Proceedings of the Seventh International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 15, Paper 5.1
Civil-Comp Press, Edinburgh, United Kingdom, 2026
ISSN: 2753-3239, doi: 10.4203/ccc.15.5.1

On the Aerodynamics of Freight Trains: Crosswind Stability, Slipstream Effects and Tunnel Overpressure

G. Tomasini, D. Rocchi, P. Schito, C. Somaschini, C. Araya, S. Negri and E. Inghilleri

Department of Mechanical Engineering, Politecnico di Milano, Italy

Abstract

Freight train aerodynamics has received considerably less attention than passenger train aerodynamics, despite its growing importance for railway safety and infrastructure design. This paper presents recent research activities carried out at Politecnico di Milano on freight trains in three key aerodynamic topics: crosswind stability, slipstream effects and tunnel overpressure for freight trains. Crosswind stability represents a major safety concern, as demonstrated by recent rollover accidents involving freight vehicles. Wind tunnel experiments and multibody simulations are employed to assess the influence of wagon typology, loading arrangement and load dynamics. Results highlight the strong dependence of crosswind stability on loading configuration and show that simplified rigid-load assumptions may significantly overestimate the stability of intermodal freight vehicles. Slipstream experimental investigations indicate that freight trains can generate, both open-air and tunnel, slipstream velocities comparable to, or exceeding, regulatory thresholds despite operating at relatively low speeds and reveal significant differences between freight and passenger train flow development. Finally, a CFD methodology for analysing train-tunnel pressure signatures is applied to freight trains. Parametric studies demonstrate the role of train length and inter-wagon gaps on pressure peaks, highlighting that tunnel overpressure may become critical for very long freight convoys.

Keywords: freight train aerodynamics, crosswind stability, slipstream, train-tunnel overpressure

1 Introduction

Railway aerodynamics has attracted increasing research interest over the last decades, mainly driven by the development of high-speed trains and by the need to improve safety, comfort and energy efficiency. Most aerodynamic studies and assessment methodologies have therefore focused on high-speed and conventional passenger vehicles, while freight train aerodynamics remains comparatively less investigated and only partially covered by current standards and regulations. In fact, the regulatory framework still provides limited and often indirect indications for freight trains [17], [12], [13.

The main aerodynamic phenomena associated with railway vehicles include aerodynamic drag, crosswind stability, slipstream effects and pressure waves generated in tunnels. Aerodynamic drag mainly affects energy consumption, crosswind influences running safety, slipstream may affect passengers and trackside workers, while tunnel pressure waves can cause passenger discomfort and increased aerodynamic loads on infrastructure and rolling stock. While aerodynamic drag is not addressed in the present work, the paper focuses on crosswind stability, slipstream effects and tunnel overpressure for freight trains.

A major challenge in freight train aerodynamics is the large variability in wagon typologies, loading conditions and train compositions, which makes their aerodynamic characterization significantly more complex than that of passenger trains ([17], [12], [13], [14]). Freight trains are characterized by discontinuous geometries, bluff bodies, inter-vehicle gaps and highly variable loading configurations. Moreover, although the available literature is steadily increasing, most studies focus on intermodal container trains, while several other freight configurations remain largely unexplored ([17]). This variability makes it difficult to generalize results and highlights the need for methodologies capable of systematically analysing different train geometries without requiring dedicated investigations for each configuration.

Despite operating at lower speeds than high-speed passenger trains, freight trains have been involved in several incidents related to aerodynamic effects. The accidents that occurred on the Great Belt Bridge in Denmark highlighted the vulnerability of freight vehicles to strong crosswinds, while slipstream-related incidents involving passengers and objects on platforms demonstrated the potential risks associated with train-induced airflow. These events further emphasize the need for improved understanding and assessment methodologies.

The progressive extension of mixed-traffic railway lines, where freight trains increasingly share infrastructure with passenger and high-speed services, is making aerodynamic phenomena associated with train passage and train crossing in tunnels even more relevant. Dedicated investigations addressing freight trains are therefore becoming increasingly necessary.

For these reasons, the POLIMI research group has investigated several aerodynamic aspects specifically related to freight trains in recent years. The present paper does not aim to provide a complete state-of-the-art review, but rather presents the main results achieved by the authors in the fields of crosswind stability, slipstream effects and tunnel overpressure, together with the experimental approaches, numerical methodologies and analysis techniques developed for the investigation of freight train aerodynamics.

2 Crosswind stability

As discussed in the introduction, freight train aerodynamics is strongly influenced by wagon typology and loading configuration, in contrast to passenger trains whose geometries are relatively standardized. The UIC classification system includes a wide variety of wagon families, such as open, covered and flat wagons for intermodal transport, each characterized by markedly different geometric features. These variations affect flow separation, vortex formation and, consequently, the aerodynamic loads acting under crosswind conditions, making the extrapolation of aerodynamic behaviour between different freight configurations inherently difficult.

Although EN 14067-6 [2] formally applies to both passenger and freight trains and defines procedures for determining aerodynamic coefficients through wind tunnel testing or CFD, it does not provide dedicated Characteristic Wind Curves (CWC) calculation procedure or modelling approaches specific to freight vehicles. Furthermore, identifying the wagon typologies most critical under crosswind conditions is not straightforward. For example, both pocket wagons such as the T3000 and conventional covered wagons (H-type) have been involved in documented incidents, despite their substantially different aerodynamic and dynamic characteristics.

2.1 Configuration-dependent aerodynamics: the role of load arrangement and gaps

For freight trains, the loading configuration represents a key aerodynamic parameter. The presence and distribution of gaps between containers, trailers or loading units strongly affect flow development and the resulting aerodynamic forces [3,4]. Previous studies have shown that different loading arrangements may generate substantially different flow regimes and force coefficients [3–8], highlighting that freight-train aerodynamics depends not only on vehicle geometry but also on inter-vehicle gap characteristics and loading conditions.

Wind-tunnel studies conducted at Politecnico di Milano on 1:20 scaled models of container freight wagons confirmed the strong influence of loading arrangement on aerodynamic loads (Figure 1a) [5]. In particular, upstream loaded wagons provide a shielding effect that reduces the aerodynamic load acting on downstream units, whereas upstream gaps expose the leading surfaces of containers to direct wind impingement, increasing both rolling moment and overturning risk.

Beyond the characterization of the aerodynamic field, this configuration dependence has direct implications for operational safety, as variations in loading arrangement may translate into substantial changes in crosswind stability.

For intermodal articulated wagons such as the T3000e, three representative loading

configurations were considered: a semi-trailer loaded on the front unit only (purple solid line), on the rear unit only (green solid line), and on both units (light blue solid line). As an initial assumption, the semi-trailers were modelled as rigidly connected to the pocket wagons, neglecting relative motion. The pocket wagon was simulated using the ADTres multi-body framework developed at Politecnico di Milano, and the Characteristic Wind Curves (CWC) were computed according to EN 14067-6 [2]. Aerodynamic coefficients were derived from similar wagon typologies available in the literature [5].
The results indicate that, when both loading positions are occupied, the overall system exhibits reduced stability compared with the single-load cases. The larger lateral exposed area generates a higher aerodynamic rolling moment on the wagon–semi-trailer system, resulting in a greater overturning tendency. However, notable differences also emerge between the asymmetric configurations. In particular, the case with a semi-trailer positioned on the front unit proves to be the most critical, yielding a critical wind speed approximately 3 m/s lower than the corresponding configuration with the semi-trailer on the rear unit.

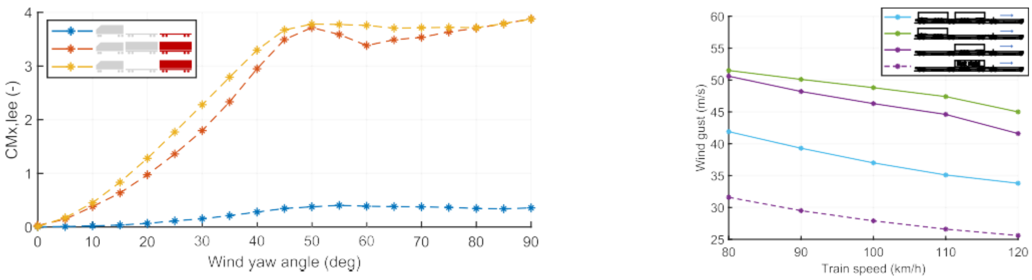


Figure 1: (a) Lee rolling moment coefficient measured in wind tunnel for the rear wagon (red in legend) for different compositions [5]. (b) Characteristic wind curves for the T3000e wagon under different loading configurations, with the semi-trailer modelled either as rigidly connected to the pocket wagon or as a dynamically independent body.

2.2 Dynamic modelling on intermodal pocket wagons

While simplified dynamic models are well established for passenger trains and supported by current standards, their direct application to intermodal freight wagons remains questionable. In pocket wagons carrying semi-trailers, the load constitutes an additional body with its own mass, inertia and potential relative motion, introducing interaction mechanisms that are not captured by conventional simplified models. For this reason, the applicability of standard approaches is currently being investigated within the UIC RERA-WIND project (conducted by UoB and POLIMI).
To assess the influence of load dynamics, a comparative analysis was carried out between two modelling approaches: one in which the semi-trailer is assumed to be rigidly connected to the pocket wagon and another in which it is treated as a dynamically independent body. In the latter case, the trailer was modelled as an additional body connected to the wagon through spring and damper elements. The Characteristic Wind Curves (CWC) were computed by adopting a 90% unloading of

the windward trailer wheels as the overturning criterion, consistently with the approach prescribed by EN 14067-6 [2] for the wagon.
The results, presented in Figure 1b, show that the dynamically independent trailer model loaded on the front pocket (purple dashed line) is significantly more susceptible to rollover than the rigidly connected configuration (purple solid line). At a train speed of 120 km/h, the characteristic wind speed decreases from 42 m/s to 26 m/s, indicating a substantial reduction in crosswind stability. The resulting value is even lower than the approximately 28 m/s typically associated with high-speed trains operating at maximum speed. These findings highlight the importance of properly accounting for load dynamics in the assessment of intermodal freight vehicles.

3 Slipstream effects

Historically, slipstream studies have mainly focused on high-speed passenger trains, with freight trains receiving comparatively less attention. Nevertheless, several investigations have addressed freight train slipstream in open-air conditions through full-scale measurements, moving-model experiments and CFD simulations [12–16]. These studies highlighted the highly turbulent nature of freight train slipstream, the strong influence of wagon geometry and loading configuration, and the capability of high-fidelity numerical approaches to reproduce the main experimentally observed flow features. More recently, tunnel investigations have been carried out through CFD simulations, showing that confinement effects and wagon geometric discontinuities significantly modify the flow structures observed in open-air conditions [18].
While the available literature mainly focuses on freight train slipstream in open-air conditions, investigations in confined environments remain very limited. In recent years, the POLIMI research group has addressed this topic through a combined experimental and numerical research program. Full-scale measurements have been carried out on different train categories, including freight trains, both in open-air and tunnel conditions, providing systematic datasets for the characterization of train slipstream in confined spaces [15,20]. In parallel, CFD simulations have been performed for a homogeneous freight-train configuration and compared with the available experimental evidence [19]. These activities constitute a first step towards the extension of the simplified coupled 2D–3D methodology proposed by Negri et al. [21] to freight-train applications.

3.1 Experimental analysis

Measurements were carried out in a site located in an open space near a tunnel portal. Although not fully compliant with standard open-air requirements, it was considered sufficiently representative for comparative slipstream analyses. Anemometers were installed both in open air and within the tunnel. According to TSI prescriptions [11], the instruments were positioned at a height of 1.2 m above the top of rail (TOR) and at a lateral distance of 2.5 m from the centre of rail (COR).
The measurements were conducted considering high-speed, conventional and freight trains. For the open-air scenario, velocity time histories are reported at a common

reference speed of 120 km/h, while tunnel measurements were analysed considering trains running at their maximum operating speed on the line.

Figure 2 compares the ensemble-averaged slipstream velocity profiles measured in open-air and tunnel conditions. For passenger trains, the tunnel environment generates an extended backflow region due to the piston effect, followed by positive velocity peaks associated with the entrainment of the tunnel flow into the train boundary layer. Freight trains exhibit a markedly different behaviour, characterized by the absence of a well-defined backflow region and by velocity peaks distributed along the train length, owing to the discontinuous geometry of the convoy and the resulting vortex shedding phenomena.

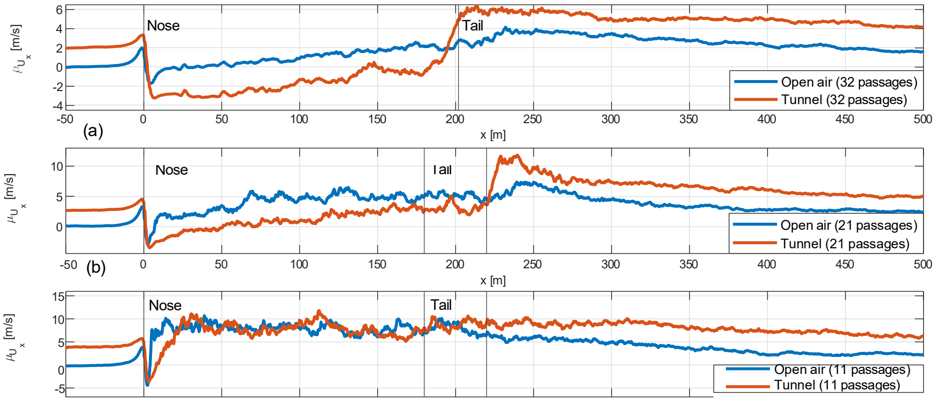


Figure 2: Comparison of slipstream profiles in open air and confined space: (a) high-speed trains, (b) conventional trains, (c) freight trains. X-axis: distance between train nose and anemometer; Y-axis: ensemble mean of longitudinal air speed [15].

Figure 3 reports the peak values of horizontal slipstream velocity for the different train categories. The results clearly show that, in open-air conditions, freight trains generate significantly higher peak velocities compared to both high-speed and conventional passenger trains. Notably, these peaks approach or even exceed the threshold values defined by TSI, despite operating at speeds well below 160 km/h, as observed by [17].

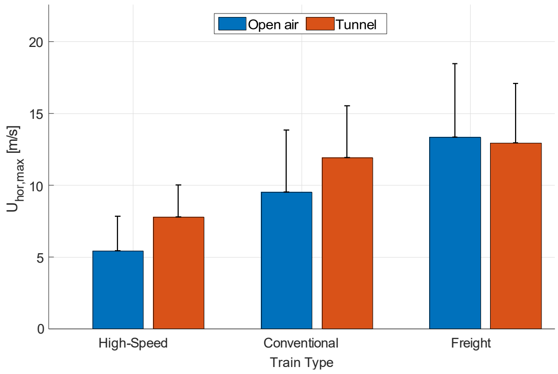


Figure 3: Peak horizontal slipstream velocities: mean and ±2 standard

deviation[1] across different train types [15].

These findings highlight a critical issue: although freight trains are not explicitly regulated in terms of slipstream safety, they can still produce airflow peaks comparable to or more severe than those of high-speed passenger trains, confirming the need for dedicated investigations and potentially revised regulatory considerations.

3.2 CFD approach: rationale and role

The experimental results highlight the complexity of freight train slipstream and the difficulty of systematically investigating the large number of parameters affecting the phenomenon. CFD therefore represents a valuable complementary tool for controlled parametric analyses. Figure 4 presents a comparison between full-scale measurements and a three-dimensional URANS simulation performed using a sliding-mesh approach. The numerical model reproduces the main features of the measured velocity signature with good accuracy, particularly in the front region of the train where the flow is governed by locomotive-induced separation. Larger discrepancies are observed downstream due to the stochastic nature of the flow and the limited number of experimental realizations available for the ensemble statistics. Overall, the results support the capability of moving-mesh CFD approaches to reproduce the dominant slipstream mechanisms generated by freight trains in tunnels. Future work will focus on extending the validation to the simplified coupled 2D–3D methodology proposed by Negri et al. [21], with the objective of enabling computationally efficient parametric analyses of freight train slipstream in confined spaces.

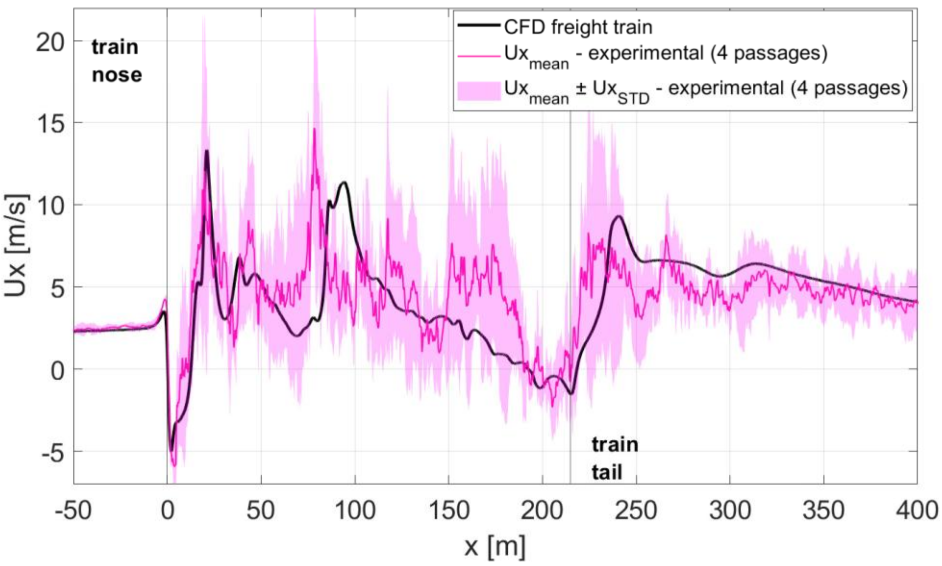


Figure 4: Freight train: CFD validation of moving mesh technique against experimental data [19].

[1] Sample size: 32 high-speed trains, 21 conventional trains and 11 freight trains (only homogeneous configurations with fully loaded container wagons).

4 Tunnel overpressure

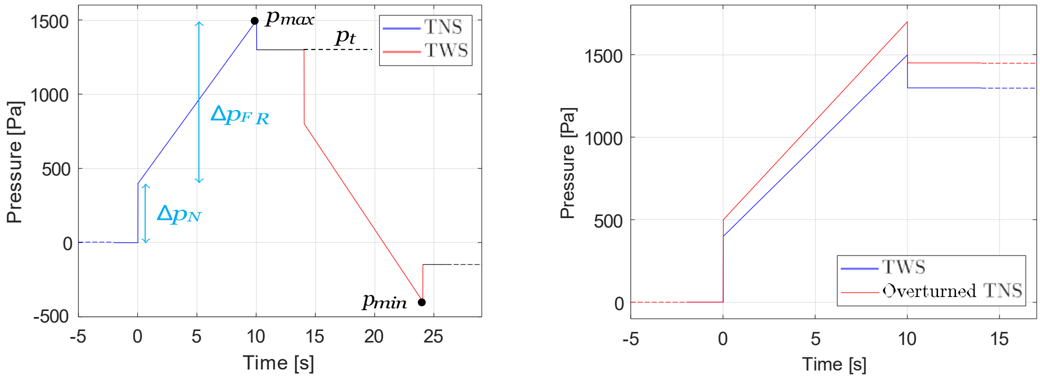
The transition from open-air conditions to a confined environment alters the pressure field within the tunnel and may generate significant pressure increases, affecting passenger comfort and increasing aerodynamic loads on infrastructure and rolling stock. According to EN 14067-5 [22] and the TSI Infrastructure [23], the maximum pressure variation induced by train passage in a tunnel shall not exceed 10 kPa under the worst operating conditions, typically corresponding to train crossings. Compliance is assessed through equivalent limits defined for single-train passage scenarios. For the reference tunnel considered by the standard (53.6 m^2 cross-sectional area), the pressure variation generated by a train running at 200 km/h should remain below 3000 Pa. Although these requirements formally apply to trains operating above 200 km/h, tunnel overpressure may also become relevant for freight trains under specific operating conditions.

The literature addressing tunnel overpressure phenomena for freight trains remains limited. To the best of the authors' knowledge, no dedicated full-scale experimental investigations have been published. The first experimental study was conducted by Iliadis et al. [24] through moving-model tests, highlighting the influence of train length and loading configuration on the generated pressure waves. Numerical investigations have subsequently employed both CFD and one-dimensional approaches to analyse flow separation around freight trains and improve the prediction of tunnel pressure signatures [18,25,26]. Nevertheless, the influence of key freight-train parameters, such as train length and inter-wagon gaps, still requires further investigation.

The present work presents an extended parametric study of freight-train pressure signatures based on a steady-state CFD methodology previously validated for high-speed train configurations [27], accounting for convoy length and further analysing inter-vehicle gap effects. Further details on the methodology and the related results are provided in [28].

4.1 CFD analysis

The numerical methodology adopted in this work is based on the steady-state approach proposed and validated by Brambilla et al. [27] for high-speed trains. Under the assumption of quasi-steady flow around the train, the Train Near-field Signature (TNS) is reconstructed through three-dimensional steady RANS simulations of a stationary train inside the tunnel. The corresponding Train Wave Signature (TWS) can then be derived through a suitable rescaling procedure. Figure 5 schematically illustrates the relationship between TNS and TWS and the overturning procedure adopted to reconstruct the train-induced pressure signature. Owing to its limited computational cost compared with moving-mesh simulations, the methodology was adopted for a parametric investigation of freight train length and inter-wagon gap effects.



(a) Example of a freight train-tunnel pressure signature.

(b) Comparison between TWS and overturned TNS.

Figure 5: Schematic representation of the TNS overturning procedure.

The TNS is reconstructed using a numerical approach that relies on CFD simulations, solving the 3D steady-state Reynolds-Averaged Navier–Stokes (RANS) equations coupled with the $k - \omega$ SST turbulence model. The problem is reformulated considering a stationary train within the tunnel while imposing a uniform airflow, thus significantly reducing the computational cost compared to the ideal moving mesh case. This numerical methodology has been adopted, upon validation against the available experimental data, for a sensitivity analysis on different train and tunnel parameters; in particular, the effects of train length and inter-wagon gaps are shown as significant examples in this paper.

The methodology was validated against full-scale measurements collected in the Monte Cellarino tunnel. The comparison between experimental and numerical TNS curves, shown in Figure 6, demonstrates a satisfactory agreement up to the arrival of the first reflected compression wave. Further details regarding the computational setup, mesh-independence analysis and validation procedure can be found in [28].

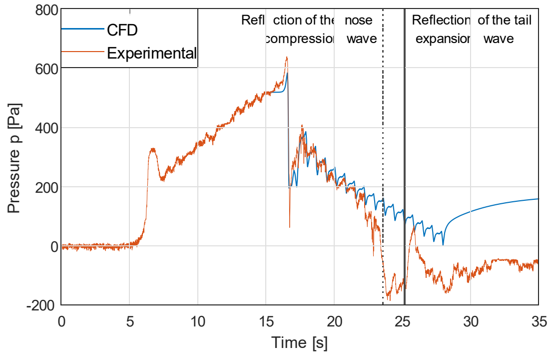


Figure 6: Comparison between experimental and numerical TNS curves.

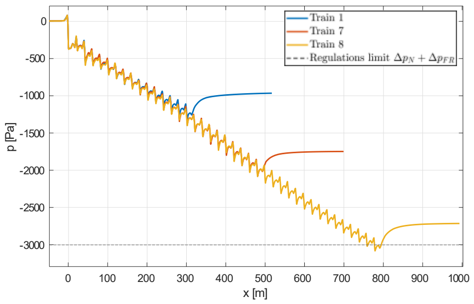
To reduce computational costs, only a portion of the tunnel is used in the simulation, i.e. 100 m upstream and 200 m downstream of the train. This choice ensures a

fully developed flow upstream of the train and a proper wake development downstream.
The mesh is defined based on an independence study, ensuring that the average pressure variation remains below 4% with respect to the most refined case analysed. Details of the computational grid are shown in Table 1. Further details on the mesh can be found in [28].
The comparison between experimental data and CFD steady-state simulation is carried out in correspondence of the TNS, up to the point where the first nose reflected compression wave passes in front of the pressure measurement location (e.g. t=22s).

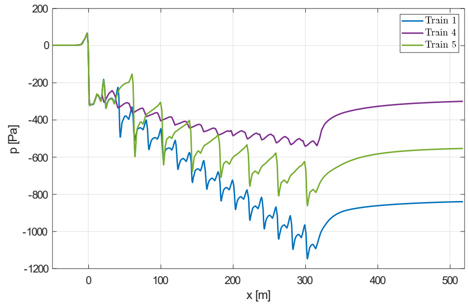
Table 1: Mesh details including characteristic cell sizes, number of cells, and average ($\epsilon_{p,avg}$) and maximum ($\epsilon_{p,max}$) pressure deviations with respect to the reference grid.

$\Delta x_{\text{blockMesh}}$	Δx_{bogies}	Δx_{train}	Number of cells	$\epsilon_{p,avg}$	$\epsilon_{p,max}$
50 cm	3.125 cm	6.25 cm	28×10^6	3.8%	7.2%

The train selected for the numerical sensitivity analysis is a uniform freight train composed of 60 ft flatbed wagons, loaded with standard 40 ft containers. The locomotive is a simplified model of the FS E494.
To assess the effects of the train length, three different train configurations have been analysed: *Train 1* consists of a locomotive and 15 flatbed 60 ft wagons loaded with 40 ft containers, resulting in a total length of 318 m, while *Train 2* and *Train 3* consist of respectively 24 and 39 wagons of the same type, resulting in total lengths of 500 m and 795 m. The results, presented in terms of pressure variation with respect to the one measured at train nose, are displayed in Figure 7a.
The results show an almost linear increase in pressure amplitude with train length. For the configurations analysed, the minimum pressure decreases from −1321 Pa for the 318 m train to −3084 Pa for the 795 m train, approaching or exceeding the regulatory reference value of 3000 Pa. These findings suggest that tunnel overpressure may become critical for long freight convoys despite their lower operating speeds. It should be noted that this limit concerns TWS whereas the CFD results are presented in terms of TNS therefore, as previously said, the pressure value should be rescaled by a specific factor. However, these outcomes highlight the potential criticality of the overpressure phenomenon also for freight trains, particularly considering that their operation may occur in smaller tunnels, where the increased blockage ratio amplifies the pressure wave. Additionally, the CFD simulations are performed with an equivalent train speed of 100 km/h (without considering the relative wind velocity due to the train piston effect), which may be lower than the maximum speed allowed for freight trains in tunnels (e.g., in Italy 120 km/h), suggesting that the phenomenon may be more severe in real operating conditions.



(a) Standard containers of 40 ft, three different convoy lengths: 318 m, 500 m and 795 m.



(b) Inter-wagon gaps effects: comparison between 40 ft fully loaded, 40 ft half loaded and 60 ft containers.

Figure 8: Inter-wagon gap effects: detail of the train schematic representation.

The effects of inter-wagon gaps are assessed by comparing simulations of three trains with the same length, i.e. 318 m, but different loading conditions. *Train 1* is loaded with standard 40 ft containers, whereas *Train 4* is loaded with 60 ft containers, and *Train 5* is half-loaded with 40 ft containers (see Figure 8).

The results, shown in Figure 7b, reveal a significant alleviation of the pressure peaks for the train loaded with 60 ft containers, highlighting the role of inter-wagon gaps as a key parameter affecting the pressure signature of freight trains. In the analysed case, the reduction of inter-wagon gaps makes *Train 4* behave as a more uniform body, leading to a 52.8% reduction in peak pressure with respect to the *Train 1* configuration.

As reported in [26], an increase in inter-wagon gaps enhances flow acceleration within the gap region and promotes a more pronounced separation bubble on the trailing vehicle. However, larger gaps do not necessarily result in higher maximum pressure values, indicating that the pressure signature is governed by the balance between pressure drop induced by flow separation and the subsequent pressure recovery along the wagon.

5 Concluding remarks

This paper presented recent research activities carried out at Politecnico di Milano on freight train aerodynamics, focusing on crosswind stability, slipstream effects and tunnel overpressure.

The main findings can be summarized as follows:

- Freight train aerodynamics is strongly influenced by wagon typology, loading configuration and train composition, making its characterization significantly more complex than that of passenger trains.
- Crosswind analyses highlighted the importance of accounting for load arrangement and load dynamics in intermodal applications, showing that simplified rigid-load assumptions may significantly overestimate vehicle stability.
- Full-scale slipstream measurements showed that freight trains can generate velocity peaks comparable to, or exceeding, those measured for passenger trains, despite operating at lower speeds and currently being only partially addressed by existing regulations.
- Tunnel slipstream investigations confirmed the different flow development generated by freight trains with respect to passenger trains and demonstrated the potential of CFD methodologies for supporting systematic parametric analyses.
- Tunnel overpressure analyses revealed the significant influence of train length and inter-wagon gaps on the pressure signature, with long freight convoys potentially approaching or exceeding current regulatory reference values.

Overall, the results confirm the need for dedicated experimental investigations and validated numerical methodologies for freight trains, whose aerodynamic behaviour cannot always be directly inferred from approaches developed for passenger rolling stock.

References

[1] EN 14067, “Railway applications — Aerodynamics”, 2025.

[2] EN 14067-6, “Railway applications — Aerodynamics: Part 6: Requirements and test procedures for cross wind assessment”, 2022.

[3] L. Siegel, A. Buhr, J. Bell, A. Henning, “Analysis of Flow Structures in Different Loading Gaps of Freight Trains”, Proceedings of the Sixth International Conference on Railway Technology: Research, Development and Maintenance, 7, Paper 3.1, Civil-Comp Press, Edinburgh, United Kingdom, 2024. DOI: 10.4203/ccc.7.3.1.

[4] J. R. Bell, D. Burton, M. C. Thompson, “The Boundary-Layer Characteristics and Unsteady Flow Topology of Full-Scale Operational Inter-Modal Freight Trains”, Journal of Wind Engineering and Industrial Aerodynamics, 201, 104164, 2020. DOI: 10.1016/j.jweia.2020.104164.

[5] S. Giappino, S. Melzi, G. Tomasini, “High-Speed Freight Trains for Intermodal Transportation: Wind Tunnel Study on the Aerodynamic Coefficients of Container Wagons”, Journal of Wind Engineering and Industrial Aerodynamics, 175, 111–119, 2018. DOI: 10.1016/j.jweia.2018.01.047.

[6] I. Krönke, H. Sockel, “Model Tests About Crosswind Effects on Containers and Wagons in Atmospheric Boundary Layers”, Journal of Wind Engineering and Industrial Aerodynamics, 52, 109–119, 1994. DOI: 10.1016/0167-6105(94)90042-6.

[7] C. Baker, N. Humphreys, “Assessment of the Adequacy of Various Wind Tunnel Techniques to Obtain Aerodynamic Data for Ground Vehicles in Crosswinds”, Journal of Wind Engineering and Industrial Aerodynamics, 60, 49–68, 1996. DOI: 10.1016/0167-6105(96)00023-2.
[8] D. Soper, C. Baker, M. Sterling, “An Experimental Investigation to Assess the Influence of Container Loading Configuration on the Effects of a Crosswind on a Container Freight Train”, Journal of Wind Engineering and Industrial Aerodynamics, 145, 304–317, 2015. DOI: 10.1016/j.jweia.2015.03.002.
[9] M. Opala, “Analysis of Safety Requirements for Securing the Semi-Trailer Truck on the Intermodal Railway Wagon”, Energies, 14, 6539, 2021. DOI: 10.3390/en14206539.
[10] EN 14067-4, “Railway applications — Aerodynamics. Part 4: Requirements and assessment procedures for aerodynamics on open track”, 2025.
[11] TSI LOC&PAS, “COMMISSION REGULATION (EU), No 1302/2014, concerning a technical specification for interoperability relating to the ‘rolling stock — locomotives and passenger rolling stock’ subsystem of the rail system in the European Union”, 2014.
[12] M. Sterling, C. J. Baker, S. C. Jordan, T. Johnson, “A Study of the Slipstreams of High-Speed Passenger Trains and Freight Trains”, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 222(2), 177-193, 2008. DOI: 10.1243/09544097JRRT133.
[13] D. Soper, C. Baker, M. Sterling, “Experimental Investigation of the Slipstream Development Around a Container Freight Train Using a Moving Model Facility”, Journal of Wind Engineering and Industrial Aerodynamics, 135, 105–117, 2014. DOI: 10.1016/j.jweia.2014.10.001.
[14] D. Soper, C. Baker, “A Full-Scale Experimental Investigation of Passenger and Freight Train Aerodynamics”, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 234(5), 482–497, 2020. DOI: 10.1177/0954409719844431.
[15] S. Negri, G. Tomasini, P. Schito, F. F. Semeraro, D. Rocchi, “Train Slipstream Assessment in Open Air and Confined Spaces Through Full-Scale Experimental Tests”, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 2025. DOI: 10.1177/09544097251364414.
[16] D. Flynn, H. Hemida, D. Soper, C. Baker, “Detached-Eddy Simulation of the Slipstream of an Operational Freight Train”, Journal of Wind Engineering and Industrial Aerodynamics, 132, 1–12, 2014. DOI: 10.1016/j.jweia.2014.06.016.
[17] L. Corniani, P. Schito, J. Bell, S. Bruni, “A review of freight train aerodynamics”, Journal of Rail and Rapid Transit, 240(2), 133–150, 2026. DOI: 10.1177/09544097251382265.
[18] P. Iliadis, H. Hemida, D. Soper, C. Baker, “Numerical Simulations of the Separated Flow Around a Freight Train Passing Through a Tunnel Using the Sliding Mesh Technique”, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 234(6), 638–654, 2020. DOI: 10.1177/0954409719851421.
[19] S. Negri, G. Tomasini, C. E. Araya Reyes, D. Rocchi, “CFD analysis of flow patterns induced by high-speed and freight trains in tunnels and their impact on

platform regions", International Journal of Rail Transportation, 2026, 1–23. DOI: 10.1080/23248378.2026.2640424.

[20] S. Negri, G. Tomasini, P. Schito, D. Rocchi, "Full Scale Experimental Tests to Evaluate the Train Slipstream in Tunnels", Journal of Wind Engineering and Industrial Aerodynamics, 240, 105514, 2023. DOI: 10.1016/J.JWEIA.2023.105514.

[21] S. Negri, G. Tomasini, P. Schito, D. Rocchi, "Coupled 2D–3D CFD Approach for Innovative Simulation of Train Slipstream in Tunnels", Journal of Wind Engineering and Industrial Aerodynamics, 273, 106432, 2026. DOI: 10.1016/j.jweia.2026.106432.

[22] EN 14067-5, "Railway applications — Aerodynamics. Part 5: Requirements and assessment procedures for aerodynamics in tunnels", 2021.

[23] TSI Infrastructures, "COMMISSION REGULATION (EU), No 1299/2014, on the technical specifications for interoperability relating to the 'infrastructure' subsystem of the rail system in the European Union, 2014.

[24] P. Iliadis, D. Soper, C. Baker, H. Hemida, "Experimental investigation of the aerodynamics of a freight train passing through a tunnel using a moving model", Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, Vol. 233, No. 8, pp. 857–868, 2019. DOI: 10.1177/0954409718811736.

[25] Z. Liu, D. Soper, H. Hemida, B. Chen, "A Study of the Influence of Separation Bubbles Around a Generic Freight Train on Pressure Waves Inside Tunnels Using 1D and 3D Numerical Methods", Journal of Wind Engineering and Industrial Aerodynamics, 240, 2023. DOI: 10.1016/j.jweia.2023.105461.

[26] Z. Liu, D. Soper, H. Hemida, B. Chen, "Numerical Modelling of a Partially Loaded Intermodal Container Freight Train Passing Through a Tunnel", arXiv preprint, arXiv:2509.09591, 2025. DOI: 10.48550/arXiv.2509.09591.

[27] E. Brambilla, P. Schito, C. Somaschini, D. Rocchi, "Virtual Homologation of High-Speed Trains in Railway Tunnels: A New Iterative Numerical Approach for Train-Tunnel Pressure Signature", Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 236(5), 511–531, 2022. DOI: 10.1177/09544097211029164.

[28] E. Inghilleri, G. Tomasini, S. Negri, "Numerical analysis of freight train-tunnel overpressure through steady-state CFD simulations.", Submitted to The Seventh International Conference on Railway Technology: Research, Development and Maintenance, Civil-Comp Press, 2026