}\nabla\phi = \frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} \quad (15)$$

For the flow above the car is the subsonic equation. So this talked about the Laplacian, which involves the sum of the second derivative of the function. The function is a scalar valued function. This is the full potential equation. In the equation, not for a set of variables, but only for one of them, the velocity field is obtained from the gradient of the function ϕ . The equation is very similar to Poisson equation, Laplace equation appears in mathematical physics.

2.3. Python code analysis

In the python code part, it defined a 'beta' first, which represents the barrier of the ambient air friction. It was altered by the density of discrepant types of gases. The cases it considered were the normal air situation, so it simply changed the data here to meet the requirements.

The specific section of the physical model was extract thought the limit of x . it changed the functions which shown in physical models into derivative forms to see the gradients. The velocity it was written in the form of kilometers per hour, so the Mach number had to be divided by 3.6. Then it included some codes to detect potential errors. The small disturbance equation was adapted to determine whether there was error in the whole loop. The equation altered when the Mach number was changed in different flows such as subsonic, trans-sonic or supersonic. Our project mainly focuses on subsonic flow, but when considering one certain case of hypothesis, it alter the equation into supersonic form.

Other parameters were determined by the boundary conditions of the small disturbance equation. It set the U and V parameter to define the shape of our streamlines, which represented the vehicle that blocked the air. The following part used the equation demonstrated in the mathematical model part, which utilized the small disturbance equation to form the whole graph shown below. In the subsonic case, it substituted both A_{xp} and A_{xm} equal to 1 minus the square of the Mach number, while B_{yp} and B_{ym} equal to 1. It got the value of C_0 , which may be then get involved in the calculation of fluid dynamics due to the equation.

Finally, it made a streamline by substituted in the velocity parameters and the limit of axis.

3. Result and discussion

Considering different types of cars, it categorized them into 4 groups.

3.1. Streamlines of different type of cars

3.1.3 Beetle cars

After the course of code-running, it got the air-flow situation around these three parts as shown in Figure 12.

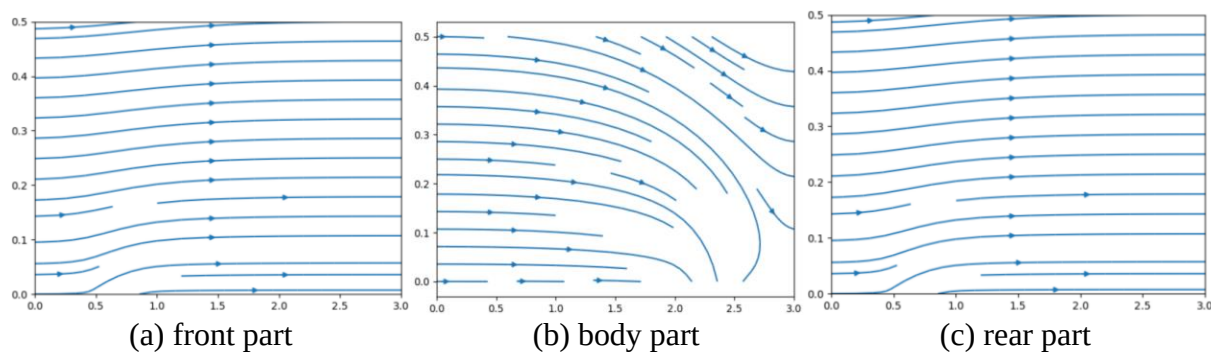


Figure 12. Streamlines of beetle cars

The three discrepant images show that beetle cars don't suffer from much air pressure in its front or middle part, since these lines seem to be rather smooth. However, when focusing on the rear part of beetle cars, it found that the curves were fierce and had many slopes. The wrapping-shaped air distribution graph was what differs the most.

3.1.2 Modern car

In Figure 13, the streamlines of modern cars were smoother with fewer bends. This characteristic reflects that modern cars are stable to drive. The characteristic also explained why the accelerating ability of sedan cars is better than other types.

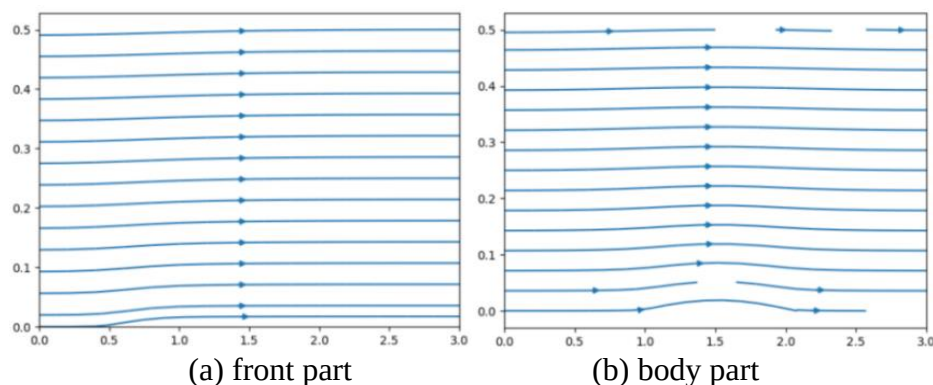


Figure 13. Streamlines of modern sedan cars

3.1.3 Jeep car

Analyzing the jeep car, the most arresting part is that the images have many angles in both the front part and the middle part. The design of jeeps emphasize son the strong stability because jeeps are usually driven on rough roads. The air pressure helps maintain the balance of the car.

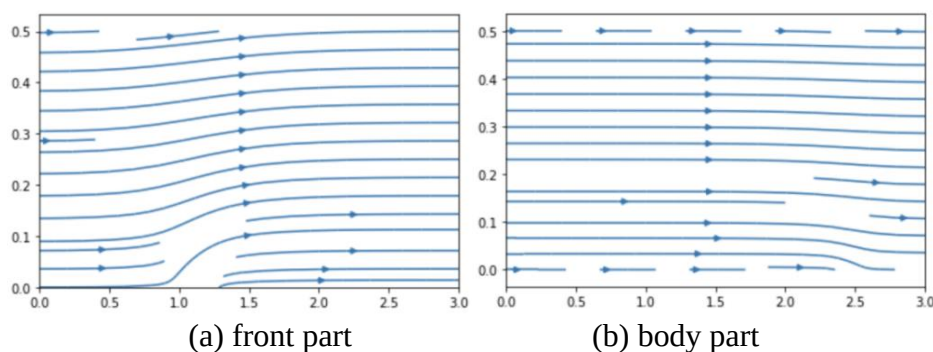


Figure 14. Streamlines of jeep cars

3.1.4 Wedge car

In this type we simulated its body shape with two curves, so it merely used two functions. The graphs of the wedge cars are the smoothest among the four car types. The design of adapting extreme

streamline tries to improve the speed to maximum. The air poses little barrier to the windshield of the wedge car. It all know that the fluid pressure will decrease when the fluid velocity increases. The low air pressure above the wedge car makes the car less stable. So wedge cars are usually designed to face diagonally down. The air pressure above the car prevents the car from being lifted by the air pressure below the car and improves driving safety.

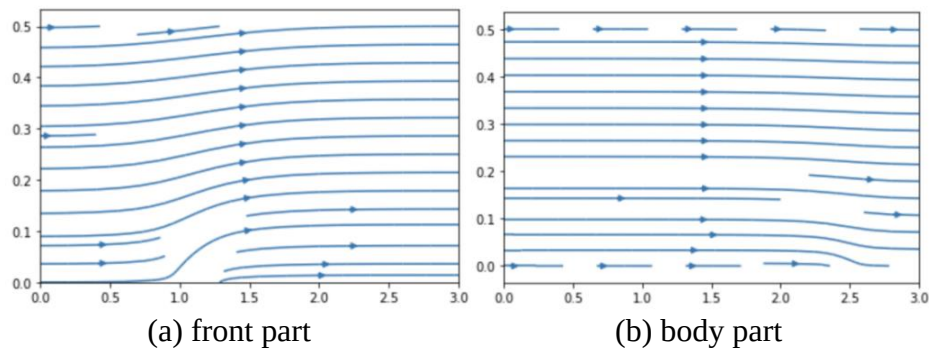


Figure 15. Streamlines of wedge cars

3.2. Comparison among streamlines

From the images it got, it concluded that each type of vehicle had some discrepancies with the other types in the ambient airflow. Initially it analyzed the front part. In the image of the beetle type, the slope of the curve is more manifest than the modern and the wedge car, and the jeep has a more gradient curve. The modern car and the wedge car are very alike in this round.

When comparing the middle part of each car, the beetle car and the modern car looks similar. They both have a hill-shaped curve in the middle. The jeep still has a big slope in its front, and the air flow is more unstable than the other types. The lines in the image of wedge car can be almost regarded as straight lines.

Looking at the rear part of these cars, the modern car is similar to the jeep. The lines in the wedge car is smoother than the others. But the air flow around the beetle car's rear part is just like a package which wraps it all over.

If there is no obstacle in the route of an air flow, it'll move straight forward. In other words, if the air-flow curve has a bigger gradient, the speed will be influenced. So jeep cars suffer more air pressure in its front glass and likewise, the beetle car is disturbed at its back.

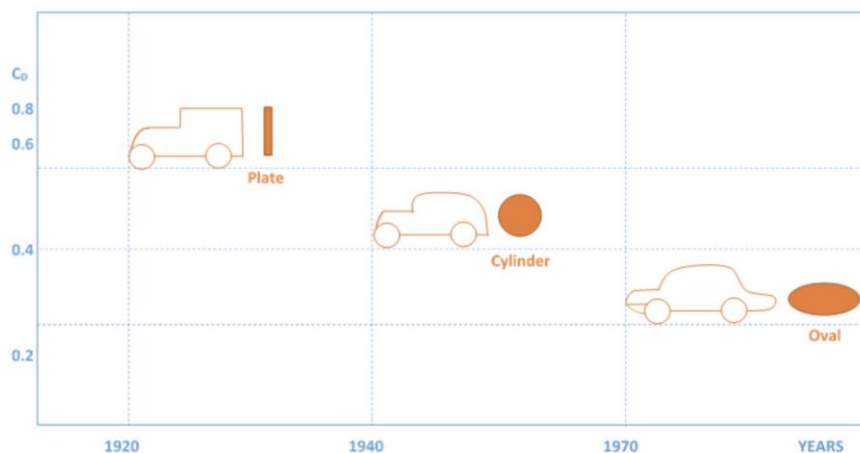


Figure 16. Car geometry in relation to air resistance

The design of the shape of the car affects the air resistance of the car (Figure 15), which further affects the speed, maneuverability and balance of the car. Cars are designed to have different air environment around because they are used for various places. The beetle car is designed to carry more items in its trunk, so the rear part is bigger than the others, which leads to its distinguishable image. Jeeps have to adapt to miscellaneous environment and sacrifice their speed to stability. The structure

of jeeps must be strong enough to endure fierce smashes. The wedge car focuses on its pace, therefore the streamlined design shows straight lines in the air distribution graph. The modern car, which is the household one and has the largest amount worldwide, combines the merits of each type and it has a balanced pursuit of speed, storage and stability.

4. Conclusion

In this paper, it used the concept of fluid dynamics of the air flow and air resistance to analysis the driving process of the cars, and through the evolving process of the design of the vehicle's structure, which are from the past and the present. In the process of applying fluid dynamics to analyze the air flow and air resistance during car driving, it used the linear function, constant function and trigonometric function in order to imitate the movement of air flow on the car surface. Then, Python was used to calculate the motion state of the air flow when it passes through the curve of the car surface, and the approximate image of the air flow motion was obtained. Furthermore, the consumption of oil will be reduced. The emission of greenhouse gases will also be decreased with little air resistance and the optimizing of the cars' shapes. It believe that the fluid dynamics will be more and more significant in our daily life. With the method it introduced above, it can calculate not only the car's surface. Numerous dynamic problems can be also simulated. For example, the air flow of the launching and landing process of the airplane, how can man reduce the air resistance when the railway is running at a rapid rate and so on. In a word, it believe our future life will get better and better with the impetus of fluid dynamics.

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