Recent Studies on Railway Aerodynamics and Noise

Kiyoshi NAGAKURA

Environmental Engineering Division

Aerodynamic phenomena cause various problems on railways. The improvement of the aerodynamic characteristics of railway vehicles and infrastructures can increase the value of railways from the view point of safety, convenience, harmony with the environment, cost reduction, etc. This paper introduces the outlines of the recent studies on railway aerodynamics and noise conducted by the Railway Technical Research Institute.

Keywords: aerodynamics, cross wind, air resistance, snow accretion, tunnel fire, thermal environment in tunnel, wayside noise, micro-pressure wave

1. Introduction

Railway vehicles essentially run through the air, causing various aerodynamic issues. Possible effects on vehicles include overturning by cross winds, air resistance, car body vibration caused by unsteady aerodynamic force and aerodynamic upward force of pantographs while those on structures and people adjacent to the track include pressure variation caused by passing trains, flying ballast, accretion of ice and snow and passing train draft pressure over the platform. Aerodynamic noise (including low-frequency sound), micro-pressure waves and other similar phenomena are environmental issues affecting wayside spaces. In tunnel sections, the thermal environment and hot gas flows in fires are also important issues.

This paper classifies these aerodynamic and noise issues into problems relating to aerodynamic force acting on vehicles, those relating to snow accretion to bogies, those relating to air flow in tunnels and those relating to the wayside environment, and presents recent studies by RTRI in each of these categories.

2. Studies on aerodynamic forces acting on vehicles

2.1 Aerodynamic characteristics of vehicles in cross winds

To ensure safe train operation in gusty conditions, there are physical measures such as installation of windbreak fences and changes to vehicle specifications as well as operational measures such as train operation control. To minimize the risk of vehicles overturning through an appropriate mix of these measures, it is necessary to clarify the characteristics of natural winds along the wayside, the dynamic characteristics of vehicles and aerodynamic characteristics of vehicles in cross winds, and combine them for comprehensive safety evaluation.

Aerodynamic forces acting on vehicles in a gusty environment are evaluated primarily through wind tunnel tests. Early studies often involved rudimentary evaluations using uniform winds blowing onto intermediate vehicles at level ground directly from the side. Today, evaluations simulate three-dimensional car body shapes, including leading vehicle and ground structure shapes, such as bridges and

embankments, and use an airflow field (turbulent boundary layer) that simulates the distribution of natural wind's average velocity and turbulence intensity [1].

Wind tunnel tests using this method on a series of typical vehicle shapes (five types) and track structure shapes (seven types) on conventional lines resulted in a set of summary tables of aerodynamic force coefficients [2], which have been used for evaluation of critical wind speed of overturning, a measure of vehicle resistance against cross winds. In addition to this work, studies are underway on aerodynamic force coefficients for other typical structures such as half-banks, half-cut sections often seen on the coast [3] and structures with sound barriers or windbreak fences [4].

The vertical distributions of wind direction and velocity in a turbulent boundary layer are not exactly the same between a stationary model vehicle in wind tunnel tests and an actual running vehicle. To create conditions that are closer to reality, wind tunnel tests were conducted using a moving vehicle model rig [5]. These tests found that, with a simplified commuter vehicle on embankment or level ground, small differences could be observed in side force coefficient, the most influential parameter on vehicle overturning, between running and stationary conditions [5, 6].

In addition to the experimental methods described above, numerical simulation methods capable of reproducing wind tunnel test results are being developed as tools to help conduct wind tunnel tests efficiently. A simulation method in which turbulent boundary layers and flows around the vehicle are computed separately from each other to reduce computation load has been developed. Computations conducted on a vehicle on a viaduct and on an embankment using this method found it had good reproducibility of results corresponding with wind tunnel tests [7].

Currently, the simulation method is being further refined for possible application to the evaluation of the aerodynamic force mitigation effect of windbreak fences.

2.2 Air resistance

With high-speed Shinkansen trains, most of the running resistance is accounted for by air resistance. Therefore, reduction in air resistance is vital to save running energy. Shinkansen train sets are long, with a streamlined nose and tail, so air resistance comes mainly from the intermediate vehicles. Smoothing every part of the

intermediate vehicles is one way to effectively reduce air resistance. Bogie side covers, cover-all hoods around couplings and other coverings installed on recent Shinkansen vehicles primarily for noise reduction are thought to also contribute to reducing air resistance. It then appears necessary to start evaluating how fine surface roughness can affect air resistance, which is an area that has not received much attention, to further reduce air resistance.

Focusing on this, wind tunnel tests were conducted to quantitatively evaluate how recesses on windows and sliding doors on a vehicle sides could affect air resistance [8]. The test found that the air resistance of a sliding door of the current design was about 20 times greater than that of a window in the current design. The tests also found that, on an intermediate vehicle with four sliding doors and 40 windows, the air resistance could be reduced by about 2.6% by smoothing all of these doors and windows.

2.3 Aerodynamic brake [9]

Higher Shinkansen speeds, if achieved, must be supported by proven safety technologies. This safety performance includes braking performance in emergencies, such as an earthquake. One aim in this respect is to reduce the stopping distance from speeds exceeding the current maximum speed. While disc brake performance, which mechanically stops the rotation of the wheel by friction, has been improved as a braking means for emergencies, work has also been carried out to develop aerodynamic brakes, which utilize aerodynamic drag, to achieve reliable braking performance at high speeds.

For aerodynamic brakes to be used on vehicles on commercial lines, the braking units need to be small to preserve passenger capacity while at the same time improving braking performance at high speeds. To meet those requirements, an aerodynamic braking method was conceived whereby a number of thin, compact units are distributed along the roofs of vehicle.

This concept involves small, lightweight units that are 65 mm thick and weigh 36 kg. The units comprise a pair of resistance panels connected by a spur gear, which utilize the difference in air pressure on the two panels and are deployed by the air flow induced by the running train. A prototype was put through wind tunnel tests to verify the braking force and the time taken to deploy. In addition, wind tunnel tests and numerical analyses found that drag could be increased effectively by staggering the units along the vehicle roof. Various other tests were also conducted, successfully verifying the unit's strength, durability, low-temperature resistance, anti-shattering performance to prevent broken pieces from flying such as when hit by birds, and other parameters.

To realize the practical application of the system, further tests and verifications are planned, including testing on actual vehicles, for aerodynamic drag characteristics, dirt accretion and deterioration of components through extended outdoor use and the effect of heat cycles (repeated exposure to solar radiation).

3. Studies on snow accretion to bogies

When vehicles run along a snow-covered track, snow is lifted and accretes under the vehicles' floors and on the bogies. Chunks of the accreted snow can fall as the vehicles

vibrate while running or when shaken as the vehicles pass turnouts, falling onto the ballast, possibly causing the ballast stones to fly and damage the vehicles, ground facilities and adjacent houses. The fallen snow can also become wedged between the rails of a turnout, possibly preventing the turnout from switching properly. While studies have been conducted to find solutions to snow accretion issues, many are simply observations, experiments or done in a simplified form, falling short of identifying the mechanisms underlying snow accretion. In one of these studies, however, a method for simulating the process of snow accretion was developed in an effort to ultimately develop railway vehicle shapes resistant to snow accretion [10].

The simulation method consists of air flow calculations, calculation of path taken by flying snow particles and calculations to estimate snow accretion, each of which involve a two-way coupled analysis. With no theorized process of snow accretion known, wind tunnel tests were conducted in which snow particles were made to accrete on a cube, and based on the shape of the accreted snow resulting from the flying velocity of the snow particles and their impact angles, an algorithm was developed capable of determining whether snow will accrete or not. In addition, an analytical simulation was made to verify the reproducibility of the flying snow accretion on a model bogie observed in wind tunnel tests. The results of the simulation were found to agree with good accuracy with those of the wind tunnel tests.

Future plans include improvement in accuracy of the simulation by comparing results with snow accretion on actual vehicles and advancing experiments using actual vehicles, testing using models and an improved simulation to develop vehicle shapes resistant to snow accretion.

4. Studies on air flow in tunnels

4.1 Flow of hot gas in tunnel fire disasters

The Hokuriku tunnel train fire in 1972 claimed 30 lives and injured 714 passengers on the train, making it a major disaster. Following the accident, the Japanese National Railways conducted a range of fire tests and, based on the results of those tests, in 1975, "Procedures for Handling a Train Fire in a Tunnel" were drafted, which state that in the event of a train fire in a tunnel, the train must not be stopped until it exits the tunnel for evacuation. However, in a derailment accident in a tunnel on the Sekisho Line in Hokkaido in 2011, a fire started after the train stopped, making it in effect a "train stopped in a tunnel after a fire started" accident.

In a tunnel fire, one of the greatest hazards for those evacuating is combustion gas containing smoke and toxic components (hereafter "flow of hot gas"). Ordinary mountain tunnels are not equipped with ventilation or smoke extraction systems. Studies on proper evacuee guidance must be based on accurate understanding of the characteristics of the flow of hot gas such as increase in temperature and velocity. Accordingly, a numerical simulation (CFD) was conducted to predict the flow of hot gas in a tunnel fire, which was then followed by a scale model experiment to verify the reproducibility of the simulation method. The results from the simulation roughly agreed with those from the experiment on temperature increase, velocity of the

gas and other parameters that was conducted using an approximately 1:10 scale model of a single line tunnel with a square section with no wind or vehicle within [11]. Verification experiments were also conducted using a horseshoe-shaped model of a tunnel to reproduce more realistic conditions [12]. Going forward, the accuracy of the simulation must be improved by factoring the possible effect of wind induced by passing trains, and vehicles staying in the tunnel.

4.2 Thermal environment in tunnels

In subways and submarine tunnels, the increase in air temperature caused by the heat generated by passing trains can become an issue. One possible solution to the thermal environment issue is the installation of ventilation systems for tunnels. However, to determine the capacity required for such a ventilation system, it would be necessary to make a prediction of fluctuations in air temperature over a year of the tunnel and ancillary facilities, which is a huge space when combined. There are a number of methods published for predicting air temperature in subway tunnels including the SES (Subway Environmental Simulation) developed primarily by the U.S. Department of Transportation. Those general computer programs, however, cannot address compression wave propagation caused by high-speed trains. In Japan, the Seikan Tunnel for Shinkansen train operation and other projects generated demand for the prediction of the thermal environment in tunnels for high-speed trains. Accordingly, RTRI developed a simulation program for thermal environments in tunnels that can also be applied to high-speed railways. The program combines a pressure change simulation of tunnels factoring in the effect of compression waves with a simulation of heat transfer in tunnels [13].

As part of the work to verify the accuracy of the simulation program, the values calculated in the program were compared with the values approximated using the fundamental equations used for calculations in the program and also with the values resulting from an experiment using a scale model of a tunnel [14, 15].

Going forward, the simulation program will be further verified in relation to moisture in and around the tunnel, a key consideration in the prediction of thermal environment in actual railway tunnels.

4.3 Analysis of air flow velocity over vehicle roofs

Air flow velocity relative to a train running in a tunnel is faster than that when the train is running in an open section, and as the velocity increases, the aerodynamic force that acts on the vehicles tends to become stronger. As a result, multiple phenomena can occur. One of them relates to aerodynamic upward force of pantographs. For vehicles running at high speeds to maintain high levels of current collection performance, the aerodynamic upward force of the pantographs must be stable. As this upward force is proportional to the square of the velocity of air flow across the pantograph head, air flow velocity is an important parameter in evaluating its effect on the upward force.

A study was conducted in which air flow velocity at a pantograph head on an actual vehicle was measured as it ran in a tunnel [16]. On the other hand, it is difficult to predict accurately air flow velocity around a pantograph

for various types of vehicle running in tunnels that have different conditions. As such, a 3D-CFD using the RANS (Reynolds Averaged Navier-Stokes Simulation) technique was conducted to evaluate the effects of boundary layers formed on a vehicle and tunnel wall surfaces and insulator shields on the distribution of air flow velocities in a tunnel [17]. In addition, a simplified method for calculating the air flow velocity in a tunnel on a personal computer was developed [17, 18].

5. Wayside environment studies

5.1 Aerodynamic noise

The noise measured along the wayside of Shinkansen lines mainly consists of rolling noise, structure borne noise and aerodynamic noise. The power of the noise generated by solid vibration such as rolling noise and structure borne noise is proportional to the square to cube of the train velocity while the power of aerodynamic noise is raised to the 6th power or more. Accordingly, the relative contribution of aerodynamic noise to the total wayside noise grows as train velocity increases. Field tests and other measurements found that more than 50% of total noise generated by trains passing at speeds above 300 km/h is accounted for by aerodynamic noise, to which the lower part of the vehicle including bogies contributes most as a sound source followed by the current collection system [19]. Studies are underway on these sources of noise, especially to determine how the noise is generated, as well as to develop mitigation measures [20, 21]. Bogies are also a primary source of low-frequency components of noise outside the audible range [22]. Accordingly, efforts are underway to develop effective mitigation measures for noise across a broad range of frequencies.

5.2 Micro-pressure waves

A train entering a tunnel at high speed generates compression waves, which travel through the tunnel at the speed of sound and radiate out the exit as pulsating pressure waves. Those waves, called micro-pressure waves, can cause wayside environmental issues such as blasting sounds near portals and the rattling of building furniture and other items. While tunnel entrance hoods have widely been installed as a means to mitigate micro-pressure waves, further improvement in their mitigation effect will be required to effectively counter future increases in train speed. Measures currently being developed to that effect include staged increase in the hood's cross-sectional area [23] and adjustable-height slits on the hood's sides [24].

6. Conclusions

Many of the effects of aerodynamic phenomena intensify significantly as train speed increases. With the anticipated increases in train speed, aerodynamics-related issues appear set to become increasingly important. In addressing those issues, highly accurate test data from actual vehicles is essential as are advanced experimental and numerical analysis methods. Any proposed measure must be evalu-

ated in various respects including ease of construction, cost and possibility of inducing other physical phenomena before being put in place. We will continue our work to clarify the mechanisms underlying outstanding issues, and to develop technological solutions for practical application while exchanging resources with railway operators. To this end, it is hoped that support and cooperation in this field of work will continue.

References

- [1] Suzuki, M. and Hibino, Y., "Field tests and wind tunnel tests on aerodynamic characteristics of train/vehicles under crosswinds," *Quarterly Report of RTRI*, Vol.57, No.1, pp.55-60, 2016.
- [2] Suzuki, M., Tanemoto, K. and Noguchi, Y., "Field test and wind tunnel test on aerodynamic force coefficients of train/vehicles in cross winds," *Proceedings of the 11th UK conference on wind engineering*, Birmingham, United Kingdom, September 8-10, 2014, pp.155-158.
- [3] Otobe, T., Tatematsu, T., Izawa, N., Suzuki, M. and Noguchi, Y., "Evaluation of the aerodynamic force on a railway vehicle in half-bank half-cut line sections," *Quarterly Report of RTRI*, Vol.60, No.3, pp.208-213, 2019.
- [4] Otobe, T., Suzuki, M. and Noguchi, Y., "Wind protection effect by the wall for a vehicle with strong wind," *RTRI Report*, Vol.31, No.9, pp.5-10, 2017 (in Japanese).
- [5] Suzuki, M., "Method of wind tunnel test on aerodynamic characteristics of vehicle under cross wind by using moving model rig," *RTRI Report*, Vol.30, No.7, pp.41-46, 2016 (in Japanese).
- [6] Suzuki, M., "Wind tunnel tests on vehicle model traveling on embankment under crosswind," *Proceedings of Mechanical Engineering Congress 2018 Japan*, G0500306, 2018 (in Japanese).
- [7] Noguchi, Y., and Nakade, K., "Numerical simulation of the wind tunnel tests on the aerodynamic characteristics of trains in crosswind," *Quarterly Report of RTRI*, Vol.59, No.2, pp.115-120, 2018.
- [8] Sakuma, Y., Ido, A., Watanabe, K. and Tatematsu, T., "Aerodynamic drag of windows and doors on the sides of Shinkansen trains," *RTRI Report*, Vol.32, No.11, pp.11-16, 2018 (in Japanese).
- [9] Takami, T., "Development of Aerodynamic Brake Device for High-speed Railway," *Quarterly Report of RTRI*, Vol.61, No.4, pp.267-272, 2020.
- [10] Murotani, K., Nakade, K., Kamata, Y., Takahashi, D., "Numerical analysis of snow accretion by airflow simulator and particle simulator," *Proceedings of the 12th World Congress on Railway Research*, 2019.
- [11] Yamauchi, Y., Saito, S., Saito, H. and Kajiyama, H., "Experiment and numerical calculation of flow characteristics of hot gas in tunnel fire," *RTRI Report*, Vol.31, No.9, pp.17-22, 2017 (in Japanese).
- [12] Yamauchi, Y. and Saito, S., "Small-scale test about flow characteristics of hot gas in horseshoe-shaped tunnel fire," *Proceedings of Mechanical Engineering Congress 2019 Japan*, S05410, 2019 (in Japanese).
- [13] Kajiyama, H., "Numerical simulation of the thermal environment in underground railways," *Proceedings of the 11th International Symposium on Aerodynamics and Ventilation of Vehicle Tunnels*, BHR Group, pp.809-816, 2003.
- [14] Saito, H., Kajiyama, H. and Saito, S., "Verification of prediction method for thermal environment in tunnel by model experiment," *Quarterly Report of RTRI*, Vol.58, No.2, pp.126-132, 2017.
- [15] Saito, H., Kajiyama, H. and Saito, S., "Verification of prediction method for thermal environment in tunnel by model experiment and analytical solution," *RTRI Report*, Vol.34, No.3, pp.17-22, 2020 (in Japanese).
- [16] Takaishi, T. and Ikeda, M., "Experimental method for wind tunnel tests to simulate turbulent flow on the roof of high-speed trains," *Quarterly Report of RTRI*, Vol.53, No.3, pp.167-172, 2012.
- [17] Kikuchi, K., Noguchi, Y., Nakade, K. and Mashimo, S., "Analysis of flow over roof of train running in a tunnel," *RTRI Report*, Vol.30, No.7, pp.29-36, 2016 (in Japanese).
- [18] Kikuchi, K., Noguchi, Y., Nakade, K. and Mashimo, S., "Simple numerical calculation method of flow velocity on roof of train running in tunnel," *Mechanical Engineering Journal*, Vol.5, No.3, pp.1-17, 2018.
- [19] Kitagawa, T., Nagakura, K. and Kurita, T., "Contribution of rolling noise and aerodynamic noise to the total noise generated from the lower part of Shinkansen cars running at high-speed," *Quarterly Report of RTRI*, Vol.54, No.4, pp.214-221, 2013.
- [20] Yamazaki, N., Uda, T., Kitagawa, T. and Wakabayashi, Y., "Influence of bogie components on aerodynamic bogie noise generated from Shinkansen trains," *Quarterly Report of RTRI*, Vol.60, No.3, pp.202-207, 2019.
- [21] Mitsumoji, T., Sato, Y., Yamazaki, N., Uda, T., Usuda, T. and Wakabayashi, Y., "Reduction of aerodynamic noise emitted from pantograph by appropriate aerodynamic interference around pantograph head support," *Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, Vol.139, pp.411-421, Springer, 2017.
- [22] Uda, T., Kitagawa, T., Saito, S. and Wakabayashi, Y., "Low frequency aerodynamic noise from high speed trains," *Quarterly Report of RTRI*, Vol.59, No.2, pp.109-114, 2018.
- [23] Fukuda, T. and Saito, S., "Model experiments on the effect of a tunnel hood with multi-step cross-section for reducing the micro-pressure wave," *Proceedings of 97th JSME-FED Congress*, S5-24, 2019 (in Japanese).
- [24] Okubo, H., Fukuda, T., Miyachi, T. and Saito, S., "Effect of the cross-sectional expansion of a tunnel hood on the reduction of micro-pressure waves," *Proceedings of the 18th International Symposium on Aerodynamics, Ventilation & Fire in Tunnels*, 2019.

Author

Kiyoshi NAGAKURA, Dr. Eng.
Director, Head of Environmental Engineering
Division
Research Areas: Railway Noise