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Contribution of computational wind engineering in train aerodynamics

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Contribution of computational wind engineering in train aerodynamics—past and future

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A R T I C L E I N F O

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Crosswinds
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Underbody flow
Pressure pulses

A B S T R A C T

This paper provides an overview to all the published computational work in the Journal of Wind Engineering and Industrial Aerodynamics in the field of train aerodynamics since 1992. It has been found that in early nineties the computational power was limited and thus simplified potential flow solves and 1D codes were the main tools for train aerodynamics. Solution of the fully viscus and turbulent flow for train aerodynamics was limited to 2D cases using the steady RANS solvers on coarse meshes. In later nineties, the increase in computational power allowed for the solution of the fully turbulent flow around 3D models of high-speed trains using RANS models. Recently and due to the significant increase in computational power, the high fidelity Detached Eddy Simulations (DES) and Large Eddy Simulations became the computational methods for the different issues in train aerodynamics. It has been found that although computational wind engineering (CWE) contributed significantly in the development of new high-speed trains in the past thirty years, there are still number of emerging issues in the aerodynamics of high-speed trains that require considerable investigations by the CWE community.

1. Introduction

The International Association for Wind Engineering (IAWE) is the international umbrella looking after the international and national activities and events related to effects of atmospheric wind on structures. The association was founded in London in 1995 during the 4th International Conference on Wind Effects on Buildings and Structures. It is worth mentioning here that since 1980 the Elsevier Journal of Wind Engineering and Industrial Aerodynamics (JWEIA) is the official journal for wind engineering and once the formation of the IAWE, it has become its official journal. Computational Wind Engineering (CWE) is a branch of wind engineering that uses computers to solve the governing equations of wind motion around structures. In early 90th the computational power started to grow and thus the computational wind engineering appeared to be a promising technique for investigating wind engineering issues. Therefore, the wind engineering community introduced the International Symposium on Computational Wind Engineering (CWE) in early 90th, and it is now one of the major periodic conferences organized under the umbrella of the IAWE. The first CWE conference was organized in 1992 in Tokyo, Japan and chaired by Murakami. Selected papers were published in JWEIA, Vol. 46–47, 1993. The second CWE conference was organized in Colorado, USA and chaired by Meroney and selected papers were published in JWEIA, Vol. 67–68, 1997. The conference is organised every four years and normally selected papers were published in JWEIA. The last of this series was organized in Seoul, Korea in 2018, and chaired by Sungsu Lee. Year 2022 is marking the thirty anniversaries of the CWE conference. The purpose of this paper is thus to summarise the contribution of the CWE field on train aerodynamics and to explain how this work significantly contributed to the development of the new generation of high-speed trains. The focus here is on the numerical work published by the wind engineering community in the JWEIA since 1992. For old heavy trains, the main focus was to estimate the aerodynamic drag that contributes in the total traction power required to pull the train. However, for the new generations of lightweight high-speed trains, various aerodynamic issues were emerged that needed considerable investigations to insure safe and sustainable running of these trains. These issues are:

1 train aerodynamic drag,
2 effect of crosswinds on train aerodynamics,
3 train slipstream,
4 aerodynamics of trains in tunnels and underground tubes,
5 effect the underbody flow on different issues of train aerodynamics, and
6 other aerodynamic issues such as noise, pantograph aerodynamics, head pressure pulses.

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The reviews of these topics are presented in the coming sections. With the ever increase in computational power and the significant development in computational fluid dynamic coding, there are merging issues that believed to be complex to investigate in the past but is possible to be done now. These emerging issues are presented at the end of the paper.

2. Computational wind engineering in train aerodynamics

Computational wind engineering relies on the use of numerical tools to solve the mathematical equations, governing the movement of fluids (wind) around engineering structures. These mathematical equations are normally a set of partial differential equations, which an exact solution is yet to be found. To find a deterministic solution of such equations, severe simplifications and assumptions must be made. Examples of this include the simplification of a 3D problem into 1D or 2D one and assuming a potential flow. Although these kinds of flow don't exist in reality, the solution may provide useful understanding on how the pressure or the flow field change around these simplified bodies. A good example of this is the 1D solution of the flow and pressure fields to obtain the pressure variations around simplified trains in tunnels.

The most comment method in wind engineering is to solve a discretised version of the Navier-Stokes (NS) equations numerically using computer algorithms—computational fluid dynamics (CFD). For most of wind engineering applications, the velocity and pressure fields are required and in few cases the temperature field is also needed. The five equations of continuity, momentum and energy are enough to provide solutions of the five unknowns: three velocity components, pressure, and temperature at each computational cell in the computational domain.

2.1. Direct numerical simulations

In Direct Numerical Simulations (DNS), the governing equations are solved in time and in space for the unknowns without being time averaged or filtered in space. Normally, the number of unknowns equal the number of equations and thus a solution of such equations is possible. The results of DNS are accurate if the resolution requirements in both time and space are fulfilled. However, due to the wide spectrum of length, velocity and time scales, the required resolutions in both time and in space make it very computationally expensive and thus not suitable for most of the wind engineering applications. To make CFD feasible for wind engineering applications, the NS equations are time averaged to create the Reynolds Averaged Navier-Stokes (RANS) equations, and this process eliminates the need for high resolution in time. In addition, if the length scales are filtered in space to resolve only the large scales, then the solution is called Large-Eddy simulations (LES).

2.2. Reynolds Averaged Navier-Stokes

In this approach the governing equations are averaged over long time or over a short time. If the equations are averaged over a long time, then it gives the Steady Reynolds Averaged Navier Stokes-Steady (steady RANS) or just RANS for short. If it is averaged for short time, then it gives the Unsteady RANS or URANS for short. The formal eliminates the time from the equations and hence no time scale is needed. The latter averages in a relatively large time scale, much larger than the turbulence dissipation time scale. Due to the averaging process, new terms in RANS and URANS equations are formed and these terms are the Reynolds stresses. These terms are unknowns, and they must be modelled to close the system. Solving the RANS and URANS equations provides explicit solutions to the time-averaged non turbulent component of the atmospheric winds, whilst the effect of the turbulence is accounted for using turbulence modelling (modelling of the Reynolds stresses). There are number of turbulence models that could be used to model the Reynolds stresses (e.g. k-ε, k-ω, k-ω SST, etc.). In RANS all the turbulence is modelled and only the time averaged picture of the flow, pressure, and temperature fields are obtained. However, for URANS, some information about the temporal evolution of the flow can be obtained but, in each time step, all the turbulence effect is modelled. Since not solving in time, the computational cost of RANS is much cheaper than that of URANS and both are much computationally cheaper than that of DNS.

Although it provides the time-averaged results and the turbulence effect is modelled in the averaged window, the information gained from RANS and URANS are still very useful for most of the wind engineering applications. Since computationally cheaper, RANS simulations can be used for the optimisation purpose since many simulations could be made for the design variables in relatively short time. Also, URANS can be used is the application for train aerodynamics in which time evolving is required such as entering and exiting tunnels. If computational resources are limited to use an accurate time solving CFD method then URANS is a good compromise, which could be used in all aspects of train aerodynamics to provide temporal and spatial insight about the flow.

2.3. Large-Eddy Simulations

The large length scales in turbulent flow are the energetic scales that receives their energy from the main flow. Those scales are important in wind engineering applications as they are responsible for causing damage to structures and for the time-dependent variation on surface pressure and hence on the accurate estimation of the aerodynamic forces. The small-scale vortices are important to sustain the energy process as they pass the energy from the large scales to the dissipative scales. However, these small-scale vortices can be modelled and their effect on the large-scale vortices can be retain. Unlike the chaotic turbulent flow, the behaviour of small scales tends to be universal and thus modelling their effects on the large-scale vortices is possible and accurate for different flows. This technique in which the effect of small-scale vortices in the large-scale ones is modelled is called Large-Eddy Simulations (LES). A mathematical filter is used to filter the large-scale vortices from the rest of the vortices in the flow. Thus, LES explicitly resolve a sizeable portion of the spectrum of the atmospheric turbulence and only synthetically account for the remaining part. There are few models for accounting of the effect of the small-scale vortices of which the standard Smagorinsky model (Smagorinsky, 1963) is suitable for most of the wind engineering applications, including train aerodynamics. The accuracy of LES depends on the filter and how much of the large-scale vortices are resolved. The simplest case in LES is to use the computational cell as a spatial filter in which any vortices smaller than the cell size are modelled while the minimum vortex size to be resolved is that of the cell size. The cut-off between large-scale and small-scale vortices should be in the inertial sub range in the energy spectra. Therefore, the filter should be in the $-5/3$ range of the spectra. However, in boundary layer flows, the large-scale vortices are relatively small and thus special care should be devoted to the mesh size in those regions of the flow in which the large-scale eddies are really small compared to those at the free stream. This makes LES simulations relatively computationally expensive compared to those using URANS. However, the results from LES provide valuable and accurate information about both time-dependent and averaged flow. They also provide accurate details of the spatial distribution of the flow. LES is thus an excellent method of obtaining the flow and pressure around small or localised geometrical details of trains, such as bogies, pantographs, cavities, and the nose of the train. It also could be used for the flow around small-scale geometries of trains in which time-dependent solution is required such as the flow in tunnels, head pressure pules, crosswinds, drag reductions and other applications. However, due to its computational costs, it is not suitable for optimisation purposes nor for full-scale trains at high speed.

2.4. Detached-eddy simulations

Detached-eddy simulations is a hybrid approach that sits in between scale-resolved simulations (e.g. RANS and URANS) and non-scale-resolved simulations techniques (e.g. DNS and LES). DES is a compromise of LES and RANS in which the technique returns LES results in places outside boundary layers flow and URANS results in the boundary layer flow and thus uses the advantages of both techniques. Unlike LES, DES doesn't need strict mesh requirements close to boundaries and therefore the computational cost is much cheaper than that of LES. Recently, DES has been used extensively in train aerodynamics and has shown promising results. However, it is still far from being suitable for shape optimisation.

3. Train aerodynamic drag

Energy is required by trains to overcome different rolling resistances opposing the movement of the train. These resistances consist of bearing resistance, train dynamic friction losses and aerodynamic drag. Measurements showed that the aerodynamic drag increases with the square of train speed. For low-speed trains, the mechanical resistance is normally greater than the aerodynamic drag whilst for high-speed train the aerodynamic drag is the dominant resistance. Measuring the actual aerodynamic drag of full-scale trains is not a straightforward task. It is believed, however, that the drag is linearly proportional to the square of train speed. Thus, the research has been focusing on measuring the proportional constant, instead of the actual drag. This proportional constant, *C* is written as:

$$C=\frac{1}{2}\rho A C_D, \qquad (1)$$

where ρ is the density of the air, A is the frontal area of the train and C_D is the drag coefficient. The drag coefficient is believed to be Reynolds number independent and thus small-scale models are normally used in estimating C_D for the different types of trains. Before the invention of high-performance computations, *Cd* was measured in wind tunnels using small-scale models. The first attempt to compute the drag coefficient of a train by the wind engineering community was done by Kisielewicz and Tabbal (1993). They conducted a computational fluid dynamics (CFD) simulation around a commuter train vehicle using RANS simulation with the $k-\varepsilon$ turbulence model. The computational mesh consisted of only 36,000 hexahedral cells. Reynolds number for the simulation was 430,000 based on the wind speed and the height of the model, representing to a fully turbulent flow around the model. They also carried out a simulation for a high-speed train model using 50,000 cells. Although the computational mesh was very coarse, the CFD results for the surface pressure coefficient agreed well with the wind tunnel data. Computational methods for the aerodynamic forces of a freight train using RANS methods have been done by Golovanevskiy et al. (2012). They compared the RANS simulation results with those from wind tunnel experiments and they found a good agreement.

Table 1 shows the computational work published in the JWEIA since 1992 to 2022 dealing with train aerodynamic forces with emphasis on aerodynamic drag. It could be noticed that computational work for train aerodynamic drag was not very active before 2012 as the aerodynamic forces could be obtained with high accuracy using physical modelling than those from CFD techniques. However, with the increase of train speed, the field of drag reduction becomes an active field aiming to reduce the overall train resistance and hence the overall energy consumption. Muñoz-Paniagua et al. (2014) and Muñoz-Paniagua and García (2020) used genetic algorithm (GA) to optimise the nose shape of trains for drag reduction. It can also be noticed that since 2019, the high fidelity CFD methods, DES and LES have been the main methods for obtaining train aerodynamic forces.

Fig. 1 shows the number of publications per year for computational wind engineering in train aerodynamic drag in JWEIA. The number of publications in the recent years have been significantly increased. This is due to the increase in computational power and the need in reducing the overall drag of trains. This increase in number of published papers is associated with an increase in the use of high-fidelity computational techniques.

Table 1
Papers published in JWEIA delt with computational methods for train aerodynamic drag since 1992.

Year	Paper	CWE technique/s	Topic
1993	Kisielewicz and Tabbal (1993)	RANS k-ε	Developing numerical method for train aerodynamics.
2012	Golovanevskiy et al. (2012)	RANS Spalart–Allmaras	Drag of freight trains.
2014	Muñoz-Paniagua et al. (2014)	Genetic algorithms (GA)	Nose optimisation for drag reduction.
2016	Li et al. (2016)	RANS k-ε	Optimisation of train's head.
2017	Maleki et al. (2017)	ELES, SAS, URANS and RANS	Assessment of different turbulence modelling on the drag prediction or freight trains.
2019	Chen et al. (2019)	IDDES	Effect of nose length on drag.
2020	Maleki et al. (2020)	LES	Aerodynamics of double-stacked freight wagons
2020	Muñoz -Paniagua and García (2020)	Genetic algorithms (GA)	Nose optimisation for drag reduction.
2020	Niu et al. (2020)	IDDES based on SST k-ω.	Aerodynamics of braking plates.
2020	Xiao et al. (2020)	IDDES	Pantograph aerodynamics.
2020	Zhai et. at. (2020)	RANS k-ε	Aerodynamics of braking plates.
2021	Huo et al. (2021)	IDDES based on SST k-ω	Effect of double-unit trains on the aerodynamic drag.
2021	Chen et al. (2021)	IDDES	Effect of effect of platoon configuration on train aerodynamic performance.
2021	Li et al. (2021)	LES	Correlation between drag and wake.

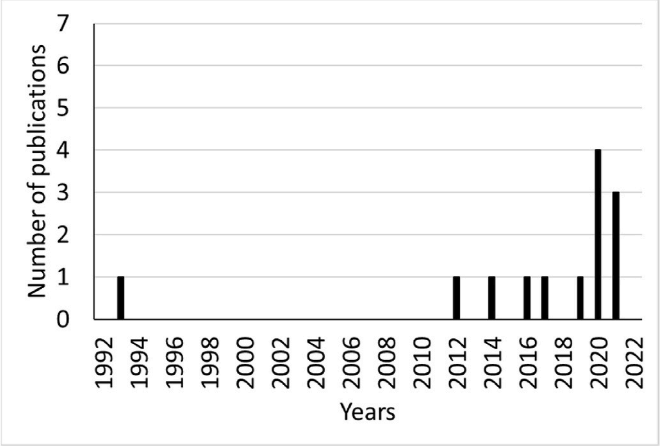

Fig. 1. Number of publications per year in the JWEIA about computational drag.

3.1. Recent trends in CWE in train aerodynamic drag

Computational wind engineering has significantly contributed to the aerodynamic drag reduction of high-speed train through shape optimisation, specifically of the train head. However, this field still needs considerable effort to investigate the use of passive and active flow control for drag reduction. The survey of literature in JWEIA showed that there is no evidence that these techniques are properly investigated using either computational methods or physical modelling. In addition to this, the increase of the aerodynamic drag of high-speed trains is also needed when stopping to reduce the pressure on the braking pads and the interaction between wheels and track. The current method of stopping trains is to use the mechanical friction between the wheels and track. However, for wet or icy track, the friction between wheels and track could be low and thus another method of breaking is needed. Although some efforts have been done in investigating the aerodynamic breaking plates (Niu et al., 2020 and Zhai et. at., 2020), this technology needs considerable research to be fully developed.

4. Effect of crosswinds on train aerodynamics

Modern high-speed trains are constructed using light but strong material and this significantly reduces the overall weight of such vehicles. This makes these trains at high risk of overturning and derailing in strong crosswinds. In the wind engineering community, the first work that used computational techniques to investigate the effect of crosswinds on trains was the work of Gawthorpe (1994), who solved the 90° flow around a 2D cross-section of a model train using RANS equations. The mesh was too coarse and at that time the computational wind engineering was not a mature field to solve a 3D flow around a train. Thus, the main work was based on a wind tunnel experiment and the simulation was made to show the expected ability of computational fluid dynamics to solve such flow. One year later, Chiu (1995) used the experimental work of Chiu (1991) to validate a numerical model based on the Panel method to obtain the aerodynamic forces on a generic train model. Since 2000, the computational power was significantly improved and the field of computational wind engineering became more mature and thus 3D simulations of the flow around trains were possible with both RANS, DES and LES. Table 2 shows the papers published in the JWEIA since 1992 delt with computational methods for crosswinds effect on trains and Fig. 2 shows the number of these publications per year.

There is an increased number of publications in the field of computational techniques for train aerodynamics with crosswinds since 2016. The research in this period focused on the following issues.

1 effect of train nose on crosswind forces,
2 effect of crosswinds on slipstream, especially for freight trains,
3 investigate the effect of wind break walls,
4 crosswind effect on trains and bridges,
5 mitigation of crosswind effect on high-speed trains using wind breakwalls, and
6 understanding the effect of bogies and ground infrastructure on aerodynamic forces under crosswind effect.

4.1. Recent trends of crosswind effect on trains

Crosswind effect on train aerodynamics was an active field of research in train aerodynamics since the introduction of high-speed trains. Any new trains must pass the aerodynamic certifications to be able to run on most of the train networks all over the world and one of the aerodynamic issues that they need to pass is the crosswind stability and its effects on trains. The EU guidelines for the crosswind assessments of railways is documented on EN14067-6 (2018). The traditional effort of wind engineering was to understand the flow behavious around trains under crosswinds (Hemida and Krajnovic, 2010; Flynn et al., 2016). There was also significant research to invistigate the effect of the shape and length of the train nose on the crosswind forces (Cheli et al., 2010; Hemida and Krajnovic, 2010). In recent years, the focus was on optimizing the nose shape (Munoz-Paniagua and García, 2019), on the effect of small geometrical details such as bogies and cavity (Xia et al., 2021), and on the mitigation methods of crosswind effect (Guo et al., 2020). The mitigation methods include windbreak walls and shielding effect on bridges (Guo et al. (2021). New problems have emerged because of the mitigation methods such as the increased instability of high-speed trains

Table 2
Papers published in JWEIA delt with computational methods for crosswinds since 1992.

Year	Paper	CWE technique/s	Topic
1992	Chiu (1991)	Experiment	Aerodynamic forces on trains for crosswinds at 90° angle
1994	Gawthorpe (1994)	2D RANS	Estimation of crosswind forces on trains.
1995	Chiu	2D and 3D Panel method	Assessment of the panel method on train aerodynamics.
2010	Cheli et al. (2010)	RANS k-ε	Effect of roof and nose on the aerodynamic forces on AnsaldoBredaEMUV250 train in crosswinds.
2010	Burlando et al. (2010)	Meteorological mesoscale model BOLAM	Wind distribution around a railway line.
2010	Hemida and Krajnovic (2010)	LES	Effect of the nose length on aerodynamic forces when subjected to crosswinds.
2016	Premoli et al. (2016)	RANS SST k-ω	Effect of the relative motion between train and infrastructure on aerodynamic forces.
2016	Flynn et al. (2016)	IDDES based on the SST κ-ω	Assessment of crosswinds on slipstream of freight trains.
2017	Muñoz-Paniagua and Lehugeur (2017)	RANS, SAS and IDDES	Evaluation of different CFD methodologies in crosswind assessment.
2017	Allegrinia and Kubilay (2017)	RANS using realizable k-ε	Effect of crosswinds on railway station and passengers' comfort.
2018	Niu et al. (2018)	DDES based on the SST κ-ω	Effect of windbreak wall on stationary and moving trains.
2018	Gallagher et al. (2018)	RANS and DES	Assessment of the accuracy of different CFD methodologies for train aerodynamics.
2019	Munoz-Paniagua and García (2019)	RANS k-ε	Optimisation of the nose shape for reduction of pressure pulses and the effect of crosswinds.
2019	Chen et al. (2019)	IDDES based on the SST κ-ω	Effect of length of train nose the aerodynamic of trains subjected to crosswinds.
2019	Guo et al. (2019)	IDDES based on the SST κ-ω	Effect of double-unit trains on aerodynamic forces when subjected to crosswinds.
2020	Guo et al. (2020)	DDES	Effect of ground infrastructure on the flow field around railways.
2021	Chen et al. (2021)	URANS based on SST k–ω	Mitigating measure of crosswind effect through an elongated hillock region next to a windbreak.
2021	Deng et al. (2021)	DDES	Effect of crosswind in a bridge-tunnel section with or without a wind barrier.
2021	Guo et al. (2021)	IDDES	Effect of crosswinds on trains on bridges.
2021	Gu et al. (2021)	IDDES	Effect of the length of wind barrier on crosswind.
2021	Xia et al. (2021)	IDDES based on the SST κ-ω	Effect of inter-carriage gap spacings on aerodynamic forces under crosswinds.
2022	Niu et al. (2022)	IDDES	Effect of windbreak walls on the aerodynamics of trains in crosswinds.
2022	Liu et al. (2022)	CFD and MBD system.	Effect of bogy aerodynamics on the overall stability of trains in crosswinds.
2022	Gu et al. (2022)	RANS and wind tunnel	Effect of the length of windbreak walls in wind tunnel testing.
2022	Yang et al. (2022)	LES	Effect of the shielding effect of bridges.
2022	Wang et al. (2022)	URANS based on k–ε	Effect of crosswind characteristics on train aerodynamics on bridges.

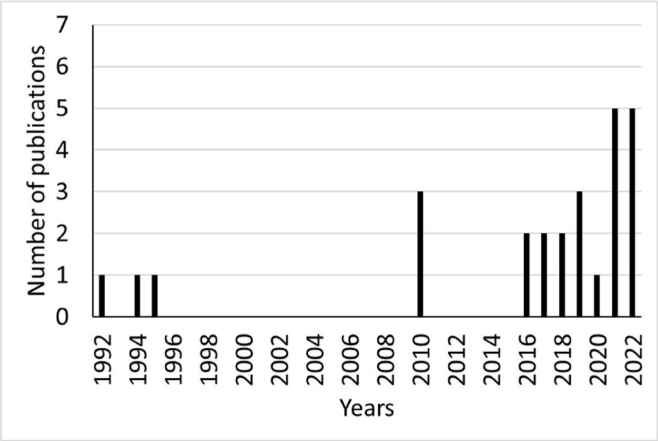

Fig. 2. Number of publications per year in the JWEIA dealing with computational techniques in crosswinds.

passing windbreak walls or passing discontinuity or opening in windbreak walls. The effect of infrastructure underneath and around high-speed trains on crosswind stability, however, deserves further investigations. In addition, most of the work that has been done on the crosswind assessment on high-speed trains focused on low turbulence wind. However, the effect of atmospheric turbulence and high turbulence crosswinds on the aerodynamic forces was not properly investigated. Computational wind engineering could be of a great help to provide an improved understanding of these issues as atmospheric turbulence can be easily generated numerically and thus different parameters can be investigated in an economical way.

5. Train slipstream

Increasing the speed of trains increases the slipstream velocity and this could affect safety of passengers waiting on platforms, safety of trackside workers, stability of pushchairs and baby carriers and forces imposed by the transient pressures and velocities on trackside and station structures. As the magnitude of aerodynamic forces are proportional to the square of train speed, the slipstream and its associated aerodynamic forces can be expected to become of more significance as train speeds become higher. Table 3 lists the work published in JWEIA dealing with computational methods for train slipstream since 1992 and Fig. 3 shows the number of publications per year during this period. Although the risk of slipstream is small in comparison to other risks, it could, however, have a significant effect on the safety of passengers on platforms and trackside workers if this risk is not managed effectively. That is probably the reason that this field of research was not active until recently. The first published numerical work about train slipstream in the JWEIA was the work of Flynn et al. (2014) after which there was a significant increase in recent years in the publications of work in the JWEIA that uses computational methods in the study of different issues around train slipstream.

The most recent work focused on the effect of underbody complexities and train passing phenomena on the magnitude of slipstream. Also, the slipstream of freight trains has seen a significant interest due to the complex geometries of such trains that result in a highly turbulent slipstream velocity.

5.1. Recent trends of slipstream of high-speed trains

It has been shown by Flynn et al. (2016) that the slipstream from freight trains is much higher in magnitude than that from passenger trains at the same speed. The largest slipstream velocity was found at the front of the train due to the non-aerodynamical shape of the of freight trains. There is international trend in increasing the speed of freight trains to accommodate more trains in the railway line and to use the existing railway network for both passenger and freight trains. This requires significant research in this area before increasing their speeds to improve our understanding on the extend of this issue. For instance, it is not well known the effect of different train loading on the slipstream. Also, there are different shapes of freight train including cylindrical and box-like containers. The effect of these is not well understood. In addition, the effects of platform height and train station shape on slipstream from both passenger and freight trains are not fully understood and need significant investigations.

Table 3
Papers published in JWEIA delt with computational methods for train slipstream since 1992.

Year	Paper	CWE technique/s	Topic
2014	Flynn et al. (2014)	DDES	Estimation of the slipstream of an operational freight train
2017	Wanga et al. (2017)	URANS, SAS and DES	Investigating the different turbulence methodologies on high-speed train aerodynamics.
2017	Xia et al. (2017)	IDDES	Effects of ground configurations on train slipstream.
2018	Guo et al. (2018)	DES	Effect of double-unit trains on slipstream
2019	Wang et al. (2019)	IDDES	effect of bogie fairings on the slipstream.
2019	Chen et al. (2019)	DES with SST k-ω	Effect of nose length on slipstream of trains under crosswinds
2019	Jiang et al. (2019)	URANS	Prediction of the slipstream caused by the trains with different marshalling forms entering a tunnel
2020	Wang et al. (2020)	IDDES with SST k-ω	Effect of rails on slipstream.
2020	Wang et al. (2020)	DES k-ω	Effect of Reynolds number on the unsteady wake and slipstream.
2020	Dong et al. (2020)	IDDES.	Effect of reducing the underbody clearance.
2020	Zampieri et al. (2020)	URANS	Slipstream produced by a high-speed train
2020	Wang et al. (2020)	IDDES	Effect of bogies and cavities on slipstream.
2020	Garcia et al. (2020)	URANS using STRUCT-ε	Slipstream around freight trains
2021	Meng et al. (2021)	IDDES with SST k-ω	Effect of train passing on slipstream
2022	He et al. (2022)	LES, IDDES and URANS	Effect of different CFD methods on the flow around trains.

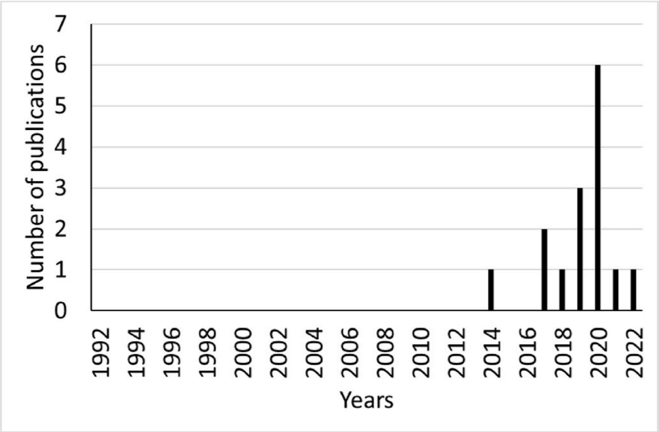

Fig. 3. Number of publications per year in the JWEIA dealing with computational techniques in train slipstream.

6. Aerodynamics of trains in tunnels and underground tubes

The pressure variation inside tunnels was one of the first issues of high-speed trains that has been investigated using computational techniques. This is due to the nature of this phenomena in which simplified versions of the continuity, momentum and energy equations can be used to obtain the pressure variation with a reasonable accuracy using a 1D version of such equations. For instance, Mok and Yoo (2001) was the first work published in the JWEIA that used simplified version of Euler equation to obtain the pressure wave in a tunnel. Table 4 and Fig. 4 show the published work in JWEIA that used computational techniques to investigate issues of trains in tunnels and underground tubes and their number per year since 1992, respectively. Since 2016, the increase of computational power and the development of computational methods for moving objects made the use of 3D solver of the flow and pressure around trains in tunnels and underground tubes possible.

6.1. Recent trends of aerodynamics of train in tunnels

The research on the effect of tunnels and subways on the aerodynamics of trains can be divided into two themes: effect on the environment around the train and the effect on the train itself and passengers in the train. The effect on the environment includes train slipstream, piston effect on the safety of workers and train equipment, micro-pressure wave at the tunnel exit, tunnel and subway pressure fluctuations and their effect on tunnel structure, the micro-pressure waves at the exit of the tunnel and their associated aerodynamic noise, effect of train on ventilation operation and fire spreading in tunnels and confined spaces. The effect of tunnels on the train and passengers inside the train includes the increase of aerodynamic drag, deterioration of passengers' comfort, effect of pressure variations on the train equipment, pressure change on train surface, the reduction the air quality inside trains, and deterioration of train ventilations. Considerable effort has been done to investigate the effect of different parameters on the previously mentioned issues as listed in Table 4. However, more effort is required to investigate the effect of tunnel cross-section, length of tunnels and ventilation arrangements within tunnels on these issues when train speed increases.

Table 4
Papers published in JWEIA delt with computational methods for pressure waves in tunnels since 1992.

Year	Paper	CWE technique/s	Topic
2001	Mok and Yoo (2001)	Euler equation	Interaction between tunnel hood and train for pressure wave.
2007	Ricco et al. (2007)	1D model and URANS RNG k-ε	Pressure waves in tunnels.
2009	Kim and Kim (2009)	URANS, k-ε	Ventilation of underground tunnels.
2011	Juraeva et al. (2011)	URANS, SST k-ω	Air circulation in tunnels.
2011	Kim et al. (2011)	URANS, SST k-ω	Flow around tube trains.
2013	Juraeva et al. (2013)	URANS, k-ε	Ventilation of underground tunnels.
2015	Cross et al. (2015)	URANS, RNG k-ε	Effect of Underground tubes blockage ratio on train aerodynamics.
2015	Khayrullina et al. (2015)	LES	Effect train slipstream an underground railroad passenger platform.
2017	Li et al. (2017)	URANS, k-ε	Effect of tunnels on aerodynamic forces.
2017	Chen et al. (2017)	URANS, RNG k-ε	Train pressure pulses in tunnels.
2018	Niu et al. (2018)	URANS, RNG k-ε	Effect of the Reynolds number on pressure waves in tunnels.
2019	Jiang et al. (2019)	URANS, RNG k-ε	Effect of a single and double-unit trains entering a tunnel.
2019	Zarnaghsh et al. (2019)	URANS, k-ε	Effect of pressure waves and flow on jet fans.
2019	Niu et al. (2019)	DDES, SST k-ω	Aerodynamics of a tube train.
2020	Lu et al. (2020)	URANS, RNG k-ε	Effect of tunnel cross-section on pressure waves.
2021	Wang et al. (2021)	URANS, SST k-ω	Crosswinds on a train exits a tunnel.
2022	Yang et al. (2022)	URANS, IDDES, LES	Effect of tunnel exit onto a bridge.
2022	Wang et al. (2022)	URANS, k-ε	Micro pressure waves in tunnels
2022	Li et al. (2022)	URANS, k-ε	Effect of tunnel lining on pressure waves.

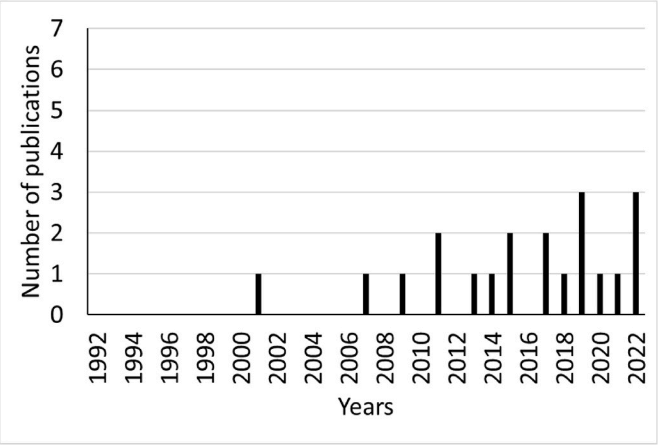

Fig. 4. Number of publications per year in the JWEIA dealing with pressure waves in tunnels.

7. Investigating the underbody flow on different issues of train aerodynamics

The aerodynamic characteristics of trains depend strongly on the flow underneath trains. Most of early work for train aerodynamics before the increase in computational power has been done using wind tunnel tests. It is well-known, however, that it is not easy to imitate reality using wind tunnel testing and one of the biggest issues of wind tunnel testing is to simulate the relative motion between trains and ground. This relative motion is very important to reproduce realistic flow underneath trains. This can be achieved in wind tunnel testing by two ways; through using moving belt underneath the train or through using small-scale moving models. One of the first effort to evaluate the effect of ground movement on train aerodynamic forces was done by Howell and Everitt (1981) using wind tunnel testing. Moving ground in computational fluid dynamics is, however, straightforward and can be achieved either by using an appropriate boundary condition or through moving the train. Once the appropriate boundaries are used on the ground and on the bottom surface of the train, other aerodynamic issues due to the flow underneath the train can be investigated. Table 5 lists the computational research papers published in the JWEIA since 1981 that dealt with the effect of underbody flow. The topics that have been investigated are the effect of underbody clearance, bogies, sleepers, and the type of tracks on the underbody flow. The effect of these flows on the aerodynamic forces and slipstream velocities and pressure was also investigated.

7.1. Recent trends of the effect of underbody flow on train aerodynamics

The underbody flow determines for a large extend the aerodynamic forces acting on train. For instance, a lower underbody flow reduces the lift force and visa vera. There are also different equipment underneath trains and the air flow, and its characteristics, affect the operation of these equipment. In addition, the flow underneath trains can significantly affect the aerodynamic drag as large clearance between the train

Table 5
Papers published in JWEIA delt with computational methods for underbody flow since 1992.

Year	Paper	CWE technique/s	Topic
1981	Howell and Everitt (1981)	None	Effect of moving ground in the flow and aerodynamic forces.
2011	Garcia et al. (2011)	RANS k-ω and k-ε	Analytical solution of underbody flow.
2017	Zhu and Hu (2017)	DDES with Spalart-Allmaras	Flow around the bogie and its effect on the ballast.
2017	Paz et al. (2017)	LES with moving sleepers	Effect of sleepers on underbody flow.
2019	Paz et al. (2019)	DDES with SST k-ω	Effect of realistic ballasted track in the underbody flow.
2020	Wang et al. (2020)	IDDES with SST k-ω	Effect of Jacobs bogie on the slipstream and wake flow.
2022	Guo et al. (2022)	IDDES with SST k-ω	Effect of cowcatcher with different clearances to the ground on the aerodynamic forces.

and the ground leads to lower aerodynamic drag (Howell and Everitt, 1981; Guo et al., 2022). In recent years, time dependent solvers have been used to investigate details of the flow underneath trains and their effect on train aerodynamics. Paz et al. (2017) used LES investigate the effect of sleepers on the turbulent characteristics of the flow underneath trains. Also, the effect of the train bogies on the slipstream velocity has been investigated by Zhu and Hu (2017) and Wang et al. (2020). However, less work has been done on the flow underneath freight trains and how these flows can be used to clean the track, for instance. In cold countries sand is used on tracks to increase the grip between the train wheels and track. However, less work has been done to understand the effect of underneath trains on the spread of sand and weather the flow helps the sand to reside on the track or otherwise. All these need further detailed investigations using the computational wind engineering techniques.

8. Other aerodynamic issues

With the recent development of computational power that allows for high fidelity time-dependent solution of the flow around high-speed trains and the implementation of advanced numerical models and tools, other aerodynamic issues have been investigated. Since 2015, there has been more use of unsteady RANS, IDDES and LES solvers to look at train aerodynamic noise, train pressure pulses and its effect on nearby structures, pantograph aerodynamics and aerodynamics of Maglev trains.

8.1. Aerodynamic noise

In 2020, Kim et al. (2020) used IDDES to investigate the aerodynamic noises from pantograph and pantograph cavity. Zhuo-ming et al. (2022) used LES to study the effect of bogies on the aerodynamic noise and their effects on far field noise. In their work, it was found that the aerodynamic noise from the bogies is much more significant than the aerodynamic noise from the other parts of the train. Since the aerodynamic noise from the bogie is affected by air flow between the bottom of the train and the ground, it was important to study the effect of ballast on the flow and thus on the aerodynamic noise. The flow underneath two trains; one with a ballast track and one with a slab track was investigated. It was found that the intensities of the dipole sources near the 1st, 2nd and 3rd bogies under ballast track are smaller, while the three downstream bogies are similar under the two ground conditions. In 2022, Yang et al. (2022a,b,c,d) used LES to investigate the aerodynamic forces on single and double noise barriers. Although some progress has been made in this field to provide improved understanding of the effect of some geometrical details on the far field noise, this field still requires conservable research to investigate some mitigation measure to reduce aerodynamic noise of high-speed trains.

8.2. Head pressure pulses

In 2015, Yang et al. (2015) used unsteady RANS to investigate the head pressure pulses of a high-speed train and its effect on overhead bridges. It was found that the slipstream velocity is noticeable above the high-speed trains in the region of thickness less than 1.5 m above the train. It was also found that there is a strong change in the pressure in a very short time when both the head and tail passes by the bridge. In 2019, Muñoz-Paniagua and Garcia (2019) used surrogate-based optimisation to optimise the nose shape of a high-speed train to minimise the pressure pulses for passing-by scenarios when subjected to crosswinds. The optimisation function was to minimise the side force on a train. They applied different conditions for the crosswind and studied the influence of different turbulence models. They found that the use of hybrid RANS/LES turbulence models is more suitable than the eddy-viscosity models when dealing with separated flows over 3D vehicles. They also recommended a balance between accuracy and computational cost as high computational cost remains a challenge for this kind of optimisation problems. In addition, Huang et al. (2019) studied the aerodynamic head pressure pulses of Maglev trains passing each other for a trial to investigate the aerodynamic issues of Maglev trains.

8.3. Pantograph aerodynamics

Pantographs add geometrical complexities on the roof of trains. They can cause an increase in drag and a change in lift forces and could create strong aerodynamic noise. Carnevale et al. (2017) utilised RANS with the SST k-ω model to investigate the lift force on pantograph as this is an important force component that could affect the contact between pantographs and overhead wires. It was revealed that high fidelity CFD is needed to obtain accurate lift forces on pantographs as they are mounted in the roof boundary layer. Li et al. (2018) used DDES with the SST κ-ω turbulence model to investigate the aerodynamics of pantographs under crosswinds. They found that aerodynamic force coefficients of the pantograph fluctuate around the averaged values. The time averaged values and fluctuation amplitudes of the aerodynamic coefficients increase gradually with increasing yaw angle. Kim et al. (2020) used IDDES to investigate the effect of pantograph and its cavity in aerodynamic noise. It was found that the overall SPL above the pantographs is much higher than that at the side. It was also found that different train running directions have no significant effect on the total noise radiated. It was also found that ‘closed’ cavity configuration contributes to the reduction of noise from the pantograph and the cavity itself generates significant noise above the high-speed train whereas contribution of it at the train side is negligible.

9. Emerging issues

Since the first conference in CWE in 1992, there has been significant contribution of computational wind engineering in traditional issues such as aerodynamic forces, head pressure pulses, pressure variations in tunnels, crosswind effect, slipstream, and aerodynamic noises. However, there are other issues that are expected to emerge in railways in the future. The reason that these issues were not investigated properly in the past is because they are complex to be investigated experimentally and the computational power and numerical technology were not capable in providing results that deemed to be accurate. Examples for such issues are train air quality and its health risk, effect of snow and rain on aerodynamic forces, splash of water in flooded regions and its effect on train electrical components, effect of sand on train structure and the effect of boundary layer of high-speed trains on the heat, ventilation, heating and air conditioning (HVAC) units.

Clean air is important for our health as well as more generally for the environment, plants, and animals. The Clean Air For Europe (CAFE) Directive 2008/50/EC is a legislation published by the EU to improve air quality and limit exposure to air pollution. As major cities across the world introduce low emission zones, there has been an increasing shift towards alternative forms of transportation and in particular the use of light rail, tram, and metro systems as well as heavy rail networks. However, whilst there has been significant research work done to date on road traffic and the associated air quality issues, the topic of air quality on-board trains is only just beginning to emerge. The sources of pollutants in railways could be from the exhaust plume of diesel trains, abrasion of rail, breaks and wheels, abrasion of pantograph and overhead wires, and pollutants from train stations. All these issues need a significant research investigation by the wind engineering community.

The effect of rain, snaw and sand on the aerodynamics of high-speed trains was investigated by Liu et al. (2020), Wang et al. (2018), Paz et al. (2015), and Yu et al. (2022). Also, a trial to study the effect of the speed of trains on the performance of the HVAC units was done by Li et al. (2019). However, the research in these fields is very limited and with the computational capability we currently have, we expect significant research into the effect of these issues in the nearest future. Also, the effect of climate change will be on increasingly significant in the future, and it is expected that the flow around train to be very complex than it is right now. For extreme cases, this flow can carry debris of different shapes and sizes and the effect of these objects will need proper investigation.

10. Conclusions

The contribution of the Computational Wind Engineering (CWE) field in the development of the train aerodynamics has been investigated through the review of computational work in train aerodynamics published in the Journal of Wind Engineering and Industrial Aerodynamics (JWEIA) since 1992 till 2022. It has been found that the since the first conference of CWE there is a significant contribution of CWE in the traditional issues of high-speed trains such as the estimation of aerodynamic forces, stability of trains in crosswinds, slipstream effect on people's safety, head pressure pulses and pressure variation in tunnels. The field started to emerge slowly in the ninetieth due to the limited computational power and thus most of the computational research undertaken on train aerodynamics used steady RANS techniques. Since 2005, the significant development of computational power and computational fluid dynamics solvers mage the use high-fidelity DES and LES and unsteady solvers URANS possible and since then they have emerged as reliable research tools for train aerodynamics. Since 2017, there was a significant increase in the number of the work published in the JWEIA that deals with computational methods for train aerodynamics. The paper also lists number of emerging issues for train aerodynamics that needs the focus of the computational wind engineering community in the future.

Credit author statement

Hassan Hemida: Conceptualization, Methodology, Data curation, Writing – original draft, Investigation, Validation, Writing- Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

Allegrinia, J., Kubilay, A., 2017. Wind sheltering effect of a small railway station shelter and its impact on wind comfort for passengers. JWEIA *164*, 82–95.

Burlando, M., Freda, A., Ratto, C., Solari, G., 2010. A pilot study of the wind speed along the Rome–Naples HS/HC railway line. Part 1—numerical modelling and wind simulations. JWEIA 98, 392–403.

Carnevale, M., Facchinetti, A., Rocchi, D., 2017. Procedure to assess the role of railway pantograph components in generating the aerodynamic uplift. JWEIA 160, 16–29.

Cheli, F., Ripamonti, F., Rocchi, D., Tomasini, G., 2010. Aerodynamic behaviour investigation of the new EMUV250 train to cross wind. JWEIA 98, 189–201.

Chen, Z., Liu, T., Zhou, X., Niu, J., 2017. Impact of ambient wind on aerodynamic performance when two trains intersect inside a tunnel. JWEIA 169, 139–155.

Chen, G., Li, X., Liu, Z., Zhou, D., Wang, Z., Liang, X., Krajnovic, S., 2019. Dynamic analysis of the effect of nose length on train aerodynamic performance. JWEIA 184, 198–208.

Chen, G., Liang, X., Li, X., Zhou, D., Lien, F., Wang, J., 2021. Dynamic analysis of the effect of platoon configuration on train aerodynamic performance. JWEIA 211, 104564.

Chiu, T.W., 1991. A two-dimensional second-order vortex panel method for the flow in a cross-wind over a train and other two-dimensional bluff bodies. JWEIA 37 (Issue 1), 43–64.

Chiu, T.W., 1995. Prediction of the aerodynamic loads on a railway train in a cross-wind at large yaw angles using an integrated two- and three-dimensional source/vortex panel method. JWEIA 57, 19–39.

Cross, D., Hughes, B., Ingham, D., Ma, L., 2015. A validated numerical investigation of the effects of high blockage ratio and train and tunnel length upon underground railway aerodynamics. JWEIA 146, 195–206.

Deng, E., Yang, W., He, X., Zhu, Z., Wang, H., Wang, Y., Wang, A., Zhou, L., 2021. Aerodynamic response of high-speed trains under crosswind in a bridge-tunnel section with or without a wind barrier. JWEIA 210, 104502.

Dong, T., Minelli, G., Wang, J., Liang, X., Krajnovic, S., 2020. The effect of reducing the underbody clearance on the aerodynamics of a high-speed train. JWEIA *204* 104249.

EN14067-6, 2018. Railway Applications – Aerodynamics. Part 6 Requirements and Test Procedures for Cross Wind Assessment.

Flynn, D., Hemida, H., Soper, D., Baker, C., 2014. Detached-eddy simulation of the slipstream of an operational freight train. JWEIA 132, 1–12.

Flynn, D., Hemida, H., Baker, C., 2016. On the effect of crosswinds on the slipstream of a freight train and associated effects. JWEIA 156, 14–28.

Gallagher, M., Morden, J., Baker, C., Soper, D., Quinn, A., Hemida, H., Sterling, M., 2018. Trains in crosswinds – comparison of full-scale on-train measurements, physical model tests and CFD calculations. JWEIA 175, 428–444.

Garcia, J., Crespo, A., Berasarte, A., Goikoetxea, J., 2011. Study of the flow between the train underbody and the ballast track. JWEIA 99, 1089–1098.

García, J., Munoz-Paniagua, J., Xub, L., Baglietto, E., 2020. A second-generation URANS model (STRUCT-ε) applied to simplified freight trains. JWEIA *205*, 104327.

Gawthorpe, R.G., 1994. Wind effects on ground transportation. JWEIA 52, 73–92.

Golovanevskiy, V.A., Chmovzh, V.V., Girka, Y.V., 2012. On the optimal model configuration for aerodynamic modeling of open cargo railway train. JWEIA 107, 131–139. *108*.

Gu, H., Liu, T., Jiang, Z., Guo, Z., 2021. Experimental and simulation research on the aerodynamic effect on a train with a wind barrier in different lengths. JWEIA 214, 104644.

Gu, H., Gao, H., Liu, T., Cheng, S., Li, J., Liu, Z., 2022. Effects of windbreak wall model lengths on aerodynamic characteristics of trains on different tracks in wind tunnel tests – a measurement strategy. JWEIA 228, 105104.

Guo, Z., Liu, T., Chen, Z., Xie, T., Jiang, Z., 2018. Comparative numerical analysis of the slipstream caused by single and double unit trains. JWEIA *172*, 395–408.

Guo, Z., Liu, T., Yu, M., Chen, Z., Li, W., Huo, X., Liu, H., 2019. Numerical study for the aerodynamic performance of double unit train under crosswind. JWEIA 191, 203–214.

Guo, Z., Liu, T., Chen, Z., Liu, Z., Monzer, A., Sheridan, J., 2020. Study of the flow around railway embankment of different heights with and without trains. JWEIA 202, 104203.

Guo, Z., Liu, T., Liu, Z., Chen, X., Li, W., 2021. An IDDES study on a train suffering a crosswind with angles of attack on a bridge. JWEIA *217*, 104735.

Guo, Z., Liu, T., Xia, Y., Liu, Z., 2022. Aerodynamic influence of the clearance under the cowcatcher of a high-speed train. JWEIA *220*, 104844.

He, K., Su, X., Gao, G., Krajnović, S., 2022. Evaluation of LES, IDDES and URANS for prediction of flow around a streamlined high-speed train. JWEIA *223*, 104952.

Howell, J., Everitt, K., 1981. The underbody flow of an EDS-type advanced ground transport vehicle. JWEIA 8, 275–294.

Huang, S., Li, Z., Yang, M., 2019. Aerodynamics of high-speed maglev trains passing each other in open air. JWEIA *188*, 151–160.

Huo, X., Liu, T., Chen, Z., Li, W., Gao, H., Wang, S., 2021. Comparative analysis of the aerodynamic characteristics on double-unit trains formed by different types of high-speed train. JWEIA *217*, 104757.

Jiang, Z., Liu, T., Chen, X., Li, W., Guo, Z., 2019. Numerical prediction of the slipstream caused by the trains with different marshalling forms entering a tunnel. JWEIA 189, 276–288.

Juraeva, M., Lee, J., Song, D., 2011. A computational analysis of the train-wind to identify the best position for the air-curtain installation. JWEIA 99, 554–559.

Juraeva, M., Ryu, K., Jeong, S., Song, D., 2013. Influence of mechanical ventilation-shaft connecting location on subway tunnel ventilation performance. JWEIA 119, 114–120.

Khayrullina, A., Blocken, B., Janssen, W., Straathof, J., 2015. CFD simulation of train aerodynamics: train-induced wind conditions at an underground railroad passenger platform. JWEIA 139, 100–110.

Kim, J., Kim, K., 2009. Effects of vent shaft location on the ventilation performance in a subway tunnel. JWEIA 97, 174–179.

Kim, T., Kim, K., Kwon, H., 2011. Aerodynamic characteristics of a tube train. JWEIA 99, 1187–1196.

Kim, H., Hu, Z., Thompson, D., 2020. Numerical investigation of the effect of cavity flow on high speed train pantograph aerodynamic noise. JWEIA *201*, 104159.

Kisielewicz, L.T., Tabbal, A., 1993. Validated Computational Aerodynamics for Trains. JWEIA, p. *49* 449458.

Krajnović, S., Hemida, H., 2010. LES study of the influence of the nose shape and yaw angles on flow structures around trains. JWEIA 98, 34–46.

Li, R., Xu, P., Peng, Y., Ji, P., 2016. Multi-objective optimization of a high-speed train head based on the FFD method. JWEIA 152, 41–49.

Li, Z., Yang, M., Huang, S., Liang, X., 2017. A new method to measure the aerodynamic drag of high-speed trains passing through tunnels. JWEIA 171, 110–120.

Li, X., Zhou, D., Jia, L., Yang, M., 2018. Effects of yaw angle on the unsteady aerodynamic performance of the pantograph of a high-speed train under crosswind. JWEIA *182*, 49–60.

Li, X., Wu, F., Tao, Y., Yang, M., Newman, R., Vainchtein, D., 2019. Numerical study of the air flow through an air-conditioning unit on high-speed trains. JWEIA *187*, 26–35.

Li, X., Liang, X., Wang, Z., Xiong, X., Chen, G., Yu, Y., Chen, C., 2021. On the correlation between aerodynamic drag and wake flow for a generic high-speed train. JWEIA 215, 104698.

Li, F., Luo, J., Wang, L., Wang, D., Gao, L., 2022. Wave effects of high-speed trains passing through different tunnel lining types. JWEIA *224*, 104971.

Liu, M., Wang, J., Zhu, H., Krajnovic, S., Zhang, Y., Gao, G., 2020. A numerical study on water spray from wheel of high-speed train. JWEIA 197, 104086.

Liu, D., Liang, X., Zhou, W., Zhang, L., Lu, Z., Zhong, M., 2022. Contributions of bogie aerodynamic loads to the crosswind safety of a high-speed train. JWEIA *228*, 105082.

Lu, Y., Wang, T., Yang, M., Qian, B., 2020. The influence of reduced cross-section on pressure transients from high-speed trains intersecting in a tunnel. JWEIA 201, 104161.

Maleki, S., Burton, D., Thompson, M., 2017. Assessment of various turbulence models (ELES, SAS, URANS and RANS) for predicting the aerodynamics of freight train container wagons. JWEIA 170, 68–80.

Maleki, S., Burton, D., Thompson, M., 2020. On the flow past and forces on double-stacked wagons within a freight train under cross-wind. JWEIA 206, 104224.

Meng, S., Meng, S., Wu, F., Li, X., Zhou, D., 2021. Comparative analysis of the slipstream of different nose lengths on two trains passing each other. JWEIA 208, 104457.

Mok, J., Yoo, J., 2001. Numerical study on high speed train and tunnel hood interaction. JWEIA 89, 17–29.

Muñoz-Paniagua, J., García, J., 2019. Aerodynamic surrogate-based optimization of the nose shape of a high-speed train for crosswind and passing-by scenarios. JWEIA *184*, 139–152.

Muñoz-Paniagua, J., García, J., 2020. Aerodynamic drag optimization of a high-speed train. JWEIA 204, 104215.

Muñoz-Paniagua, J., Lehugeur, J.G., 2017. Evaluation of RANS, SAS and IDDES models for the simulation of the flow around a high-speed train subjected to crosswind. JWEIA 171, 50–66.

Muñoz-Paniagua, J., García, J., Crespo, A., 2014. Genetically aerodynamic optimization of the nose shape of a high-speed train entering a tunnel. JWEIA 130, 48–61.

Niu, J., Zhou, D., Liang, X., Liu, S., Liu, T., 2018. Numerical simulation of the Reynolds number effect on the aerodynamic pressure in tunnels. JWEIA 173, 187–198.

Niu, J., Sui, Y., Yu, Q., Cao, X., Yuan, Y., 2019. Numerical study on the impact of Mach number on the coupling effect of aerodynamic heating and aerodynamic pressure caused by a tube train. JWEIA 190, 100–111.

Niu, J., Wang, Y., Liu, F., Chen, Z., 2020. Comparative study on the effect of aerodynamic braking plates mounted at the inter-carriage region of a high-speed train with pantograph and air-conditioning unit for enhanced braking. JWEIA 206, 104360.

Niu, J., Zhang, Y., Li, R., Chen, Z., Yao, H., Wang, Y., 2022. Aerodynamic simulation of effects of one- and two-side windbreak walls on a moving train running on a double track railway line subjected to strong crosswind. JWEIA 221, 104912.

Paz, C., Suárez, E., Gil, C., Concheiro, M., 2015. Numerical study of the impact of wind blown sand particles on a high-speed train. JWEIA 145, 87–93.

Paz, C., Suarez, E., Gil, C., 2017. Numerical methodology for evaluating the effect of sleepers in the underbody flow of a high-speed train. JWEIA 167, 140–147.

Paz, C., Suarez, E., Gil, C., Cabarcos, A., 2019. Effect of realistic ballasted track in the underbody flow of a high-speed train via CFD simulations. JWEIA 184, 1–9.

Premoli, A., Rocchi, D., Schito, P., Tomasin, G., 2016. Comparison between steady and moving railway vehicles subjected to crosswind by CFD analysis. JWEIA 156, 29–40.

Ricco, P., Baron, A., Molteni, P., 2007. Nature of pressure waves induced by a high-speed train travelling through a tunnel. JWEIA 95, 781–808.

Smagorinsky, J., 1963. General circulation experiments with the primitive equations I. The Basic Experiment. Monthly Weather Review 91 (3), 99–164.

Wang, J., Gao, G., Liu, M., Xie, F., Zhang, J., 2018. Numerical study of snow accumulation on the bogies of a high-speed train using URANS coupled with discrete phase model. JWEIA *183*, 295–314.

Wang, J., Minelli, G., Dong, T., Chen, G., Krajnovic, S., 2019. The effect of bogie fairings on the slipstream and wake flow of a high-speed train. An IDDES study. JWEIA 191, 183–202.

Wang, D., Chen, C., Hu, J., He, Z., 2020. The effect of Reynolds number on the unsteady wake of a high-speed train. JWEIA 204, 104223.

Wang, L., Luo, J., Li, F., Guo, D., Gao, L., Wang, D., 2021. Aerodynamic performance and flow evolution of a high-speed train exiting a tunnel with crosswinds. JWEIA *218*, 104786.

Wang, M., Fu, P., Zhou, Y., Li, Z., Li, X., 2022. Shielding and internode effects of truss bridge on the aerodynamic characteristics of high-speed train under crosswinds. JWEIA 220, 104831.

Wang, T., Hu, C., Zhang, L., Tian, X., Shi, F., Wang, J., 2022. Research on the mechanism of micro-pressure waves in a high-speed train passing through a high geo-temperature tunnel. JWEIA *226*, 105031.

Wanga, S., Bella, J., Burtona, D., Herbstb, A., Sheridana, J., Thompsona, M., 2017. The performance of different turbulence models (URANS, SAS and DES) for predicting high-speed train slipstream. JWEIA 165, 46–57.

Xia, C., Wang, H., Shan, X., Yang, Z., Li, Q., 2017. Effects of ground configurations on the slipstream and near wake of a high-speed train. JWEIA 168, 177–189.

Xia, Y., Liu, T., Li, W., Dong, X., Chen, Z., Guo, Z., 2021. Numerical comparisons of the aerodynamic performances of wind-tunnel train models with different inter-carriage gap spacings under crosswind. JWEIA 214, 104680.

Xiao, C., Yang, M., Tan, C., Lu, Z., 2020. Effects of platform sinking height on the unsteady aerodynamic performance of high-speed train pantograph. JWEIA 204, 104284.

Yang, N., Zheng, X., Zhang, J., Lawa, S., Yang, Q., 2015. Experimental and numerical studies on aerodynamic loads on an over head bridge due to passage of high-speed train. JWEIA 140, 19–33.

Yang, W., Liu, Y., Deng, E., Wang, Y., He, X., Huang, Y., Zou, Y., 2022a. Moving model test on the aerodynamic pressure of bilateral inverted-L-shaped noise barriers caused by high-speed trains. JWEIA *228*, 105083.

Yang, W., Ouyang, D., Deng, E., He, X., Zou, Y., Huang, Y., 2022b. Aerodynamic characteristics of two noise barriers (fully enclosed and semi-enclosed) caused by a passing train: a comparative study. JWEIA *226*, 105028.

Yang, W., Yue, H., Deng, E., He, X., Zou, Y., Wang, Y., 2022c. Comparison of aerodynamic performance of high-speed train driving on tunnel-bridge section under fluctuating winds based on three turbulence models. JWEIA *228*, 105081.

Yang, W., Yue, H., Deng, E., Wang, Y., He, X., Zou, Y., 2022d. Influence of the turbulence conditions of crosswind on the aerodynamic responses of the train when running at tunnel-bridge-tunnel. JWEIA 229, 105138.

Yu, M., Liu, J., Zhang, Q., Dai, Z., 2022. Unsteady aerodynamic characteristics on trains exposed to strong wind and rain environment. JWEIA *226*, 105032.

Zampieri, A., Rocchi, D., Schito, P., Somaschini, C., 2020. Numerical-experimental analysis of the slipstream produced by a high speed train. JWEIA 196, 104022.

Zarnaghsh, A., Abouali, O., Emdad, H., Ahmadi, G., 2019. A numerical study of the train-induced unsteady air effects on the performance of jet fans. JWEIA 187, 1–14.

Zhai, Y., Niu, J., Wang, Y., Liu, F., Li, R., 2020. Unsteady flow and aerodynamic behavior of high-speed train braking plates with and without crosswinds. JWEIA 206, 104309.

Zhu, J., Hu, Z., 2017. Flow between the train underbody and trackbed around the bogie area and its impact on ballast flight. JWEIA 166, 20–28.

Zhuo-ming, L., Qi-liang, L., Zhi-gang, Y., 2022. Flow structure and far-field noise of high-speed train under ballast track. JWEIA *220*, 104858.