

# Simulation Analysis of Aerodynamics Characteristics of Different Two-Dimensional Automobile Shapes

Li-Xin Guo\*, Yi-Min Zhang, Wei-Jun Shen

School of Mechanical Engineering and Automation, Northeastern University, Shenyang, China

\*Email: lxguo@mail.neu.edu.cn

**Abstract**—The aerodynamic characteristics directly affect driving characteristics, stability, operation, oil consumption, and safety of automobiles. The aerodynamic analyses of automobiles, such as the virtual wind tunnel experiment simulation, based on finite element methods have provided useful theoretical reference to automobile bodywork design. In this study, the air flow vector variation and distribution of air pressure was obtained. The simulation results show that air flow yields high pressure area on the top and the bottom of the cars. The vortex flow yields behind cars and varies from intensity to infirmness. The air resistance force to car bodywork increases and the air lifting force decreases with the slantwise angle of back windshield increasing.

**Index Terms**—automobile shape; aerodynamics; air resistance; finite element analysis; computational fluid dynamics

## I. INTRODUCTION

With increasing of automobile speed, people begin to pay attention to dynamic performance of automobiles. Due to increasing of oil price, high demands bring forward to automobile design, especially to aerodynamic characteristics of automobiles and the aerodynamic characteristics directly affect driving characteristics, stability, operation, oil consumption, and safety of automobiles [1-2].

The main design basis of bodywork shape of automobiles is mechanics, ergonomics and aerodynamics. Mechanics and ergonomics restrict inside the basal shape of automobiles and aerodynamics restricts outside the final shape of the automobiles. During moving, a car may suffer from action of air which can be divided into resistance force, lifting force, lateral force, flexion moment, lateral bending moment and torsional moment. Because the power consumed by air resistance force is at least equal to that of wheel rolling friction against ground, the air resistance coefficient of automobiles has been regarded as the basic parameter to evaluate the aerodynamic characteristics of automobiles. Therefore, the main research problem of automobile aerodynamics is

to decrease the air resistance coefficient of automobiles. After research and development for many years, the air resistance coefficient has been decreased in an extreme, especially for foreign automobiles. However, some wind tunnel experiment results show that homemade vehicles have higher air resistance than the foreign automobiles [3-5]. A current primary task is to carry out the research of automobile aerodynamics.

Computational fluid dynamics (CFD) is established on the basis of classic mechanics, numerical computation methods and computer technologies [6-9]. The applications of computational fluid dynamics in vehicle engineering were beginning since 1960s. The method is mainly used to some problems, such as aerodynamics numerical simulation of automobile shapes, the admission and flow of gas mixture in engines, and so on. Due to the strongpoint, such as low research cost, short research period and detailed description to fluid dynamic behavior, computational fluid dynamics have received rapid development in recent decades. In the field of automobile industry, computational fluid dynamics has been applied in simulating aerodynamics parameters of automobile outside fluid field and received wide application in shape design of automobile bodywork. In this study, a commercial software of finite element analysis was used to simulate the aerodynamic characteristics of cars.

## II. MATHEMATIC MODEL

Generally, two kinds of equations were used to describe the outside fluid field of automobiles, (1) The potential fluid theory equations and (2) Navier-Stokes equations [1,3,4,6]. The rules of fluid flowing are the law of conservation of mass, the law of conservation of momentum and the law of conservation of energy.

The motion of automobiles is regarded as breakage to smooth air fluxion. The mutual action between automobile bodywork and high speed air flow causes the fluid field around the automobiles complicated and large change appears in the direction and velocity of the air flow [6-9]. The K- $\varepsilon$  model is adopted for turbulent flow computation.

The consecutive equation of fluid field is

\*Corresponding author: Li-Xin Guo, PhD, Professor, School of Mechanical Engineering and Automation, Northeastern University, Shenyang 110004, China. \*Email: lxguo@mail.neu.edu.cn

$$\frac{\partial v_i}{\partial x_i} = 0 \quad (1)$$

where,  $v_i$  is a velocity of fluid field;  $x_i$  is a variable of No.  $i$  coordinate of fluid field;

The Renault average equation is

$$\frac{\partial}{\partial x_j}(v_j v_i) - \frac{\partial}{\partial x_j}(\mu \frac{\partial v_i}{\partial x_j} + \frac{\partial p}{\partial x_i} - \frac{\mu}{3} \frac{\partial}{\partial x_j}(\frac{\partial v_j}{\partial x_i})) = 0 \quad (2)$$

where,  $t$  is time variable;  $v_i$  and  $v_j$  are velocities of fluid field;  $x_i$  and  $x_j$  are variables of No.  $i$  and No.  $j$  coordinates of fluid field;  $p$  is pressure of fluid field;  $\mu$  is fluid viscosity.

The air resistance force of running automobiles is

$$T = \frac{1}{2} \rho v^2 A C_D \quad (3)$$

where,  $\rho$  is air density;  $v$  is automobile speed;  $A$  is windward area of automobiles;  $C_D$  is air resistance coefficient

### III. INFLUENCE OF HEAD SHAPE ON AUTOMOBILE AERODYNAMIC CHARACTERISTICS

During running with a high speed, automobiles may produce large air resistance force. The air action force directly affects the driving characteristics, stability, operation, oil consumption of automobiles [1,2]. Because different bodywork shapes of automobiles might produce different air resistance forces, appropriate improvement to the bodywork is significant to improve aerodynamic characteristics of automobiles. In this section, the changing and improvement to the head shape of an automobile were carried out to analyze the influence of the changing on aerodynamic characteristics of the automobile.

#### *Modeling of car bodywork*

The head shape was improved for smooth treatment according to actual bodywork as shown in Figure 1. Figure 1 shows the profile of car bodywork in the longitudinal middle section

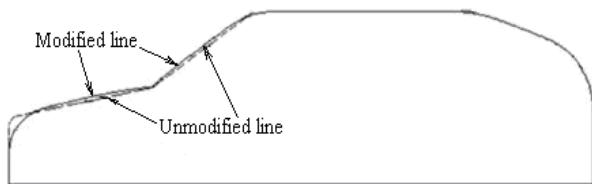


Figure 1. The bodywork shape of the automobile in the longitudinal middle section.

For consideration of simplification and modeling convenience, the rearview mirrors and wheels were neglected in modeling of the car finite element model. In addition, the bottom of car bodywork were simplified and assumed as a flat surface and the wind gaps in the

bodywork head were also neglected. For consideration of symmetry of car bodywork in longitudinal direction and for neglect of the influence of lateral wind on the car bodywork, a two-dimensional finite element model was used to analyze the aerodynamic characteristics of automobiles in this study. The modeling and analysis were carried out in ANSYS software. Figure 2 is the finite element model of virtual wind tunnel experiment of automobile bodywork. The grid area is created by two-dimensional FLOTTRAN 141 element to mimic the air field around the automobile.

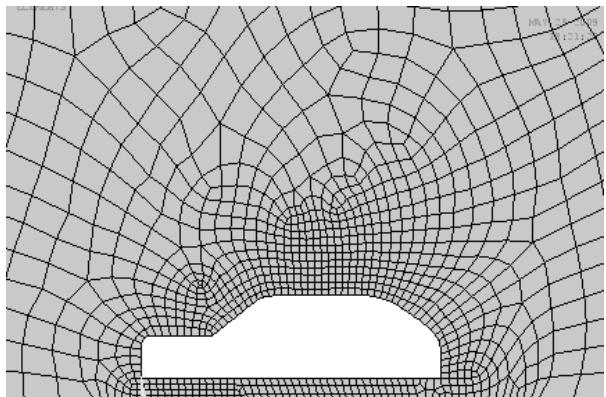


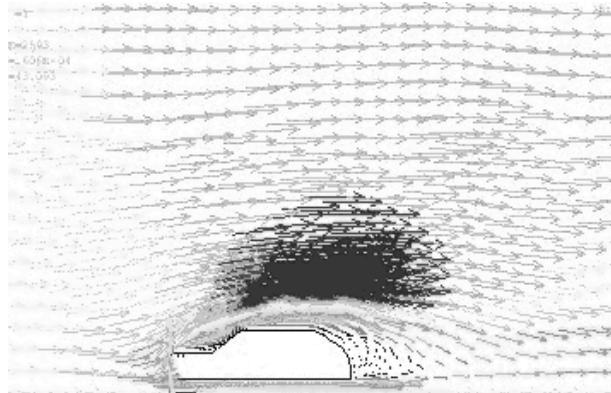
Figure 2. The finite element model of virtual wind tunnel experiment of automobile bodywork.

#### *Simulation*

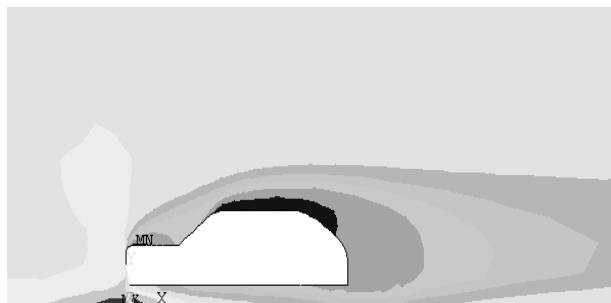
In this study, ANSYS Fluid package was used to conduct the hydrodynamics analysis of car air field. The boundary conditions of the model were divided into 3 kinds of boundary conditions to impose on the model, i.e., entry boundary condition, outlet boundary condition and wall boundary condition (including car bodywork boundary, ground boundary and upper air boundary). The entry air velocity of wind tunnel is set as  $v=32\text{m/s}$  (115.2km/h).

Figure 3 and Figure 4 show the numerical analytical results of air fluid field around the automobile for unmodified and modified bodywork shapes. From Figure 3(a) and Figure 4(a), it can be found that the air flow comes into a stagnation point at the front of bodywork and the stagnation point shrinks for the modified bodywork shape. Similar condition also emerges between windshield and engine-shield and another stagnation point also becomes small due to the car bodywork modification. In addition, it can be seen that the resort area of air flow decrease markedly around the end of the automobile.

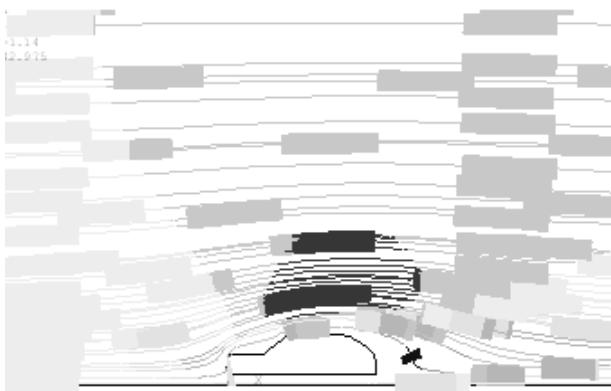
From the pressure cloud map in Figure 4(b), it can be seen that the high pressure area (at the bottom of bodywork) becomes small at the automobile head, which can reduce air lifting force on the car bodywork and improves operation stability of automobiles. In addition, the negative pressure area at the end of the modified car bodywork also becomes small, which is advantageous for decreasing air lifting force on the car bodywork.



(a) Velocity vector map



(b) Pressure cloud map



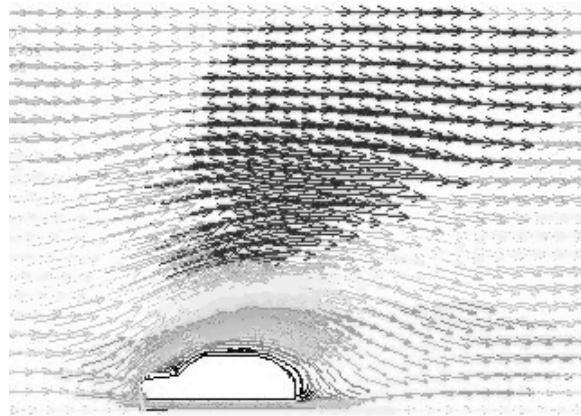
(c) Stream line map

Figure 3. The aerodynamics results of virtual wind tunnel experiment to the un-modified bodywork.

In addition, from the stream line map of the modified car bodywork in Figure 4(c), it can be seen that the stream lines of air for the modified car bodywork is smoother than that of the un-modified car bodywork. This implies that the modified car bodywork has a low wind resistance coefficient which is advantageous for decreasing air resistance during automobiles running in high-speed.

#### IV. INFLUENCE OF SLANTWISE ANGLE OF BACK WINDSHIELD ON BODYWORK AERODYNAMIC CHARACTERISTICS

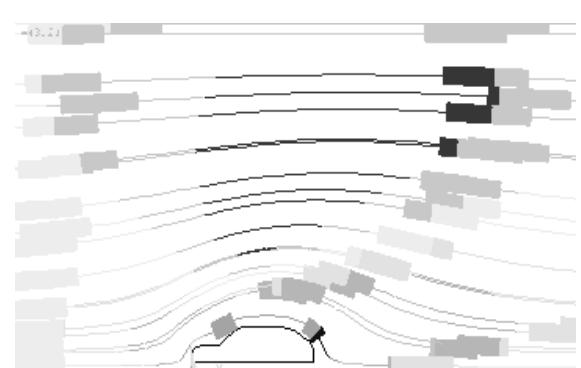
In practice, slantwise degree of back windshield, as well as empennages, might affect significantly on the aerodynamic characteristics of automobiles. It also



(a) Velocity vector map



(b) Pressure cloud map



(c) Stream line map

Figure 4. The aerodynamics results of virtual wind tunnel experiment to the modified bodywork.

affects the effect of air on the resistance force and lifting force, which might affect driving characteristics, stability, operation, oil consumption, and safety of automobiles. Figure 5 is a sketch map of the slantwise angle variation of back windshield and  $\beta$  is the inclination angle between the back windshield and level plane. In the following simulation, three inclination angles were selected, i.e.,  $\beta=17^\circ$ ,  $\beta=23^\circ$  and  $\beta=30^\circ$ . The entry air velocity of wind tunnel is set as  $v=32\text{m/s}$  ( $115.2\text{km/h}$ ).

After analysis, the pressure cloud maps are shown in Figure 6. From the air pressure cloud maps in Figure 6 (a), (b) and (c), it can be found that there is a high pressure area in front of the car head near the ground for the three figures. From these figures, the pressure distribution condition of Figure 6(a) and Figure 6(b) is very similar. However, the air pressure value in Figure

6(b) (for  $\beta=23^\circ$ ) is the largest one in the three figures and the pressure value in the Figure 6(a) (for  $\beta=17^\circ$ ) is the smallest one. For the different slantwise angles of back windshield, the air resistance force increases by 3.0% (for  $\beta=23^\circ$ ) and 12.1% (for  $\beta=30^\circ$ ) compared with the slantwise angle of  $\beta=17^\circ$ . In addition, there is a negative pressure area behind the end of the three kinds of automobiles and the negative pressure areas are different for the three kinds of slantwise angles of back windshield. The simulation results show that the value of the negative pressure value for the first model (for  $\beta=17^\circ$ ) is the largest one and the negative pressure value of the third model (for  $\beta=30^\circ$ ) is the smallest one. For the different slantwise angles of back windshield, the air lifting force decreases by 2.3% (for  $\beta=23^\circ$ ) and 5.7% (for  $\beta=30^\circ$ ) compared with the slantwise angle of  $\beta=17^\circ$ . The high pressure areas and the negative pressure areas all affect the mechanics characteristics of automobiles including air resistance forces and the air lifting forces and the

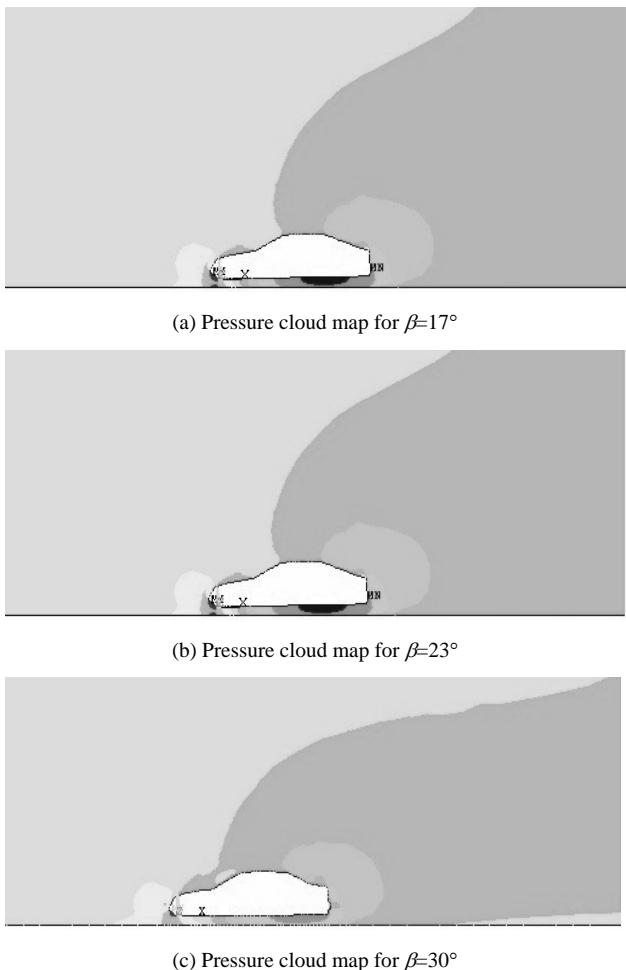


Figure 6. The aerodynamics results of virtual wind tunnel experiment to the car bodywork with different slantwise angle of back windshield for  $\beta=17^\circ$ ,  $\beta=23^\circ$  and  $\beta=30^\circ$ , respectively.

## V. INFLUENCE OF DIFFERENT CAR-TAIL SHAPES ON AERODYNAMIC CHARACTERISTICS

magnitude of pressure areas determines the force values imposed on the automobiles.

The aerodynamics results of virtual wind tunnel experiment to the car bodywork with different slantwise angle of back windshield for  $\beta=17^\circ$ ,  $\beta=23^\circ$  and  $\beta=30^\circ$ , respectively.

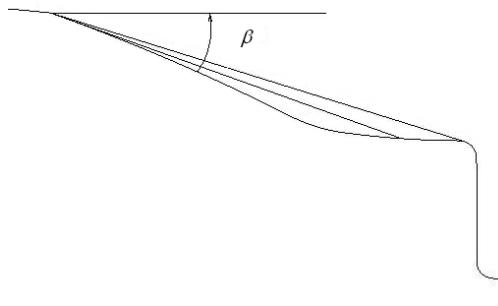


Figure 5. Sketch map of the slantwise angle variation of back windshield.

In this study, the aerodynamic analyses were also carried out on four car models with different car-tails, i.e., step-back (A-back), straight-back (B-back), fast-back (C-back) and distributor-installed back (D-back) as shown in Figure 7.

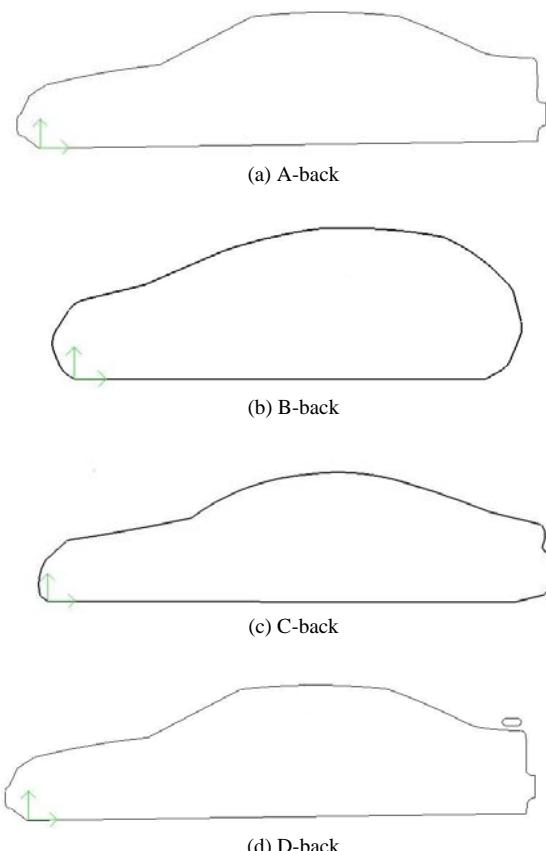


Figure 7. Different car bodywork shapes for car-tails. (a), (b), (c) and (d) are the models for step-back (A-back), straight-back (B-back), fast-back (C-back) and distributor-installed back, respectively.

The finite element models for different car bodywork shapes in Figure 7 are shown in Figure 8, respectively.

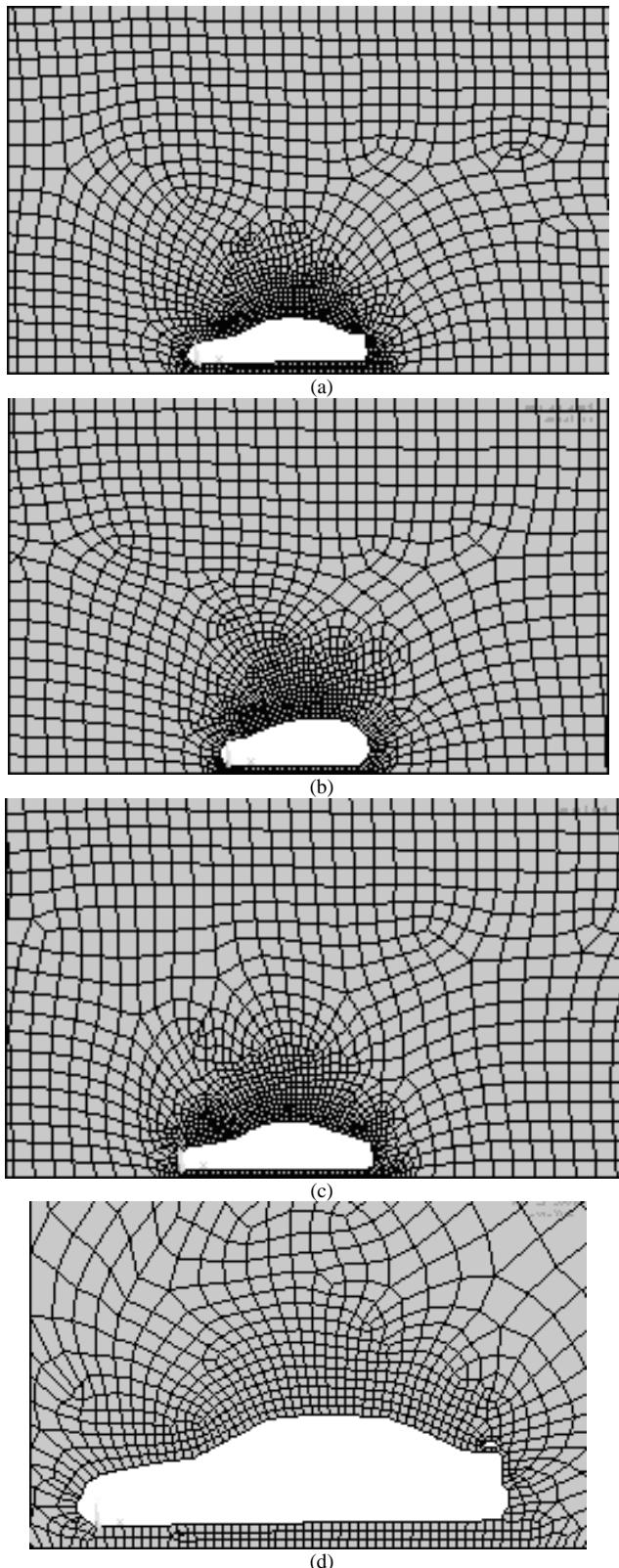


Figure 8. The finite element models of different 2-D car bodywork shapes. (a), (b), (c) and (d) are the models for step-back (A-back), straight-back (B-back), fast-back (C-back) and distributor-installed back, respectively.

Figure 9 shows the velocity vector maps for the four car models with different car-tails. From Figure 9, it can be seen that air flow velocities on the front bodywork for different car models are similar and large difference appear at the car-tails of their bodyworks. The size of circumfluence areas for the four models including step-back, straight-back, fast-back and distributor-installed back decrease in turn. The circumfluence area decreasing means it is advantageous for air flow passing.

Figure 10 shows the velocity vector maps for the four car models with different car-tails. From Figure 10, it can be seen that the air flow on front of car bodywork decreases to zero and this means that large air resistance yields on the car bodywork. A large high pressure area appears at the bottom and front of the car bodywork, this gives a high lifting force to the bodywork and it is disadvantageous for the operating stability. In addition, negative pressure areas all appear for the car bodywork models with step-back, straight-back and fast-back but no negative pressure area appears for the car bodywork with distributor-installed back. This means the air distributor can decrease the lifting force problem during car driving with high speed.

Figure 11 shows the air stream maps around the car bodyworks for the four car models with different car-tails. From Figure 11, it can be seen that acute degree of air flow changing around the car bodyworks are different although the air flow directions passing the car bodyworks have changed. It can also find that the car bodywork models with step-back, fast-back and distributor-installed back have a good streamline and it is helpful for decreasing the air resistance.

## VI. CONCLUSION

By finite element analysis to aerodynamic characteristics of automobiles, fluid field information around the automobiles is obtained, which may provide useful reference for configuration design of automobiles. Due to acting on the car bodywork, air flow yields high pressure area on the top and the bottom of the automobiles. The vortex flow yields in the end of automobiles and varies from intensity to infirmness. By analysis on effect of slantwise angle variation of back windshield on bodywork aerodynamic characteristics, it can be seen that the air resistance force to car bodywork increases and the air lifting force decreases with the slantwise angle increasing.

## ACKNOWLEDGMENT

We are grateful for the research grants from the Program for New Century Excellent Talents in University (NCET-08-0103), the Scientific Research Foundation of China Postdoctor (20070420203 and 200801391), the Natural Science Foundation of China (50875041), the Fundamental Research Fund of Central Universities (N090503001), the National Basic Research Program (973 Program) (2007CB210305-2), and the Program for Changjiang Scholars and Innovative Research Team in University, China.

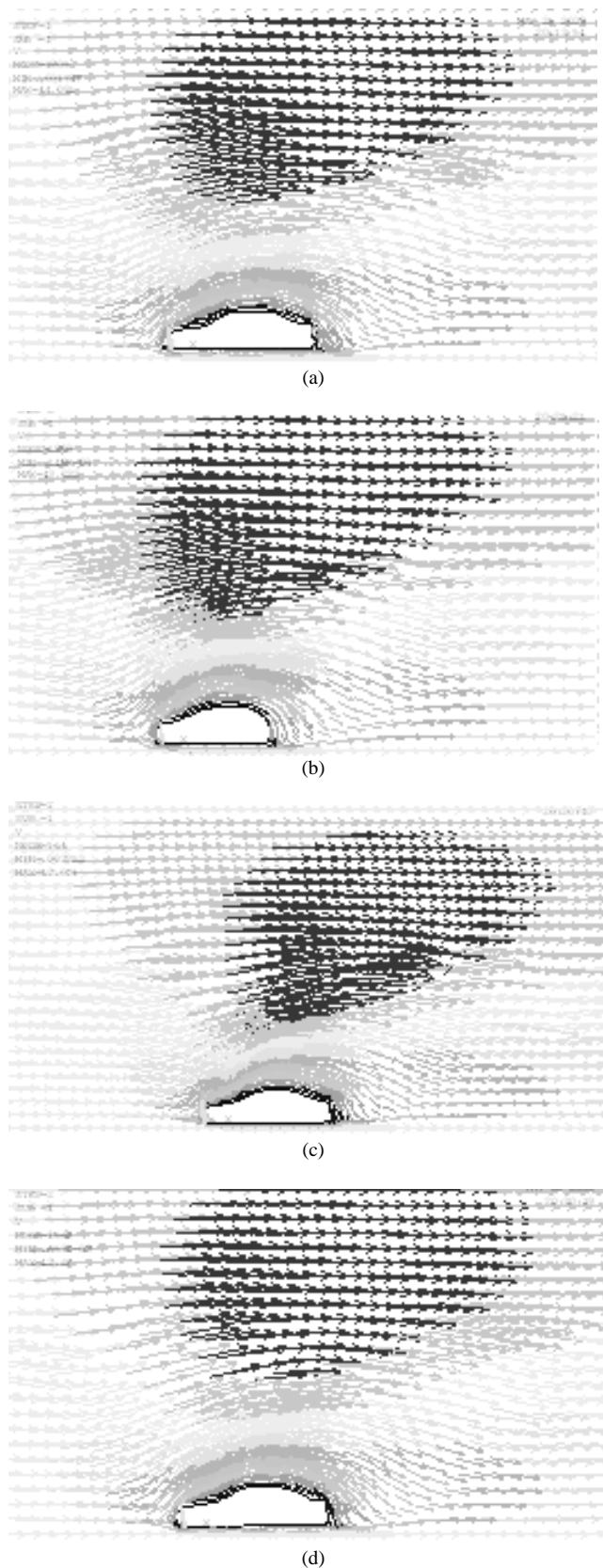


Figure 9. The velocity vector maps of the different 2-D car bodywork shapes. (a), (b), (c) and (d) are the models for step-back (A-back), straight-back (B-back), fast-back (C-back) and distributor-installed back, respectively.

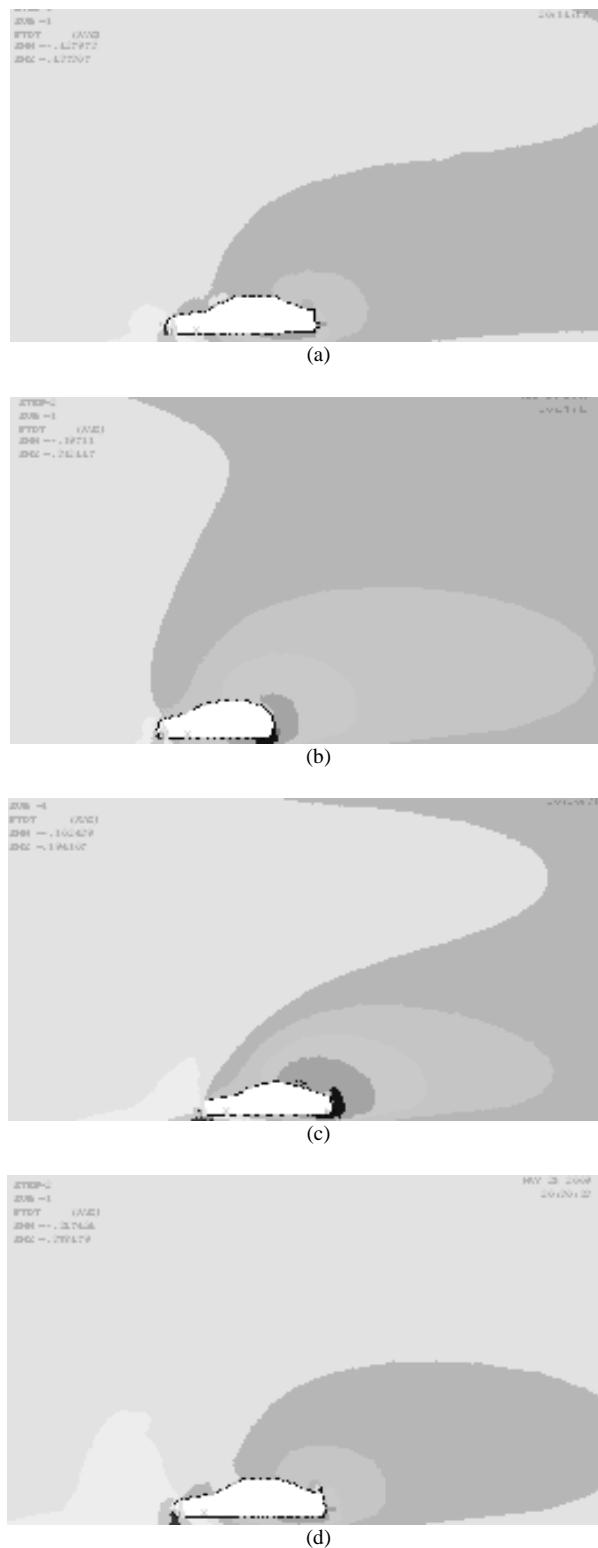


Figure 10. The pressure cloud vector maps of the different 2-D car bodywork shapes. (a), (b), (c) and (d) are the models for step-back (A-back), straight-back (B-back), fast-back (C-back) and distributor-installed back, respectively.

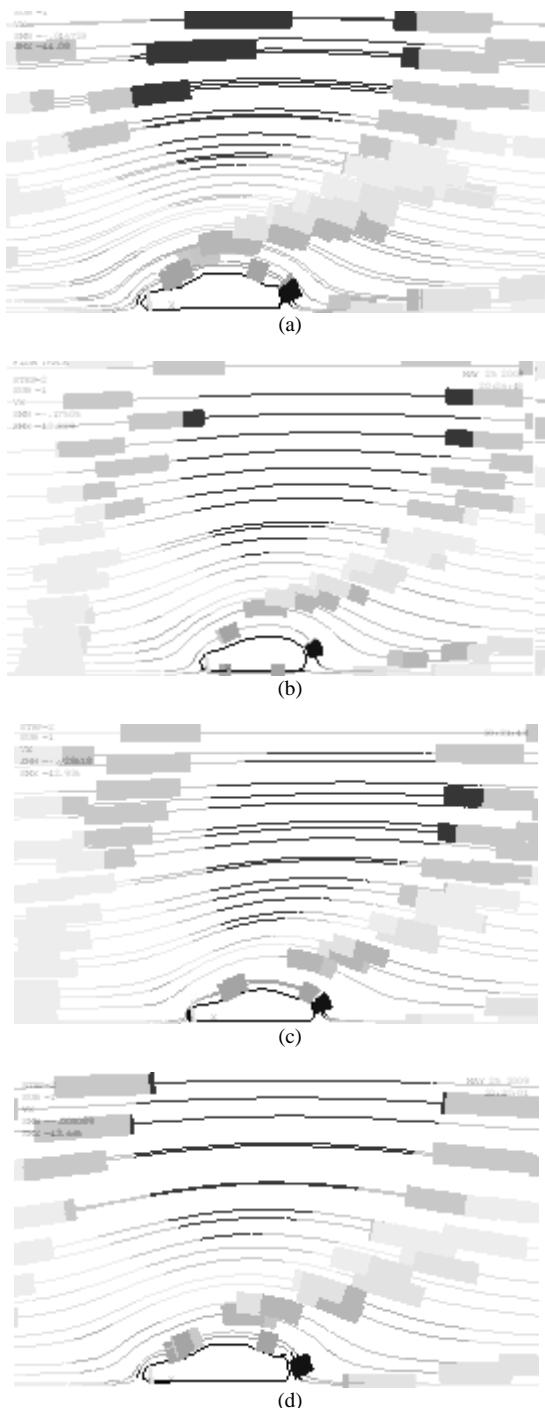


Figure 11. The air stream maps of out flow fields for the different 2-D car bodywork shapes. (a), (b), (c) and (d) are the models for step-back (A-back), straight-back (B-back), fast-back (C-back) and distributor-installed back, respectively.

## REFERENCES

- [1] L.M. Fu, Numerical Computation of Automotive aerodynamics. Beijing, China: Press of Beijing Institute of Technology, 2001
- [2] Z.Q. Gu, L.H. Jiang, J. Wu, and G. Fang, "A computer simulation on 3-D outer flow field around a passenger car," *Automotive Engineering*, vol. 22, pp. 296-298, 2000
- [3] H.O. Kreiss, and J. Lorenz, Initial boundary value problems and the Navier-Stokes equations. Academic Press Inc., 1989
- [4] A.M. Kuethe, and C.Y. Chow, Foundations of aerodynamics. John Wiley, New York, 1976
- [5] L. Gao, W. Fang, H.M. Cai, R.X. Zhou, and Y.X. Shangguan, "Study on wind-tunnel test for domestic bus model," *Automobile Technology*, Vol.7, pp.27-31, 2002
- [6] Z.S. Zhang, and G.X. Cui, Fluid mechanics. Beijing, China, Tsinghua University Press, 1999
- [7] F. Muyl, L. Dumas, and V. Herbert, "Hybrid method for aerodynamic shape optimization in automotive industry," *Computers & Fluids*, vol. 33, pp.849- 848, 2004
- [8] L.M. Fu, and Y.F. Fu, "Numerical simulation on characteristics of turbulent flow around two cars driving side-by-side," *Journal of Jilin University of Technology*, vol.35, pp.358-362, 2005
- [9] A. Luca, M. Vincenzo, P.V. Pier, et al, "A CFD-FEM approach to study wind Aerodynamics under deformation," *SAE World Congress, Vehicle Aerodynamics*, pp.444-451, 2004

**Li-Xin Guo** received his PhD from the Northeastern University in 2000. Since 2004, he has been with the Northeastern University, China and now he is a professor in School of Mechanical Engineering and Automation, Northeastern University. He was a Postdoctoral Fellow in the Shenyang Institute of Automation, Chinese Academy of Sciences from 2000 to 2002. He was also a Research Fellow Nanyang Technological University, Singapore from 2002 to 2004, and The Hong Kong Polytechnic University in 2007. His research interests focus on robot motion planning and control, mechanical vibration analysis, finite element analysis and biomechanics.

**Yi-Min Zhang** received his PhD from the Jilin University, China in 1995. Now he is a Professor in the Northeastern University. He received the honour of Changjiang Scholar, China in 2004.

**Wei-Jun Shen** received his Bachelor degree in Vehicle Engineering from Northeastern University. His current research interests include Computational Simulation, Vehicle CAE Technology.