

AIR SPEEDS NEAR SERVICES ON TUNNEL WALLS

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ABSTRACT

Tunnel services can be exposed to pressures and airflows that subject them and their supports to fatigue loads. The fatigue loads can be significant in high-speed tunnels. Pressure changes from train movements in tunnels are well covered by available modelling techniques, and for services completely immersed in the pressure these changes do not often form the design cases. Air speeds in train wakes are less well predicted by numerical modelling, specifically the range and scale of the 3-D velocity fluctuations generated by their highly turbulent nature.

This paper describes testing of moving trains in 1/25th scale tunnels. Model trains were fired at high-speed into the scale model tunnels and the tunnel air speeds near the walls measured at high frequency in three directions and at several locations. Different diameter tunnels and train designs and consists were tested. The data from the testing was interpreted using rainflow counting to estimate fatigue loads for discrete (small) items of equipment in the tunnels as well as longer elements where the wake velocity may affect the equipment in different ways.

Keywords: Air speeds, aerodynamics, scale model testing, fatigue, tunnel services.

1. INTRODUCTION

1.1. Project context

Services are required within tunnels to support operational, life safety and firefighting objectives. Services are often located on tunnel walls, which exposes them to the pressures and air speeds resulting from vehicle movement in the tunnels. The services tend to be immersed within the pressure environment meaning that a differential pressure, and thus pressure loading, does not manifest. The air speeds, however, can impact upon the services causing differential pressure loading because of the stagnation of the air on face of the element perpendicular to the flow direction. These loadings from air speeds can be frequent and fluctuating, creating a fatigue loading that must be accounted for in the design. The air speeds tend to be higher in high-speed tunnels.

In the UK a new high-speed railway (HS2) is under construction that differs from other recent high-speed railways. Firstly, the tunnels combine high line speeds with relatively small tunnel cross-section due to a decision to require more stringent train stiffness to manage interior pressure comfort rather than larger tunnels. Secondly, the train speeds will be higher than typical - there will be approximately 50 km of tunnels on the route with a typical train speed of 320 km/h (88 m/s) in the tunnels longer than 3 km and 360 km/h (100 m/s) in the shorter tunnels. Finally, high-level side walkways are used which for several reasons make the

embedment of many of the services into the walkway more difficult and hence tunnel services will be mounted onto the tunnel walls. Collectively, these factors made it important for HS2 to understand the air speeds and fatigue loads to which the tunnel services will be exposed and account for these in their design, fabrication and fixing.

1.2. The Nature of Train Induced Air speeds in Tunnels

The air movement around trains is usually referred to as the slipstream and is caused by air being dragged by the movement of a train due to friction between the train and the air [1]. Exemplar slipstream research [2][3] often presented results in a non-dimensional coefficient form, normalized by train speed for the U (along the train length), V (side to side perpendicular to the train) and W (up and down perpendicular to the train). The square root of the sum of the squares of the dimensionless U and V elements (which tend to be the dominant) is often reported as U_{res} .

Results from several studies conducted in the open air have identified specific flow regions created within the slipstream of passenger trains [4]. They include (a) an upstream and nose region characterized by an increase in flow velocity before the front of the vehicle; (b) a highly turbulent boundary layer region growing along the side of the vehicle; (c) a near wake region with a large velocity peak; and (d) a far wake region with turbulent flow with shedding vortices induced by the train (see Figure 1). Similar findings have been observed across a range of scales and techniques, from full-scale, operational trackside studies [5], to reduced scale physical modelling experiments [6] and computational fluid dynamics (CFD) simulations [7]. A detailed overview of characteristics associated with each region can be found in [1].

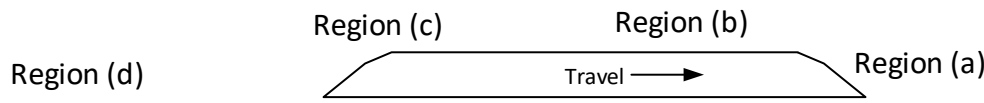


Figure 1: Wake regions

For tunnels, aerodynamic research has historically focused on the initiation and development of pressure waves and the emission of micro-pressure waves [1]. Whilst data related to slipstream flow development within tunnels is sparse, a small number of papers can be found [8][9][10]. These have observed similar flow regions to those discussed for the open air above, albeit with different aerodynamic characteristics due to confinement [10][11]. Within a tunnel key facets of the flow field include:

- Upstream – characterized by an increase in flow velocity due to a piston effect created by the solid train nose pushing air along the confined tunnel environment.
- Nose region - characterized by a sharp positive increase in flow velocity magnitude directly before the front of the vehicle, leading to a localized velocity peak. This is highly dependent on the train shape and is followed by a large reduction in flow magnitude to a negative velocity peak, caused by separation from the leading edge of the train nose and the influence of the small gap in the annulus between the train surface and tunnel wall.
- Boundary layer region – characterized by a reversal in the dominant flow direction due to an annulus flow effect created by the very confined space between the train surface and the tunnel wall. This region has highly turbulent flow with rapid changes in localized flow direction and a decreasing flow magnitude with train length.
- Tail and near wake region – characterized by further reversal in flow direction following the passage of the train tail. Here a positive peak in velocity is created by the air being dragged along behind the train within the tunnel.

- Far wake region - characterized by turbulent flow with shedding vortices induced by the train. Overall, flow magnitudes decrease in this region, and the flow again is influenced by localized pressure wave effects.

These general flow characteristics have been observed across a range of scales and techniques, from full-scale trackside studies [10], to reduced scale physical modelling experiments [11] [12] and computational fluid dynamics (CFD) simulations [8][9][13][14][15]. Further studies [10] have illustrated the influence of train type (high-speed, conventional and freight trains) on each characteristic flow region. However, to date, it has not been possible to identify any studies that appropriately consider further velocity components beyond U or U_{res} .

1.3. Motivation for Testing

HS2 originally set out their design criteria for tunnel air speeds based on published scale model tests [12]. Concept design studies and prototype testing of cable management systems resulted in several fatigue failures, some of which indicated genuine areas where design improvements would be required and some of which were difficult to explain considering that similar designs had been used with success, albeit in slower tunnels, without reported issues. The data from the Gilbert tests [12] had some uncertainties regarding the downward direction W velocity components, which is important for horizontal cable ladder, and did not include a side walkway which was speculated may assist in disrupting the wake before it became impingent on the tunnel services. The data set also did not provide adequate data to evaluate the number of fatigue cycles. Additional data was therefore sought by HS2. Full-scale measurements within the somewhat similar HS1 tunnels were not possible in the required time scales and CFD modelling was considered unlikely to be able to confidently predict the wake region. Therefore, further scale modelling was undertaken.

2. SCALE MODEL SETUP

2.1. General

WSP Ltd, on behalf of HS2, and the University of Birmingham (UoB), collaborated to develop a series of requirements for tests which UoB conducted and both parties interpreted and reported on. The tests used the TRansient Aerodynamic INvestigation (TRAIN) rig which is a moving model testing facility specifically designed to examine the transient aerodynamics of vehicles [16]. Reduced scale vehicles are propelled at speeds up to 75 m/s, along three 150 m tracks. Aerodynamic flow properties around the train, acting on a train or trackside structures were measured. Moving model testing facilities are advantageous, in comparison to typical stationary wind tunnels, due to the capability of correctly simulating the relative motion between a vehicle and the ground/structures and tunnel micro-pressure waves relative to a moving train, which in turn is important for accurately modelling the characteristic development and magnitude of slipstream velocities within the tunnel environment. Moving model techniques have been thoroughly validated against full-scale experimental data in numerous studies [4][16][17] and are therefore a good route for providing a detailed understanding of the aerodynamic flow development around potential high-speed passenger trains within the confined tunnel configurations identified in this project.

A pre-tensioned elastic bungee cord system is used to accelerate reduced scale models in a 50 m firing section to a specified experiment speed. This method ensures no additional propulsion devices are needed; however, a slight reduction in model speed is observed as a result of friction and aerodynamic drag. In the open-air test section, an average deceleration of 2.5 m/s²

has been estimated for this study. Models are brought to a stop in a 40 m braking section using a friction device.

2.2. Tunnels

Two tunnel configurations were considered for this study. At full-scale, the majority of HS2 tunnels have an internal diameter of 8.8 m, with the central axis at approximately 3.1 m above top of rail, whereas the HS1 tunnel has a 7.15 m internal diameter with the central axis approximately 2.5 m above the top of rail. Both tunnels have an escape walkway that extends approximately 0.76 m above the top of rail. The HS1 tunnel also includes a maintenance walkway that extends 0.5 m above the top or rail.

Each model tunnel was 24 m in length at model-scale, equivalent to a 600 m long tunnel at full-scale considering a 1:25 modelling scale. The remainder of the 150m test track was utilised for the acceleration section, the open route wake verification section and (after the 24m test tunnel) a braking/deceleration section. The tunnels were cast in 2.4 m long sections from glass reinforced plastic, with the escape walkways included in the tunnel section but modelled separately in medium-density fibreboard. Further modelling details, i.e. several small cable ladders as per engineering drawings of the full-scale case, were installed along the tunnel length. These cable ladders were modelled in aluminium, with the adopted design chosen to provide a representative structure with a similar blockage ratio to that of the full-scale case loaded with cables.

2.3. Trains

Representative train models and configurations were used based on models that were available from prior tests. These were (1) Alstom AGV – 5 car configuration; (2) Alstom AGV – 8 car configuration (5 car + 3 car); (3) Alstom Class 373 Eurostar – 5 car configuration; and (4) Alstom Class 373 Eurostar – 8 car configuration (5 car + 3 car). The basic dimensions at model scale are given in Table 1.

Table 1: Train Characteristics

Train Type	Number of Cars	Length (mm)	Width (mm)	Height (mm)
AGV	5	3870	118	166
AGV	8	6324	118	166
Class 373	5	4393	108	152.5
Class 373	8	7015	108	152.5

The configurations of a 5-car and 8-car train were chosen to enable modelling of the ‘V-shape’ section between joined train sets, which affects the overall flow dynamics. The train lengths were chosen as a balance based on maximum operating weights at the TRAIN rig facility, with a view to realizing high test speeds to maximize Reynolds numbers, and the need to appropriately capture aerodynamic transitions along the length of train within different flow regions, as discussed in the results.

The trains were created using a cast and mould system. Simplifications to the overall geometry through the removal of many small components were made to ensure that Reynolds number effects due to small scale train details were not created, but the overall geometry was maintained accurately. The model shells were mounted to a specially designed chassis and trailing wheel system and attached the propulsion/braking devices.

Figure 2 shows images of a typical test tunnel and two of the train models.



Figure 2: Model Features

2.4. Instrumentation

A series of Dantec triple fibre-film wire hot-wire probes were used to measure instantaneous three components of velocity in the tunnel (**Figure 3**). Similarly, a series of Turbulent Flow Instrumentation multi-hole pressure probes were used to measure instantaneous local static pressure and three components of velocity in the open-air test section.

The hot-wire probes were calibrated for each test configuration using a Dantec StreamLine Pro Automatic Calibrator, with automatic temperature compensation built into the multichannel constant temperature anemometry system. The probes were calibrated in steps across the typical range of expected velocities, for 0° and 25° flow angles to within ± 0.1 m/s and $\pm 1^\circ$ for velocities. The sensors form an orthogonal system with an acceptance cone of 70.4° . To account for this acceptance cone when the train is passing the probes were mounted in two orientations: longitudinally along the tunnel facing the on-coming train (Case 1) and longitudinally along the tunnel facing away from the on-coming train (Case 2). The relative uncertainty of results based on the instrumentation accuracy, using a propagation of error approach, was found to be on average 2%. The positions of these probes are shown in Table 2.

Measurements were also made of slipstream outside of the tunnels to allow for comparison against open-air standards and measurements. For all slipstream measurements at least 20 runs were made for each measuring location and each train configuration examined, aligning with typical methodologies for slipstream measurements outlined in [20]. All instrumentation was set to record at a 5000 Hz sampling frequency.

Table 2: Probe locations

Probe Number Probe Number	HS1 test tunnel		HS2 test tunnel		Distance along tunnel (m)
	Distance from track centre (m)	Height above track (m)	Distance from track centre (m)	Height above track (m)	
1	2.40	4.26	3.80	3.85	150
2	2.90	3.26	3.80	2.85	150
3	2.40	4.26	3.80	3.85	154
4	2.90	3.26	3.80	2.85	154
5	2.40	4.26	3.80	3.85	450
6	2.90	3.26	3.80	2.85	450

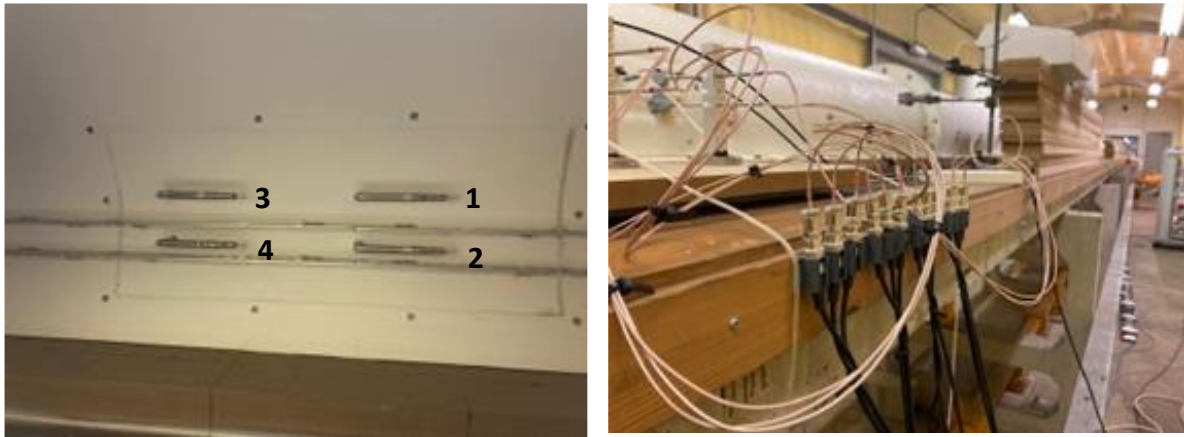


Figure 3: Sensor head inside the tunnel (left) and supports and connections outside the tunnel (right)

3. KEY RESULTS

For brevity, only key findings and results can be described. In terms of the influence of train type, the AGV train was observed to generate the greatest magnitude of air speeds, U_{res} , within the tunnels and the Class 373 the largest magnitude peak W speeds. The AGV train is physically larger than the Class 373 and thus resulted in a higher blockage ratio. In the open air, the Class 373 likely generated a more turbulent slipstream because of features around the train bogeys that were less aerodynamic than the AGV.

In terms of the influence of train configuration, the eight car trains, with the inter-car gaps, were observed to result in slightly lower peaks and troughs in air speeds, but with more velocity fluctuations caused by the expansion and contraction at the inter-car gap.

In terms of sensor locations, the lower sensors (typically Position 2) were observed to result in higher air speeds than the upper sensors. From open-air measurements it is known that the air speeds closer to the train wheels are larger than those higher up the train body and hence this is explicable. However, the differences between Position 1 and 2, for both positive and negative air speed directions were small.

The tunnel type was observed to result in a significant difference between measured air speeds. Figure 4 shows the difference between the HS1 and HS2 tunnels for the 8-car trains. The solid lines represent the average of 20 test runs. The averages have become smooth due to small offsets in peaks and troughs affecting the mean. The results are non-dimensionalized with respect to train position with 0 representing the nose passing the sensor and 1.0 representing the tail of the train passing the sensor.

The general pattern of a positive airflow in advance of the train, a rapid flow reversal as train passes the sensor, a large peak in the immediate wake of the train and then a gradual decay of the wake is observed. The wake is observed to pulse up and down which occurred because of the pressure pulses in the tunnel causing density changes as they travel up and down the tunnel and affect the wake.

The air speeds were higher in the HS1 tunnel for several reasons: (1) the HS1 tunnel was smaller and thus presented a higher blockage ratio than the HS2 tunnels; (2) the tunnel walls and thus sensors were closer to the train body in the HS1 tunnels, and hence exposed to higher air speeds; and (3) the sensors were lower in the HS1 tunnels (as is the cable management system) and thus closer to the lower portions of the trains where the train wake is generated.

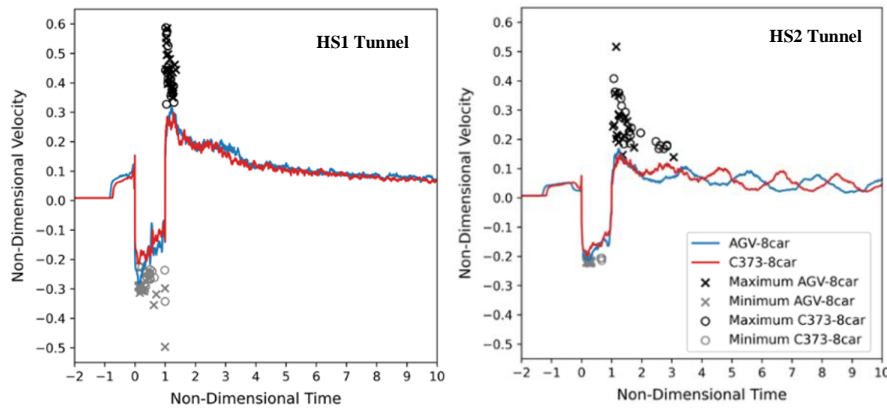


Figure 4: U_{res} (inc W component) comparison between tunnels

Figure 5 shows examples of the dimensionless U, V and W components for the AGV 8-car trains at Position 2 for the different tunnel types. The U direction air speeds are highest as they are coplanar with the wake. The U direction air speeds are important for features such as signal marker boards. The W direction components are important for features such as cable ladders, where the upwards/downwards air speeds will stagnate against the horizontal services and cause pressure differential loadings.

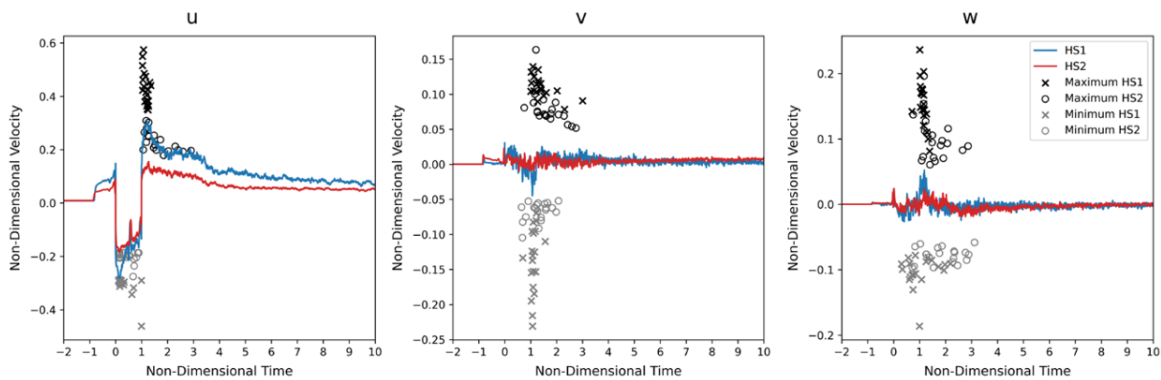


Figure 5: U, V and W dimensionless coefficients

4. FATIGUE

The maximum and minimum air speed results provided valuable information to determine the ultimate strength of the cable management systems. However, many smaller magnitude flow fluctuations were observed which may be more damaging to the systems in terms of fatigue.

A rainflow counting approach [18] was adopted to understand the fatigue loadings. The HS2 railway may ultimately operate at 20 trains per hour. Each of the 20 test runs therefore represented one equiprobable cycle of an hour of train operations. The 20 test run data were therefore conjugated to develop a single data file for one hour of train operations. The data was then passed through a rainflow counting algorithm to first extract the damaging cycles, which were then grouped into bins according to the mean value from the cycle and the range. The process was undertaken twice, once for the dimensionless coefficients and once for stagnation pressure, accounting for the train speeds that the tunnels will operate at. In this paper, for brevity, we present only the dimensionless velocity cycles. Figure 6 shows the fatigue cycles for the HS1 tunnels for the U, V and W components.

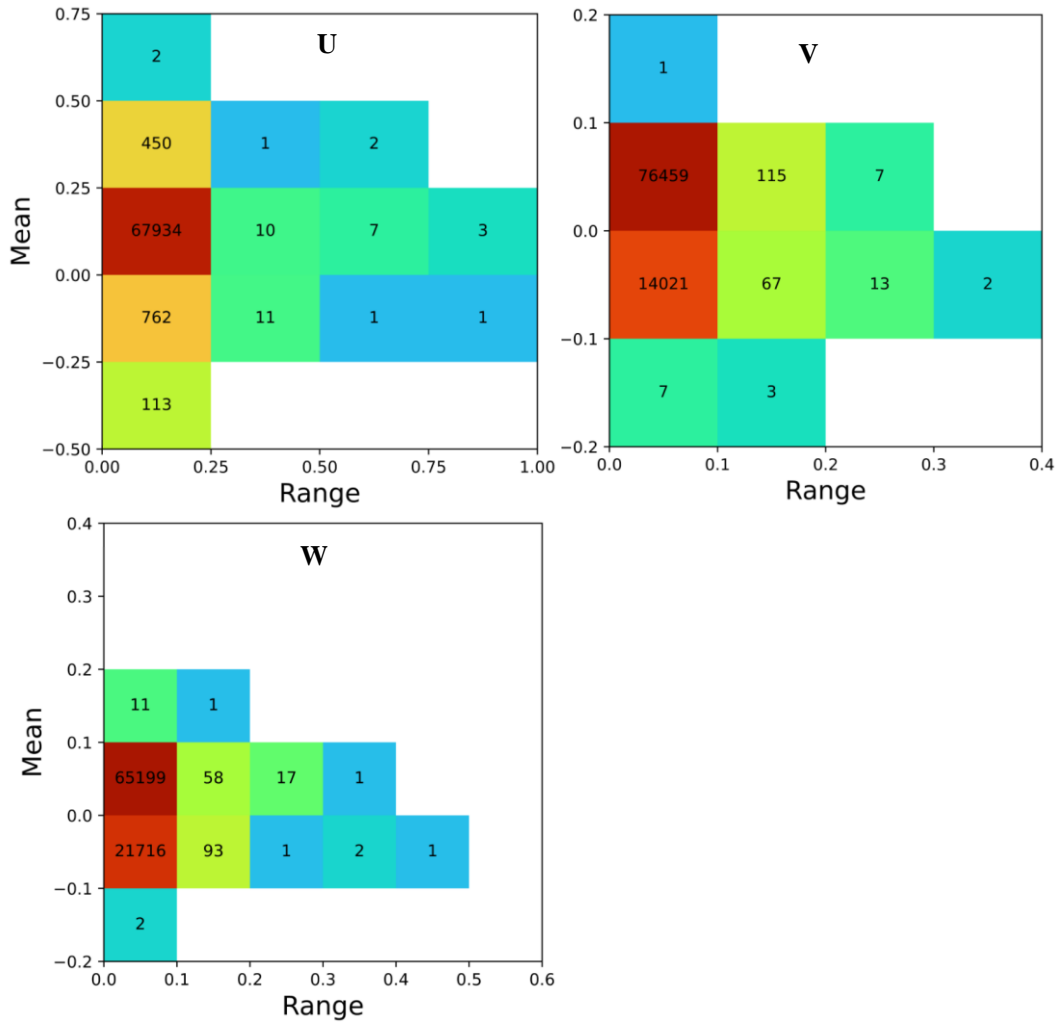


Figure 6: Fatigue cycles

The stagnation pressure calculated from the fatigue cycles can be converted into a force loading by multiplying it by a drag coefficient (typically around 2.0) and the projected area of the body perpendicular to the airflow direction. Each data bin will generate two load cases, a maximum load of the mean plus half the range and minimum of the mean minus half of the range. These two load cases can be used in a structural analysis to allow the stress range in any of the components to be predicted or measured. The stress range can then be interpreted on a material S-N diagram to determine the number of cycles that the component can tolerate before failure for each of the data bins. Based on Miner’s rule [19] the damage for each data bin can be estimated by comparing the number of cycles in that range to the maximum permissible to give a damage assessment. The damage in each bin can be summated and if that sum exceeds 1.0 failure is likely.

The results indicate that there are substantially more lower magnitude cycles than higher. Given the extremely high cycle count of the smaller cycles, the component design must result in these being within the material’s infinite fatigue life. The presented data relates to a discrete (small) object. Conversely, a 4m long span of cable ladder, for example, will be exposed to high-frequency fluctuations in speed due to small-scale turbulence and lower frequency fluctuations due to larger vortices. The forces due to the high-frequency fluctuations will cancel over the length of the span, resulting in a lower frequency, smoothed load compared to that experienced by a discrete object. The test data was further interpreted and smoothed using a Butterworth filter to account for this, resulting in fewer fatigue cycles for longer span objects. The peak fatigue cycles were considerably lower than originally expected and afford

the opportunity to optimize the tunnel services supports to save on both embodied carbon and costs, as well as develop and implement the design at lower risk.

5. SUMMARY AND CONCLUSION

Scale model testing has allowed for improved data and understanding of air speeds in tunnels to inform the design of tunnel services. Train speed, train to tunnel blockage ratio, proximity of the services to the train, height of the services in the tunnel, train aerodynamic characteristics and presence of an inter-car gap emerge as considerations that influence the slipstream and number of cycles within a tunnel.

The data has allowed for peak air speeds to be established, as well as interpretation of the overall pattern and nature of the wake to establish damaging fatigue cycles. Whilst the data is particularly important for high-speed tunnels due to their high train speeds, lower train-speed tunnels are normally smaller and thus have services closer to the train body. Industry would likely benefit from a series of air speed measurements being collected and published for a range of tunnel and train types.

6. REFERENCES

- [1] C. Baker, T. Johnson, D. Flynn, H. Hemida, A. Quinn, D. Soper, M. Sterling. “Train aerodynamics: fundamentals and applications”. Butterworth-Heinemann, 2019.
- [2] B. Schulte-Werning, C. Heine, G. Matschke, “Slipstream Development and Wake Flow Characteristics of modern High-Speed trains”, *Journal of Applied Mathematics and Mechanics*, Volume 81, Issue 53, 2001.
- [3] RAPIDE: Railway aerodynamics for passing and interactions with dynamic effects, EU project number: BE97-4089. 2001.
- [4] D. Soper, M. Gallagher, C. Baker, A. Quinn, “A model-scale study to assess the influence of ground geometries on aerodynamic flow development around a train.” *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 231(8), pp.916-933. 2017
- [5] M. Sterling, C. Baker, S. 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. <https://doi.org/10.1243/09544097JRRT133M>. 2008
- [6] C. Baker, S. Dalley, T. Johnson, A. Quinn, N. Wright. “The slipstream and wake of a high-speed train”. *Proceedings of the Institution of Mechanical Engineers. Part F Journal of Rail and Rapid Transit* 215 (2) 83-99. <https://doi.org/10.1243/0954409011531422>. 2001.
- [7] M. Gallagher, J. Morden, C. Baker, D. Soper, A. Quinn, H. Hemida, M. Sterling. “Trains in crosswinds—comparison of full-scale on-train measurements, physical model tests and CFD calculations”. *Journal of Wind Engineering and Industrial Aerodynamics*, 175, pp.428-444. <https://doi.org/10.1016/j.jweia.2018.03.002>. 2018.
- [8] W. Li, T. Liu, Z. Chen, Z. Guo, X. Huo. “Comparative study on the unsteady slipstream induced by a single train and two trains passing each other in a tunnel”. *Journal of Wind Engineering and Industrial Aerodynamics*, 198, p.104095. <https://doi.org/10.1016/j.jweia.2020.104095>. 2020.

- [9] Z. Liu, D. Zhou, D. Soper, G. Chen, H. Hemida, Z. Guo, X. Li, X. “Numerical investigation of the slipstream characteristics of a maglev train in a tunnel”. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 237(2), pp.179-192. <https://doi.org/10.1177/09544097221100658>. 2023
- [10] 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, p.105514. <https://doi.org/10.1016/j.jweia.2023.105514S>. 2023.
- [11] S. Meng, D. Zhou, Z. Wang, “Moving model analysis on the transient pressure and slipstream caused by a metro train passing through a tunnel”. *Plos one*, 14(9), p.e0222151. <https://doi.org/10.1371/journal.pone.0222151>. 2019
- [12] T. Gilbert, C. Baker, A. Quinn. “Gusts caused by high-speed trains in confined spaces and tunnels”. *Journal of wind engineering and industrial aerodynamics*, 121, pp.39-48. <https://doi.org/10.1016/j.jweia.2013.07.015>. 2013.
- [13] M. Fu, P. Li, X.F. Liang. “Numerical analysis of the slipstream development around a high-speed train in a double-track tunnel”. *PloS one*, 12(3), p.e0175044. <https://doi.org/10.1371/journal.pone.0175044>. 2017.
- [14] S. Meng, X. Li, G. Chen, D. Zhou, Z. Chen, S. Krajnovic. “Numerical simulation of slipstreams and wake flows of trains with different nose lengths passing through a tunnel”. *Tunnelling and Underground Space Technology*, 108, p.103701. <https://doi.org/10.1016/j.tust.2020.103701>. 2021.
- [15] X. Xiong, R. Cong, X. Li, Y. Geng, M. Tang, S. Zhou, Y. Na, C. Jiang. “Unsteady slipstream of a train passing through a high-speed railway tunnel with a cave”. *Transportation Safety and Environment*, 4(4). <https://doi.org/10.1093/tse/tdac032>. 2022.
- [16] D. Soper, C. Baker, A. Jackson, D.R. Milne, L. Le Pen, G. Watson, W. Powrie. “Full scale measurements of train underbody flows and track forces”. *Journal of Wind Engineering and Industrial Aerodynamics*, 169, pp.251-264. 2017.
- [17] D. Soper, D. Flynn, C. Baker, A. Jackson, H. Hemida. “A comparative study of methods to simulate aerodynamic flow beneath a high-speed train”. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 232(5), pp.1464-1482. 2018.
- [18] ASTM. “Standard practices for cycle counting in fatigue analysis”. ASTM E 1049-85. ASTM International. 2005.
- [19] M. A. Miner. "Cumulative damage in fatigue". *Journal of Applied Mechanics*. 12: 149–164. 1945.
- [20] British Standards (BS). Railway applications — Aerodynamics. Part 4: Requirements and assessments procedures for aerodynamics in tunnels. BS EN 14067-5:2021.