

Analysis of the principle and applications of aerodynamics in high-speed railway

Shuhao Zhang *

Ningbo Huamao International School, Zhejiang, China

* Corresponding author: Peter.Zhang@nbhis.com

Abstract. In recent years, high speed railway trains are a main part of modern transportation which brings extremely convenient. In this case, studies on aerodynamic performances and phenomenon of trains are the core for further development of high-speed trains. With this in mind, this paper briefly introduced aerodynamic formulae as well as summarized some major computational designs of train noses, with the corresponding experimental results of some designs. On this basis, the application of some designs was explained, with follow up limitations and outlooks of aerodynamics of high-speed trains. According to the analysis, results show that designs in China focus more on reducing aerodynamic drag, while the flatter design in Japan has a better overall aerodynamic performance. In addition, the limitations of current facilities as well as the prospects for the high-speed railway systems are demonstrated. Overall, these results shed light on guiding further exploration of high speed railway development.

Keywords: Aerodynamics, train nose, design.

1. Introduction

Looking back through the history of mankind, railway and trains are inevitable characters that contributes to the development and well-being of people. The expansion in Britain during the 1860s was largely supported by improved locomotives and new rails built using steels [1]. The railway system in Britain developed from only important routes and spots in 1850 to a huge system that covers the whole country and numerous numbers of different routes in 1920. In many other countries, railway systems and trains are the key to development.

The history of railway and trains begin with Watt's improved steam engine. Then, a famous British engineer, the father of railways, George Stephenson, built the first steam locomotive in 1814, and that is the start of trains. After the first industrial revolution, and during the second industrial revolution, the famous German engineer Siemens, successfully built an electric locomotive in 1879. During the twentieth century, internal combustion locomotives with diesel engines were built and used firstly in Germany, France, Britain, and then in many countries. Until the late twentieth century and the beginning of the twenty-first century, high-speed railways are developed, and trains start to look more like modern high-speed trains. Over the past few decades, high-speed trains and railways are developing rapidly.

With the rapid development of railways over the past few decades, many researches are also done to suggest new designs or to make improvements on the old designs. Since railway vehicles are close to the ground and has aspect ratios much larger than other transport, the aerodynamic characteristics will be much more complex [2]. Therefore, it is important to research on ways that improve the aerodynamic performance of high-speed railway vehicles. Recent studies of high-speed trains focus more on designing train noses, or optimizing the streamline of trains. Methods used on optimization of aerodynamics of aircraft such as the Adjoint method has been used on high-speed trains to obtain optimal results [3]. Several technologies such as train aerodynamic drag-reduction technology, train ventilation technology, train/tunnel aerodynamics are been discussed and inquired [4], and many different designs of train noses are compared.

The motivation of this paper is to explore about recent studies and researches on the aerodynamic performances of high-speed trains and new ideas of designing of high-speed trains. A few useful aerodynamic formulae will be mentioned, followed by recent designs and experiment results of train

noses, with their applications. Limitations and future outlooks of high-speed railway transportation will be discussed before conclusion.

2. Aerodynamic formulae

When objects travel in air, they will experience aerodynamic drag. One formula that is commonly used for calculation of aerodynamic drag experienced by a railway vehicle is the Davis formula [5, 6]:

$$R_t = a + bv + cv^2 \quad (1)$$

where R_t is the total drag experienced by the vehicle, and v is the velocity of the vehicle. Terms a and bv in the formula are non-aerodynamic drags experienced by the vehicle, they represent mechanical resistances and other types of resistances respectively. The most important term when discussing aerodynamic drag is the third term in the formula, cv^2 . It represents the aerodynamic resistances that the vehicle experience during motion. It is clear that when the velocity of the vehicle is high, aerodynamic drag will be a huge proportion of the total drag due to the square of velocity. Therefore, to increase the efficiency of high-speed railway vehicles, parameter c needs to be minimized. The parameter can be expanded as the following [5, 6]:

$$c = \frac{1}{2}C_xS\rho \quad (2)$$

where C_x is a dimensionless coefficient called the coefficient of air penetration, S is the cross-sectional area of the vehicle's frontal surface, and ρ is the air density. The inclusion of S shows the importance of the designing of train heads in reducing the aerodynamic resistances of trains during motion. Apart from this general formula, three major forces that influence the stability of railway vehicles are the lift force, the side force, and rolling moment [7]. Their corresponding formulae are shown as following:

$$F_L = \frac{1}{2}C_L\rho V_H^2 A \quad (3)$$

$$F_S = \frac{1}{2}C_S\rho V_H^2 A \quad (4)$$

$$M = \frac{1}{2}C_M\rho V_H^2 A \quad (5)$$

where F_L is the lift force, F_S is the side force, M is the rolling moment, and C_L , C_S , C_M are their coefficient respectively. Parameters ρ , V_H , A represents the air density, relative wind speed of the train at the height of train body's mass center, the cross-sectional side area of the train respectively. Another dimensionless number that is important to identify the property of fluid (air) and to calculate the resistance experienced by objects in fluids is the Reynolds number. The formula of Reynolds number of air specifically in tunnel is:

$$Re = \frac{\rho v H_t}{\mu} \quad (6)$$

where ρ is the air density, v is the velocity of air, H_t is the height of tunnel, and μ is the dynamic viscosity. In some cases, for experimental purpose, v in the formula can be replaced by the velocity of train passing through the tunnel.

3. Principles and Designs

With the general aerodynamic formulae and computational methods like CFD (Computational Fluid Dynamics), various mathematical models are built for the designing of high-speed trains. A lot of different designs have been suggested throughout the past few decades, with their own principles and ideas. According to previous aerodynamic formulae, one thing that can help to achieve a better performance of reducing aerodynamic drag or reducing aerodynamic pressure variation is the design of streamlines, or the train nose. Theoretically, within the limited designing space, trains perform better aerodynamic properties with long streamline length [8]. However, the purpose of railway vehicles like trains is to transport passengers. If the streamline length of the design is not restricted to a certain extent, even though it can give great aerodynamic performance, the efficiency of the train will be decreased due to the decrease number of passengers the train can carry. Therefore, finding the balance is the core concept of all designs.

To design aerodynamic shapes using computational methods, a huge number of mesh is often needed for the calculation of only a single point. Based on that requirement for the capability of the algorithm, popular parametric methods like the Free Form Deformation (FFD) and Non-Uniform Rational B-Splines (NURBS) are not suitable for the case [9]. The modified vehicle modeling function (MVMF) parametric method was used instead by the authors of “A modified multi-objective sorting particle swarm optimization and its application to the design of the nose shape of a high-speed train.” By using the method and doing adjustments of variables, a few different designs of streamlines are obtained (seen from Fig. 1).



Figure 1. Different streamlines obtained from MVMF.

It is clear to observe that going toward the very front of the train noses, they get thinner and a bit pointy. What these designs have in common shows the trend of current designs of high-speed trains, that the train head should be in similar shape like a bullet, with the thinnest part at front. However, like what is shown in Figure 1, although different designs do look similar in general, the shape of the part at the very front of the nose is different. The reason why different designs have different kind of noses is because they perform well in different areas. To inquire deeper, the multi-objective optimization process is helpful with its evolutionary algorithm, and the process will give a set of solutions named Pareto-optimal solution [10]. The authors of “Multi-Objective Design Optimization of High-Speed Train Nose” used two objective functions and classified the Pareto-optimal results into two representative types of train nose that serves different aerodynamic purpose (Fig. 2 and Fig. 3).

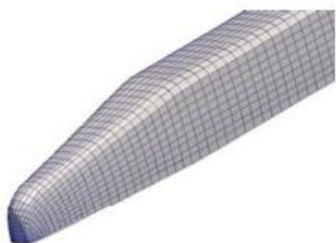


Figure 2. Example shape with minimum aerodynamic drag.



Figure 3. Example shape with minimum pressure variation.

Fig. 1 shows the type of train nose that has the minimum aerodynamic drag. It is clear that the nose is thinning horizontally towards the very front, which is fairly different from what is shown in Fig. 2. The type of train nose that has the minimum pressure variation (as illustrated in Fig. 2) is thinning vertically towards the front of the train nose, so that it looks flatter. However, even though these two types of train noses are “optimum,” it is not suitable to be used in real life since they are too extreme.

Today’s train noses are more like a combination of the two, with different designs taking different proportion of each and put them together to achieve the desired performance.

4. Simulations and Experiment Results

Enabling computational designs to be suitable and achieve the desired performance, experiments and simulations of the designs will be carried out to ensure they are improved versions of the past designs. During the experiments, particular special situations will also need to be considered to test the ability of trains. There are four classical designs of the streamlined structures of train noses among a huge number of different noses: double-arch ellipsoid, single-arch ellipsoid, a spindle shape with a front cowcatcher, and a double-arch wide-flat shape [11]. These four traditional nose shapes are modified into the same cross-sectional area since their different cross sections will affect the ambient flow, the modified models are as the following:

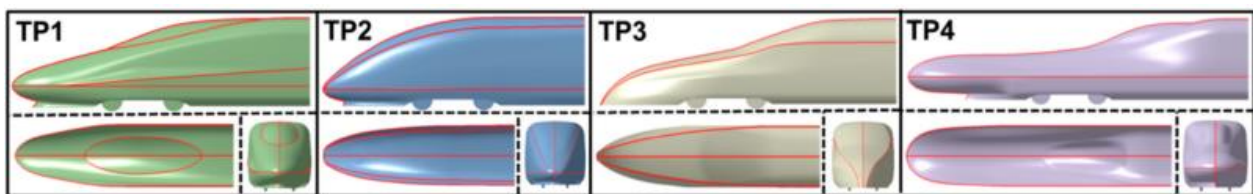


Figure 4. Modified version of the four classical designs of train noses.

Fig. 4 shows the models of the modified train noses. One can observe that TP4 is the longest, with TP1 and TP3 having the same length at the middle, and TP2 having the shortest length. The models were tested using Detached-eddy simulation (DES) with modified dissipation rate [11] and wind tunnel experiments. The results of the drag coefficient of each carriage numbered from 1 to 8 are shown in Table 1.

Table 1. Time-averaged drag coefficient of the four models.

Models	C_{dw}	C_{d1}	C_{d2}	C_{d3}	C_{d4}	C_{d5}	C_{d6}	C_{d7}	C_{d8}
TP1	0.764	0.172	0.081	0.079	0.085	0.084	0.085	0.083	0.096
TP2	0.752	0.157	0.084	0.075	0.078	0.086	0.087	0.076	0.109
TP3	0.752	0.173	0.082	0.079	0.085	0.080	0.080	0.080	0.093
TP4	0.733	0.162	0.081	0.078	0.076	0.081	0.083	0.080	0.092

Table 2. Peak-to-peak pressure value on the tunnel wall of the four designs [8]

Distance from tunnel entrance /m	Peak-to-peak pressure value /Pa				
	Bulge-broad	Ellipsoidal	Flat-board	Fusiform	Maximum deviation
20	2578	2546	2462	2465	4.7%
100	3211	3176	3108	3114	3.3%
250	6180	6152	6118	6144	1.0%
400	6575	6523	6484	6492	1.4%
500	6040	5946	5862	5847	3.3%
600	6642	6564	6518	6537	1.9%
750	6134	6094	6084	6089	0.8%
900	3115	3083	3015	3007	3.6%
980	2531	2512	2475	2477	2.2%

In Table 1, C_{dw} corresponds to the drag coefficient of the whole train, and C_{dn} corresponds to the n^{th} carriage of the train (excluding nose and wake). According to the table, TP4 has the best overall performance with C_{dw} of 0.733. TP2 has the lowest drag coefficient for the leading carriage, but the highest drag coefficient for the trailing carriage. TP3 performed well for the back carriages after the fourth carriage, while TP4 has a good performance for the front carriages. From the results, even though TP4 did not have the lowest drag coefficients for the leading carriage or the middle carriages,

it has lowest drag coefficient for the whole train. Based on that, drag coefficient of the leading carriage or the middle carriages should not be the only things to consider when designing, the importance is to design trains that has the best overall performance [11]. Apart from the regular situations where only a single train is in motion, particular situations like when two trains meet in a tunnel opposingly should also be considered and tested. Authors of “Aerodynamic Study of Two Opposing Moving Trains in a Tunnel Based on Different Nose Contours” came up with four different designs of train noses: Flat-board, Bulge-board, Fusiform, and Ellipsoidal [8]. An unsteady, compressible, renormalization group (RNG) $k-\epsilon$ turbulence model was applied for the purpose of simulating complex aerodynamic phenomenon generated by two opposing trains in a tunnel [8]. The experiments results are shown as Table. 2. It shows the results of difference between positive maximum pressure and negative maximum pressure on the tunnel wall corresponding to different distance from tunnel entrance of the four different designs. According to the table, the Flat-board design has the best overall performance of reducing pressure when two opposing trains meet in a tunnel, with only slightly more pascals for the experiments of 500 meters and 900 meters from the tunnel entrance. The pressure values increase from 20 meters up to maximum at the 600 meters experiment, then decreases from 600 meters to 980 meters since train movements are symmetrical. The maximum deviations were all below 5%, showing the degree of accuracy of the model and results.

5. Application

The final aim of all computational design and experiments is to ensure that the design can be used in reality, and is better than the older version. To judge whether a design is qualified, except doing multiple experiments, the last part is to really put it into use. Therefore, real world examples can often be found to support various designs. Taking the train of CRH380A, a train that runs in China. The train was originally designed into five different models [12].

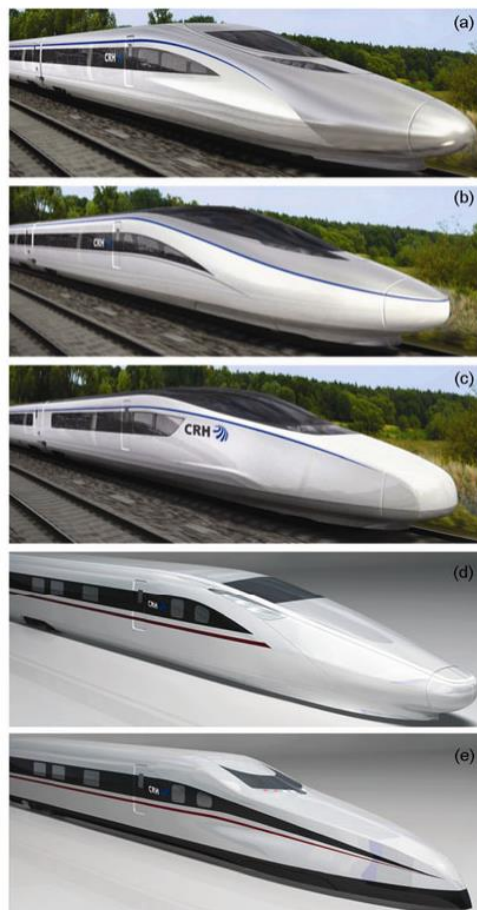


Figure 5. Five different models of CRH380A [12]

Fig. 5 (a)-(e) shows model 1-5 designs of CRH380A respectively. Except that model 5 has a nose that is thinning horizontally, model 1-4 looks similar. From the models, it is clear to observe that all the models show a degree of similarity comparing with the computational models shown previously. Model 1-4 is very similar with TP1, and model 5 looks similar to TP3. Almost all computational designs and other form of designs are based the theory that the train nose needs to be pointy and the streamline should be thinnest at front. All modern high-speed trains are designed based on that since it is the general shape with best aerodynamic performance. However, even though the general shape of modern train noses is similar, every country has trains with different lengths, different cross-sectional areas, different rail gauges, different law requirements. Therefore, the design of train noses must be different for different countries. That is why TP1, TP2, TP3, TP4 shown in Fig. 4 is very different from each other. TP1, TP2, TP3, TP4 that were mentioned previously are actually models that are modified from real trains: CRH380A, CRH380B, CRH380AM, E6. CRH380A, CRH380B, CRH380AM are all trains that are used in China, the first two types were officially in use in the year of 2010, while CRH380AM was officially used in 2016. E6 is a type of train that was used in Japan since 2013. From the corresponding year number which the type of trains was officially used, one can observe that CRH380AM is the newest design among all four types. It is clear that an ellipsoidal shape that is used on both CRH380A and CRH380B (with arch difference), but E6 has a flatter and longer train nose, and CRH380AM has a train nose that is thinning horizontally like a sword. A deduction can be made that ellipsoidal train noses that are popular a decade ago is now slowly replaced by fresher designs. If ellipsoidal noses are more balanced for the performance of aerodynamic drag and pressure variance, then the sword-like shape that is used on CRH380AM is more on the purpose of reducing aerodynamic drag like the model shown in Fig. 2. One reason may be that with the development of modern material science, reducing aerodynamic drag is more and more important rather than reducing the pressure variance on the train nose.

It takes very long for a new design to become a real train that is officially used to pick up passengers. Despite of the long process, to accept a new design and put it into use also cost a lot of money. Today, new train designs are based on new materials or new designs of parts like rail, train nose, or carriages. New designs need patience, and it is close to the limit.

6. Limitations and Future outlooks

Within the past few decades, high-speed trains are developing and improving rapidly. One century ago, the speed of trains is below 50 kilometers per hour. These days, trains have speeds that are above 500 kilometers per hour. However, they are all closing to the limits. Not only the engineering limit, but also biological limit. Firstly, engineering limit. It includes the limitation of materials and new engineering ideas. Different materials have their own strength and weaknesses, if there are no major findings in the field of material science, then the materials used to build trains will not have a major change. With the same properties, designs are restricted since whether the material can hold the design needs to be considered. Also, modern designs are toward one direction, which the direction is considered optimal and reasonable. However, walking further on the road, new ideas will be lesser, and there is always an end. Safety problems are also included into engineering limit. Safety contains both material problem and designing problems. Countries have their own requirement of the maximum aerodynamic load the train experience when moving in a particular speed. Taking an example of China, the amplitude of pressure pulse needs to be within the range of ± 6000 Pa for a train moving at a speed of 350 kilometers per hour [13].

Secondly, biological limit. When trains pass through tunnels in a high speed, human ears get uncomfortable. Ears will experience sudden changes in pressure, therefore feeling uncomfortable, and this is also a point that needs to be considered in the list of safety issues. Different countries have different standards for the safety of human ears. For example, the standard in China is the change of pressure inside the train in 3 seconds, while there are still standards like pressure amplitude or

pressure gradient that are used by other countries [13]. Biological limit of human is also a limit on the design of high-speed trains, the safety of passengers needs to be secured.

Although there are limitations, there is still a future that can be look forward to. First, except coming up with new designs of trains, there can be researches that focus on auxiliary facilities that not on the train itself. There can be new facilities that are built in tunnels or beside railways that gives a better environment for trains to operate. Second, the main focus now on improving trains is to reduce aerodynamic drag and improve their aerodynamic performances. Based on that, there is a condition that aerodynamic drag will be reduced hugely: vacuum. It is a dangerous but exciting field to explore since vacuum transportation is very new. If trains are operating in vacuum, it will be energy efficient, and the speed of trains will be much higher. However, even though this is an idea that can bring huge benefits, there are still many problems. More complex aerodynamic phenomenon will appear if vehicles are travelling inside vacuum, for example shock waves and sonic boom [13]. Moreover, safety concerns are bigger when encountering with vacuum transportation.

7. Conclusion

To sum up, this paper focuses on the aerodynamics of high-speed railway trains and various designs of train noses for improving aerodynamic performance of trains. With more and more new designs of train noses, the trend of design is from an overall ellipsoidal shape to a sword-like shape, which focuses more on reducing the aerodynamic drag rather than reducing pressure variance. However, experiment results show that a flatter train nose perform slightly better than the sword-like train nose. Those are two different directions of train nose designs. For modern high-speed trains, there are engineering limit and biology limit blocking in front of development, but auxiliary facilities and fresher ideas like vacuum transportation can still lead to a road for improvements. Different from methods of achieving huge improvement that changes the whole structure of the system, designs of high-speed trains can focus on different situations when the train is in motion, and to design a train nose that has the optimal performance for all situations.

References

- [1] Schwartz R, Gregory I, Thévenin T. Spatial history: Railways, uneven development, and population change in France and Great Britain, 1850–1914. *Journal of Interdisciplinary History*, 2011, 42 (1): 53 - 88.
- [2] Yao S B, Guo D L, Sun Z X, et al. multi-objective optimization of the streamlined head of high-speed trains based on the Kriging model. *Science China Technological Sciences*, 2012, 55: 3495 - 3509.
- [3] Munoz P J, Garcia J, Crespo A, et al. Aerodynamic optimization of the nose shape of a train using the adjoint method. *SID Report*, 2015.
- [4] Tian H Q. Review of research on high-speed railway aerodynamics in China. *Transportation Safety and Environment*, 2019, 1 (1).
- [5] Sebesan I, Tarus B. The impact of aerodynamics on fuel consumption in railway applications. *Incas Bulletin*, 2012, 4 (1): 93.
- [6] Sebesan I, Arsene S, Railway D R S. Study on aerodynamic resistance to electric rail vehicles generated by the power supply. *Incas Bulletin*, 2014, 6: 151 - 158.
- [7] Wang X, Qian Y, Chen Z, et al. Numerical studies on aerodynamics of high-speed railway train subjected to strong crosswind. *Advances in Mechanical Engineering*, 2019, 11 (11): 1687814019887270.
- [8] Li W H, Liu T H, Zhang J, et al. Aerodynamic study of two opposing moving trains in a tunnel based on different nose contours. *Journal of Applied Fluid Mechanics*, 2017, 10 (5): 1375 - 1386.
- [9] Yao S, Guo D, Sun Z, et al. A modified multi-objective sorting particle swarm optimization and its application to the design of the nose shape of a high-speed train. *Engineering Applications of Computational Fluid Mechanics*, 2015, 9 (1): 513 - 527.

- [10] Suzuki M, Nakade K. Multi-objective design optimization of high-speed train nose. *Journal of Mechanical Systems for Transportation and Logistics*, 2013, 6 (1): 54 - 64.
- [11] Sun Z, Yao S, Wei L, et al. Numerical investigation on the influence of the streamlined structures of the high-speed train's nose on aerodynamic performances. *Applied Sciences*, 2021, 11 (2): 784.
- [12] Yang G, Guo D L, Yao S B, et al. Aerodynamic design for China new high-speed trains. *Science China Technological Sciences*, 2012, 55: 1923 - 1928.
- [13] Niu J, Sui Y, Yu Q, et al. Aerodynamics of railway train/tunnel system: A review of recent research. *Energy and Built Environment*, 2020, 1 (4): 351 - 375.