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Federal Railroad Administration

High-Speed Rail Aerodynamic Assessment and Mitigation Report

Office of Research, Development, and Technologygh
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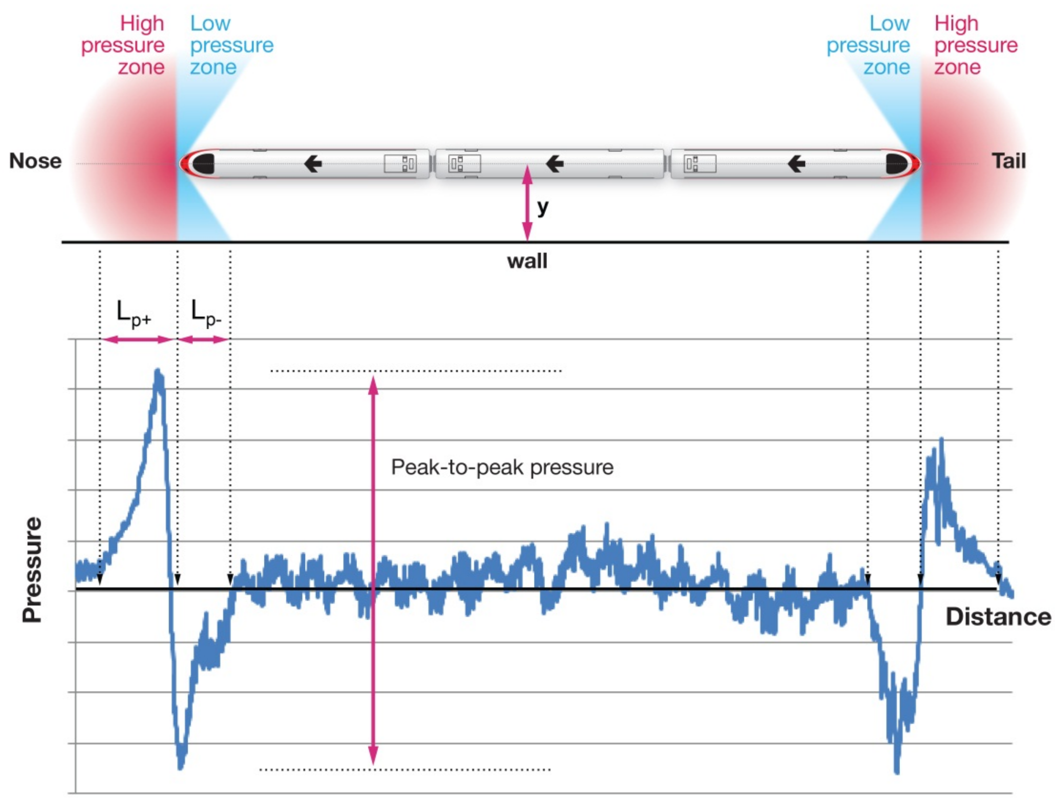

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This report advances the current state of knowledge, as well as shared understanding and evaluation of present procedures used to mitigate the impacts effects from high-speed trains (HST) operating at speeds between 110 mph and 250 mph. This work gathers and summarizes existing international knowledge and standards and forms the basis for a future design and mitigation guidance manual.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)		
1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)
AREA (APPROXIMATE)		
1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)
MASS - WEIGHT (APPROXIMATE)		
1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)
VOLUME (APPROXIMATE)		
1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)
TEMPERATURE (EXACT)		
[(x-32)(5/9)] °F	=	y °C

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LENGTH (APPROXIMATE)		
1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)
AREA (APPROXIMATE)		
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1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres
MASS - WEIGHT (APPROXIMATE)		
1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons
VOLUME (APPROXIMATE)		
1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)
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[(9/5) y + 32] °C	=	x °F

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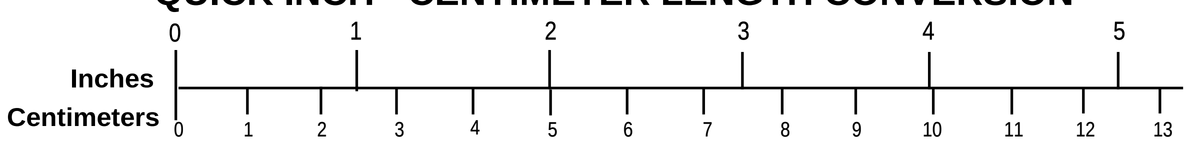

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°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Executive Summary

Arup USA Inc., in partnership with Transportation Technology Center, Inc. (TTCI), the University of Birmingham (UK), and Dundee Tunnel Research (UK), conducted a review of existing knowledge, and shared understanding of the practices and standards applicable to the aerodynamic effects of high-speed trains (HST), and issued recommendations for the development of a high-speed rail aerodynamic design and mitigation guidance manual.

The analysis and assessments identified numerous studies, standards, design guidelines and criteria, and operating procedures for high-speed train systems throughout the world. For some aerodynamic phenomena there are well-established test and calculation methods, assessment criteria, and mitigation strategies, which can be adopted in the United States with relatively minor changes. In many other cases, there are substantial information gaps, such as lack of assessment criteria, formulae, test methodology, or information specific to the trains operating in the United States. In addition, many of the existing standards concern HST operating at speeds much slower than the 250 mph (402 km/h) envisioned for the next generation of high-speed passenger rail operations planned or under development in the United States. Because some of the aerodynamic effects are proportional to the square or the cube of the speed of the train, the required mitigation measures for speeds up to 250 mph will be planned high-speed passenger rail more substantial than for existing operating speeds. Initial analyses were performed as to whether comparative or full assessments would be the more appropriate method of utilizing existing information for development of the future guidelines.

In summary, while a substantial portion of the existing knowledge base can be extrapolated for use in the future guidelines, additional testing and assessments will need to be performed to reflect higher speeds and the specific operating characteristics, conditions, experiences, and expectations associated with North American rail operations. Additionally, close coordination with and by the Federal Railroad Administration (FRA) will be necessary to address these factors.

This report concludes Phase I of the project. A Phase II effort will be required to address the identified information gaps and to develop a design and mitigation guidance manual.

This effort will benefit the United States railway industry in implementing safe high-speed rail services, preventing injuries to railroad employees and the traveling public, and reducing damage to infrastructure, equipment and cargo.

1. Introduction

Modern high-speed passenger trains (HST) routinely operate at speeds as high as 200 mph (320 km/h), and speeds in excess of 350 mph (560 km/h) have been achieved on experimental trains. Under these conditions, trains are capable of generating significant aerodynamic effects including wind gusts and air pressure changes, which makes it necessary to address HST aerodynamics during the planning stage of high-speed rail (HSR) lines.

1.1 Background

Over several decades, there has been increased interest in high-speed rail (HSR) in the United States. In the Northeast Corridor (NEC) between Boston and Washington, DC Amtrak operates Acela trains at speeds up to 150 mph (241 km/h), and additional high-speed rail corridors are under development in different parts of the country (Figure 1).

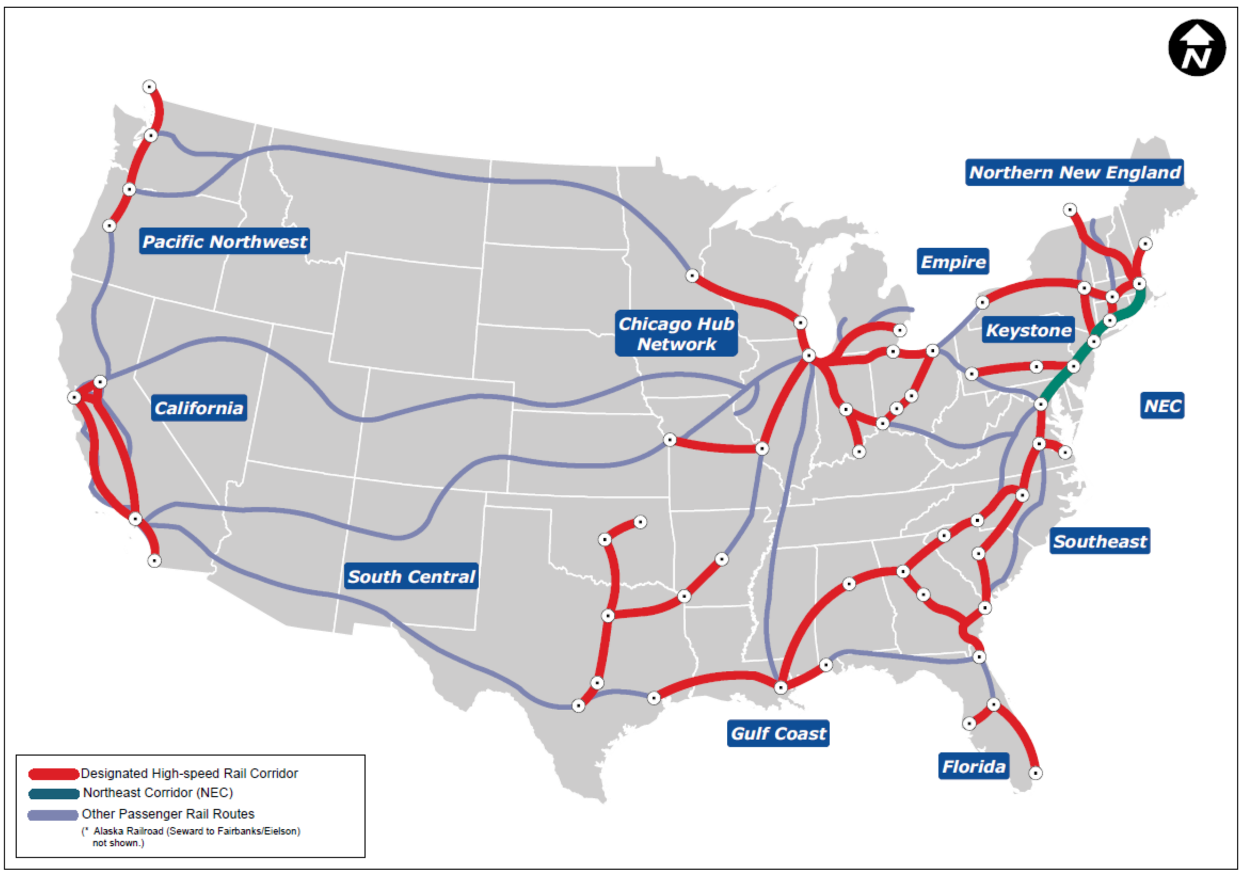

Figure 1. Current and proposed high-speed rail corridors in the United States [1]

As train speeds on existing rail lines are increased, and as more HSR corridors are being planned, there is a growing need for guidance materials tailored to the specifics of North American HSR, including aerodynamic design and mitigation guidelines.

The need for such guidance is well recognized. Over the past two decades, the Federal Railroad Administration (FRA) has sponsored a number of studies relating to aerodynamic performance and effects of HST operating on the Northeast Corridor. Other HSR projects, such as the proposed California High-Speed Rail Train Systems, have also included design and engineering recommendations that are based on train aerodynamics. However, these studies had a limited scope and were specific to distinct operating conditions.

Countries such as Germany, France, and Japan have a longer history of operating HSR lines and have accumulated a large volume of knowledge about train aerodynamics. For some aerodynamic issues, national and international standards and regulations exist.

Nevertheless, the international experience is not always applicable to the United States for the following reasons:

- Train aerodynamics is a constantly evolving field, and some of the existing standards need to be updated.
- The public, lawmakers, and rail industry in North America desire standards that are more flexible and which can accommodate varied train types and dimensions.
- In the US, existing and planned HSTs typically operate adjacent to or are commingledf with conventional passenger and freight traffic. In other countries (with the exception of Russia and China) this situation is extremely uncommon and exists only on very limited railroad segments.
- FRA is interested in the development of guidelines for speeds up to 250 mph (402 km/h), for which most foreign standards and guidelines do not apply.

Therefore, it is necessary to carefully analyze both domestic and foreign sources of information to develop guidelines that are specific to North American conditions.

1.2 Objective

The objective of the report is to provide the FRA with the necessary information and recommendations for the development of a HSR aerodynamic design and mitigation guidance manual. The report includes:

- Existing data regarding concepts, assessments, standards, and mitigations.
- Identification of issues and gaps of information.
- Recommendations for addressing those issues and gaps.

It is recognized that any standard, regulation, or guideline is a compromise between conflicting goals: minimization of risks and expenses for standard developers and its users while maximizing ease of use, and flexibility. Therefore, close coordination and decisions with and by the FRA will be necessary to develop an aerodynamic design and mitigation guidance manual.

1.3 Overall Approach

After establishing the objectives and identifying the areas of focus, the authors conducted a comprehensive literature search using multiple scientific and engineering databases. It yielded hundreds of publications, including books, articles, regulations, standards, guidelines, and operating procedures. These publications were screened for relevance and sorted by the specific aerodynamic phenomena they covered. This process resulted in a bibliography of approximately 280 sources, which were analyzed and used in preparation of this report.

Information from the sources was categorized by topic, summarized and analyzed. Conflicts between sources were identified and, whenever possible, resolved. If these conflicts could not be resolved, information was prioritized based on these principles:

- Full-scale tests were given priority over reduced scale tests.
- Tests were prioritized over analytical or numerical studies or analyses.
- More recent studies were given priority.
- Results from tests with well-documented test methodologies were given priority over tests for which little information on methods was available.

Gaps in information were identified. These gaps were sorted by their priority, and recommendations on filling these gaps were made.

1.4 Scope

The information in the report is based on existing research and best practices from North America, Europe, and Asia. Information and recommendations in the report are focused on:

- Basic concepts of aerodynamic effects associated with HST.
- Means to evaluate these aerodynamic effects.
- Mitigation methods and procedures.

The aerodynamic phenomena covered in the report relate to open environment, tunnels, or both. They include:

- Slipstreams caused by the passage of a HST.
- Pressures on structures and other trains caused by the passage of a HST.
- Effects of crosswinds on HST.
- Pressure changes caused by HST passage through tunnels.
- Micro-pressure waves emitted from HSR tunnels.
- Aerodynamic drag on HST.
- Ballast flight on HSR lines.

FRA classifies passenger equipment on US railroads into three tiers:

- Tier I equipment has maximum operational speed below 125 mph (201 km/h). It can be intermixed with other passenger and freight operations.
- Tier II equipment has maximum operational speed above 125 mph (201 km/h) but , at the time of writing, below 150 mph (241 km/h). It can be intermixed with other passenger and freight operations. It should be noted that FRA pending rulemaking may increase the maximum Tier II speed to 160 mph (257 km/h).
- Tier III equipment currently has maximum operational speed above 125 mph (201 km/h) up to 220 mph (354 km/h) but can only intermix with Tier I and II equipment when operating at speeds below 125 mph (201 km/h).

The report is limited to the aerodynamic effects of Tier II and Tier III equipment per FRA classification and to additional speeds up to 250 mph (402 km/h). Aerodynamics of Tier I trains are outside the scope of this report.

1.5 Organization of the Report

The report consists of 11 chapters.

Chapter 1 (Introduction) provides general information about the purpose and organization of the report.

Each of the Chapters 2 through 10 describes in detail a specific phenomenon in high-speed train aerodynamics.

- Chapters 2 through 5 discuss issues relevant to train operation in open environment:
    - Chapter 2 discusses the slipstream (wind caused by the passage of a train), which is a primary concern for the safety of passengers at platforms.
    - Chapter 3 discusses the localized pressure pulses that develop around a high-speed train and their effects on structures adjacent to the tracks.
    - Chapter 4 discusses the pressure pulses that develop when two trains meet or pass each other.
    - Chapter 5 discusses the effects of crosswind on high-speed trains.
- Chapter 6 discusses methods of testing and assessment.
- Chapters 7 and 8 discuss issues relevant to train operation in tunnel environment:
    - Chapter 7 discusses the issue of pressure transients observed inside a railroad tunnel when a high-speed train passes through it.
    - Chapter 8 discusses the micro-pressure waves (pulses of air pressure emitted from railroad tunnel entrances) that can manifest as audible noise or vibration.
- Chapters 9 and 10 cover issues that are common to open and tunnel environment:
    - Chapter 9 discusses the aerodynamic drag experienced by high-speed trains.
    - Chapter 10 discusses the problem of ballast flight (motion of ballast particles by the wind underneath a high-speed train)

Finally, Chapter 11 (Conclusions and Recommendations) sets out the way forward, explaining the recommended next steps towards the creation of a design and mitigation guidance manual.

All chapters, with the exception of Chapters 1, 6, and 11, are organized in the following fashion:

- A short introduction and summary of the chapter content is given.
- The nature of the aerodynamic phenomenon in question is explained in detail.
- When applicable, formulae for aerodynamic assessment and measurement methods are discussed.
- Impacts of the phenomenon on trains, people, and structures are described and ways to mitigate these impacts are discussed.

- An overview of the relevant existing regulations, standards, and acceptability criteria is given.
- The relevant data from the literature are summarized, including evaluation and assessment methods, as well as experimental data.
- Overall conclusions are summarized, information gaps are identified, and recommendations to address these gaps are presented.

2. Open Air Considerations: Slipstreams

The wind caused by the passage of a train is known as the "slipstream" and causes a continual rapidly varying pressure on adjacent objects during the passage of a train. These slipstreams and their resultant pressures can have a large impact on workers and passengers adjacent to the passing train.

2.1 Introduction and Summary

This chapter examines the slipstream and its resultant pressures and impacts. It includes:

- basic aerodynamic concepts;
- influencing factors;
- measurement and calculations;
- known and potential impacts;
- existing mitigations;
- standards;
- data from the literature reviews including: studies, criteria, evaluation and assessment methodology, conclusions, and recommendations including operational procedures.

This chapter has the following general conclusions and recommendations:

- while the aerodynamic theory and concepts have been assessed, the quantitative effect on human stability is not fully accounted for in existing safety criteria;
- care must be taken when comparing velocities or velocity coefficients from different sources;
- in the United States there are no standards or regulations relative to aerodynamic effects for safety distances between people and passing trains;
- a proposed limit on wind speed produced by a slipstream should have an associated time period;
- existing mitigation measures can be utilized with enhancements;
- recommendations for addressing processing methods for wind velocity studies; and,
- potential Tier II and Tier III operation procedures guidelines.

2.2 Nature of Slipstreams

2.2.1 Basic Aerodynamic Concepts

A moving train induces an air flow in the general direction of the train motion, consisting of several parts [2].

- The nose region, dominated by large inviscid pressure and velocity transients.
- The boundary layer, containing highly turbulent air alongside the train. The thickness of the boundary layer is similar to the width and height of the train, and increases towards the back of the train.

- The near wake, dominated by large-scale unsteady flow vortices spreading laterally behind the train.
- The far wake, in which the velocities gradually decrease.

Collectively, these flow regions are known as the slipstream. When measuring air velocity from well-streamlined high speed trains at positions to the side of the track, the highest velocities are usually found in the near wake, shortly after the train has passed. Examples of measured air velocities are given in Figure 2. The four graphs are from the same train passing the same measurement point at the same speed in four separate runs. Note the large differences from run to run. This is characteristic of turbulent flows.

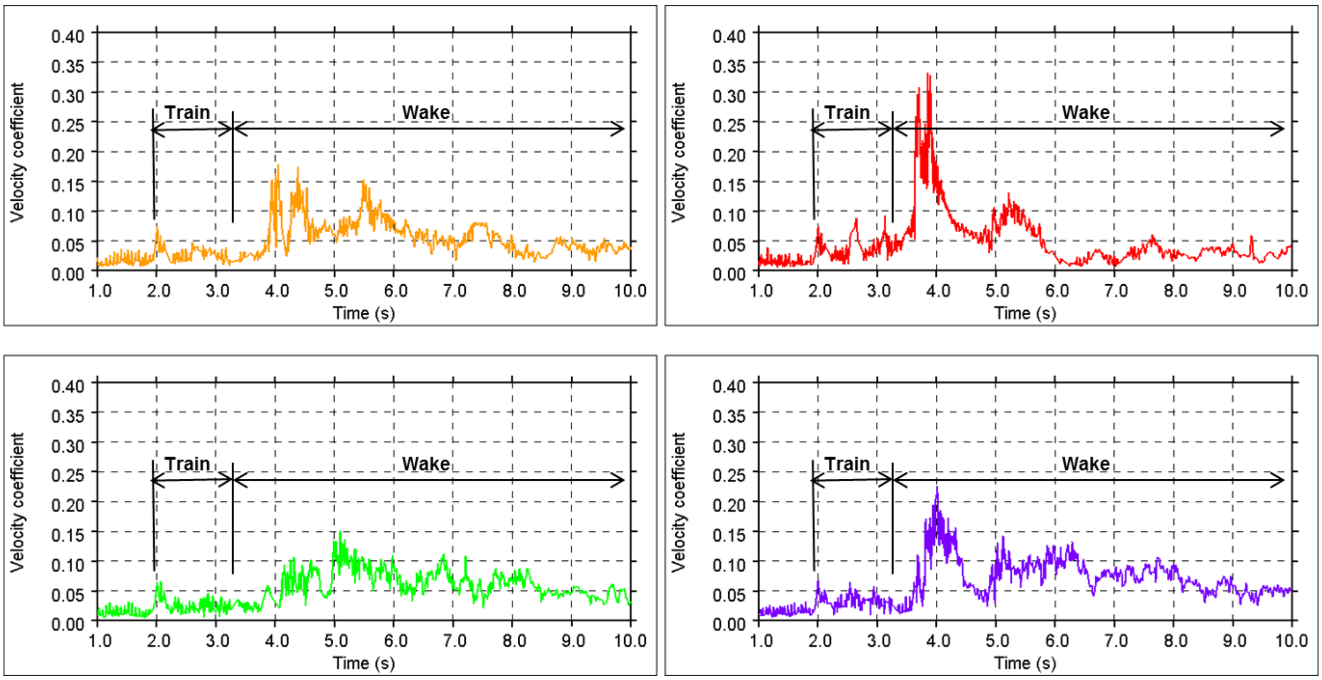

Figure 2. Air velocity coefficient (air velocity divided by speed of train) measured 10 ft (3.0 m) from the track; four separate runs with the same well-streamlined train passing the same measurement point.

2.2.2 Influencing Factors

There is a strong random variation from run to run even when the same train passes the same measurement point at the same speed under nominally identical conditions, as illustrated in Figure 2. The variability is inherent in the turbulent nature of the slipstream. Data processing methods that allow for the variability are discussed below.

Air velocities around the train and in the wake are proportional to train speed. The turbulent effects in the wake are subject to a high degree of random variation. When measuring air velocities, a large number of train passes must be recorded to build up a statistically representative picture. For well-streamlined high speed trains, the most turbulent part of the wake is associated with the wheels and trucks. The European collaborative project, AeroTRAIN, has studied extensively the statistics of wind gust speeds in train slipstreams [3].

The air velocities are strongly influenced by the aerodynamic design of the train. Most trains capable of high speeds have well-designed aerodynamic shapes. In some cases, the difference due to aerodynamic train design more than compensates for the higher speeds at which the trains run. For example, the majority of recorded instances of adverse impacts of train-induced air flows on station platforms arose from freight trains, not from passenger trains, passing the same platforms at higher speeds [4].

Air velocity decreases with distance from the track. Mitigation measures for high speed railways include increased separation distances between the high speed tracks and vulnerable people, structures, or other tracks, along with reducing the speed of the train.

Air velocity on platforms is reduced by the height of the platform because the vertical face of the platform blocks the slipstream from the wheels and the trucks. Lower platforms (e.g., 1 ft or 0.3 m in height) do not reduce the air velocity as significantly as taller UK-style platforms (3.3 ft, or 1 m, above rail). When the tracks are laid on ballast, the heads and bodies of people next to the ballast shoulder can be level with the wheels and the trucks of the train and hence can be exposed to the highest slipstream air velocities.

Crosswinds can increase the slipstream air velocity because the faster-moving portion of the wake is displaced from its normal position above the rails to a trackside position where people may be standing.

2.2.3 Measurement and Calculation of Velocity Coefficient

Most published sources express air velocity as a non-dimensional "velocity coefficient". This is important because it allows a straightforward comparison between train types and air velocity measurements. The velocity coefficient is represented as "c_v", where

$$\boldsymbol{c_v = \frac{u}{v}} \qquad \textbf{Equation 1}$$

Here, *u* is the air velocity (usually the resultant velocity in the horizontal plane) and *v* is the train speed.

As shown in Figure 2, the air velocity varies greatly during and after passage of a train. Quoted velocity coefficients generally refer to the maximum value of *u* occurring at the measurement position.

Effect on Velocity Coefficient of Data Processing Methods

Care must be taken when comparing velocities or velocity coefficients from different sources because the result is strongly affected by the data processing method, e.g., a 3-second moving average. The European Technical Specifications for Interoperability (TSI) method for processing slipstream velocity measurements is described in Section 2.5.

Issues associated with various data processing methods include the following:

- The velocity-time histories may be presented raw (as measured), or filtered such that short sharp peaks (and hence the maximum value and the quoted coefficient) are reduced. The choice of filtering time-constant has a very significant effect on the quoted result.
- The reported velocity should be the combined results from several train passages. The results are less reliable if the number of train passages is less than 20.

- The velocity coefficient, in the case of the TSI method, is the mean average plus two standard deviations (this effectively is the 95% confidence limit and typically increases the result by about 40%).

Figure 3 shows the same measured velocity coefficient time-history processed using moving averages with 0.3-second, 1-second and 3-second time-constants. The resulting velocity coefficient maxima are 0.16, 0.11 and 0.09 respectively. The typical human response time to wind gusts is thought to be on the order of 0.3-seconds. Ideally, the processing method should reflect closely the way that people respond to wind gusts so that a larger velocity coefficient result always indicates greater risk. However, none of the well-known processing methods relates directly to human response.

Reports [5] note large effects of processing method for non-uniform wind, including the 3-second moving average method used by Murakami and Deguchi [6] and the "equivalent steady wind speed" method by Hunt et al [7], which is based on average speed and root-mean-square turbulent velocity components.

The two methods give very different results. For example, airflow velocities in the wake of the same train measured at the same point in space were 51 mph (23 m/s) in terms of a moving average of 0.032 seconds, versus 53 mph (24 m/s) in terms of "equivalent steady wind" criterion by Hunt et al, and 28 mph (13 m/s) in terms of 3-second moving average (Figure 3).

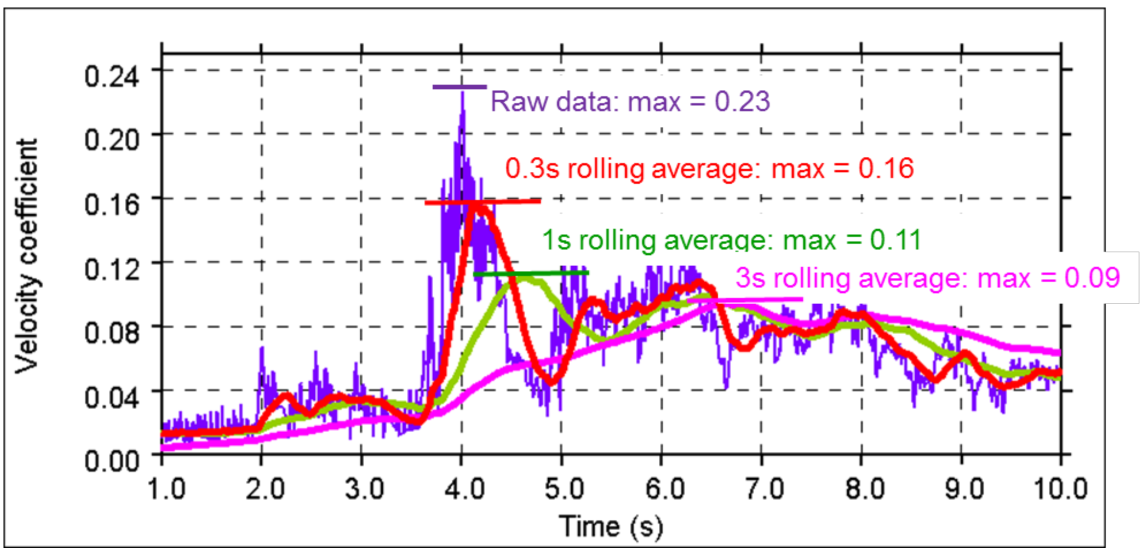

Figure 3. Example showing effect of filter time constant on maximum velocity coefficient

Figure 4 shows a typical ensemble of 20 individual runs under nominally identical conditions, processed with a 1-second moving average. In this example, the maxima from the individual runs vary from 0.072 to 0.143. When the coefficient is calculated by the TSI method, two standard deviations are added to the mean. This increases the mean coefficient by about 40%, from 0.107 to 0.146.

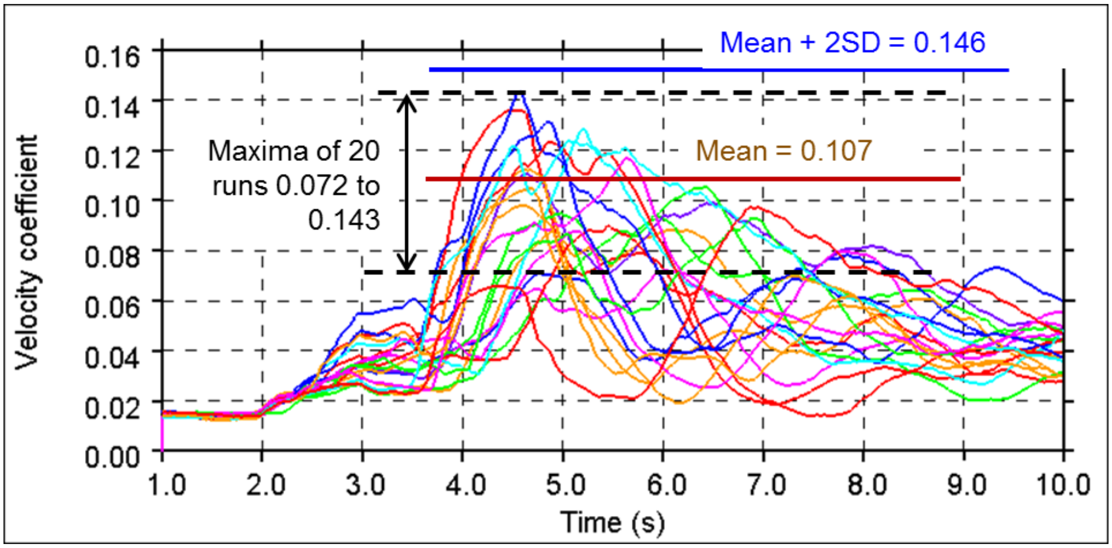

Figure 4. Velocity coefficients from 20 nominally identical runs (1-second moving averages)

Estimating Slipstream Air Velocity

Air velocity (*U*) caused by passage of a train may be estimated by multiplying the "velocity coefficient" by the train speed:

$$U = c_v V_{tr} \qquad \textbf{Equation 2}$$

where c_v is a velocity coefficient specific to the measurement position, processing method, and the train, and V_{tr} is the speed of the train.

Velocity coefficients are unique to the train type and to the measurement position. For certain standard measurement positions (such as those used in the European TSIs), published velocity coefficients are available in the literature for a range of train types (see Table 3).

If velocity coefficients are required for non-standard positions, there is little data available in the literature. Some approximate relationships exist that could be used to extrapolate from the standard positions. Indeed, because of the random variation inherent in velocity measurements, any predictive formulae would inevitably be approximate.

Where velocity coefficients are unavailable, they can be obtained by full-scale testing or reduced scale model testing. Computational Fluid Dynamics (CFD) analysis can provide mean values, but not the important gust behavior. In the future, predictive methods using Large Eddy Simulation (LES) may be available, but these are still at an early stage of development. Wind tunnel testing is not suitable for measuring slipstream air velocity due to the difficulties of fitting a sufficient length of train into the wind tunnel, and the necessity to support the train model above a moving ground plane.

Simplified Examples of Calculation of Velocities

Example 1 – Calculation of maximum slipstream air velocity from a velocity coefficient

The velocity coefficient of a certain train has been measured as 0.18 at the standard TSI trackside position of 0.66 ft (0.2 m) above rail and 10 ft (3.0 m) from the track center. If the train will run at 250 mph, the maximum air velocity at that position in the absence of crosswinds will be 0.18 x 250 = 45 mph (20 m/s).

Example 2 – Determination of Tier III speed limit for platform tracks

Please note: the purpose of this example is to demonstrate the method by which rules for safe standing distance and/or train speed may be derived. There is no implication that the assumptions presented here are recommended or that the speed limits shown should be adopted.

Assumptions in the example:

- Safety criterion for passengers on platforms: maximum slipstream velocity should not exceed 34 mph (15 m/s) at the closest position where passengers stand.
- Lines or barriers are on the platform such that passengers should be no closer than 10 ft (3.0 m) from the track centerline, or roughly 5 ft from the side of the trains.
- Trains will be compliant with the European TSI.

Answer:

- Since the trains are compliant with the TSI, the velocity coefficient 10 ft (3.0 m) from the track centerline above a platform can be assumed not to exceed 0.28.
- The maximum train speed is 34 mph/0.28 = 121 mph.

Note that freight trains have higher velocity coefficients (typically about three times higher than streamlined high speed trains) so for freight trains, the maximum speed on platform tracks would be about 40 mph to limit the slipstream velocities to those for streamlined high speed trains. When considering speed limits for high speed trains, the need for consistent limits for freight trains is sometimes overlooked. This is important, especially in the light of the record of slipstream-related accidents on platforms, most of which involve freight trains [4].

2.3 Impacts and Mitigation

2.3.1 Impacts

Impacts on Passengers Waiting on Platforms

Winds created by the slipstreams of trains passing through stations can have the following impacts on passengers waiting on platforms:

- Cause them to lose their balance, fall and be injured. As the wake behind a train is turbulent, an object or person exposed to it will experience rapidly changing forces acting in a range of different directions. These effects can be destabilizing.
- Startle them.
- Blow dust, snow, and debris towards them.
- Cause child strollers to roll, overturn, or be blown along the platform with a subsequent rolling into the train (fatalities from this effect have been known to occur). Wheelchairs and baggage carts may be similarly affected.
- Loose items or equipment (trash cans, drain covers, etc.) might be lifted or thrown against passengers, or create a tripping hazard.

Train slipstreams are like gusty wind conditions. Their impacts depend not only on the maximum wind speed, but also on the duration for which that speed occurs. Higher speeds can be tolerated if the duration is shorter. *The quantitative effect on human stability of the speed and duration of wind gusts is poorly understood (despite research efforts in several countries) and not properly accounted for in existing safety criteria for train slipstreams*.

Pope reports in a 2008 study no serious falling incidents due to train slipstream effects were recorded in the 13 years of data researched [4]. The descriptions within the data included "almost swept off feet". Train speeds in this study were no greater than 125 mph.

This 2008 study by Pope [4] also presents data for incidents in the UK involving risks to passengers on platforms from train slipstreams. There were 25 recorded incidents in these 13 years: 13 incidents involved a baby stroller being moved (10 of these were caused by freight trains, with the remaining three being caused by passenger trains). An incident was recorded in which a stroller was drawn into the side of a train from an initial position 13 ft (4 m) from the platform edge. The more streamlined high speed trains caused the least movement of the strollers while the freight trains caused the most movement. No lower limit was found on the air speed at which strollers begin to be moved by train slipstreams when a mix of train types passed the platform.

Pope reports that in Germany, at least one infant fatality was recorded when a stroller was moved by the slipstream of a freight train. Tests as part of the RAPIDE project, again reported by Pope, found no movement of strollers as a result of high-speed ICE trains passing a platform at 110-122 mph (177-196 km/h); but, locomotive-hauled passenger trains and freight trains at lower speeds did cause the strollers to move. When comparing German and UK experience, note that the platforms are higher in the UK, offering some protection from the train slipstreams.

Impacts on Track Workers

Impacts on track workers are potentially the same as those on passengers on platforms, consisting principally of injuries from falling. Compared to passengers on a raised platform, track workers may be standing at a lower position relative to the train, especially if the track is on ballast. They may therefore be exposed to the most turbulent part of the slipstream associated with the wheels and the trucks where air velocities are highest. However, because track workers have undergone required safety training, the limits of acceptability for track workers are sometimes set at a higher air velocity than for the general public.

Pope [4] describes two track worker incidents in the UK:

- A track worker sustained back injuries after being spun around and thrown to the ground by a train slipstream.
- A track worker suffered a broken arm after the shovel he was carrying was caught and moved by the slipstream of a train.

Other Platform Hazards Related to Slipstreams

Another concern is the presence of unsecured items (such as trash cans) on some station platforms. These objects can potentially be dislodged and overturned by trains' slipstreams [8].

Impacts on the General Public Away From Stations

In addition to passengers on platforms, other members of the public can be affected by train slipstreams. In the United States, so called rails-with-trails, or RWT (pedestrian passages adjacent to rail tracks) are becoming increasingly common, and, if the distance between the tracks and the trails is not sufficiently large, pedestrians may experience some negative effects associated with train slipstreams. The same assessment methodology and criteria can be applied to passenger and pedestrian safety, although larger emphasis may be put on comfort factors such as noise and startling effects. The subjective response of pedestrians to approaching trains is different from that of passengers standing on the platform. For example, they do not have the advantage of observing the track and having an opportunity to prepare for train passage by stepping further away from the tracks [5, 9].

Impacts on Trains

Slipstreams from high speed passenger trains are not considered within current rail practices to impact negatively on other trains because those other trains are exposed to winds of higher speed from their own motion and from ambient winds. The nose and tail pressure pulses, described in Chapter 4, are more of a cause for concern.

Additionally, the authors have postulated several potential impacts from train slipstreams that could occur where conventional freight tracks are immediately adjacent to high speed tracks. These potential impacts include:

- The slipstream wind from high speed trains might damage freight.
    - Particles carried in the wind might damage paintwork on automobiles or other valuable freight.
    - Wind might lift and carry away particles of coal or other freight, which might then pose a hazard to people standing by the track.
- Freight might cause damage or hazard to high speed trains.
    - Particles of coal or other freight might be lifted by the slipstream from the freight train or by crosswinds and deposited on the high speed tracks, leading to damage to rails and wheels.
    - Fabric covers or other lightweight equipment or cargo might be blown onto the high speed tracks leading to risk of derailment.

For Tier III operation, it will be necessary to decide the minimum permissible separation between dedicated high speed and conventional tracks such that aerodynamic impacts will be acceptably small. Where right-of-way is not available to achieve minimum permissible separation distances, then other mitigation measures, such as installation of physical barriers, may be required.

2.3.2 Existing Mitigation Methods

Minimum Safe Distances

In the United States, there is no standard or regulation relative to aerodynamic effects for safe distances between people and passing trains. Where safe distance lines are present on platforms, they are designed to keep the passengers from falling onto the tracks or being hit by a train, rather than to protect them from aerodynamic effects. On the Northeast Corridor, the distances between the line and the platform edges used to range from less than 2 ft to over 4 ft (0.6-1.2 m) [10]. More recently, AMTRAK started marking 38 in (1.0 m) wide safety zones on these platforms. Lee [5] recommended that lines be marked at 5.25 ft from the platform edge. Tactile strips with truncated cones should be installed per the Americans with Disabilities Act (ADA) requirements.

is given in Table 1 gives an overview of minimum safe distances from passing trains for different countries. These distances should be compared with caution due to the differences between these countries' design guidelines for elements such as platform height, track gage, and train width.

Table 1. Recommended distances from passing train by country (adopted from Lee [5] unless otherwise stated)

Country	Speed	Application	Distance to nearest rail	Distance to edge of platform or side of train
UK	<99 mph (160 km/h)	Workers [4]	4.1 ft (1.25m)	
	<124 mph (200 km/h)	Workers	6.6 ft (2.0 m)	
	<124 mph (200 km/h)	Passengers		4.9 ft (1.5 m)
France	<99 mph (160 km/h)	Workers	4.9 ft (1.5 m)	
	>99 mph (160 km/h)	Workers	6.6 ft (2.0 m)	
	<99 mph (160 km/h)	Passengers	5.9 ft (1.8 m)	
	<124 mph (200 km/h)	Passengers	8.2 ft (2.5 m)	
Russia (for Velaro RUS HST)	<99 mph (160 km/h)	Passengers [11]		1.6 ft (0.5 m)
	<112 mph (180 km/h)	Passengers		3.3 ft (1.0 m)
	<124 mph (200 km/h)	Passengers		4.9 ft (1.5 m)
	<155 mph	Passengers		6.6 ft

Country	Speed	Application	Distance to nearest rail	Distance to edge of platform or side of train
	(250 km/h)			(2.0 m)
Germany	<25 mph (40 km/h)	Workers	3.6 ft (1.1 m)	
	<99mph (160 km/h)	Workers [12]	5.7 ft (1.75m)	
	<174 mph (280 km/h)	Workers	7.5 ft (2.25 m)	
	<186 mph (300 km/h)	Workers	8.5 ft (2.55 m)	
	<99 mph (160 km/h)	Passengers		3.3 ft (1.0 m)
	<124 mph (200 km/h)	Passengers		4.9 ft (1.5 m)
	<143 mph (230 km/h)	Passengers (one line only)		7.2 ft (2.2 m)
China	<99 mph (160 km/h)	Workers	9.8 ft (3.0 m)	
	<99 mph (160 km/h)	Passengers (existing lines)		4.9 ft (1.5 m)
	<99 mph (160 km/h)	Passengers (new lines)		5.6 ft (1.7 m)
Japan	<59 mph (95 km/h)	Passengers		2.6 ft (0.8 m)
	<155 mph (250 km/h)	Passengers		8.2 ft (2.5 m)

Minimum Safe Distances for Northeast Corridor

Based on analysis of literature and on results of multiple full-scale experiments, previously recommended minimum safety zone widths in the United States for train speeds up to 150 mph (241 km/h) are as follows:

Table 2. Recommended distances from passing train for the US (adopted from Lee [5])

	Minimum Lateral Distance		
	Distance from centerline of nearest track	**Distance from outer edge of nearest rail**	**Nominal distance from side of train**
Passengers on low-level platform	10.25 ft (3.1 m)	7.7 ft (2.3 m)	5.25 ft (1.6 m)
Workers on trackside at low-level platform height	8.9 ft (2.7 m)	6.3 ft (1.9 m)	3.9 ft (1.2 m)

The recommendations are based on acceptable airflow velocity criteria by Murakami and Deguchi [6], which were confirmed by recent numerical studies in the US. Other assumptions and limitations include:

- The recommended distances apply to Acela Express trains with speeds up to 150 mph (241 km/h) and Amfleet trains at speeds up to 125 mph (201 km/h).
- The distances apply to low-level platforms (0.75 ft (0.2 m) above top of the rail).
- Passengers were assumed to be walking (less stable position), while track workers were assumed to be standing (more stable position).
- Wind speed is based on a 3-second moving average, longer than the response time of humans to wind gusts. This criterion may therefore be non-conservative for slipstreams that generate short-duration gusts.
- Ambient wind was not considered.

The Figure 5 compares the recommended minimum safe distance for passengers for the Northeast Corridor with international practice for high speed railways.

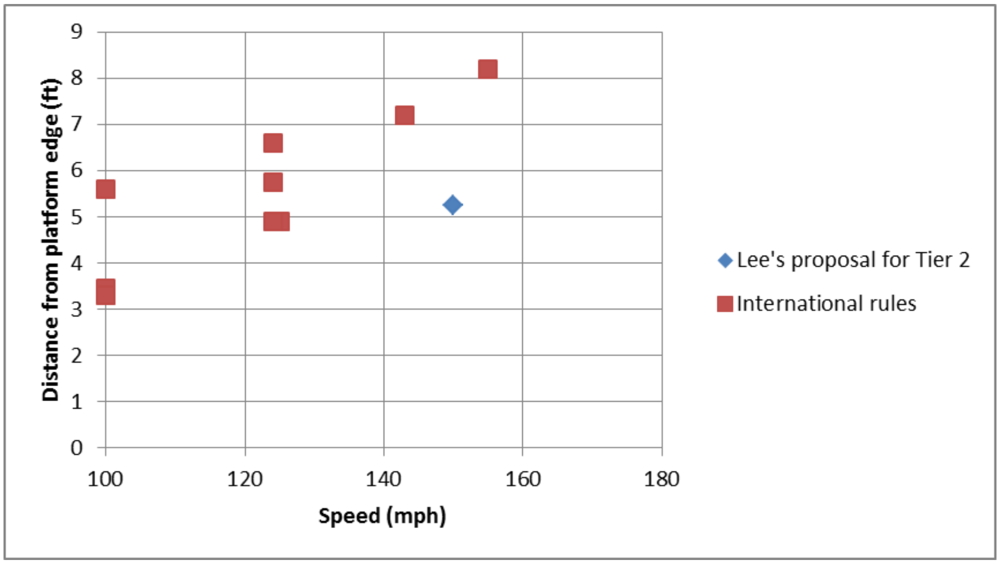

Figure 5. Safe distances for passengers from the platform edge based on data from Lee [5] and other sources

The platform distance proposed by Lee for 150 mph (241 km/h) is lower than international practice would suggest. Possible reasons for this are:

- The Acela train has better aerodynamic properties than assumed in the various national rules. This seems likely from the data in Lee's report, but cannot be assessed quantitatively because the data have not been processed according to the TSI method and the number of train passes is less than the required 20.
- The 3-second time-constant used in processing is longer than the response time of humans to wind gusts (thought to be around 0.3-seconds) and might lead to the results being non-conservative in some cases.

The recommendations for safe distance for track workers for the Northeast Corridor are compared against international practice from Table 1 in Figure 6. The recommended distance is broadly consistent with the standards in other countries.

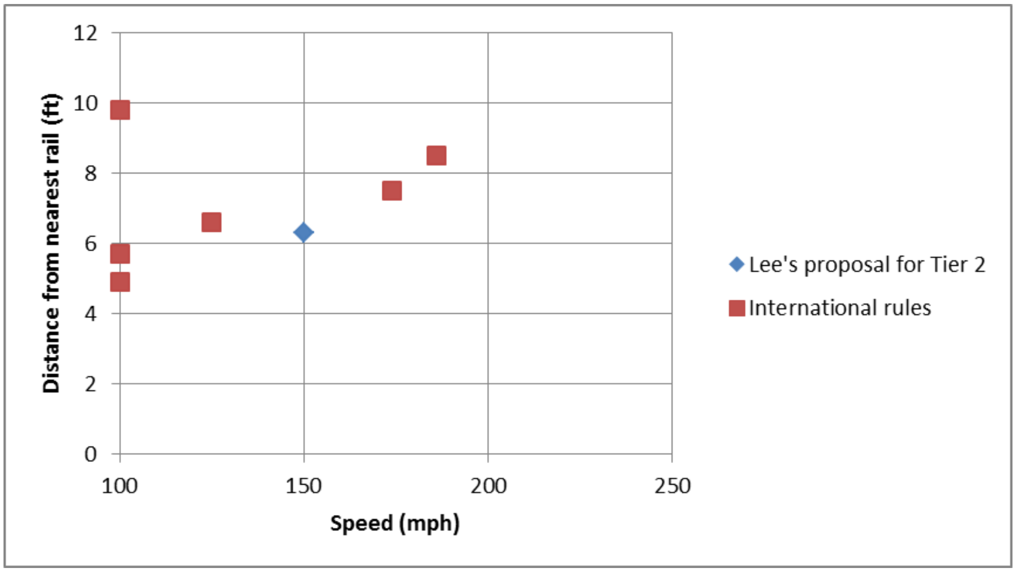

Figure 6. Safe distances for track workers from nearest rail

Slipstream Mitigation for Passengers on Platforms

In Europe, the mitigation for high speed trains is summarized as follows:

- The maximum speed on a track alongside a platform is 155 mph (250 km/h) according to Europe-wide regulations [13] although most countries adopt lower national limits.
- If non-stopping high speed trains pass through stations, the main lines ("passage tracks") do not have platforms. The stopping trains divert onto platform tracks. The platform tracks lie between the platform and the passage tracks, creating a larger separation between passengers and the non-stop trains. Platform speed limits are not applied to the passage tracks.
- The trains must comply with the TSI (Rolling Stock) [14] in respect to air velocity above a platform.
- The minimum safe distance is identified by safety markings on the platform at a set distance from the platform edge. For this point, there is no Europe-wide standard and national rules apply.

Speed Limits for Platform Tracks

Some European national speed limits for high speed trains passing platforms are:

- France: 124 mph (200 km/h) for conventional lines, 137 mph (220 km/h) for TGV [15].
- Germany: 124 mph (200 km/h) except on the Hamburg-Berlin line where 143 mph (230 km/h) is permitted due to special measures [16].
- UK: 143 mph (230 km/h).

Platform Height

Substantial reductions in air velocity above the platform, and hence, substantial reduction of impact on passengers, can be achieved by raising the height of the platform above rail level to 3.3 ft (1.0 m).

Safe Markings on Platforms

Since the distance between the train sidewall and the platform edge is fixed by train geometry, and physical barriers between a platform and a train are not common practice, it is necessary to introduce safe zones several feet wide along the platform edge that passengers must avoid except when boarding. These zones should be marked with clearly visible safe lines along with tactile strips of truncated cones per ADA requirements.

In the future, more sophisticated methods such as infrared intrusion detection systems could be used to warn visually impaired passengers [17].

Warning Devices

In addition to standard warning signs urging passengers to stay back, Supervisory Control and Data Acquisition (SCADA) systems, such as electronic message boards, flashing lights, and automated audio announcements, could be installed. These are activated when a train is approaching [10]. Stations of the Washington Metro have flashing red lights mounted in the floor near the platform edge to warn passengers about approaching trains and several have additional tactile strips. These measures have been effective in keeping passengers away from the platform edge [18].

The train horn should also be sounded on approach to the platform.

Baby stroller users may be targeted with signs, leaflets, and audio announcements informing them of the dangers of strollers being blown across platforms by slipstreams.

Securing of Loose Items

Trash cans, covers of drains or inspection pits, or other loose equipment on the platform may be lifted or blown towards passengers by train slipstreams. These items should be secured to the platform.

Separate “Passage Tracks”

Many high-speed rail stations have separate tracks (“passage tracks”) for trains that proceed through the station without stopping [10, 19]. In general, the distance from the passage tracks to the platform is sufficient to prevent passengers from experiencing high air velocities, even though the speed of trains on these lines may be very high. If this distance is insufficient, separating walls or even tunnels inside the station may be built to isolate them from passengers [15, 20].

Based on local criteria, some European stations have noise barriers between the high speed passage tracks and the lower speed stopping tracks. These may have additional benefits in preventing passing high speed trains from causing trains stopped at the platform to jolt in response to the suddenly applied pressure pulse, and may also reduce the air velocity experienced by passengers on the platform.

Train Screens

If separate passage tracks cannot be built, platforms can be isolated from the tracks by train screens (walls with doors which only open for boarding if and when a train stops). This design is used on some urban rapid transit systems. While it increases passenger safety, it typically increases station construction and maintenance costs and puts limitations on train geometry. Since the distance between this barrier and the train wall will be minimal, it would have to be designed to withstand high aerodynamic loads. At the same time, when used for newly built underground stations, train screens can sometimes decrease construction costs because they can be used as structural members to support the station ceiling, and because they decrease the need for pressure relief shafts before stations [21].

Mitigation for Track Workers

In the United States, the safety of track workers is regulated by the 49 CFR 214 Subpart C (Roadway Worker Protection) [22]. The current version of the Code states that upon notification of an approaching train, workers must cease work and move from the track occupied by the approaching train to a predetermined place of safety. Furthermore, workers working on a track adjacent to the track occupied by the approaching train must also move to a predetermined place of safety. The "adjacent track safety rule" is expected to go into effect in 2014. However, the regulations do not specify the minimum distance between the tracks and the place of safety.

In Europe and Asia the safety of track workers is achieved by specifying a minimum standard of aerodynamic performance of the train [14]. A further essential component is to specify the "place of safety" in terms of minimum distance from the occupied track at which track workers may stand. Table 1 shows specified "place of safety" distances for some of the European countries. These vary with line speed, but *the existing rules do not cover speeds as high as 250 mph.*

Mitigation for Public Outside of Stations

High speed railways normally have a fence or other barrier preventing members of the public from accessing the railway. The distance of the fence from the tracks is large enough that air velocity experienced by people standing on the other side of the fence does not exceed safe levels. However, people may still be startled by trains.

In the case of pedestrian trails and walkways, a wind-proof barrier may be built between the tracks and the walkway. In addition to protecting the pedestrians from slipstreams, the barrier may also be designed to protect the trains from crosswinds and to suppress train noise.

2.4 Standards

2.4.1 European Technical Specifications for Interoperability (TSI): Infrastructure

The Infrastructure TSI [13] permits a maximum speed of 155 mph (250 km/h) on tracks next to platforms. In many cases national standards enforce a lower speed.

2.4.2 European Technical Specifications for Interoperability (TSI): Rolling Stock

The Rolling Stock TSI [14] contains two requirements for slipstreams:

- Protection of passengers: when a train passes a platform at 124 mph (200 km/h) the air velocity should not exceed 35 mph (15.5 m/s) measured at 10 ft (3.0 m) horizontally from the track center and at a height of 4 ft (1.2 m) above a platform. In future versions of the TSI, the requirement for measurement above a platform will be replaced by measurement at an equivalent height at the wayside.
- Protection of track workers at the wayside: when a train passes at 186 mph (300 km/h) the air velocity should not exceed 49 mph (22 m/s) measured at 10 ft (3.0 m) horizontally from the track center and 0.75 ft (0.2 m) above the level of the rail head. For trains with maximum speed less than 186 mph (300 km/h), the test is performed at the maximum speed of the train. If that speed is less than 155 mph (250 km/h) the maximum limiting air velocity is 45 mph (20 m/s) instead of 49 mph (22 m/s).

These requirements enforce at least a minimum standard of streamlining of trains, which is the first part of the mitigation of slipstream effects. The second part of the mitigation is to define the safe distance at which people can stand. Such distances are not given in the TSIs, but are left to national standards in each country as shown in Table 1.

2.4.3 EN 14067

The European Standard for rail aerodynamics EN 14067 [23, 24] gives extensive details of the testing procedures for measuring slipstream velocity and processing the data into the required form, but does not offer acceptability criteria.

2.4.4 Customs Union Technical Regulation TP TC 002/2011

The issue of slipstreams is briefly addressed in the Technical Regulation TP TC 002/2011 "On Safety of High-Speed Rail Transport" [25] and whose jurisdiction includes the Customs Union of Belarus, Kazakhstan and Russia (CU). This document applies to all high-speed rail vehicles operating in CU on 5 ft (1520 mm) gage tracks at speeds above 124 mph (200 km/h). Specifically, Section 86 (b) requires:

"In order to protect people from aerodynamic effects of moving high-speed rolling stock, passenger platforms shall not be located directly adjacent to the main rail tracks."

This rule effectively requires high-speed trains to use "passage tracks" when moving through the stations without stopping.

2.4.5 National Standards

Most countries have national standards covering speed of trains passing platforms, and the safe distance for passengers on platforms and track workers. These are given in Section 2.3.2 describing mitigation measures for slipstream effects.

2.5 Data from Literature Including Studies, Criteria, Assessments, and Evaluation Methodology

This section of the report gives supplementary information gathered from the literature search.

2.5.1 Studies on Effects of Slipstream Wind Speeds

Effect of Train Type on Slipstream Wind Speeds

Multiple slipstream velocity coefficients from full-scale tests described in the literature are given in Table 3, with explanatory notes below. Coefficients at or close to the TSI measurement positions are given for distances of 0.75 ft (0.2 m) above the top of rail for track workers, 4 ft (1.2 m) above the platform for passengers, and 10 ft (3.0 m) horizontally from the track centerline in both cases. Some sources give the mean velocity coefficient (i.e., the mean of the maxima from an ensemble of runs), while others give the TSI coefficient (mean plus two standard deviations). Not all sources make clear how many of passing trains contributed to the quoted mean values.

Table 3. Slipstream velocity coefficients from the European literature

Train type	Source	Trackside		Platform	
		Mean velocity coefficient	TSI velocity coefficient	Mean velocity coefficient	TSI velocity coefficient
S-103/Velaro	[3, 26]	0.1	0.14 (s) 0.17 (d)		
S-100/TGV	[3, 26]	0.15	0.19 (s)		
ICE-2	[3, 26]		0.27 (d)		0.23-0.28
High-speed trains	[27]			0.15	
Conventional passenger trains	[3, 26] [4]		0.2-0.35	 0.26	0.23-0.38
Freight trains	[28] [4] [27]	0.4-0.5		0.4-0.5 0.57 0.4	
TSI limit (+)	[14]		0.26		0.28
Acela/Amfleet	[5]			0.15-0.18 (*)	0.19-0.23 (*)

(+) – See Standards section below for more details
(*) – Measurements not directly compatible with European measurements – see below

Notes:

- (s) means single unit trains; (d) means two units coupled together into a double-length train.
- Deeg [27] quotes measurements by Deutsche Bahn at 4.9 ft (1.5 m) from the platform edge: freight trains running at 62 mph (100 km/h) induced peak air velocities of about 26 mph (11.5 m/s), while high speed trains running at 240 km/h generated about 22 mph (9.7 m/s).
- Pope [4] reports measured air velocity on station platforms 4.9 ft (1.5 m) from the platform edge. The maximum recorded was 43 mph (19.4 m/s) for freight trains passing

at 75 mph (120 km/h) or less. Passenger trains travelling at 99-124 mph (160-200 km/h) generated up to 33 mph (15 m/s) at the same position.

- Temple and Johnson [12] report that container freight trains at 75 mph generate higher slipstream air velocities than Advanced Passenger Trains (APT) high speed trains at 155 mph (250 km/h). In open track, passenger trains travelling at 124 mph (200 km/h) generated comparable slipstream velocities to those produced by freight trains at 75 mph (120 km/h) [4].
- In the US, a series of studies on slipstreams of high-speed and conventional trains were conducted in the Northeast Corridor between 1998 and 2002 and presented in the FRA report by Lee [5]. Differences in the data processing methods and measurement positions prevent Lee's results from being directly comparable with the European data. Data calculated from Lee's report is as follows:
    - Measurement position 5 ft (1.52 m) from the side of the train has been selected from Lee's Report Figure 69 (closest to TSI position of the available data).
    - Data were measured at two heights above a low platform, and then interpolated to 4.4 ft (1.53 m) above top of rail.
    - Velocity was measured in the longitudinal direction only.
    - Velocity was processed with 3-second moving average, not 1-second as would be the case for the European TSI data. The 1-second moving averages would be higher.
    - The data points given are obtained from a mix of Acela at 150 mph and Amfleet at 125 mph. The report does not indicate which data corresponds to which type of train.
    - The mean air velocity at 4.4 ft according to Lee's Report Figure 69 is 22 mph. The mean coefficients must lie between 22/125 and 22/150, i.e., 0.15 to 0.18.

Lee also gives results for mean plus two standard deviations air velocity (29 mph). The same calculation yields a coefficient lying between 29/125 and 29/150, i.e., 0.19 to 0.23.

Effect of Distance from the Track

There is no agreed relationship between air velocity and distance from the track. This is not surprising for a number of reasons:

- Velocities vary strongly with time. Results depend on how these are smoothed and how peaks are defined.
- Velocities are extremely variable from test-to-test. The result obtained depends on how the data from multiple tests are aggregated.
- Peak velocity during a given test depends on whether the critical structures in the flow happen to pass over the measurement position.
- The width of the boundary layer and the sharpness of the velocity peak when the tail passes vary strongly according to train design. Therefore, the relationships of velocity with distance may also vary with train design.

Therefore, at best, only a rough guide to the effect of distance is available now.

A series of measured and predicted velocity coefficients exist as functions of distance from the side of a passing train [29, 30] (Figure 7). It should be noted that the data used in developing these coefficients does not reflect the aerodynamics of modern high-speed trains (HSTs). Coefficients based on more modern HSTs are shown in Figure 8.

Deeg [27] suggests a power law to establish the relationship of the air velocity relative to the distance from the track with an exponent n=1.18 for the platform case, and n=1.51 for open track.

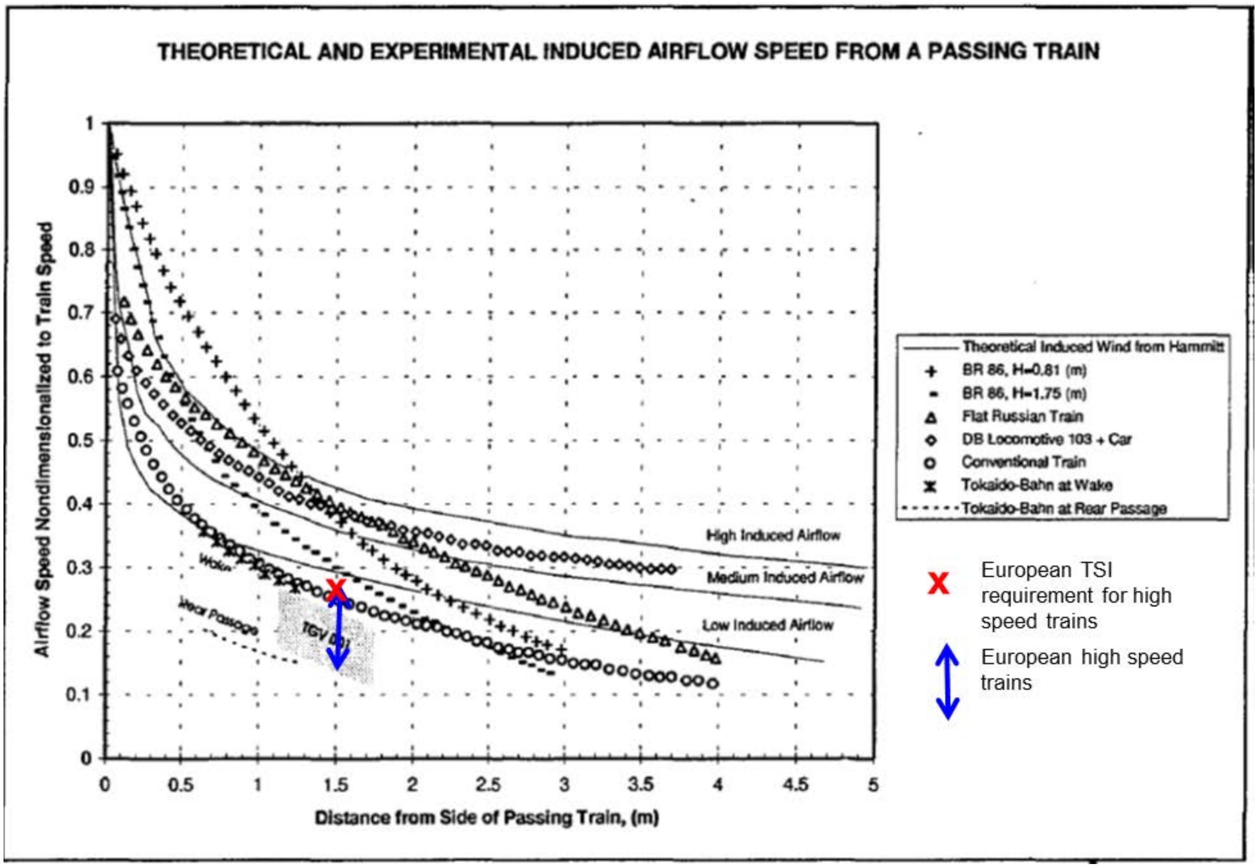

Figure 7. Variation of slipstream velocity with distance from the side of a passing train [10]

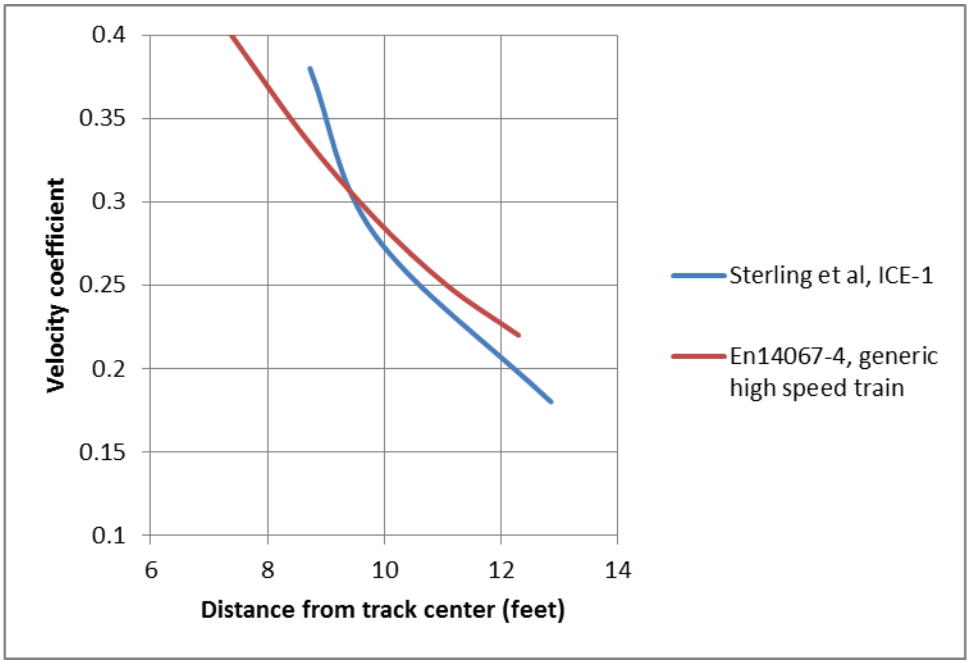

Figure 8. Approximate relationships between velocity coefficient and distance from track center [24, 28]

Effect of Wind Conditions on People

Endoh et al [31] performed wind tunnel experiments in which 29 healthy adults were subjected to triangle-form pulses of wind (the wind speed rose to a maximum linearly with time, then decayed to zero linearly with time). The duration of the pulses ranged from 0.5 to 2-seconds. The subjects stood with their backs to the wind (apparently the most vulnerable position). Changes of posture of the subjects were recorded: heels rising off the ground, or in more extreme cases taking a step forward. The latter occurred with probability 10% for wind speeds of 31-40 mph (14-18 m/s) depending on duration – lower wind speeds for 2-seconds duration, and with probability 50% for wind speeds of 45-58 mph (20-26 m/s). The study did not include any frail, elderly subjects or children.

Jordan et al [32] calibrated the response of a mathematical model of a standing human to “sharp-edged” sudden wind gusts. The person was assumed to behave as a rigid body for the first 0.375 seconds, after which the person braces and the response becomes that of a mass-spring system. Using 1,000 randomly generated mathematical models of passengers (varying parameters such as weight, height, age, standing position and orientation) with a mathematical idealization of slipstream velocity time-histories, they predicted that 10% of humans standing 1.6-4.9 ft (0.5-1.5 m) from the platform edge would be destabilized when the train speed exceeds 190 mph (85 m/s). This suggests that slipstreams from well streamlined high speed trains at typical maximum speeds for platform tracks (125 to 150 mph) would not pose a significant risk to passengers. However, there have been cases in Europe of individuals being destabilized by freight trains at speeds of around 60-70 mph.

There have been no direct measurements of the effect of typical slipstream gusts on people. All the proposed “safety criteria” have been inferred from different types of experiments that are only indirectly relevant, such as the effects of idealized gusts. *This represents a major weakness in the science.*

Given the random distribution of gusts within slipstreams, the random distribution of the stability of different individuals to gusts of different strengths and durations, and the random distribution of numbers and positions of people on platforms, a risk based approach would be preferred if available. In other words, the result of the calculation would be the expected number of people falling over due to slipstreams within a given time period. A proposed method for this is expected to be published by Baker in late 2014. An acceptability limit could be set, against which the calculation result could be compared and mitigation measures developed.

Effect of Platform Height

Johnson and Holding [33] report results of moving scale model experiments in which velocity coefficients were measured for a number of positions above a platform. Two platform heights were considered: a "German-style" platform of 1 ft (0.31 m) above rail level, and a "UK-style" platform of 3.3 ft (1.0 m) above rail level. The measurement positions were 4.4 ft (1.34 m) above the platform, and at 8.7 ft, 10.3 ft and 12 ft (2.65 m, 3.15 m and 3.65 m) from track center. Measurements from the scale model are presented in Figure 9 as the full-scale equivalent.

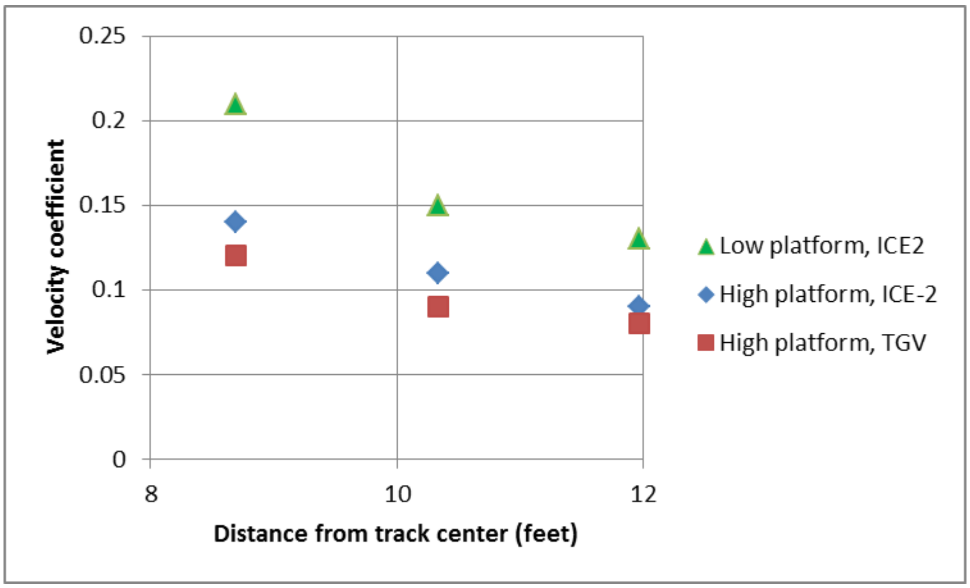

Figure 9. Velocity coefficient - effect of platform height, distance and train type, data from Johnson [33]

Not only were the maximum velocities about 30% lower for the "UK" platform, but the duration of the maximum velocity was much shorter. Considering only the long-duration wake, the velocity for the UK platform was less than half that of the German platform, suggesting that impacts on passengers can be substantially reduced using high platforms.

2.5.2 Criteria

Criteria for Slipstreams

Passenger comfort and safety are usually assessed in terms of air velocity. Other measures recorded in the literature include peak pressure, pressure change rate, induced aerodynamic force, and noise level [5, 8, 10, 34]. These criteria are typically based on outdoor observations or on wind tunnel experiments.

In the US, there are no regulations pertaining to train slipstreams. The US DOT Subway Environmental Design Handbook [21] recommends limiting horizontal air speed to which subway passengers are exposed to 1,000 ft/min (11 mph, or 5 m/s) under normal conditions, and under 2,500 ft/min (28 mph, or 13 m/s) under emergency conditions. The limits apply to platforms and other locations. These recommendations are based on application of the Beaufort Scale which is an empirical measure that relates wind speed to observed conditions on land or on the sea. *Note that the Beaufort Scale is now considered by a number of wind experts to be very misleading in the context of safe wind speeds for people.* One could opine that the FRA should either ignore or very cautiously use any proposed safety criteria based on the Beaufort Scale.

There are no regulations in Europe directly controlling the slipstream velocities to which people may be exposed. For high speed trains there is an assumption that if the trains are at least as well streamlined as required by the Rolling Stock TSI, then slipstream velocities will remain within safe levels. However, this relies on people standing sufficiently far from the tracks, which in turn depends on national rules that vary from country to country. The overall approach to slipstreams in Europe is not complete and consistent.

Acceptability criteria for slipstreams for any high speed rail operation could be developed along the following lines. This is the process followed for the Northeast Corridor [5]:

- Enforce a minimum standard of streamlining for trains, as per the European TSI (a generic "reference train"), or find the velocity coefficients of particular trains by full-scale testing at different distances from the track.
- Determine safe limits for air velocity for passengers and for track workers, or select from the existing proposed criteria.
- Find the distance from the track at which train slipstreams will not exceed the safe air velocity. This would be the "safe distance".
- Create rules that prevent people from standing closer than the safe distance.
- For platform tracks, set the maximum speed of trains and the distance at which passengers can stand.

The major obstacle to deriving these criteria is that there are no internationally agreed safe limits for air velocity. Different sources propose different limits, as shown in Table 4. It is also important to note that the velocity alone does not sufficiently describe the effects that a human will experience when standing in the flow. A steady wind has a different effect than a gusty wind, and the duration of the highest wind speeds in the slipstream of a train has an important influence on whether a particular maximum wind speed is "safe". The science of how train slipstream winds can destabilize people is poorly understood. As a minimum, any proposed wind speed limit should have an associated time period.

Table 4. Air velocity criteria

Limit			Source	Notes
mph	m/s	Type *		
11	5		[35]	Comfort limit for platforms of underground stations
11	5		[27]	“Unpleasant” comfort class for people sitting
11	5		[21]	Recommended limit for subway stations (US) under normal conditions
13	6		[8]	Air velocity that is considered capable of moving dust, leaves, etc.
20	9	NU	[5, 7]	“To avoid momentary loss of balance and to be able to walk straight”
20	9	3S	[5, 36]	Japanese safety limit for passengers on platforms
22	10		[27]	“Unpleasant” comfort class for people standing
22-34	10-15	3S	[5, 6]	“Serious Effect: Walking difficult to control”
25	11		[10]	British Rail limit for passengers on platforms
28	13		[21]	Recommended limit for subway stations (US) under emergency conditions
29-45	13-20	NU	[5, 7]	“For safety (for elderly people, this criterion may be too high)”
31-40	14-18	TG	[31]	Wind speed at which there is 10% chance of healthy adults having to take a step to remain upright
32	14	M	(Beaufort scale)	Lower limit of Beaufort Scale 7 “inconvenience in walking against the wind”
33	15	G	[4]	Gust speed sufficient to displace a significant proportion of people in a large wind-tunnel test, but the same gust speed measured on station platforms did not appear to be unsafe, possibly due to the shorter duration of the slipstream gusts.
33	15		[27]	“Unpleasant” comfort class for people walking
34	15	3S	[5, 6]	“Dangerous for elderly person; walking impossible to control”
35	15.5	TSI	[14]	TSI for passengers on platforms. Intended as a rolling stock acceptance criterion but sometimes interpreted as a safety limit for passengers
38	17		[12]	Deutsche Bahn and British Rail limit for track workers
39	17.4	M	(Beaufort scale)	Lower limit of Beaufort Scale 8 “generally impedes progress”
44	20		[37]	“Wind speeds greater than 20 m/s are dangerous for people”
45	20	SU	[5, 7]	Lower limit for safety of walking

Limit			Source	Notes
mph	m/s	Type *		
45-58	20-26	TG	[31]	Wind speed at which there is 50% chance of healthy adults having to take a step to remain upright
49	22	TSI	[14]	TSI for track workers. Intended as a rolling stock acceptance criterion but sometimes interpreted as a safety limit for passengers

* Types: M = mean wind speed; SU = steady uniform wind; NU = non-uniform wind; 3S = 3-second moving average; TSI = 1-second moving average, mean + 2SD; G = Gust, unknown shape; TG = triangular gust 0.5 to 2.0 seconds duration.

When assessing slipstream safety for passengers in the Northeast Corridor, a safety criterion of 3-second moving average wind speed < 22-34 mph (10-15 m/s) was selected [5] based on the work of Murakami and Deguchi [6].

Analysis of Slipstream Wind Speed Criteria

As can be seen from the large number of differing criteria, there is no consensus on what slipstream wind conditions should be considered "safe". Human response to wind is insufficiently understood to allow wind speed and duration limits to be set with confidence. The response time of a human to a wind gust is on the order of 0.3 seconds. The research indicates that it is unlikely that simple processing methods such as moving averages can reliably predict the boundary between safe and unsafe conditions for humans. The underlying science is too poorly understood to be able to recommend any of the available criteria for determining whether a given proposed operation is either safe or unsafe.

For use in comparative assessments, the "safe" wind speed is effectively defined by the existing operation against which the proposed new operation is being compared. The processing method by which the wind speeds are calculated is important. However, in the absence of any better method, the 1-second moving average method used by the European TSI is recommended on the basis that the time constant is reasonably short and measured data are available. This is suitable for comparative assessments between one high speed rail operation and another when both have streamlined trains. It may be misleading if used for unlike train types. Slipstreams from freight trains seem particularly prone to causing adverse impacts, but none of the assessment methods reflects this.

2.5.3 Evaluation and Assessment Methods

Types of Evaluation

As with other aerodynamic phenomena, slipstream evaluations fall into two types:

- Direct assessment:
    - Is the predicted air velocity safe?
    - At what distance from the track will the air velocity be safe?
- Comparative assessment:
    - Is the predicted air velocity greater or less than the air velocity for an existing operation with a good safety record for slipstream effects?

- At what distance from the track will the air velocity for the new operation be the same as the air velocity for the existing operation?

As discussed in the section on acceptability criteria, *there is no well-established definition of "safe" slipstream winds that relates reliably to human response. Therefore comparative assessments are recommended where possible.*

Allowance for Crosswinds

The effect of crosswinds on slipstream air velocity is difficult to estimate, and is usually excluded from assessments and evaluations. Baker et al [2] concluded that there are insufficient data to enable quantitative assessments of the effect of crosswinds on slipstream velocities. The paper includes some full-scale test results that show large scatter, and an underlying trend of velocity coefficients increasing by roughly 0.1 for each 5 degrees of yaw angle. *Reduced scale moving model testing may be able to clarify this.*

Application to Speeds up to 250 mph

There is likely to be an upper limit on train speed beyond which the coefficients do not remain constant due to compressibility or Mach number effects. The European Standard EN 14067 Part 4 [24] recommends that where the Mach number exceeds 0.25 (corresponding to train speeds over about 185 mph), testing should be carried out at the actual maximum speed of the trains to ensure that the derived coefficients are valid. *However, the extent to which the velocity coefficients vary at speeds from 185 mph up to 250 mph (300-400 km/h) is not known*. Thus, for speeds up to 250 mph, the assessment method is the same at lower speeds, but the assumption about coefficients remaining constant needs to be confirmed by full-scale or scale model testing.

Risk Assessment

Gilmartin and Griffin [38] describe a risk-assessment method for the aerodynamic effects of passing trains at platforms. The inputs to the assessment include geographic location (indicating exposure to cross winds), platform layout (open or enclosed), number of trains stopping at the platform, number, and the type and speed of trains passing the platform without stopping. *The method is semi-quantified.* Input parameters are estimated by staff with local knowledge and some inputs require a degree of professional judgment. The output is a number indicating the level of risk relative to other station platforms. Mitigation measures to reduce risk were listed in the report and their benefits were compared, but the presence of mitigation measures is not included in the risk assessment. The risk assessment and associated reports are the copyright of Rail Safety and Standards Board (RSSB) [39].

2.6 Conclusions and Recommendations

2.6.1 Conclusions

The following conclusions have been determined through the literature review.

- Basic aerodynamic concepts have been studied. Care should be taken when comparing velocities or velocity coefficients of these studies due to the use of different data processing methods.
- The severity of impacts from slipstreams can include injury and death.

- Mitigation methods exist and can be used with enhancements.
- In the United States there is no standard or regulation relative to aerodynamic effects for safe distances between people and passing trains. International standards do exist.
- Resultant air velocity criteria have been established by international agencies.
- Testing and analysis methods exist for developing assessments for high speed train impacts on adjacent objects and people.

2.6.2 Gaps and Issues

Concepts and Theories

None of the well-known processing methods for studying velocities and velocity coefficients relate directly to human response.

Impacts on Passengers Waiting on Platforms and Track Workers

The quantitative effect on human stability of the speed and duration of wind gusts has gaps of understanding and is not properly accounted for in existing safety criteria for train slipstreams. Current international criteria consider only certain types of streamlined high speed trains.

Impacts on Adjacent Trains

Slipstreams are not currently considered within the rail industry as having negative impacts on adjacent trains due to the assumption that the adjacent train would be exposed to higher wind speeds from their own motions and ambient wind. However, the potential exists for resultant winds caused by slipstreams of both high speed trains and adjacent freight trains to transport fine particles to such an extent that damage to train vehicles and freight could result.

2.6.3 Recommendations to Address Gaps and Issues

Concepts and Theories

The 1-second moving average method is recommended for future studies and assessments in that the time constant is reasonably short and measured data are available. Development of a risk assessment method to relate the velocity measurements to risk of injury is also recommended. Inclusion of ambient winds should be assessed.

Impacts on Passengers Waiting on Platforms and Track Workers

A comprehensive approach to safety should include methods of assessing all train types and separate criteria for less aerodynamic train types such as freight trains. The 1-second moving average method is recommended for future studies and assessments. Development of a risk assessment method to relate the velocity measurements to risk of injury is also recommended. Inclusion of ambient winds should be assessed.

Impacts on Adjacent Trains

Scale model and full-scale moving tests should be conducted and analyzed to determine the extent of potential impacts and to develop mitigation measures.

2.6.4 Operation Procedure Recommendations

Tier II operations

Recommended minimum safe distances for passengers and track workers for Acela trains up to 150 mph and Amfleet trains up to 125 mph have been developed [5].

The existing safety record for passengers and track workers along these routes is currently being reviewed to determine the suitability of these guideline distances at these lower speeds. In the event they are shown to be safe then the authors recommend obtaining more measurements compatible with the type of data likely to be available for Tier III trains. The authors recommend the following:

- Perform measurements of air velocity at platforms and at open track to gather data for at least 20 runs for each train type at each measurement position where this has not already been done.
- Measure at the European TSI position and at the minimum safety distance recommended by Lee [5], as well as at larger distances.
- Process data according to the European TSI method so that velocity coefficients can be compared like-for-like with measurements from potential Tier III trains, including Acela operations.

Having established a reference based on a good safety record, this reference should be used in comparative analyses to support introduction of new trains. Full-scale measurements should be made to obtain velocity coefficients. For further speed increases, safe distances could be derived by reference to existing safe distance versus speed curves.

Tier III operations

For Tier III, rules are required for the United States covering:

- Speed limit for platform tracks, considering children in strollers as well as standing passengers.
- Safe distance for passengers, according to the speed limit on platform tracks.
- Safe distance for track workers, according to line speeds up to 250 mph.

These rules would allow operators or other bodies an option to design Tier III railways with a method that compensates for slipstream effects (see Table 5).

As described in Chapter 11, we recommend a two-part approach in the Aerodynamic Guidance Manual (applicable for remaining sections also): simple guidance for trains that satisfy certain aerodynamic criteria and speeds up to 200 mph ("Part 1"), and a fully flexible system that includes all train types and speeds up to 250 mph ("Part 2").

Table 5 outlines the two approaches for developing guidance for slipstream safety. The table also compares the advantages and disadvantages of the two approaches.

Table 5. Development of rules for HST operations: slipstream effects

		Simple system ("Part 1")	**Fully flexible system ("Part 2")**
APPLICABILITY	Train size	Same as European TSI	Any
	Train aerodynamic performance	Same as European TSI	Any
	Maximum speed	200 mph	250 mph
RULES/GUIDANCE POINTS	Speed limit for platform tracks	125 mph (as in France and Germany)	To be developed in coordination with FRA.
	Safety distance for passengers from platform edge	5 ft (if maximum platform speed limit is 125 mph).	Testing to find effect of train width and height. If train size/speed is same as Acela, use same safety distance as NE Corridor. Use comparative analysis based on speed or train size if different from Acela.
	Safe distance for track workers	Select distances based on Figure 6 (distance dependent on line speed)	Reduced scale model testing to obtain coefficients at larger distances, and speeds up to 250 mph. Comparative analysis to develop guidance
Advantages		System ready-made and in the public domain. Lower cost/effort to develop rules Most trains are already developed to pass European rules – no further testing of trains is needed. Safe distances for speeds up to 186 mph backed up by history of safe operation.	Less restriction for operators: can select any train.
Disadvantages		Excludes some trains e.g. double-deck Shinkhansen. "Safety" criteria do not relate directly to risk of adverse impacts.	Cost and time to develop rules, e.g. for testing. Operators or train makers need to perform tests to show trains meet USA rules. No history of operations above 150 mph.

All Tiers

There are instances in Europe of fatalities due to train slipstreams blowing baby strollers into the side of trains. Consideration must be given to mitigation measures such as safety notices, staff training, etc.

A speed limit for freight trains passing passenger platforms should be considered taking account of the safety of standing passengers and children in strollers.

Risk-Based Assessment System

In the longer term, it would be desirable to develop a risk-based assessment system with acceptability criteria based on the probability of unacceptable impacts occurring, and taking into account the naturally-occurring variations in train slipstreams, human response and other factors. Substantial research efforts would be needed to achieve this.

3. Open Air Considerations: Pressures on Wayside Structures

As a high speed train (HST) passes a stationary object adjacent to the track, a pressure pulse impacts the object at the moment of passing (manifested in the gust or jolt of wind experienced by the object). The magnitude of this pulse determines the impact and fatigue structural loads on an object and also vibrations that may be experienced by nearby buildings.

3.1 Introduction and Summary

This chapter will examine this pressure pulse and the resultant pressures on wayside structures. It includes:

- basic aerodynamic concepts;
- influencing factors;
- measurement and calculation of pressure pulses;
- known and potential impacts;
- existing mitigations;
- standards;
- data from the literature review including measurements, criteria, and evaluation and assessment methodology; and,
- conclusions and recommendations including additional mitigation studies.

This chapter has the following general conclusions and recommendations:

- acceptability criteria are not presently required by the rail industry with the expectation that the structures will be designed to accommodate the pressure loadings or will be positioned further away from the tracks;
- existing formulae for the calculation of pressure pulse loads exist but development of factors to account for the 250 mph speeds and North American type trains are needed;
- acceptability criteria for pressure pulses acting on nearby buildings is lacking and needs to be developed; and
- mitigation measures for nearby building vibrations and potential damage to train cars need to be developed and evaluated.

3.2 Pressure Pulse

3.2.1 Basic Aerodynamic Concepts

A zone of high pressure (highly compressed) air moves with the train just in front of the train's nose, with a zone of low pressure (negative pressure) air immediately behind the nose.

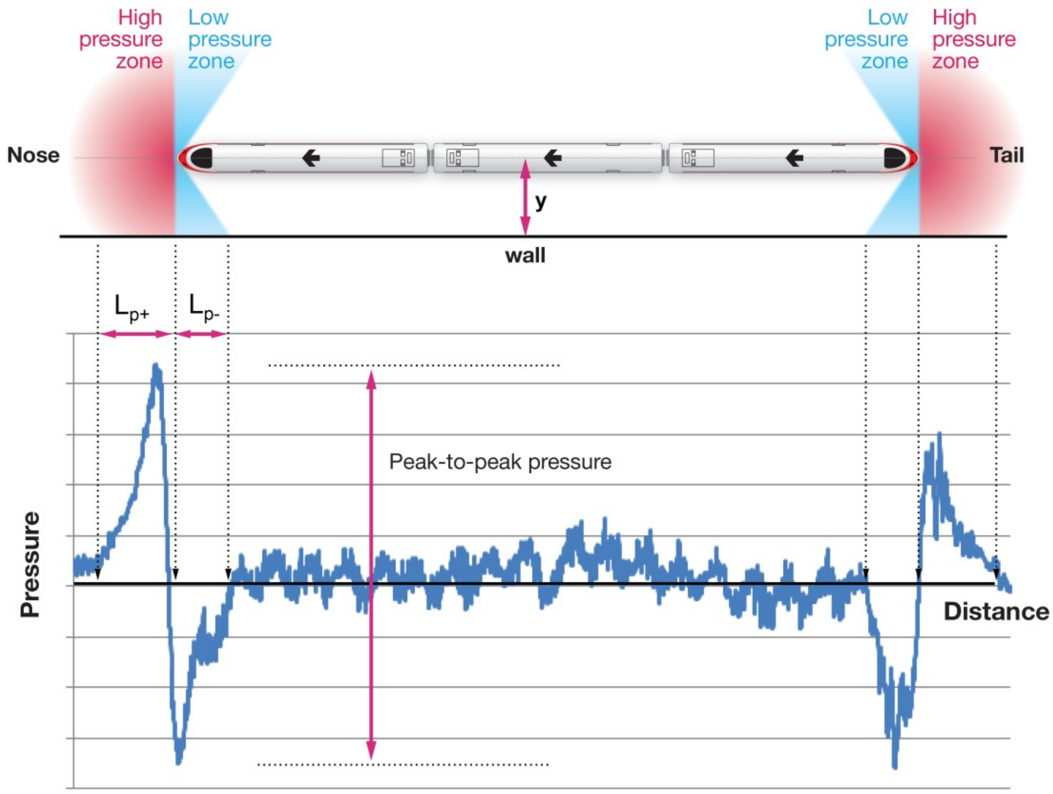

Figure 10. Pressures near the nose and tail of a train

The situation is reversed at the tail of the train, where there is a zone of negative pressure air just ahead of the tail of the train, and a zone of higher pressure immediately behind the tail. The tail pressure pulse is generally smaller than the nose pressure pulse. Figure 10 shows these typical pressure pulses.

Any structures, objects, people or other trains close to the passing train experience a rapid pulse of positive then negative pressure as the zones pass over them (i.e., a push away from the train and then a pull towards the train). Where a fixed structure such as a wall is present parallel to the track, the pressures are increased by a factor of 1.5 to 2 [40]. A factor of 2 would be expected from a simple analysis based on image sources. The wall experiences the pressure distribution shown in the bottom half of Figure 10 moving along the wall at the speed of the train. The train itself also experiences the increased high and low pressures local to the nose and tail. The pulses are characterized by the peak-to-peak pressure difference, and the dimensions of the high and low pressure zones (shown as L_{p+} and L_{p-} in Figure 10). Some authors give the magnitudes of the positive and negative pressure peaks separately.

In addition to the nose and tail of the train, pressure pulses can be generated at the coupler of nose-to-nose coupled trains.

A similar situation exists when one train passes another on adjacent tracks. Chapter 4 discusses this situation in detail.

Pressure pulse amplitude, Δp, is often normalized against the passing train speed v and air density ρ and is expressed as a non-dimensional quality called pressure coefficient c_p:

$$c_p = \frac{\Delta p}{\frac{1}{2}\rho v^2}$$ **Equation 3**

The reason that pressure coefficients are useful is that they remain constant as the train speed varies. The pressure coefficient depends only on geometry (shape of the train, distance between wayside structures and track, etc.) *This is important because experiments may be performed at lower speeds, and the results extrapolated to higher speeds.*

3.2.2 Influencing Factors

Pressure is proportional to the train speed squared. For example, a given object at a certain distance from the track will experience four times the pressure when a train passes at 250 mph (402 km/h), compared to the same train passing at 125 mph (201 km/h). The pressure pulses are very repeatable, unlike slipstream velocity measurements which are not repeatable. This is because the pressure pulses depend on the air flow around the train nose, which remains steady, while the velocities depend on random turbulent effects in the slipstream. If the same train passes the same measuring position at the same speed a number of times, the pressure pulses will typically be within +/- 2% of each other.

The spatial distribution of pressure moves with the train, depends on the shape of the nose and tail, and is insensitive to train speed. Thus, the length of the high pressure zone at the nose of the train (typically 15-25 ft, or 5-8 m) does not alter significantly at speeds between 125 and 250 mph.

The time taken for the high pressure zone to pass over a certain point on a wayside structure is proportional to the inverse of train speed. The higher the speed, the shorter the time for the high pressure zone to traverse that point. For example, the duration of the high pressure loading is halved at 250 mph compared to 125 mph.

The pressure normal to the surface of the structure reduces with distance from the track, approximately with distance from the track center squared.

The magnitude of the pressure pulse is strongly influenced by the aerodynamic design of the train. Trains capable of high speeds must have well-designed aerodynamic shapes, resulting in lower pressure coefficients. Therefore, the pressures generated by streamlined high speed trains are less than would be the case for a less aerodynamic train running at the same speed.

3.2.3 Measurement and Calculation of Pressure Pulses

Calculation of Aerodynamic Loads on Wayside Structures Using Existing Formulae

Well-accepted formulae exist in Europe for estimating loads on the surfaces of wayside structures. These have been adopted in the Standards EN 1991-2, EN 14067-4 and UIC leaflet 779-1. For example, for a vertical surface such as a noise barrier or wall parallel to the track, the pressure distribution is idealized as shown in Figure 11.

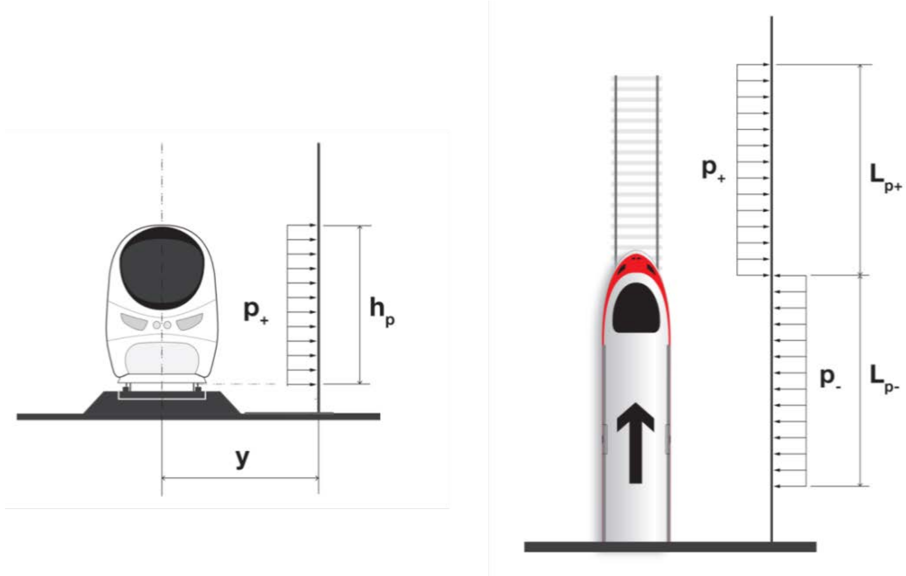

Figure 11. Idealization of pressure pulse on vertical wayside structure, EN 14067 Part 4

L_{p+} and L_{p-} in Figure 11 are assumed to be 16.4 ft (5.0 m). The height of the loading h_p is taken as 16.4 ft (5.0 m) above rail level, or the height of the structure if less than 16.4 ft.

The formulae give the area-averaged pressure, not the peak value. The standard gives a factor 1.3 to convert from area-averaged to localized peak value if required. The formulae may be adapted to allow conversion to the Imperial unit system using the factors below. In the case of the vertical wall, the formula may be written as:

$$\boldsymbol{p_+ = p_- = k_u k_{ap} c_{p,y} \frac{1}{2}\rho v^2 = k_u k_{ap} k_t \left[\frac{A_0}{(y+e)^2} + c_2\right] \times \frac{1}{2}\rho v^2} \qquad \textbf{Equation 4}$$

valid for $y > 2.3$m (7.5ft)

Table 6. Definition of formulae symbols

Symbol	Meaning	Imperial units		Metric units	
		Unit	Value	Unit	Value
p_+	Amplitude of positive pressure pulse	psi		Pa	
p_-	Amplitude of negative pressure pulse	psi		Pa	
k_u	Unit conversion constant	psi $ft^3/(lb\text{-}mph^2)$	4.64×10^{-4}	-	1.0
k_{ap}	Factor to convert from area-averaged to localized peak pressure, if required	-	(1.3)	-	(1.3)
$c_{p,y}$	Pressure coefficient at a distance y from the track centerline	-		-	
ρ	Air density	lb/ft^3		kg/m^3	
v	Speed of the train	mph		m/s	
k_t	Train shape factor	-	(*)	-	(*)
A_0	Reference area	ft^2	26.9	m^2	2.5
y	Distance from track center	ft		m	
e	Constant distance	ft	0.82	m	0.25
c_2	Constant	-	0.02	-	0.02

(*) Values for k_t may be derived from moving-model scale model testing, full-scale testing or CFD analysis based on the shape of the particular train. According to EN 14067-4, for purposes of design, k_t may be taken as 1.0 for freight trains, 0.85 for passenger trains, or 0.6 for aerodynamically shaped high speed trains. In this context, "aerodynamically shaped" is often taken to mean a train that meets the aerodynamic requirements of the European Rolling stock TSI. *Note, however, that although these factors are widely used, they are contradicted by some experimental data. Preferably, experiments should be undertaken to confirm the suitability of the formulae for use in the United States.*

Figure 12 shows the area-averaged pressure pulse magnitude Δp_+ calculated from Equation

$$4p_+ = p_- = k_u k_{ap} c_{p,y} \frac{1}{2} \rho v^2 = k_u k_{ap} k_t \left[\frac{A_0}{(y+e)^2} + c_2\right] \times \frac{1}{2} \rho v^2 \qquad \text{Equation 4}$$

for various speeds.

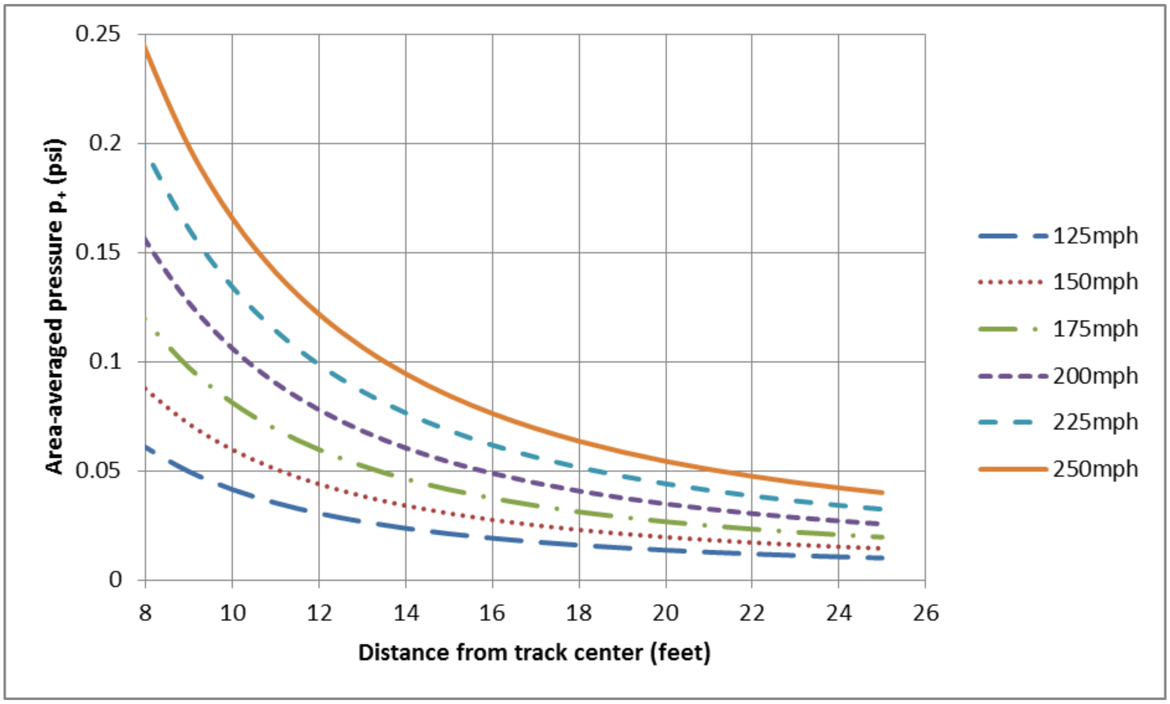

Figure 12. Magnitude of area-averaged pressure pulse on vertical surface (p_+) versus distance from track center for streamlined high speed train, from Equations 4 and 5, EN 14067 Part 4.

Similar formulae are provided for horizontal surfaces above or close to the track, for mixed vertical and horizontal surfaces, and for structures enclosing the track up to 66 ft (20 m) long such as bridges. These formulae are included in EN 14067 Part 4.

Calculation of the Effect of the Loading on the Structures

Having calculated the amplitude of the pressure pulse, (Figure 12, area-averaged pressure) the next part of the assessment is to calculate the effect of the pressure loading on the structure in question. Such calculations should be performed according to the relevant national design codes for structures.

EN 14067-4 notes that the load on the structure is not a static load and that the dynamic response of the structure should be considered. Dependent on the type of structure, there may be dynamic amplification of the applied loading, and for fatigue evaluation, the number of cycles per train passing event may be increased by dynamic oscillations of the structure. The duration of the positive and negative parts of the pressure pulse (Δt_{p+} and Δt_{p-}) are derived from the assumed spatial length L_p of 16.4 ft (5 m):

$$\Delta t_{p+} = \Delta t_{p-} = k_{vu} L_p / v \qquad \textbf{Equation 5}$$

where v is the train speed and k_{vu} is a unit conversion constant (e.g. k_{vu} =1.0 if L_p is in meters and v in meters per second; k_{vu} =0.682 if L_p is in feet and v in mph).

In regards to application to the United States, the formulae in the European standards are well accepted, but have some gaps and limitations. These are:

- The formulae assume a train with European width and height. The standards do not indicate how to vary the formulae for wider or taller trains. For example, the European standards make no reference to double-stacked container consists, but these might be expected to exert pressure over a greater height than other trains.
- The shape factor values may not apply to all North American trains. Work should be done to quantify suitable shape factors for the United States.
- Baker et al [41] highlighted some elements of over-conservatism and inconsistency in the standard formulae and provided alternatives.

Full-scale or reduced scale testing, or CFD analysis, could be undertaken to fill these gaps.

Simplified Examples of Calculation of Pressures

Example 1

It is found that a certain train travelling at 150 mph (241 km/h) exerts a peak-to-peak pressure of 0.12 psi (827 Pa) on a vertical surface 10 ft (3.0 m) from the track centerline. The line speed is to be increased to 250 mph (402 km/h). What peak-to-peak pressure is expected to act on the same surface if the same trains run at 250 mph?

Pressure is proportional to train speed squared, so:

$$\Delta p_{250mph} = \Delta p_{150mph} \times \left(\frac{250}{150}\right)^2 = 0.12 \times 1.667^2 = 0.33\, psi$$

Example 2

A new noise barrier is to be erected 15 ft (4.6 m) from the track centerline. Well streamlined high speed trains will pass at 250 mph. Using Equation 4 above, estimate the magnitude and duration of the positive and negative parts of the area-averaged pressure pulse (p_+ and p_-) on the noise barrier.

Input data:

- y = 15 ft (4.6 m) from track centerline
- Train speed v = 250 mph (402 km/h)
- Assume air density 0.076 lb/ft^3 (1.22 kg/m^3)
- Well streamlined high speed train, so assume k_t =0.6

$$\Delta p_+ = \Delta p_- = 4.64 \times 10^{-4} \times 0.6 \times \left\{\frac{26.9}{(15 + 0.82)^2} + 0.02\right\} \times \frac{1}{2} \times 0.076 \times 250^2$$

$$\Delta p_+ = \Delta p_- = 0.084\, psi$$

The duration of the positive phase is 0.682x16.4/250 = 0.0045 seconds (reference Equation 5 and Figure 11 for the spatial length of 16.4 ft); the duration of the negative phase is also 0.0045 seconds.

3.3 Impacts and Mitigation

3.3.1 Impacts

The principal impacts of the pressure pulses are (a) the potential for damage to wayside structures (described below) and (b) the effects on other trains (see Chapter 4). There are other impacts identified in this section which receive less attention from the rail industry internationally and at current operational speeds are assumed to be of secondary importance. However, for speeds up to 250 mph these impacts may become more significant.

The pressure pulses from the nose and tail of high speed trains pass within about 0.1 - 0.2-seconds. A person's reaction time to wind gusts is around 0.3 seconds or more. It has been determined that the pressure pulse from the train is too rapid to cause a person standing near the track to fall over. A person standing very close to the track would experience a very rapid change of pressure when the nose pressure pulse passes over, which might cause aural discomfort. People are much more affected by the slipstreams from trains, discussed in Chapter 2. Therefore the effect of this pressure pulse from the nose and tail of a train on people is usually classified by the rail industry as being minor compared to slipstream effects. However, as train speeds approach 250 mph a confirmation assessment is recommended.

Passengers inside Trains

Passengers in a train may experience lateral acceleration (a jerking motion) when the train passes a structure close to the track. For high speeds and structures very close to the track, the acceleration could be uncomfortable or startling ("jolting" effect).

Impacts of Pressure Changes within Enclosed or Underground Stations

Pressure pulses can be especially severe within enclosed stations, although pressure load estimates vary widely. There are two separate factors that contribute to the pressure pulse:

- The loading from transient pressure pulses local to the train's nose and tail is increased
- The train causes a "piston effect" in an underground station. (When a train enters a tunnel the magnitude of the compression of the air is dependent on the ratio of train cross-sectional area to station cross-sectional area).

In general, these effects become more significant with increasing train speed through the station.

In Korea high-speed trains frequently pass enclosed stations at full or near full speed. To protect the passengers from the pressure changes, special station designs were developed. In these stations, passing tracks were enclosed in a tunnel-like structure, which reduced the pressure changes within the main station enclosed air space, but increased it within that tunnel. Pressure changes in such tunnels are similar to pressure changes in regular railroad tunnels, and can be approximated with the same formulae that are used to describe compression waves in tunnels, as discussed in Chapter 7. Towing tank experiments and numerical simulations were also performed [20].

In Japan, formulae for pressure changes inside enclosed and semi-enclosed stations were derived from scaled moving model experiments, and a method was proposed for determining the fatigue strength of station structural members subjected to aerodynamic loads [19]. These formulae were later confirmed by full-scale experiments [42] and are discussed in Section 3.5.4.

Damage to Wayside Structures

The problem of aerodynamic loads caused by pressure pulses on structures and equipment adjacent to the track has long been recognized and is not limited to high speed trains. Although magnitudes of the loads may not be high, the large number of occurrences of loadings raises concerns about possibility of failure by fatigue [10, 19, 43]. The literature survey did not reveal any descriptions of catastrophic structural damage due to aerodynamic loads by a single passing train. This is perhaps because it is common practice to design structures near the track to resist the pressure loading. European standards EN 1991-2 [44], EN 14067-4 [24], UIC leaflet 779-1 [45] and others describe how to calculate dynamic loading on horizontal and vertical planes parallel to the track. This is described under "Evaluation" below. Cases of fatigue failure of wayside signs [8], station wall finishing materials, as well as loosening of screws on structural elements due to aerodynamic loads have been reported in the literature [19, 42, 46]. Anecdotal evidence suggests incidences of collapse of fragile wayside buildings or walls due to repeated aerodynamic loading.

Takei et al [19] carried out fatigue testing of station finish materials based on Japanese standard JIS-A1414 [47]. It was confirmed that testing of panels by concentrated load, in the manner described by the authors, produces a stress distribution that is nearly identical to that due to air pressure variation.

Vibration in Nearby Buildings

Complaints have arisen in Japan from the rattling of windows, shutters and doors of residential buildings close to the track when trains pass [48]. This is caused by the pressure pulses at the nose and tail of the trains acting on loose parts of the buildings. Several papers describe field measurements and state that the pressure reduces with distance from the track squared.

Impacts on Infrastructure Design and Cost

To mitigate the increased pressures, noise barriers and other wayside structures will need to be strong enough to resist the pressure loading from trains. This may require that track is relocated if additional right of way is available, or that existing structures are strengthened. In the case of noise barriers, reduced efficiency in attenuating noise may occur if they are placed further from the tracks.

Potential Structural Damage to Trains

When a train passes a wall or other wayside structure close to the track, the nose of the train itself (and to a lesser extent the tail) experiences an increased pressure, which could lead to vehicle damage. For example, the nose cowl may crack or suffer fatigue damage.

The effect of train-induced pressure pulses on other trains on adjacent tracks in an open environment is addressed in Chapter 4.

3.3.2 Mitigation

Mitigation for Pressure on Wayside Structures

Loading on wayside structures is mitigated by (a) specifying the minimum distance from the track at which structures may be built and/or (b) designing the structures to resist the expected pressure loading from trains. The dynamic nature of the loading must be considered, both in terms of maximum stress being affected by dynamic amplification, and also the number of cycles for fatigue life assessment.

Mitigation for Pressure Pulse Causing Vibration of Buildings

The problem of pressure pulses from trains rattling doors and windows of neighboring residential buildings can be mitigated to some extent by constructing high barriers between the tracks and the buildings. Kikuchi et al [48-50] measured the efficacy of several different barrier heights and types in reducing pressures caused by trains running up to 168 mph (270 km/h) on a building 26-33 ft (8-10 m) from the track.

Figure 13. Barrier to mitigate noise and pressure pulse affecting buildings close to the track, from Kikuchi et al [48]
Reproduced by permission of RTRI

Since these pressures increase with speed squared but reduce with distance squared, the need for mitigation depends strongly on the speed of trains and the proximity of the buildings to the tracks. Part of the motivation for Kikuchi's studies was an appreciation that, as speeds increase, buildings further from the track will become affected and therefore the requirement for mitigation will increase. *The likelihood of residential or other sensitive buildings being located relatively close to high speed tracks (or vice versa) in the United States should be considered.*

3.4 Standards

The same guidance and formulae for calculating loads on wayside structures appears in European standards EN 1991-2 [44], EN14067-4 [24] and UIC leaflet 779-1 [45], and in Taiwanese Design Specifications for Civil Works [51], as described in Section 3.2.3. The methods were originally developed by the European Railway Research Institute (ERRI) D189 committee.

The European Technical Specifications for Interoperability (TSIs) [13, 14] do not contain clauses directly relevant to calculating or setting limits on the aerodynamic loading on wayside structures. They do, however, contain advice on testing methods, and also set minimum standards for the aerodynamic performance of high speed trains.

The TSI test standard of most relevance to wayside structures is the following:

- The pressure pulse caused by a train running at (250 km/h) will not exceed 0.12 psi (795 Pa) peak-to-peak when measured in open air at 8.2 ft (2.5 m) horizontally from the track center and 4.9 to 10.8 ft (1.5 to 3.3 m) vertically above the rail head.

3.5 Data from Literature Including Measurements, Criteria, and Assessment/Evaluation Methodology

3.5.1 Aerodynamic Loading Criteria on Wayside Structures

No acceptability criteria have been found for aerodynamic pressure loading on wayside structures. However, the loads may be calculated and the structures may then be designed according to the relevant design code to resist the expected aerodynamic loading. If a fixed structure is desired for use, it can be positioned sufficiently far from the track so that the pressures exerted on it lie within the capability of the structure to resist them.

3.5.2 Use of Formulae for Speeds up to 250 mph

The formulae are expected to remain valid at speeds as high as 250 mph, *except that a small correction may be needed for Mach number effects (Mach 1 is the speed of sound and is approximately 765 mph at sea level).* The European standards do not include a Mach number correction in the formulae. The standards state that Mach effects can be neglected for speeds below Mach 0.25 (approximately 190 mph). However, Lee [10] suggests multiplying the pressure by a correction factor f_v:

$$\boldsymbol{f_v = \frac{1}{\sqrt{1-M^2}}} \qquad \textbf{Equation 6}$$

where M is the Mach number, i.e., the speed of the train divided by the speed of sound. For 250 mph, f_v is approximately 1.06. The correction factor is based on the Prandtl-Glauert transformation and is valid for two dimensional potential flow. The pressure pulses around the head and tail of the train are a potential flow phenomenon, *but the validity of the correction factor for three dimensional situations needs to be confirmed with experimental data.*

3.5.3 Vibration of Buildings

Acceptability criteria for the pressure pulse acting on nearby buildings (and possibly causing rattling of doors, windows, shutters, etc.) are in general lacking. The Japanese Ministry of the Environment [52] publishes a “rattling threshold” for doors and shutters in the form of 1/3-octave spectra of Sound Peak Level. Kikuchi et al [49] compared spectra from micro-pressure waves emitted by tunnels against these criteria. They could also potentially be used to assess open environment pressure pulses. The criteria were derived from laboratory tests with continuous infrasound where Japanese building products were tested. *The applicability of the criteria to American building materials which are generally heavier and may have different vibration characteristics should be further evaluated.*

Further research is recommended into this topic, as a criterion of this type could also be valuable when assessing micro pressure waves from tunnels. New data needs to be measured for North American-style building hardware (doors, windows, shutters, etc.) to support USA-specific equivalents of these criteria. Any acceptability criteria developed in the future should differentiate between air-borne and ground-borne vibration, which can cause similar effects.

3.5.4 Enclosed and Partially Enclosed Stations

Takei et al [19] analyzed a case where a train passes through a partially covered station. Two simplified formulae were derived using metric units.

In the first instance for a fully covered station (with a narrow slit in the roof), the authors modeled a train passing through a square tunnel with a slit parallel to the track. The maximum pulse pressure was estimated as:

$$\boldsymbol{P_{max} = C_{p,max}\frac{1}{2}\,\rho V^2} \qquad \textbf{Equation 7}$$

$$\boldsymbol{C_{p,max} = 2(1 - 15R_O)R_B\left(\frac{L}{L_O}\right)^k} \qquad \textbf{Equation 8}$$

$$\boldsymbol{k = -0.037R_O R_B^{-3.1}} \qquad \textbf{Equation 9}$$

where C_p is the pressure coefficient, R_O is the opening ratio (ratio of slit width to station cross-section's perimeter), R_B is the blockage ratio (ratio of train's and station's cross-sectional areas), L is the distance from the adjacent wall to the center of the track, L_O is the standard distance (13 m, or 42.7 ft), and k is a power exponent defining attenuation by distance.

The formula is valid for train speeds 200-350 km/h (124-217 mph), blockage ratios 0.04-0.08, opening ratios 0.005-0.035 and distances to lateral wall 6-20 m (20-66 ft). Air compressibility effects are ignored. The ranges of applications were determined from field measurements.

In the second instance for a partially covered station, Takei et al modified a formula used for estimating pressures in the open environment:

$$\boldsymbol{P_{max} = \alpha\frac{2}{3\sqrt{3}}\frac{\rho A V^2}{2\pi Y^2}} \qquad \textbf{Equation 10}$$

where A is the train's cross-sectional area, Y is the distance between the measurement point and the center of the track, and α is a corrective coefficient based on the measurements taken in multiple partially covered stations of Japanese high-speed railroads. For measurements taken near walls of the stations, $\alpha = 2.3$. The formula is valid for train speeds of 230-360 km/h (143-224 mph) and Y of 6-18 m (20-59 ft). α also needs to be adjusted for different train shapes.

Discrepancies between formulae prediction and experimental data, as reported by the authors, can be as much as 25%, with the largest discrepancies occurring in partially covered stations with small cross-sectional areas.

3.5.5 Pressure Loads on Trains Caused by the Presence of Wayside Structures

The data from the literature review revealed this issue is not considered to be problematic internationally. However, *as train speeds increase up to 250 mph there may come a point where the impacts on the train of passing wayside structures very close to the track become significant*, either in terms of damage to the nose of the train or in terms of startling passengers. In the absence of any published methods, a “comparative assessment” method might be possible for the open environment, as described for trains passing other trains in Chapter 4.

For determination of the pressure pulse, Baker et al [41] used a reduced scale moving model test rig to derive pressure coefficients for three British train types and several types of wayside structures. One of the aims of the work was to develop design curves similar to those in the European standards, but specific to British trains which are smaller than European trains on which the standards are based. The study showed that application of the European standards to UK railway design can be overly conservative. While not directly corresponding to North American conditions, this study demonstrated that train size must be accounted for in any aerodynamic design rules or standards. In the case of canopies above the track, the formulae in the European standards were shown to be overly conservative irrespective of train size.

For enclosed and partially enclosed stations, Takei et al [19] analyzed a case where a train passed through a partially covered station and then derived formulae for application to both scenarios. However, deviations between predicted and experimental data may be as much as 25% in certain situations. A factor of safety applicable to the formulae may be required.

3.5.6 Assessment Methods

Reduced Scale Moving Model Testing

Reduced scale moving model tests are a quick and economical way to assess loads on wayside structures, including types of structure for which the simple formulae are inappropriate, e.g. very short structures where three-dimensional effects are significant. Because pressure pulses show little test-to-test variation, it is common practice to perform three nominally identical runs for each condition tested. The model structure is instrumented with pressure gauges. Pressure coefficients measured at model scale are assumed to be the same at full-scale, provided that the geometry of train, structures, and measurement positions are all to scale in the model. Pressure coefficients measured at reduced scale typically match full-scale to within 5%.

Wind Tunnel Tests

Wind tunnel testing may be used to assess the pressure pulse acting on a long fixed structure, such as a noise barrier where the pressure pulse reaches a steady state in the frame of reference relative to the moving train. However, wind tunnel testing cannot be used for short structures or other situations where transient effects are important [24].

Full-Scale Tests

Full-scale testing is used to obtain coefficients for a particular train, or for a particular train/structure combination. These may be used in train design and in the assessments of wayside structure designs. When measuring pressures on fixed structures, it is preferred to place the pressure tappings through the surface (i.e., within holes drilled in the structure), or, if that is impossible, a thin flat mounting board may be used (i.e., ¾ inch thick) with rounded edges to minimize disturbance to the flow.

Computational Fluid Dynamics (CFD)

Any CFD method that solves the potential flow equations is suitable for assessing the pressure pulse acting on a continuous wayside structure. Since viscous and turbulent effects are of secondary significance, the panel method, Reynolds Averaged Navier-Stokes (RANS) procedures and other methods may all be used. The train model should move past the structure in the simulation, starting at least one car length behind and finishing at least one car length in front of the point where the pressure is being measured.

3.6 Conclusions and Recommendations

These conclusions and recommendations are principally directed toward Tier III operations on new tracks, but have relevance to assessments of proposed speed increases on existing Tier II tracks.

3.6.1 Conclusions

The following conclusions have been determined through the review of the literature:

- Aerodynamic concepts are well understood.
- The results of experiments and assessments performed at lower speeds can be extrapolated to higher speed conditions.
- Existing pressure formulae have been developed based on European type trains.
- Pressure pulse impacts to track workers are currently considered minor compared to the effect of slipstreams.
- Current mitigation methods are based on increasing separation distances between the train and wayside structure or calculating the loads and designing the wayside structure to accommodate the loading.
- Current mitigation methods for vibration effects are based on increasing the separation distance or constructing barrier walls and structures.

3.6.2 Gaps and Issues

Impacts on Track Workers

At current operating speeds the impacts of slipstreams are included in assessments while the impacts of pressure pulses are ignored. No verification of this assumption for ignoring pressure pulse impacts was found.

Criteria for Loading on Wayside Structures

No assessment or acceptability criteria by the general rail industry have been found to specifically address aerodynamic pressure loading on wayside structures.

Criteria for Vibration of Wayside Structures

Acceptability criteria for vibrations of nearby buildings from pressure pulses are in general lacking.

Adjustment Factors in Formulae to Accommodate North American Vehicle Types and Mach Number Effect

Adjustment factors to apply to the existing formulae may be required.

Mitigation for Loading on Trains when Passing Wayside Structures

Loading on trains due to passing wayside structures is not currently seen as a problem internationally. Traditionally, the minimum distance between the track and wayside structures is determined from the dynamic envelope of the trainset, but this may be insufficient for speeds as high as 250 mph. A mitigation could be to specify the minimum distance from the track at which structures may be built as a function of train speed. For new structures this would address the potential issue of damage to the trains, and also the potential impact of the jolting effect on passengers as the train passes the structure. For lines with existing structures close to the track there are presently no methods for assessing the potential effect of the pressures on trains.

3.6.3 Recommendations to Address Gaps and Issues

Track Workers

Tests and assessments should be conducted to confirm impact of pressure pulses on workers for trains reaching 250 mph.

Loading on Wayside Structures

It is recommended to set a rule for new Tier III tracks governing the minimum distance from the track at which structures may be built, as a function of line speed. The rule could be developed by comparative analysis, using existing United States operational experience as a baseline, to ensure that pressures on structures are no higher than for existing Tier I and Tier II operations despite the higher speeds of the Tier III operations.

For Tier II operations applications for increases in line speed should be checked against the likelihood of damage to existing structures. Comparative analysis methods can be used to check whether the pressure from high speed trains at the proposed new speed would exceed the pressures already experienced by the same structures from less aerodynamic lower speed trains.

Vibration of Wayside Structures

The thresholds at which pressure pulses from passing trains could cause doors, windows, shutters, etc., to rattle for typical North American buildings should be measured. This would allow acceptable limits to be set on such pressure pulses, so that the need for mitigation measures such as barriers can be determined. Differentiation should be made between air-borne pressures and ground-born vibrations. Compatibility with existing rules for ground-borne vibration is recommended.

Adjustment Factors

A discussion of the derivation of the formulae in the standards is included in this study, and alternatives to those formulae are presented that offer a better fit to the experimental results. The existing European formulae for calculating aerodynamic loads on wayside structures could be adopted in the United States *but require confirmation or adaptation in some areas*.

It is recommended to perform full-scale or reduced scale model testing to fill these potential gaps:

- *Shape factors are required for North American train shapes where no similar train type exists in Europe, especially if pressure loads from freight trains are to be considered (e.g., double-stacked containers).*
- *Adaptations to the European formulae may be required for different widths or heights of trains.*
- *For speeds above 190 mph (Mach 0.24), a Mach effect correction factor should be included in the formulae as a conservative measure.*

Loading on Trains

In Europe, there is a regulatory system that ensures at least a minimum standard of aerodynamic design of high speed trains (Rolling Stock TSI [14]). This enables designers to calculate the maximum likely aerodynamic loading on wayside structures without needing to know exactly which high speed trains will pass. The benefits of adopting such a system in the United States should be considered.

It is recommended to consider adopting the European TSI criteria for aerodynamic performance of high speed trains for Tier III operations, or alternatively adopt an equivalent set of criteria based on North American high-speed experience (e.g. Acela).

4. Open Air Considerations: Trains Meeting/Passing

As a high speed train (HST) meets or passes another train, the pressure pulses of the moving train(s) act on the adjacent train. The magnitude of these pressures can cause effects including an unpleasant jolt felt by a passenger and cargo damage in the adjacent train.

4.1 Introduction and Summary

This chapter examines the pressure pulse and the resultant pressures on adjacent trains. It includes:

- basic aerodynamic concepts;
- influencing factors;
- measurement and calculation of pressures between trains;
- known and potential impacts;
- mitigations;
- standards;
- data from literature including methodology, experimental data, formulae development, and assessment criteria; and,
- conclusions and recommendations including Tier II and III operational procedures.

This chapter has the following general conclusions and recommendations:

- aerodynamic concepts and theories are well understood, but little information is available as to what resultant pressures should be deemed acceptable;
- factors for various formulae have been developed to accommodate the experimental data from non-United States type train vehicles;
- existing mitigation methods in many instances can be used with specialized enhancements;
- testing should be conducted for applicability of existing formulae with United States type train vehicles and establishment of formulae for correlation with computer simulation modeling; and
- EN 14067 – Part 4 formulae should be adopted with revisions to accommodate United States train types and operations for determination of track spacing and pressure impacts.

4.2 Pressure Pulses between Trains

4.2.1 Basic Aerodynamic Concepts

As described in Chapter 3, a zone of high pressure (positive) air moves with the train just in front of the train's nose, with a zone of low pressure (negative) air immediately behind the nose. The situation is reversed at the tail of the train. The pressure pulses generated by a moving train act on a train on an adjacent track. If both trains are moving, each has high and low pressure zones at the nose and tail that affect the other train. A passenger seated in one train experiences a jolt as the pressure pulse from the other train moves along the car in which the passenger is sitting. Although slipstreams from trains could potentially affect trains on neighboring tracks, the effects of slipstreams on trains are small compared to the effects of pressure pulses. From the literature search they are not included by the rail industry in current assessments.

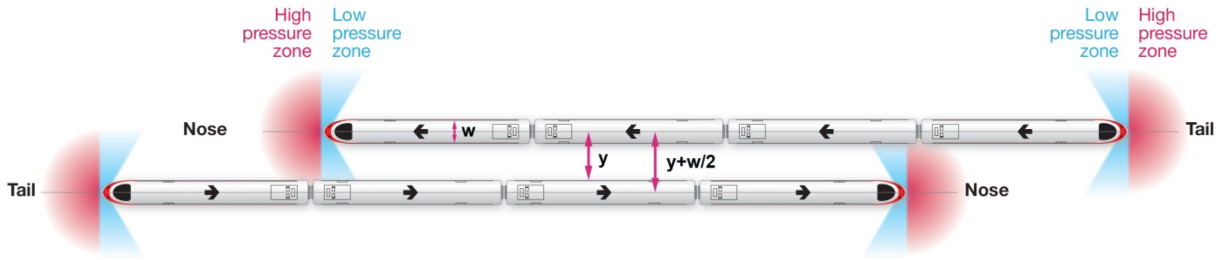

Figure 14. Pressure pulses acting between high speed trains

Peak-to-peak pulse amplitude is typically on the order of 0.1-0.3 psi (0.5-2 kPa) and depends principally on train speed, track spacing, and the aerodynamic design of the train. High speed trains are not necessarily the worst case as the effects of higher speeds can be compensated by improved train car streamlining. Conversely, freight trains can generate high pressures due to their poor aerodynamics.

Pulse duration depends on a train's speed and nose length and is in the range 0.1-0.4 seconds [53-59]. The pressure pulse associated with the train nose is greater than the pulse associated with the train tail and these pressure pulses depend heavily on train shape [60]. Smaller pressure pulses may arise from the gaps between railcars, from the point where two train sets are joined into a multiple unit, or from pantograph cowls.

The pressure pulse amplitude, Δp, is often normalized by the passing train speed v and air density ρ and expressed as a non-dimensional quality called pressure coefficient c_p:

$$c_p = \frac{\Delta p}{\frac{1}{2}\rho v^2} \qquad \textbf{Equation 11}$$

When describing measurements of pressure pulses, one train is described as the "passing" train (which generates the measured pressure) and the other train is the "observing" train (on which the pressure measurements are made).

It should also be noted that in some international publications the term "crossing" is used to describe any event in which two trains move past each other on adjacent tracks. In the United States, the general practice is to use the term "passing" to describe a situation where trains move in the same direction at different speeds (or if one of the trains is stationary), and to use the term "meeting" if the two trains are moving in the opposite directions. The terms "passing train" and "observing train", as defined earlier, are still applicable whether the situation is described as "passing" or "meeting".

4.2.2 Influencing Factors

Train Speed

As with aerodynamic pressures on any surface near the track, the amplitude (magnitude) of the pressure peak experienced by a stationary observing train is proportional to the square of the speed of the passing train. If both trains are moving, the amplitude of pressure change on the observing train's surface depends mainly on the speed of the passing train, while the speed of the observing train has a lesser effect on the passing train [10, 43, 61-63]. This effect can be explained as follows [43]:

"The amplitude of the pulse, however, is set mainly by the passing train and is virtually unaffected by the observing train, except by way of its presence and the distance of the observer away from the passing train. This is because the pulse is a far-field manifestation of the train nose surface pressure distribution, which will only be affected by a change of the free-stream onset flow velocity and direction. The presence of the observing train is only likely to affect these to a very small extent for streamlined high-speed trains […] the wall pressure amplitude at the observing train will be double that of the free-air value without it."

Crosswind

There are very few studies analyzing a situation when two trains are passing or meeting and experiencing crosswind at the same time. The headwind or tailwind component of the wind may be accounted for by using the train speeds relative to the wind in aerodynamic calculations (i.e., a headwind increases the effective train speed) as seen from results obtained by Holmes et al [64]. This assumption is also recommended when calculating the pressure loading on wayside structures [24]. The component of the wind perpendicular to the track is likely to affect the pressures generated by passing or meeting trains on each other, *but no research on this topic has been found.*

Track Spacing

The distance between the track centers has a major influence on the magnitude of pressures during train passing or meeting. There is approximately an inverse-square law relating pressure on passing trains to the distance between the track center of the passing train and the surface of the observing train, i.e., pressures decrease with increasing track spacing distances [65]. Different formulae for this are given by different authors (see Section 4.2.3).

Aerodynamic Design of the Train

This plays an important role in determining the pressures acting between passing and meeting trains, with the more aerodynamically designed high speed trains showing up to 2.5 times lower pressure coefficients for the train-passing situation than their less streamlined counterparts [57, 58]. In this report, we are concerned only with aerodynamic effects arising from trains with speeds over 110 mph, therefore pressures generated by freight trains as they pass other trains, which can be large, are not discussed here as their speeds are less than 110 mph. *However, if there are future plans to have freight trains exceed 110 mph additional research will be required.*

Embankments and Bridges

There is very little difference on pressure pulse magnitudes between the cases of trains meeting or passing on level ground, on an embankment, and on a bridge [54].

Tunnels

When trains meet or pass in single-tube (twin-track) tunnels, the situation is complex and very different from the open air case. Pressure waves caused by entry and exit of the trains propagate along the tunnel and act on both trains. These are additional to (and generally larger than) the pressure zones local to the train nose and tail. The nose and tail pressure zones are also modified compared to the open air case because of the confinement of the tunnel and the movement of the air along the tunnel and over the train. This condition is included and discussed more fully in Chapter 7.

4.2.3 Measurement and Calculation of Pressure Pulses between Trains

When pressures are measured on a stationary train, the square-law dependence of pressure on the speed of the passing train is well-established [66, 67].

Different authors provide different estimates of the influence of the speed of the observing train when both trains are moving. Recent Chinese experimental and numerical studies show that if two trains are moving at equal speeds, the pressure change will be 10-25% higher than if one of them is standing still [62]. From the TRANSAERO project, full-scale tests showed about 25% increase [68], and a “panel method” analysis also showed about 25% increase [69], when the speeds of both trains were equal compared to the case where one is stationary. Earlier French and German experiments showed a difference of about 30-40% [10, 70].

Pressures are affected by the vertical position of the point at which the pressure pulse is measured. Some published data includes measurement points above the level of the roof of the passing train. Unsurprisingly, these show lower pressures. The published data from full-scale experiments [55, 56, 64] show that for 12 ft (3.7 m) track spacing, pressure changes at 9 ft (2.7 m) and 17.5 ft (5.3 m) above the top of rail differ by nearly by a factor of two. Data from numerical experiments [60] indicate that for 16.4 ft (5m) track spacing, the maximum pressure changes occur at a height of approximately 1.6-3.3 ft (0.5-1 m) above the rail and become about 30%-40% lower at a height of 9.7 ft (3 m).

Calculation of Aerodynamic Loads by Formulae

There is no universally-agreed formula for predicting the peak-to-peak pressure generated when trains pass or meet each other. In Section 4.5.4, two similar formulae are discussed, the Gaillard formula, and the formula from EN 14067-Part 4 intended for calculating pressure loads on wayside structures but relevant also to an observing train. Either of these could be used in assessments. Data in the literature does not conclusively suggest which formula is more accurate though the results given from the formula of EN 14067-Part 4 are marginally closer to the observed experimental data than the Gaillard formulae. For this reason the authors propose that the EN 14067-4 formula be adopted for North American assessments of the train-passing situation by including factors not present in the original standard (see Chapter 3):

$$\boldsymbol{p_+ = p_- = k_u f_v k_d k_{ap} k_t \left[\frac{A_0}{(T-\frac{w}{2}+e)^2} + c_2\right] \times \frac{1}{2}\rho v^2}$$ **Equation 12**

where:

Table 7. Definitions of formulae variables

Symbol	Meaning	Imperial units		Metric units	
		Unit	Value	Unit	Value
p_+	Amplitude of positive pressure pulse	psi		Pa	
p_-	Amplitude of negative pressure pulse	psi		Pa	
k_u	Unit conversion constant	psi $ft^3/(lb\text{-}mph^2)$	4.64×10^{-4}	-	1.0
f_v	Mach number correction	-	See above		
k_d	Correction factor for speed of observing train	-	1 to 1.25	-	1 to 1.25
k_{ap}	Factor to convert from area-averaged to localized peak pressure, if required	-	1 to 1.3	-	1 to 1.3
$c_{p,y}$	Pressure coefficient at a distance y from the track centerline	-		-	
ρ	Air density	lb/ft^3		kg/m^3	
v	Speed of the train	mph		m/s	
k_t	Train shape factor	-	(*)	-	(*)
A_0	Reference area	ft^3	26.9	m^2	2.5
y	Distance from track center	ft		m	
e	Constant distance	ft	0.82	m	0.25
c_2	Constant	-	0.02	-	0.02

The unit conversion factor k_u allows for non-consistent unit systems so that $k_u = 4.64 \times 10^{-4}$psi $ft^3/(lb.mph^2)$ if v is in mph, ρ is in lb/ft^3, T and w are in feet, A_t is in square feet, and the pressure is required in psi.

Pressure coefficients and formulae for pressures induced by train meeting can be used for higher speeds since the proportionality of induced pressure to train speed squared has been well established. Such extrapolation is possible until speeds become so high that air compressibility can no longer be ignored. In these cases, a correction factor based on the Prandtl-Glauert transformation (previously presented in the discussion of **Equation 6**) has been proposed [10] where M is Mach number (Mach 1 is approximately 765 miles per hour) corresponding to train speed:

$$\boldsymbol{f_v = \frac{1}{\sqrt{1-M^2}}}$$ **Equation 13**

For 150 mph, the correction factor equals 1.02; for 250 mph, it equals 1.06. *The validity of the correction factor for three dimensional situations needs to be checked against experiments,* as discussed in the Wayside Structures section of this report.

The dynamic factor k_d adjusts for the speed of the observing train. It takes the value 1.0 when the observing train is stationary, and is estimated at 1.25 for the case where the speed of both trains is the same [68, 69].

The need for the factor k_{ap} depends on how the calculated pressure will be used. For assessments of localized stress or failure, the peak pressure is required, and therefore k_{ap} would be set to 1.3. If the overall force on a vehicle of the observing train is to be calculated, then the area-averaged pressure is more appropriate, and k_{ap} would be set to 1.0.

There are some gaps in the knowledge related to this formula:

- The above formula in its entirety (including k_u, f_v, k_d) has not been published or verified. The authors have proposed the additional factors based on the sources mentioned in the notes above.
- The validity of the proposed Mach number effect needs to be confirmed.
- The formula is intended for European train sizes, and for trains that comply with the European TSI requirements for aerodynamic performance.

It is recommended to verify by testing how well the formula represents behavior at speeds up to 250 mph to obtain shape factors for the high speed trains likely to be used in North American conditions, and to determine the adaptations needed for trains of significantly different cross-sectional areas or widths. *This could be done by reduced scale model testing.*

Tian et al [62, 71] and Li [59] have published substantial volumes of data on aerodynamic loading from train meeting. Their data may be helpful in validating the proposed formula. *Further assessment is required.*

4.2.4 Simplified Examples

Example 1: Estimation of Peak-to-Peak Pressure

The tracks for 250 mph trains are separated by T = 18 ft center-to-center. The train cross-sectional area is 113 sq ft and the width is 10 ft. The shape factor for the Gaillard formula for these trains is 0.25. The air density is 0.07lb/ft^3. What peak-to-peak pressure is expected to act on a train on the adjacent track, when both trains are travelling at 250 mph?

Using Equations 12 and 13:

$$\Delta p = k_u f_v k_d k_t \frac{A_t}{(T - \frac{w}{2})^2} \times \frac{1}{2}\rho v^2$$

$$= 4.64\text{x}10^{-4} \times 1.06 \times 1.25 \times 0.25 \times \frac{113}{\left(18 - \frac{10}{2}\right)^2} \times 0.07 \times \frac{250^2}{2}$$

Hence Δp=0.22 psi.

Note: this is not a recommendation for actual track separation for 250 mph. This is purely an arithmetic example of the method by which an initial assessment of the pressure pulse might be made.

Example 2: Comparative Assessment Using Modified EN 14067-4 Formula

A certain high speed railway operates at 200 mph and a track spacing of 14.8 ft without unacceptable aerodynamic impacts when trains meet. The trains are 9.8 ft wide. If the same trains are to operate on a new railway at 250 mph, what track spacing is required such that the pressures arising from train crossing are no greater than on the existing railway?

In this case, we need:

$$\Delta \boldsymbol{p}_{\boldsymbol{200mph}} = \Delta \boldsymbol{p}_{\boldsymbol{250mph}}$$

From Equations 12 and 13 and the previous Example 1:

$$k_u f_{v,200} k_d k_{tG} \frac{A_t}{(T_{200mph} - \frac{w}{2})^2} \times \frac{1}{2} \rho v_{200mph}{}^2 = k_u f_{v,250} k_d k_{tG} \frac{A_t}{(T_{250mph} - \frac{w}{2})^2} \times \frac{1}{2} \rho v_{250mph}{}^2$$

Therefore, after cancelling the terms that are the same on both sides,

$$\frac{1.036 \times 200^2}{(14.8 - \frac{9.8}{2})^2} = \frac{1.058 \times 250^2}{(T_{250mph} - \frac{9.8}{2})^2}$$

From which the track spacing for 250 mph would be T_{250} = 17.4 ft.

4.3 Impacts and Mitigation

4.3.1 Passenger, Vehicle, Equipment, and Freight Impacts

When trains meet or pass each other on adjacent tracks, the pressure zone from one train arrives suddenly on the other train and passes down its length, causing a lateral dynamic disturbance. The impacts are described in terms of passengers being startled by a noise or uncomfortable lateral acceleration (jolting motion) [72]. Although one might imagine such dynamic disturbances leading to safety concerns, no record has been found in the literature of derailment or other safety issues arising from this.

Some publications describe other potential negative impacts [54, 59, 62, 69, 73], such as:

- excessive deformation of train bodies;
- fatigue damage to train bodies;
- shattering of train windows;
- deterioration of running safety; and,
- excessive wheel and rail wear.

However, none of the publications clarify whether these impacts have actually been observed. Only anecdotal evidence of the effects noted previously on passenger comfort has been documented.

In regards to high speed trains meeting or passing conventional trains, secondary impacts causing damage to the conventional train cars have been reported.

Tier III Operational Impacts

For Tier III operations in the United States, it is likely that dedicated new-build tracks will carry the high speed trains, and that there will be a large separation from any conventional tracks. It is also likely that, where new Tier III trains run on existing lines (for example, on the approach to city terminals), current speed limits on those lines will apply such that aerodynamic interactions are no worse than those currently experienced on those lines. Therefore, for Tier III trains, the aerodynamic impacts with conventional passenger trains or freight trains could be completely mitigated.

Tier II Operational Impacts

For Tier II operation with high speed trains alongside conventional traffic, the aerodynamic interactions might conceivably cause adverse effects. According to Tielkes [16], for lines with mixed traffic it is necessary to consider the following train-induced aerodynamic loads on conventional rolling stock:

- Pressure pulse effects - the pressure pulse from the high speed train might damage freight railcars or their contents:
    - Railcar doors might be subject to additional loading contributing to fatigue damage.
    - Double-stacked container cars or other high-sided vehicles might derail or the containers might slide or topple.
- Slipstream effects - the wind from high speed trains might affect cargo:
    - Bulk cargo, such as coal, transported in open gondola cars can, in principle, be blown out by air movement during train passing. The impacts might be loss of cargo, or hazard to people standing by the track. This problem has not been addressed in any publications found in the literature search.
    - Particles carried in the wind might damage paintwork on automobiles or other valuable cargoes.
- Cargo effects - freight cargo might cause damage or hazard to high speed trains:
    - Particles of coal or other cargo might be lifted by crosswinds and deposited on the high speed tracks, leading to damage to rails and wheels.
    - Fabric covers or other lightweight equipment might be blown onto the high speed tracks leading to risk of derailment.

No evidence of these impacts actually occurring during railway operation has been found in the literature search; but, this may be because few countries operate high speed and conventional traffic alongside each other. The Tier II situation in the United States is experienced on Acela with its current speeds, and has been studied extensively [5, 55, 56]. While numerical models indicate the potential for derailment of the freight train no such incidents have been recorded.

4.3.2 Mitigation

Track Spacing between High Speed Lines

The key standard mitigation measure to minimize the aerodynamic effects from trains meeting or passing is to increase the minimum center-to-center distance between the adjacent tracks. This may lead to higher costs; it is estimated that a one foot (30 cm) increase in subgrade width increases construction costs by 1% [74]. Track spacing is normally determined by reference to national standards, which were developed taking aerodynamic considerations into account.

Minimum track spacing of the high-speed lines around the world are summarized in Table 8 and Figure 15 below. These are based on maximum speeds less than 217 mph (350 km/h).

Table 8. Minimum track spacing in various HST systems

Country	Railway line	Design speed	Max service speed	Min track spacing	Source
Japan	Tokaido Shinkansen		167 mph (270 km/h)	13.8 ft (4.2 m)	[75, 76]
Japan	Sanyo Shinkansen	186 mph (300 km/h)	186 mph (300 km/h)	14.1 ft (4.3 m)	[75-77]
Japan	Tokyo Joetsu Shinkansen		171 mph (275 km/h)	14.1 ft (4.3 m)	[75, 76]
Korea	KTX	217 mph (350 km/h)	186 mph (300 km/h)	16.4 ft (5.0 m)	[63, 78]
Taiwan	THSR	217 mph (350 km/h)	186 mph (300 km/h)	14.8 ft (4.5 m)	[51, 63]
France	SNCF TGV Southeast	186 mph (300 km/h)	167 mph (270 km/h)	13.8 ft (4.2 m)	[75-77]
France	SNCF TGV Mediterranean	217 mph (350 km/h)	186 mph (300 km/h)	15.7 ft (4.8 m)	[77, 79]
Sweden	BV Botniabanan	155 mph (250 km/h)	155 mph (250 km/h)	13.8 ft (4.2 m)	[75, 76]
Germany	ICE Frankfurt-Cologne	186 mph (300 km/h)	186 mph (300 km/h)	14.8 ft (4.5 m)	[77]
China	Beijing-Shanghai	217 mph (350 km/h)		16.4 ft (5.0 m)	[77]
China	*(regulations)*	155 mph (250 km/h)		15.1 ft (4.6 m)	[80]
China	*(regulations)*	186 mph (300 km/h)		15.7 ft (4.8 m)	[80]
China	*(regulations)*	217 mph (350 km/h)		16.4 ft (5.0 m)	[80]

Country	Railway line	Design speed	Max service speed	Min track spacing	Source
USA	Amtrak Acela		150 mph (241 km/h)	13.0 ft* (4.0 m)	[5, 81]
EU	*(regulations)*	143-155 mph (230-250 km/h)		13.0 ft (4.0 m)	[13]
EU	*(regulations)*	156-186 mph (251-300 km/h)		13.8 ft (4.2 m)	[13]
EU	*(regulations)*	186-217 mph* (300-350 km/h)		14.8 ft (4.5 m)	[13]

* Upper limit not stated but the TSI regulations overall are for train speeds up to 217 mph (350 km/h)
* 12 ft (3.7 m) in some areas [5]

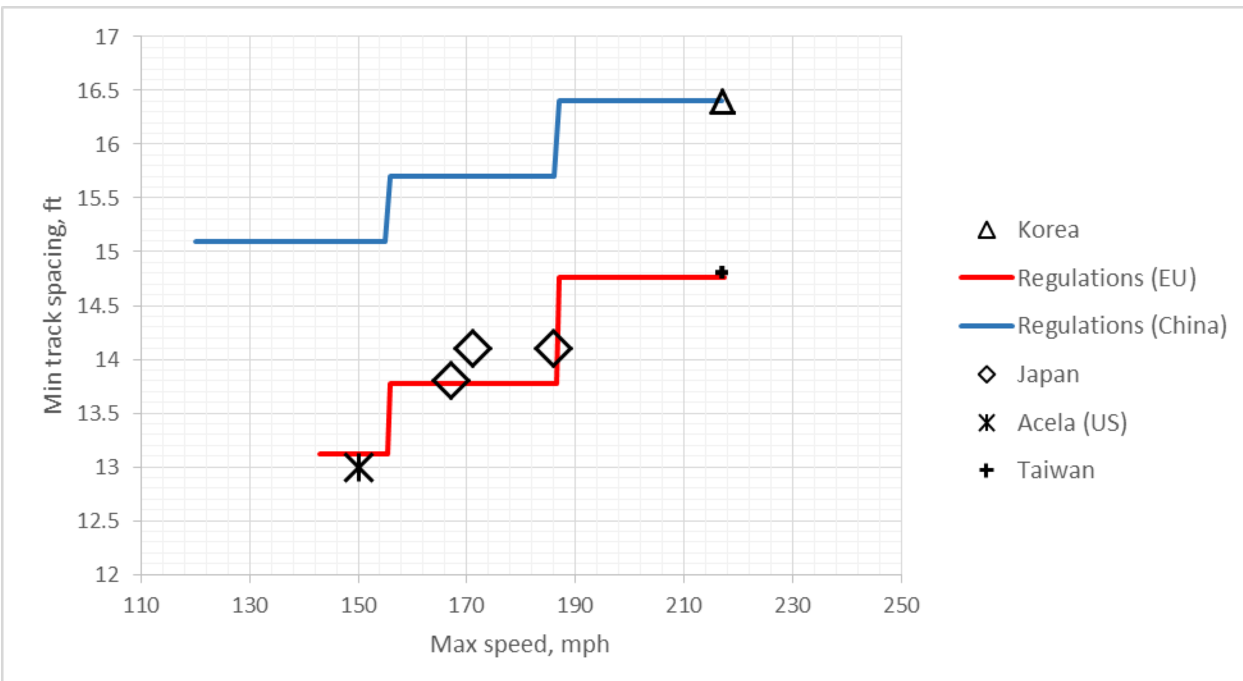

Figure 15. Track spacing in various HST systems

Japanese regulations [82] state that track spacing must be designed to prevent interference between railcars and to prevent injuries to passengers leaning from windows. Specific values are not given.

In the United States, regulations for track spacing for conventional rail lines vary between different jurisdictions, and some states do not have such regulations at all. AREMA best practices state 14 ft (4.3 m) track spacing, but these standards are not meant for high-speed lines. Many railroads have adopted 15 ft (4.6 m) minimum spacing, although some older lines have spacing as small as 13 ft (4.0 m) [83]. In the Northeast Corridor, where high-speed trains are currently operated, minimum spacing on main lines is 13 ft (4.0 m) [10] and 12 ft (3.7 m) in some areas [5].

Track Spacing between High Speed Lines and Conventional Lines

Little information is available on track spacing between conventional and high-speed rail tracks, due to the fact that most countries avoid operating high-speed and conventional trains side by side. However, there are exceptions to this rule. In a report on a proposed California high-speed rail project [84] some of these exceptions are described as follows:

- In the vicinity of Taipei Station (Taiwan) freight tracks run parallel to HST tracks. The speed limits for both passenger and freight trains in these sections are below 43 mph (70 km/h).
- On the approach to Tsoying Station (Taiwan), HST tracks are spaced approximately 20-30 ft (6-9 m) from freight tracks. Speed limits are 87 and 75 mph (140 and 120 km/h) on HST and freight tracks, respectively. There is a fence of unspecified type between the tracks.
- On the TGV Atlantic line between Auneau and Bonneval (France) there is a 25 mi (40 km) segment of HST and freight tracks running in parallel with no intrusion protection, but the operating speeds on that section are only 62 and 50 mph (100 and 80 km/h) for HST and freight trains, respectively. On another segment, between Paris and Le Mans, HST tracks and freight tracks (unspecified speed) are located approximately 40 ft (12 m) from the freight tracks. In addition to distance separation, earth ditches and mounds are constructed between the tracks to prevent an intrusion of derailed freight trains into HST tracks. Track spacing is larger in curves and in places where freight tracks are higher than HST tracks.
- In the UK, a HST line between Ashford and the Channel Tunnel, designed for speeds up to 186 mph (300 km/h), runs parallel to a conventional line. Track spacing between the two lines is approximately 50 ft (15 m). Based on a risk analysis, only selected high-risk areas were chosen to have structures for derailment containment (guardrails, containment parapets, etc.)

Some publications from the literature search implied that in China there are lines where conventional and high-speed trains operate side by side, but no information in regards to track spacing could be found.

Russian Railroads (RZD) have been operating Siemens Velaro RUS trains between Moscow and St. Petersburg at service speeds up to 155 mph (250 km/h), sharing tracks with conventional passenger and freight trains. Minimum track spacing on this line is reported to be 13.5 ft (4.1 m) [11].

A number of recommendations were developed in the United States regarding the separation of conventional and high-speed tracks. These recommendations are based not on aerodynamic considerations but rather on the need to protect HST tracks from intrusion by freight cars in case of derailment. For Florida HSR, a minimum of 25 ft (7.6m) separation between freight and high-speed passenger lines has been recommended [85, 86]. California HSR report [84] gives stricter recommendations:

- In case of track separation greater than 102 ft (31.1 m), or if HST tracks are 10 ft (3.0 m) or higher above the conventional tracks, no additional measures are necessary.
- If track separation is less than 102 ft (31.1 m), an earthwork barrier should be constructed. Track separation will vary depending on the specific barrier design, but will generally be at least 58 ft (17.7 m).
- If smaller track separation is required, an intrusion barrier must be constructed between HST and conventional tracks. With the intrusion barrier, the minimum track spacing is 50 ft (15.2 m), or 37 ft (11.3 m) with railroad approval.

With separations as large as these, aerodynamic interactions between high speed and conventional traffic is expected to be insignificant.

We recommend that in coordination with the FRA and railroad operators, a table of values presenting minimum track spacing versus line speed be drawn up for the United States, for speeds up to 250 mph. This is discussed in the Recommendations section below.

Train Design

The impact of trains meeting and passing can be minimized by the appropriate selection of train types.

There are two aspects of train design as it applies to train crossing events:

- minimize the magnitude of the pressure wave; and,
- minimize the effects of the pressure wave on the train.

The first point may be addressed by design of the train nose and tail shape. In general, longer noses generate smaller pressure peaks and are also likely to have other aerodynamic benefits such as reduced drag.

For the second aspect of the design (resilience to the effects of the pressure wave), it is clear that train body, windows, doors, etc., must be designed to withstand the pressure transients during the train meeting and passing event, but very few guidelines are available. For windows, not only the strength of the glass itself but also strength of the entire window assembly must be adequate. For two windows with equal area, the one with larger perimeter would be preferable [10, 87]. It is desirable also to ensure that the stiffness of the side-structure of the vehicles is sufficient to prevent pressures from passing trains causing unacceptable motion of tables, etc., inside the vehicles [72].

Operating Speed

The literature search yielded one example of speed restrictions to reduce pressures during trains meeting. On some German high speed lines that have mixed traffic, the high speed trains are limited to 155 mph (250 km/h) to avoid risk of damage to freight trains in tunnels.

Other Operational Issues

In addition to increasing track spacing for mitigation measures, another method is by careful train scheduling [88] so as to minimize the number of passing and meeting events.

Train marshaling is yet another issue. Scaled experiments have demonstrated that if a consist is a mix of single- and double-deck cars, the pressure peak during meeting can be 15-20% larger than if all the cars, as well as the locomotive, were of the same height. Therefore, such mixed consists should be considered in design or avoided operationally, whenever possible [10, 88, 89], if aerodynamic impacts of trains meeting or passing are thought likely.

4.4 Standards

Standards exist in the EU TSI [13], China (TB10621-2009, section 4.3.2) [80] and other countries relating to track spacing for high speed trains as a mitigation measure for aerodynamic loads during train meeting. Detailed discussions of the assessment criteria and methodology are presented in Section 4.5.

4.5 Data from Literature including Experimental Data, Criteria, and Assessment Methodology

4.5.1 Assessment Overview

An assessment in the context of trains meeting or passing each other is the evaluation or estimation (from a method) to quantify or approximate the impact of one train on another. The assessment is performed to establish numerical values that define pressures on the trains and for developing assumptions as to the likely functionality of a proposed operating procedure based on the performance of an existing procedure. There are two methods used for assessments.

4.5.2 Methods

The two general assessment methods are:

- <u>Comparative assessment method:</u>
    - This method uses a like-for-like comparison for approximating numeric values or developing assumptions for operating procedures. Examples would include the estimation of an approximate pressure value for a proposed condition based on known values from an existing condition and, assumptions as to the acceptability of a proposed new operation based on an existing operation that performs acceptably well.
- <u>Absolute assessment method:</u>
    - This method develops numeric values and evaluations of operating procedures based on complete definition and calculation of a condition or by the testing of an operating procedure. An example would be identifying and quantifying all parameters that constitute the components of a pressure load condition and then calculating the pressure value. Another example would be full-scale model testing of an operating procedure to determine its acceptability.

The primary differences between the two methods are (a) the comparative method produces approximations while the absolute method results in precise values and (b) the comparative assessment method normally requires less effort and cost than the absolute assessment method.

Comparative Assessments

The advantages of comparative assessments include:

- The effects of uncertainties or inaccuracies tend to cancel out. These factors affect the calculations or evaluations equally and only the relative resultant values are important.
- By comparing a proposed operation with an existing successful operation, it may not matter whether the worst case has been considered for the proposed operation. For example, the effects of headwinds or trains meeting or passing in tunnels are the same conditions experienced by the current successful operation. The comparative assessment will check whether the proposed new operation will be "better" or "worse".
- Acceptability criteria are sometimes very difficult to quantify. Comparative assessments do not require these criteria.

Comparative assessments have the potential to develop track spacing rules for speeds up to 250 mph based on approximations and "order of magnitude" assumptions.

The disadvantages of comparative assessments include:

- The quantification of a pressure value is based on approximations and assumptions. Application of safety factors to the resultant value may be overly conservative.
- Evaluation of a proposed operating procedure encompasses greater risk due to acceptance of the assumption that uncertainties and inaccuracies cancel out.

Absolute Assessments

The advantages of absolute assessments include:

- Ascertainment of a precise value or evaluation due to the identification and quantification of impacting factors and conditions.
- Reduced risks due to the identification of uncertainties and inaccuracies.

Absolute assessments can develop more precise spacing rules for speeds up to 250 mph.

The disadvantages of absolute assessments include:

- Substantial greater effort and cost to develop and conduct.
- Lack of being able to locate and utilize full-scale model test vehicles and facilities.

4.5.3 Experiments and Results

During the literature search, reports of experiments and resultant data were identified. These experiments form the basis for the existing standards, criteria, and formulae that evaluate and quantify the impacts of trains on one another as they meet and pass. Summaries of these experiments are presented in the next four sections of the report, upon which future experiments and analyses can be based in the development of formulae and criteria specific for United States type vehicles and operational procedures.

Full-Scale Experiments

Mancini and Malfatti [68] measured pressures acting on high speed trains and on freight trains in full-scale train meeting events. A large database of information was compiled, of which a small sample is presented in the paper.

The published data includes (a) a high speed ETR 500 train meeting another ETR 500 train; and (b) an ETR 500 train meeting a freight train. The speed of the high speed trains varied from zero to 175 mph (280 km/h) and the speed of the freight train varied from zero to 75 mph (120 km/h).

The experiment determined there was little difference in the pressure coefficients when measuring pressures on high speed trains versus on freight trains (provided that the speed of the trains was accounted for).

This indicated the existing data and formulae, derived from high speed trains meeting other high speed trains, may be used to estimate pressure loading when high speed trains meet freight trains. The data also demonstrates the relatively moderate difference in peak to peak pressures between the situations of train-meeting-stationary-train and of train-meeting-moving-train. This difference in peak to peak pressures is about 25% for the two high-speed trains (175 mph + 175 mph versus 175 mph + 0 mph), and 10% for the high speed train meeting a freight train (175 mph + 75 mph versus 175 mph + 0 mph).

A study was conducted for the United States Department of Transportation on the subject of a high-speed passenger train passing a freight train [5, 55, 56, 64]. Full-scale tests were performed on a high speed non-electric locomotive train (HSNEL) passing a stationary freight train (consisting of a well car and two empty stacked shipping containers) at up to 130 mph (209 km/h) with 12-ft (3.7 m) track spacing. The gap between the high speed train and the side of the containers was 32 in (81 cm). When the high speed train passed at 130 mph, the peak-to-peak pressure coefficients measured on the side of the container ranged between 0.27 and 0.63 (depending on the measurement location). The duration of the pressure pulses was approximately 0.75 seconds.

Some of the older studies on train meeting and passing were reviewed by Lee [10] and are summarized in Table 3-2**,** along with the studies by Mancini and Malfatti and by Holmes et al.

In particular, Lee mentions testing conducted by the FRA in the 1960's for the High-Speed Ground Transportation Program, which involved two Silverliner multiple unit trains meeting at various speeds [90]. Also of interest are tests done in France in the late 1970's involving the prototype of TGV train [91].

It is worth noting that although these tests involved older and presumably less aerodynamic streamlined trains, the pressure coefficients obtained during these experiments are within the range of the data from more recent experiment.

Liu et al [60] provide a limited amount of data from a full-scale test conducted in China involving CRH2 train. The results are used to verify the CFD simulations conducted by authors of the study.

Nam and Kwon [63] conducted multiple full-scale experiments on trains meeting and passing. They quantified the relationship between pressure changes in the case of a train passing a stationary train compared to a train passing a stationary pressure probe in open air. The pressure probe was mounted at the same point where the measurement point on the sidewall of the second train would be. This ratio was determined to be between 1.9 and 2.0.

Gawthorpe [10, 43] in a separate study, estimated the ratio to be about two. A simple theoretical analysis of pressure waves reflecting off a wall by superposition of image sources also suggests a factor of 2.

The closeness of these ratios is important because they indicate future experiments on train meeting and passing can be simplified by the use of a wayside probe instead of a more complicated experiment employing two separate trains.

In Russia, Lazarenko and Kapuskin [11] conducted a series of studies to investigate the aerodynamic effects of Siemens Velaro RUS high-speed train on passengers standing on platforms and on commuter trains during meeting and passing events. Meeting and passing studies consisted of a series of full-scale experiments in which Velaro RUS met a conventional ET2M commuter train at track spacing 13.5 ft (4.1 m). Peak positive pressures are reported which makes it difficult to compare them to other experimental data.

Other experiments on train crossing have been conducted in Japan and China [89, 92], but with minimal details published. One exception is a recent Chinese study stating that if two trains meet while traveling at equal speeds, the pressure change will be 10 to 25% greater than if one of them is not in motion [88, 89].

A summary of some of the experimental data discussed above is shown in Table 9.

Table 9. Data from full-scale experiments on 2 trains meeting

Passing train	Speed of passing train	Observing train	Speed of observing train	Center-to-center track spacing	Side to side spacing	Peak to peak pressure on observing train (approx.)	Pressure coefficient. (approx.)	Source
ETR500	174 mph (280 km/h)	ETR500	0	13.8 ft (4.2 m)	32 in (0.81 m)	0.18 psi (1,250 Pa)	0.34	[68]
ETR500	174 mph (280 km/h)	ETR500	174 mph (280 km/h)	13.8 ft (4.2 m)	32 in (0.81 m)	0.23 psi (1,550 Pa)	0.42	[68]
ETR500	155 mph (250 km/h)	Freight	0	13.8 ft (4.2 m)	32 in (0.81 m)	0.15 psi (1,050 Pa)	0.35	[68]
ETR500	155 mph (250 km/h)	Freight	75 mph (120 km/h)	13.8 ft (4.2 m)	32 in (0.81 m)	0.17 psi (1,150 Pa)	0.39	[68]
Silverliner	100 mph (161 km/h)	Silverliner	-128 mph (-206 km/h)			0.07 psi (483 Pa)	0.39	[10, 90]
Silverliner	138 mph (222 km/h)	Silverliner	-100 mph (-161 km/h)			0.12 Pa (827 Pa)	0.35	[10, 90]
TGV 001	195 mph (314 km/h)	TGV 001	0	11. 5 ft (3.5 m)			0.4	[10, 91]
HSNEL	130 mph (209 km/h)	Freight	0	12.0 ft (3.7 m)	0.81 m (32 in)		0.27-0.63*	[55, 56, 64]
CRH2	186 mph (300 km/h)	CRH2	-186 mph (-300 km/h)	16.4 ft (5.0 m)		0.16 psi (1,135 Pa)	0.27	[60]

*Coefficient of 0.63 recorded 9 ft (2.7 m) above the rail, 0.27 recorded 17.5 ft (5.3 m) above the rail.

Full-Scale Experiments: Trains Meeting and Passing in Tunnels

Li et al [87] describe cases where the pressure peaks were approximately doubled in a tunnel compared to the open air case. Furthermore, a strong suction pressure existed during the time that the trains were in the process of meeting each other.

Mancini and Malfatti [68] report measurements from the TRANSAERO project of two high speed trains meeting within a tunnel. The peak-to-peak pressure changes when two ETR 500 trains met in a tunnel were more than twice those in open air, but the pressure time-history was almost identical on both sides of the train. This suggests that one-dimensional pressure waves were the dominant effect. The forces on the windows, other external surfaces of trains, and any net lateral force due to train meeting were not amplified by being confined within a tunnel. Measurements were taken of an ETR 500 train meeting a freight train with similar conclusions. High pressures occurred due to the one-dimensional pressure waves, but there was little evidence of strong lateral loads on the railcars.

Novak and Konig [93] performed measurements in Melk tunnel of an ICE train passing a freight train at up to 186 mph (300 km/h). The freight train included rail cars with sliding doors and open cars containing wood chips. As the nose of the high speed train passed, the pressure on the freight train changed by up to 0.44 psi (3 kPa). No substantial unloading of wood chips occurred, and there was no structural damage to the rail cars.

Data from Numerical Analysis

Zhu et al [94] conducted a 3-dimensional CFD simulation based on incompressible Navier-Stokes equations and k-ε turbulence model. The simulation involved an unspecified passenger train at 99 mph (160 km/h) meeting a double-stacked container train at 75 mph (120 km/h) with 13.1 ft (4.0 m) spacing between the track centers. Peak-to-peak pressure variation was calculated for various points along the containers. The highest recorded variation was 0.145 psi (1,002 Pa), which corresponds to a pressure coefficient of 0.8 (a value that is much higher than data from full-scale experiments). This higher value was theorized by Zhu to have been due to the very blunt nose shape of the passenger train model used in the simulation.

Li et al [59] conducted a series of CFD studies of the crossing of two China Railway CRH3 high-speed trains, consisting of approximately 100 operating cases. Speeds ranged from 0 mph to 310 mph (0 km/h to 500 km/h) and the track spacing ranged from 14.0 ft to 17.3 ft (4.26 m to 5.26 m). The outputs were the peak-to-peak pressure changes as functions of the two trains' speeds and track spacing.

As an example, at 14.4 ft (4.4 m) track spacing and a speed of 250 mph (402 km/h) for each train, the peak-to-peak pressure change was 0.48 psi (3,310 Pa). This corresponds to a pressure coefficient of 0.44.

The data derived from these studies were then used to formulate custom empirical equations for pressure change as a function of train speed and track spacing.

Liu et al [60] conducted a series of CFD studies on crossing of ICE, CRH2, and CRH3 trains at speeds up to 249 mph (400 km/h) and distance between the side walls of 2.6 to 6.6 ft (0.8 to 2 m). Similar to Li et al, the data was used to derive custom empirical equations for pressure change as a function of train speed and track spacing.

A CFD study was conducted in the US [55, 64] of a high-speed Acela Express train passing a consist of articulated well cars loaded with double-stacked shipping containers and having a track spacing of 12 ft (3.7 m). CFD was used to predict the net forces and moments on the containers. It was also used for rail vehicle dynamic simulation to predict the response of the freight train (see Figure 16).

The authors of the study covered a range of train and wind speeds. The speed of the train varied from 120 to 150 mph (193 to 241 km/h). The speed of the freight train varied from -50 to 50 mph (-80 to 80 km/h). The wind speed (both headwind and crosswind) varied from 0 to 50 mph (0 to 80 km/h).

The study showed that a risk of derailment (based on wheel unloading and/or high lateral wheel forces) existed when a high-speed train and a freight train with empty containers traveled in the same direction and faced a 50 mph (80 km/h) headwind. The results showed derailment to be more likely when the two trains travelled in the same direction because the pressure pulse from the high speed train acts on the shipping containers for a longer time in this configuration (i.e., the impulse is greater) than when compared to the trains travelling in opposite directions. The headwind is the most onerous condition because it amplifies the pressure pulse from the high speed train by 78% in this study. The study concluded that it was unlikely that containers could become dislodged.

A follow-up study of the above on the Acela was conducted later [5] using a simplified model of a container car. A high-speed train was traveling at 150 mph (241 km/h) and passing a well car with empty double-stacked containers traveling at relative speeds between -80 to 80 mph (-129 to 129 km/h). Headwind speeds from 15 to 50 mph (24 to 80 km/h) were considered, and track spacing was 12 ft (3.7 m). Tangent and curved tracks were also simulated to investigate the effects of cant deficiency.

Although a simplified single-degree-of-freedom mathematical model for a well car was used, the results of car roll angles were in good agreement with a full-scale experiment. The study confirmed the results of the earlier studies [55, 64] and expanded upon them.

It was shown that under unfavorable conditions (strong headwind and low freight train speeds) carbody roll angles of 0.6 to 1.2 degrees can be observed. This corresponds to severe wheel unloading and a risk of derailment (Figure 16, Figure 17).

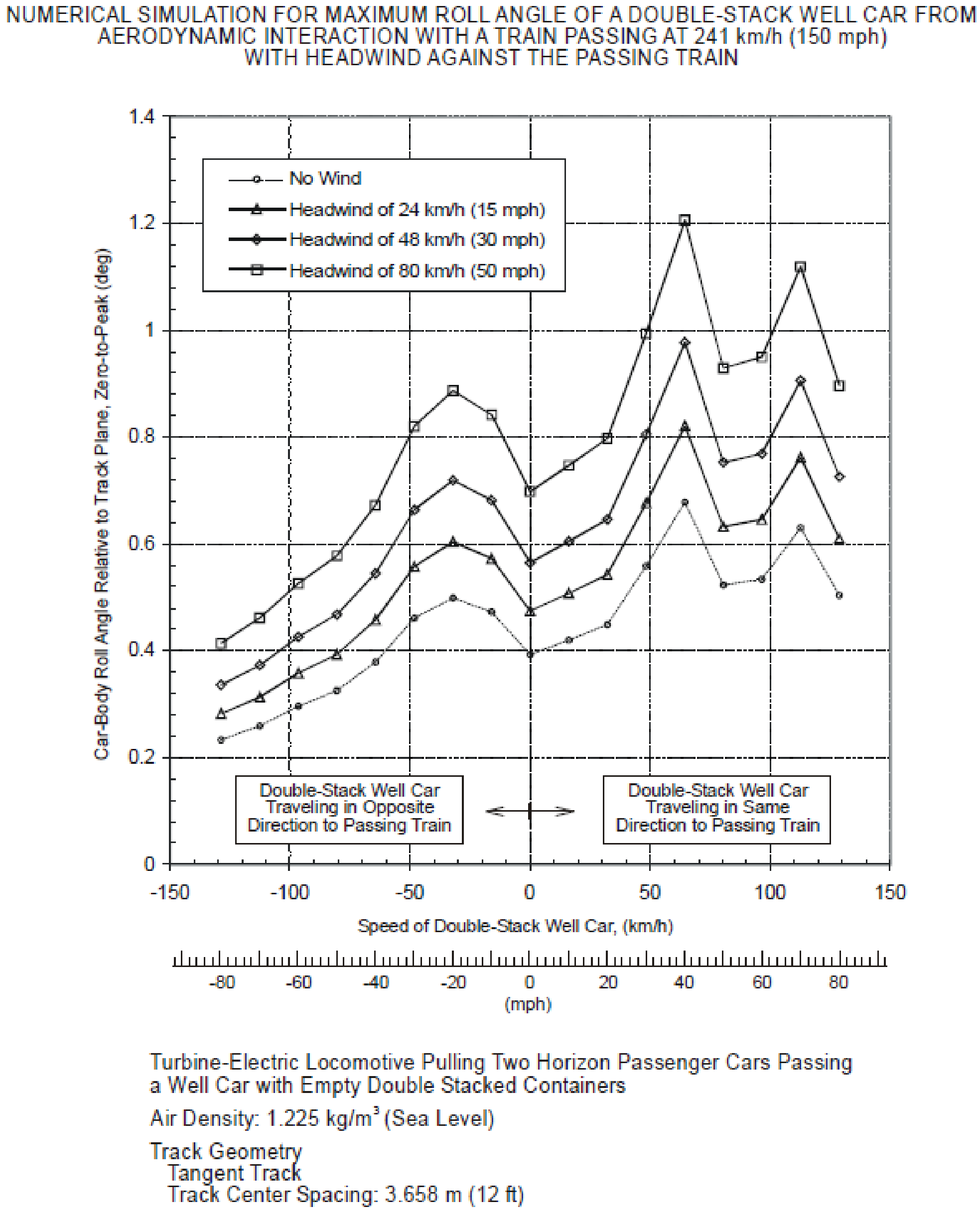

Figure 16. Results of a simulation of high-speed train and freight train crossing [5]: carbody roll angle of a container car under various conditions

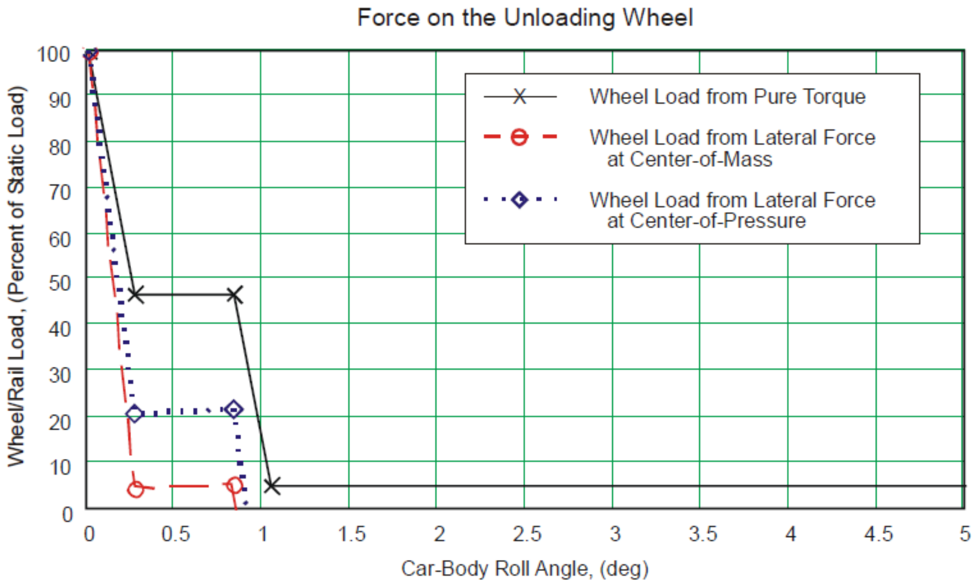

Figure 17. Wheel/rail load as a function of carbody roll angle for the simulated car [5]

Data on Damage to Train Body and Windows

High speed trains are designed to withstand the pressures induced when trains meet or pass each other with no damage to the trains. The few publications treating damage to trains focus on the case of high speed trains passing or meeting conventional trains that may not have been designed with this loading in mind.

Numerical studies have been conducted in China [95] to determine whether the bodies and windows of certain conventional Chinese railcars can withstand the pressure waves developed when they meet high-speed trains at speeds of about 124 mph (200 km/h).

Pressure waves with peak amplitudes as high as 1.6 psi (11 kPa) were simulated. The reason the authors chose to simulate such unusually high amplitudes was their assumption of a “worst case” scenario, i.e. meeting of trains in a tunnel. They quote the results of French and German studies involving meeting of HSTs in tunnels at speeds from 112 to 124 mph (180 to 200 km/h) and resulting in pressure waves with magnitudes of 1.16 to 1.31 psi (8 to 9 kPa).

Train windows were evaluated based on glass impact strength and tearing strength of the rubber sealing around glass. The car body structure was evaluated based on yield strength and maximum allowable deformation of train bodies.

The results were that at peak-to-peak pressure amplitudes of 0.2 psi (1.4 kPa) windows of conventional cars would fail, and at 1.4 psi (9.5 kPa) lateral car wall displacement would be greater than 1.2 in (30 mm). However, stresses would still be below the yield strength of the materials.

The results from the Chinese study indicate that pressure waves observed during train meeting in an open environment (typically up to 0.15 to 0.3 psi (1 to 2 kPa) peak to peak) are too small to cause car body damage, but the *possibility of glazing damage in conventional cars should be investigated*.

Holmes and Schroeder [55] performed a mixed numerical and analytical study on the windows of a representative bi-level conventional commuter car meeting a high-speed train at 150 mph (241 km/h) but the results were inconclusive.

Lee [10] evaluated the peak transient aerodynamic pressures on glazing of conventional railcars for the case of meeting a high-speed train at speeds up to 150 mph (241 km/h). These pressures were converted to equivalent static pressures and the resulting forces were compared to the static strength of glass.

Stress per unit length of window perimeter was also estimated, but no data on window perimeter strength was available. It was concluded that based on equivalent static loads, pressures developed during train meeting speeds up to 150 mph (241 km/h) were not expected to be a problem for the existing US passenger car fleet on the Northeast Corridor.

Li et al [87] conducted CFD simulations of a high-speed train (shape similar to an ICE train) meeting in an open environment and in tunnels at speeds from 155 to 249 mph (250 to 400 km/h) and with a 5.3 ft (1.62 m) distance between train walls.

Forces on the windows were estimated. Peak pressures and forces on the windows in tunnels were about twice as large as in an open environment. Furthermore, in tunnels large negative pressure (suction between the trains) was sustained for the entire duration of the trains meeting each other.

4.5.4 Formulae Development

Lateral Acceleration of Trains during Passing and Meeting

The amplitude of lateral acceleration of the train bodies during passing and meeting has a strong effect on passenger comfort, *yet little data are available*.

The data that are published [96] suggests that the amplitude is proportional to the square of train speed. For Shinkansen trains (0, 100, 300, 300X, and 700 series), the values of the accelerations are about 0.09 to 0.15 times the force of gravity (g) at 93 mph (150 km/h), 0.15 to 0.27 g at 155 mph (250 km/h), and 0.28 to 0.30 g at 217 mph (350 km/h). There is substantial variation between train types as well as between the individual runs.

Effect of Track Spacing: Formulae and Measured Data (Open Environment)

A formula for the peak-to-peak pressure generated when a moving train passes a stationary train was proposed by Gaillard [65] and used subsequently by other authors:

$$\Delta p = c_{p,y} . \frac{1}{2}\rho v^2 = k_t \frac{A_t}{(T-\frac{w}{2})^2} \, x \, \frac{1}{2}\rho v^2 \qquad \textbf{Equation 14}$$

where k_t is a train-dependent shape factor, A_t is the train cross-sectional area, T is the track spacing center to center, and w is the train width. The remaining symbols are identified in Section 4.2.3 for Equation 12.

Johnson and Dalley [66] showed that the relationship of pressure to track spacing was in reasonable agreement with the Gaillard formula. However, this conclusion is based on only three different track spacings of 11.2 ft, 13.8 ft and 14.8 ft (3.4m, 4.2m and 4.5m). For an ETR500 train meeting another ETR500 in open air, k_t can be estimated from the scale model tests as 0.2 for measurement points on the side of the observing train. Meanwhile, the full-scale test data from Mancini and Malfatti presented above for ETR500 trains imply k_t= 0.24. The full-scale test data is more likely to be reliable.

Other formulae for predicting pressure coefficients during trains meeting and passing have been developed, such as formulae by Steinbeuer [97], Gawthorpe [70], Li et al [59] and Tian et al [62, 88, 89, 92]. These formulae are based on numerical simulations or a combination of experimental and numerical data. They account for more factors than Gaillard's formula (train nose shape, observing and passing trains' speed ratio, boundary layer thickness, etc.), but are more cumbersome to use.

The European standard EN14067 Part 4 [24] does not offer formulae for the pressures on trains during meeting or passing. However, when the observing train is stationary the side of the observing train is an almost vertical surface parallel to the track. It therefore might be expected that the formula given in the standard for pressures on vertical wayside structures would offer a reasonable approximation to the pressure on the observing train (provided that "(T-w/2)" is substituted for "y" as shown in Figure 18). Therefore, the EN 14067-Part 4 formula has been included in the analysis presented below.

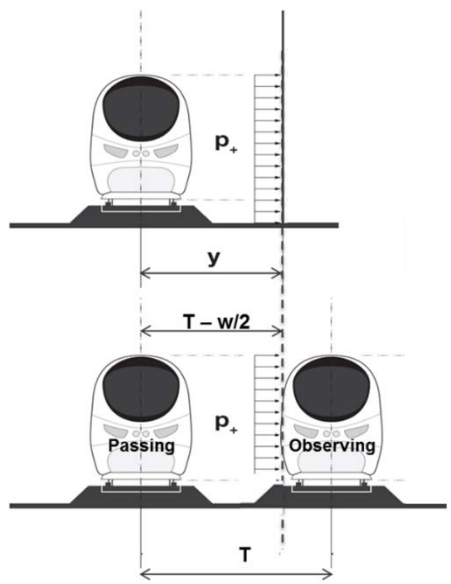

Figure 18. Train passing wayside structure; train passing another train.

Figure 19 compares the peak-to-peak pressure coefficients derived from the EN 14067-4 formula, and from Gaillard's and Steinbeuer's formulae. Predictions of the formulae are compared to experimental [10, 60, 68, 91] and numerical [59, 60] data.

Data appropriate to well-streamlined high speed trains has been used. Assumptions used in deriving the curves are listed below.

- The observing train is stationary.
- For the Gaillard case, the shape factor 0.24 has been used, as per Mancini and Malfatti's full-scale test data with the ETR500 train [68].
- Cross-sectional area of the train is assumed to be 113 ft^2 (10.5 m^2).
- Perimeter of train is assumed to be 40 ft (12.2 m), and hydraulic radius is 5.65 ft (1.72 m).

- Width of train is assumed to be 9.8 ft (2.99 m).
- Length of nose is assumed to be 16 ft (4.88 m).
- For the formula derived from EN14067 Part 4, the shape factor 0.6 (appropriate to high speed trains) has been used. The 1.3 factor to convert from area-averaged to localized peak pressure has been applied, and the peak-to-peak pressure is assumed to be twice the positive pressure pulse value.
- Note that the EN14067 Part 4 formula gives a "characteristic" loading for design purposes. This is expected to be greater than the mean loading measured in experiments.

The actual peak-to-peak pressure is derived from the coefficient c_p in Figure 19 using the following formula:

$$\Delta p = k_u c_p \, x \, \frac{1}{2}\rho v^2 \quad \textbf{Equation 15}$$

The unit conversion factor $k_u = 4.64 \times 10^{-4}$ psi ft^3/(lb.mph^2) if v is in mph, ρ is in lb/ft^3, T and w are in feet, A_t is in square feet, and the pressure is in psi.

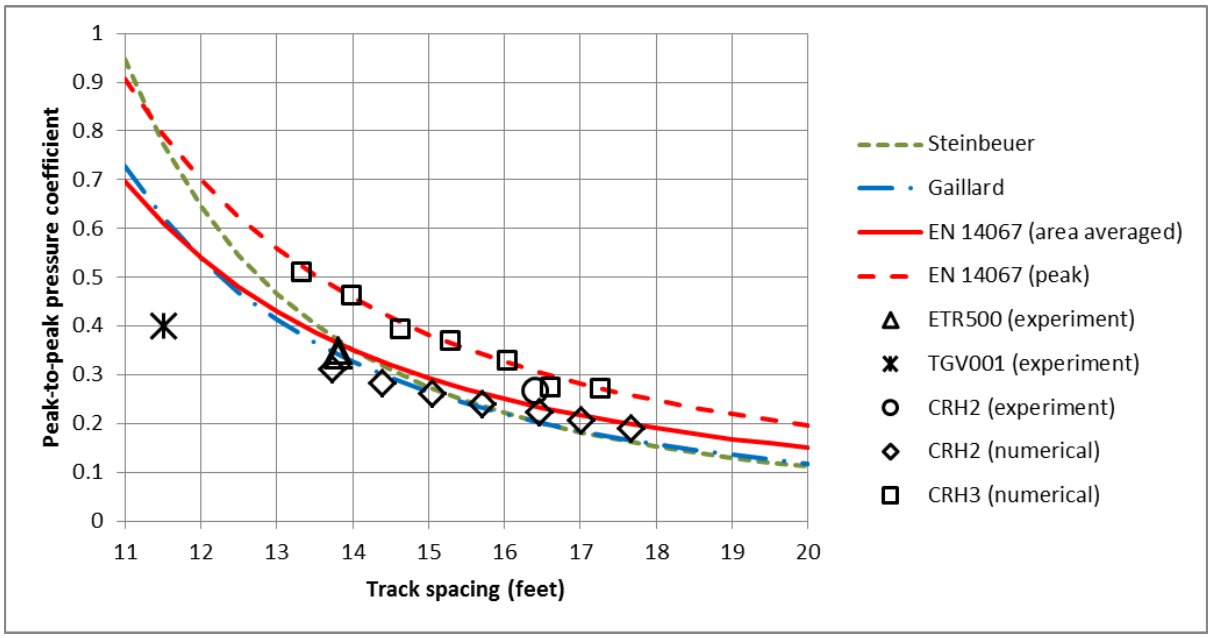

Figure 19. Pressure coefficients as a function of track spacing. EN 14067 refers to EN 14067 Part 4.

All the formulae provide a reasonable approximation to the form of the relationship between the measured coefficients and the track spacing, with the equations derived from EN 14067 being marginally closer to the experiments than the other two. However, there are large differences in the coefficients for different trains at the same track spacing. The formulae can be made to fit the experimental data by adjusting the "train shape factor" for each particular train. Streamlining tends to improve with each new generation of high speed train.

Data from full-scale experiments in Japan [96] show that the Shinkansen 700 series train (28 ft (8.5 m) nose length) produces a pressure pulse about 40% lower than the 300 series train (20 ft (6.0 m) nose length).

Multiple studies have demonstrated that train nose shapes that are close to 2-dimensional produce smaller peak pressures than 3-dimensional shapes because they displace air upwards rather than sideways [10, 58, 98, 99]. However such shapes have disadvantages from other points of view, such as higher drag coefficients.

Tests have shown that a drum-shaped cross-section shape (i.e., the train sidewall is slightly convex) can also reduce the peak pressures by 10 to 17% or more compared to a rectangular cross-section [88, 89].

4.5.5 Assessment Criteria and Assessment

Assessment Criteria

Currently there are no standards or regulations in North America pertaining to the aerodynamics of high-speed trains, including train meetings. A previous review of existing standards and regulations in East Asia also did not reveal assessment criteria for the aerodynamic performance of trains during meeting [100].

For train passing, few assessment criteria have been found for pressure loads on trains caused by trains on adjacent tracks. In the European Union (EU) and China, for high speed trains passing each other, assessment is not performed provided that the regulations for track spacing are observed.

There is a British Railway Group Standard requiring a limit of 1.44 kPa (0.209 psi) peak-to-peak pressure pulse when a train moving at its full operating speed passes a stationary observing train [72]. This was introduced following complaints of passengers being startled or drinks being spilled. However, the 1.44 kPa limit is intended to enforce a standard of aerodynamic design of trains and does not imply that 1.44 kPa is a necessary or sufficient condition for railway operation.

Russian safety regulation NB ZhT CT 03-98 ("Electric Multiple Unit Trains: Safety Norms") [101] sets the following requirements for aerodynamic performance of EMU trains with speeds between 99 and 249 mph (160 and 400 km/h):

"8.1.1. During the movement at design speed onto a vertical surface located in parallel to the track center axis [pressure of the nose wave] shall be no more than 0.26 psi (1800 Pa) at the following distances from the track center axis:

> *7.7 ft (2.35 m) for EMU trains with design speeds greater than 100 mph (160 km/h) but less than 155 mph (250 km/h);*
>
> *8.0 ft (2.45 m) for EMU trains with design speeds greater than 155 mph (250 km/h) but less than 218 mph (350 km/h);*
>
> *9.0 ft (2.75 m) for EMU trains with design speeds greater than 218 mph (350 km/h) but less than 248 mph (400 km/h).*

8.1.2. Pressure of the nose wave shall be no more than 0.03 psi (200 Pa) at a distance greater than 4m (applies to EMU trains with design speed above 100 mph (160 km/h))."

The regulations specify peak pressures, as opposed to peak-to-peak pressures.

No criteria have been found for the aerodynamic interaction between high speed trains and freight trains. Such criteria could include:

- the pressure or impulse that would cause trains carrying double-stacked containers to derail;
- the pressure that would cause fatigue or other damage to freight car doors, sides, etc.; and
- the wind speed that could carry away coal or other particulate cargo leading to hazards to people at the trackside.

The pressure effects could be significant for Tier II lines in the United States. Even if they existed, international criteria would not be relevant because American freight trains are not the same as those in other countries.

Criteria specific to North American freight trains are needed. Slipstream (wind speed) effects of high speed rail on freight might be compared against the effects of crosswinds that freight trains already experience. If the resultant slipstream air speed is less than the crosswind air speed then it would be possible to dismiss the significance of high speed train slipstreams on this basis.

The assessment criteria for train behavior can be separated into the four categories below.

Safety against Derailment and Rollover

Wheel unloading ratio and lateral to vertical force ratio can be used as acceptance criteria, since high values indicate risk of overturning and derailment. These qualities can be measured on real trains with instrumented wheelsets, or determined from multi-body simulation [55] .

Safety against Glazing Failure

Safety against glazing failures can be determined analytically or numerically, provided that the failure load is known. Some of the failure modes to consider are:

- Shattering of a window by exceeding maximum allowable equivalent static load. The methodology for such assessment is given in [10].
- Shattering of a window by exceeding maximum allowable impulse. The methodology is described in [55] .
- Exceeding the maximum allowable stress in a window seal as described in [95].
- Exceeding the maximum allowable stress per unit length of window perimeter [10, 87].
- Failure by fatigue, i.e., exceeding glazing's endurance limit [10, 102].

FRA regulations (49 CFR 223) require passenger car glazing to withstand an impact of a corner of a 24-lb (6.4 kg) cinderblock moving at 12 ft/s (3.7 m/s), which is equivalent to an impact energy of 72.81 J (0.069 BTU); but, these requirements do not easily translate into the ability of glazing to withstand aerodynamic load [10].

Section 3.5.2.2 of German regulation 6.2 VwV NEA [103] prescribes a procedure for fatigue testing of glazing on trains. The maximum applied pressure load is +/- 1.2 psi (+/- 8.1 kPa).

Alstom and other HST manufacturers' testing procedures can be found in the survey of international HSR practices by Banko and Hue [15].

Safety against Car Body Failure

It seems highly unlikely that structural damage could result from trains meeting, even for conventional railcars being passed by high speed trains in exceptional circumstances. However, the possibility of assessments being required has been included here for completeness. Unlike the assessment of glazing, this assessment will be specific to a particular vehicle and the results cannot be easily related to other trains.

Possible failure modes could include:

- Failure by exceeding yield stress. This failure mode has been investigated by Tian [95] using numerical methods.
- Failure by excessive deformation of railcar walls [95].
- Failure by fatigue.

There is very little information in the public domain regarding these modes of failure. China South Locomotive & Rolling Stock Corporation Limited (CSR) reported that Chinese Ministry of Railway required carbody fatigue testing to pressure fluctuation of ±0.87 psi (±6 kPa), based on 0.58 psi (4 kPa) pressure pulse measured during trains meeting at 218 mph (350 km/h) [15].

Passenger Comfort and Safety

Passenger comfort and safety can be assessed in terms of:

- *Car body accelerations.* The California High Speed Rail Authority has adopted a maximum lateral acceleration of 0.1 g for purposes of track geometry design. The same criterion could potentially be used for accelerations from aerodynamic effects.
- *Pressure change inside railcars during meeting and passing.* Although this is an important parameter to consider for train/tunnel interaction, it is not generally considered a problem for train meeting or passing in open air [10]. One experimental study that measures pressure change inside the passenger trains meeting at 137 mph (220 km/h) each [104] found that the pressure change amplitude and the pressure change rate inside the trains were both well below the suggested limits found in literature [10].
- High speed trains for Tier III operation are presently expected to be sealed (see Chapter 7 on pressure comfort in tunnels). The pressure pulses from meeting and passing trains have such short duration that the resulting pressure changes inside sealed railcars would be negligible.

4.5.6 Assessment

Assessment of Pressures by Wind Tunnel Testing

Since train meeting experiments involve two trains moving at different speeds with respect to the ground, wind tunnels cannot be used for train meeting or passing experiments.

Assessment of Pressures by Reduced Scale Model Testing

Train meeting experiments using moving reduced-scale models are widely reported in the literature [66, 98, 99]. A large 1/16 to 1/20 scale facility is operated in China [92] and is used to investigate different aspects of train aerodynamics, including train crossing in the open environment and in tunnels. It is reported that data from scaled and full-scale experiments can match to within 3% [88].

The experiments are normally carried out with the observing train stationary. Pressure tappings are placed in the sides (and sometimes in the front and roof) of the observing train. Some test facilities are capable of firing both trains simultaneously but there are practical difficulties of such experiments, namely, recording pressures on a moving model, and synchronizing the firing of the two trains from opposite ends of the track.

Assessment of Pressures by Full-Scale Testing

Based on many experimental studies found in the literature search, the following conclusions can be made about full-scale testing.

- Multiple runs should be made to generate a statistically representative sample.
- Runs at different speeds should be made and with different speed ratios between the two trains.
- When applicable, not only averaged values of pressure coefficients but also the variations between individual runs should be presented in the findings.
- If possible, the experiment should be conducted on a number of different center-to-center track spacings. If not possible, measurements with free-standing pressure probes at different distances can be made. The pressure pulse observed at a free-standing probe will be approximately 1.85-2.0 times lower than a pulse on an observing train.
- Since the European TSI requirements for aerodynamic performance of high speed trains includes a free-standing pressure probe test, but not a test of pressures on a fixed wall or observing train, the ability to convert between the two situations could be useful.
- Since the height of the pressure probe has a strong impact on the pressure coefficients, it is desirable to take measurements in multiple locations. If this is not possible, measurements should be taken at a height of about 3 ft (1 m) above the rail, where pressure changes are expected to be highest.
- Wind speed and direction during the experiments should be measured and reported.
- Train speed should be measured to an accuracy of ±1%. Methods for correcting measured results from the actual train speed to a standard train speed are given in EN14067 Part 4.
- If possible, the amplitude of lateral accelerations on a train body should be measured.
- The following geometry parameters should be reported: center-to-center track spacing, distance between train sidewalls, train nose length, train width, and train cross-sectional area.
- Sampling frequency of at least 1.0 kHz should be used, otherwise the magnitude of the air pressure pulse may be underestimated [105].

Further guidelines and requirements are given in EN 14067 Part 4.

Assessment of Pressures by Numerical Modeling

Numerical studies enable the creation of a large experimental matrix and varying multiple parameters such as track spacing, train speeds, train nose shape, and crosswind conditions. In addition, they are generally less time consuming and less expensive than full-scale experimental studies.

Numerical studies on train meeting date back to before the 1970s. A study by Steinbeuer [97] applied a panel method, a predecessor of modern CFD methods, to derive a formula for the pressure pulse between trains. Modern studies involve large 2D or 3D flow domains with increasingly fine mesh. Small details, such as pantographs and suspension elements, are sometimes simulated.

Although most of these type studies limit themselves to describing the pressure wave shape and magnitude, some use these data to compute the train's dynamic response as well. Since the pressure pulse is essentially a potential flow problem, it is not critical which turbulence or viscosity model is used. Some authors have used an Euler solution (i.e., a solution ignoring viscosity effects) successfully.

The challenging points of simulating trains passing are:

- the need for at least one of the trains to move, necessitating sliding boundaries around the moving train; and
- the lengths of the trains lead to a requirement for large domains and hence long computing times.

Very few publications compare the results of CFD simulations and full-scale experiments. Holmes and Schroeder's study [55] yielded a stated very close convergence between a full-scale experiment and a CFD simulation (the exact value not reported). Tian and Lu [89] report that CFD and experimental results differ by less than 10%. Liu et al [60] report less than 7% difference between CFD and experimental data. Although these results are encouraging, *more comparative studies encompassing a wide range of conditions are needed to make a more definite conclusion*.

Assessment of Aerodynamic Loading Caused by Trains Meeting/Passing in Tunnels

No formulae are available for the case of trains meeting in tunnels. CFD may be the only predictive tool capable of treating all the aspects of this situation.

The one-dimensional pressure wave effects, which may constitute the largest contribution to pressure loading on windows and the train body, can be estimated by one-dimensional analysis using specialized software such as ThermoTun [106].

Assessment of Vehicle's Dynamic Response

The majority of studies on train meeting are limited to studying the aerodynamic effects without analyzing the train's resulting dynamic behavior.

Holmes and Schroeder [55] used their CFD data for train passing as an input to multibody dynamics software to predict the train's response and evaluate the potential for derailment or overturn. No other such studies were found during the literature search. Allowances for mitigating such effects are presently included in recommended track separation distances by the rail industry.

Due to the transient nature of meeting or passing event, it is unlikely that quasi-static balance analysis would be appropriate. A more complex analytical model, which accounts for the train suspension's resonance, may potentially be useful. It should be emphasized that no matter what method is used, not only pressure peak magnitude but also the impulse of the pressure wave must be accounted for in order for a model to be useful [55].

4.6 Conclusions and Recommendations

4.6.1 Conclusions

The following conclusions have been determined through an assessment and review of the documentation and data identified in the literature search:

- Basic aerodynamic concepts are well understood.
- Comparative assessments can be used for establishment of guidelines. Testing will be required to develop any modifying factors to accommodate United States train types and operations.
- Numerous experiments and studies have been performed but are difficult to use in developing guidance.
- Current mitigation measures include primarily increased track spacing, and secondarily limitations of train speeds.

4.6.2 Gaps and Issues

Acceptability Criteria

While basic aerodynamic concepts are well understood there is an absence of guidelines or criteria for acceptability of aerodynamic loads on trains needed primarily for conventional rail traffic in corridors shared with HST.

Standard Formulae

Numerous formulae have been developed for use by other countries and are based on experimental and observed data that accommodates the train types operating in that country. Standard formulae for use by the United States rail industry for Tier II and III operations are required.

Operational and Assessment Procedures

Guidelines for mitigation (track spacing) are available internationally only for limited train types and speeds up to 220 mph. No operational and assessment procedures are available to limit resultant meeting and passing train pressures.

4.6.3 Recommendations to Address Gaps and Issues

Acceptability Criteria

Existing international criteria are limited. We do not recommend adopting these in the U.S. Acceptability criteria for older train types could be derived by comparative assessment based on existing operations. For newer train types, criteria could be developed utilizing fatigue and structural design limitations provided by train manufacturers. Testing will be required to confirm assessment results.

Standard Formulae

It is recommended that the EN 14067-Part 4 formula (adapted as shown in Equation 12, Section 4.2.3) be adopted for future comparative assessments of train meeting and passing. Testing will need to be performed to quantify factors for the formula to accommodate United States train types and operations. Reduced scale model testing and CFD are the most economical ways to do this.

Operational and Assessment Procedures

Tier III Operation on New Tracks

Aerodynamic impacts of high speed trains on each other during meeting and passing events can be controlled by a two-part regulatory system that encompasses sufficient spacing between tracks, and sufficiently aerodynamic trains. Such a system, based on information found for existing high speed railways, avoids the need for detailed assessments of pressure loading in different train meeting and passing situations. We recommend that rules be established in conjunction with the FRA for the United States governing:

(a) The minimum spacing between high speed tracks, as a function of line speeds up to 250 mph.
(b) For any Tier III high speed train that is to operate in the United States, the maximum peak-to-peak pressure coefficient must be measured in a standard test.

Additionally, the trains must be designed to accommodate the pressure loading without fatigue damage.

One option would be for the United States to adopt the same rules that already exist internationally.

A possible process for developing the detail of the requirements for item (a) above for minimum spacing between high speed tracks is as follows:

- Begin with the same track spacing requirements as currently exist in Europe ("TSI Infrastructure" [13]) or China for speeds up to 218 mph.
- Perform reduced-scale experiments to fill the gaps in the information.
    - Establish the validity of the proposed formulae for comparative assessments.
    - Establish how the formulae should be adapted for trains of different widths or heights contemplated for use in the United States.
    - The testing will also yield estimates of the train shape factors.
- Use comparative assessment methods to extrapolate the existing rules up to 250 mph.

Tier III Operation on Newly Built Tracks Adjacent To Conventional Rail Operations

The minimum spacing between Tier III (high speed) and conventional tracks carrying freight and other traffic should be set such that aerodynamic impacts between the two types of traffic will be negligible even at 250 mph. A large spacing may be required in case of derailment, irrespective of any aerodynamic issues.

Engineering assessments of existing studies can be performed. Additionally a comparative analysis method could be used for ensuring that pressures from high speed trains at 250 mph are no higher than the pressures already tolerated when conventional trains pass each other.

Tier III Operation for Trains Passing or Meeting in Tunnels

If twin tube tunnels (single track per tube) are used train meeting and passing situations will not occur in tunnels. If single tube tunnels are used (dual tracks per tube) comparative assessments of existing high speed operations and studies from Europe and Asia can be performed to establish criteria.

Tier II Operation on Existing Tracks with the Establishment of the Maximum Speed for High Speed Trains

On existing tracks the spacing is fixed. The question becomes, what maximum speed can be permitted without unacceptable aerodynamic impacts of high speed trains on each other, or on freight or other conventional traffic?

Although the pressures exerted by the trains on each other can be estimated by formulae or measured by reduced scale model testing, limiting pressures must be established at which window blow-out or other damage might occur to older North American rolling stock. For example, existing operational experience shows that two freight trains, both with double-stacked containers, can pass and meet without the containers sliding or toppling, or the trains derailing. That situation could be used as a benchmark of acceptability against which higher speed Acela operation can be compared.

Full assessment involving multi-body simulations to determine the response of the freight train (as reported by Holmes and Shroeder [55, 64] and Lee [5]) may offer another way forward, but validation of the analysis to the extent that might be expected for a proof of safety would be required.

Tier II Operation in Tunnels

The Northeast Corridor has only one tunnel where the speed is not limited by switches, curves, stations and grades. If speeds through this tunnel were to be increased (subject to satisfactory aural comfort performance), or where new Tier II lines through tunnels are planned, the aerodynamic impacts of trains meeting within the tunnels must be considered. There is little published information that assists with this task and additional assessments and testing including full-scale testing will be required.

5. Crosswinds

Crosswinds cause a variety of impacts to train operations ranging from increase wear on the rail to risk of rollover of the train. During the past two decades, especially since the introduction of high speed trains, crosswinds and their impacts have been studied and assessed in depth.

There are numerous existing standards on assessment of crosswind effects on the rail vehicles. Many of these standards focus on the development of Characteristic Wind Curves (CWC) and their application to identify safe operating limits.

5.1 Introduction and Summary

This chapter will examine the components of crosswinds, existing standards, and mitigation issues including:

- basic aerodynamic concepts;
- influencing factors;
- measurement and calculation of crosswind characteristics and components;
- impacts;
- mitigation measures;
- standards;
- data from the literature search including measurements, experiment and testing results, criteria, and evaluations and assessments; and,
- conclusions and recommendations, including a strategy for development of a United States standard for crosswinds.

This chapter has the following general conclusions and recommendations:

- strong crosswinds are known to cause derailment and overturning of trains;
- standards for assessment developed by Great Britain, Germany, the European Union, and Japan can be used as an initial basis for the development of an United States standard; and
- risk-based assessment methods could be adopted.

5.2 Nature of Crosswinds

5.2.1 Basic Aerodynamic Concept

A "crosswind" is any wind that has a perpendicular component to the rail line or direction of travel. A crosswind can be separated into the perpendicular component and a headwind or tailwind component.

Crosswind speed and direction may be described relative to the ground, or relative to the train. Figure 20 is a vector diagram that illustrates the components that describe wind speed and direction.

For an observer positioned on the ground, the wind can be described by the natural wind velocity vector, V_w. The magnitude of this vector is the natural wind speed and its direction is β_w (the direction of the wind relative to the ground).

The motion of the train can be described by the velocity vector, V_T. The magnitude of this vector is the speed of the train and its direction is the direction of travel of the train.

The vectors V_w and V_T can be combined into a resultant vector, U, which is the wind velocity relative to the train and shown in Figure 20. The magnitude of U, is called the "crosswind speed", and its direction is shown by the angle β, called the "yaw angle".

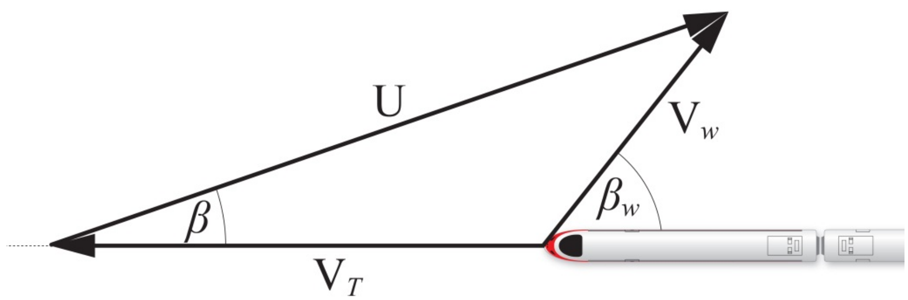

Figure 20. Definition of wind speed and angle, relative to ground (Vw and β_w) and relative to train (U and β).

5.2.2 Influencing Factors

Wind Speed and Train Speed Factors

For any given angle β, aerodynamic forces and moments are proportional to the square of the crosswind speed (U^2). (See Figure 20). This rule is expected to apply at train speeds up to and beyond 250 mph. Note that U depends on both the wind speed and direction and the train speed. There is no simple direct relationship between wind speed and aerodynamic load or between train speed and aerodynamic load. However, it is always the case that train stability in a crosswind reduces with increasing train speed. In other words, the wind speed in which the train can run safely reduces as the train speed increases.

Yaw Angle Factor

The relationship between aerodynamic coefficients and wind yaw angle is a fundamental property of the shape and dimensions of the vehicle. The coefficients are typically assessed by experiments or CFD analysis at several different yaw angles. In some cases, β around 45 to 55° leads to the highest aerodynamic coefficients, while in other cases it may be β=90° [107, 108].

Aerodynamic Characteristics of the Vehicle

The force and moment coefficients depend on the dimensions and shape of the train. For example, given the same height, railcars with arc-shaped roofs are more stable under crosswinds than cars with triangle-shaped or flat roofs [108-110].

Restoring Moment Factors and Dynamic Responses

As a train is subjected to crosswinds, a force is created along the exposed side of the train relative to the train's y-axis that results in a tendency for the train to tip to one side. This action is commonly called the "tipping moment" or also known more formally as the "aerodynamic moment", M_A. The weight of the vehicle creates a moment in the opposing direction to the tipping moment (to restore the train to equilibrium) called the "restoring moment", M_R.

The mass of the vehicle (especially the leading vehicle that is exposed to the greatest effects of a crosswind) is the primary influence. In general, the risk of derailment is greater if a lighter vehicle is at the front [111] of the train.

The restoring moment (see Figure 21) is reduced by lateral displacement and roll of the vehicle suspension (dimension y2), and by unbalanced lateral acceleration. When the rail line curves into the wind with cant deficiency, the tendency to rollover increases.

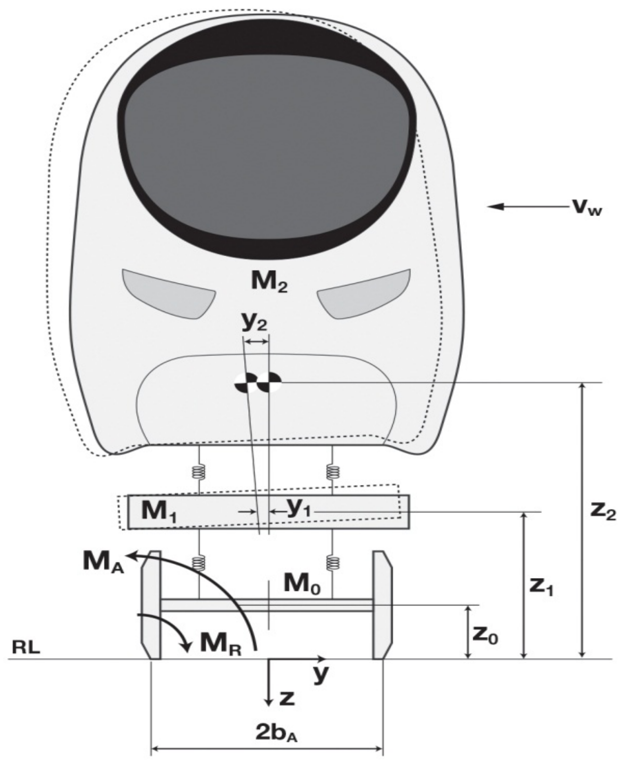

Figure 21. "Three (3) mass model". Restoring moment is reduced by roll of the suspension

V_w = lateral component of wind velocity
M_R = restoring moment
M_O = mass of wheelset
M_2 = mass of car body
Z_0 = height to center of wheelset
Z_2 = height to center of mass of car body
Y_2 = lateral deflection of car body

M_A = aerodynamic moment
b_A = ½ of track gage
M_1 = mass of truck
RL = rail level (top of rail)
Z_1 = height to center of truck
Y_1 = lateral deflection of truck

The dynamic response of a train to the forces and moments generated by a crosswind depend on its speed, suspension characteristics, mass, and line characteristics such as radius and cant.

Embankments, Bridges, and Other Vulnerable Locations Factors

Trains are more vulnerable to overturning in crosswinds where they are more exposed to the wind, for example on embankments and bridges [58, 112, 113]. Identification of such local wind hot-spots is an important aspect of route assessment.

Embankments cause the wind to accelerate as it passes up the embankment and over the railway. Effects of such parameters as embankment height and slope angle on the aerodynamic forces experienced by a train have been investigated. Increase in embankment height leads to increased side force. For example, an increase in embankment height from 7 to 46 ft (2 to 14 m) can lead to an increase of side force by 20% to 40%. Increasing the embankment slope from 0.9:1 to 1.7:1 can increase side forces by up to 15%, depending on the crosswind angle [107, 108].

A speed-up factor for embankments ("orography factor") may be calculated from EN 1991-1-4 Section A3 [114]. The orography factor at the windward edge of the horizontal surface of the embankment is given approximately by

$$\boldsymbol{c_0 \approx 1 + max\left(0.48, \frac{1.6H}{L}\right)} \qquad \textbf{Equation 16}$$

where H is the height of the embankment, L is the horizontal length of the slope, and the term to be added to 1 is the maximum of whichever is greater, 0.48 or $1.6H/L$. However, there is a spatial distribution of the orography factor. Also the factor at the windward edge is an over-estimate of the factor at the side of the train.

Increased wind loading occurs on viaducts because the wind speed increases with height above the ground.

Effects of a wind gust can also be exacerbated if it occurs at the same time as a train emerges from a tunnel or from behind a wind fence [115].

5.2.3 Measurement and Calculation of Crosswinds and Associated Factors

Wind properties vary with location. *There is great variability in the way that wind properties are measured and reported, with high potential for misuse or misinterpretation of the data*. Specialist assistance in this matter is recommended. There are many aspects of the crosswinds that are relevant:

- "Mean wind speed" is measured over a particular time period, typically one hour, and at a particular height above the ground, typically 33 ft (10 m).
- The frequency (or probability) distribution of wind speeds at a given location is an important property of wind. There is no "upper limit" on the wind speed that can occur, but higher wind speeds occur less frequently.
- Extreme wind speeds may be expressed in terms of the frequency with which a given mean wind speed is exceeded. For example, a "50 year return mean wind speed" would be an hourly mean speed that is expected to be exceeded once per fifty years.
- Train rollover typically occurs in response to gusts. Of most relevance is the gust speed measured over a period of one to three seconds. The gust speed is often considered to be linked to mean wind speed, for example via a formula, but the relationship between these properties of the wind may vary from site to site and between regions within a country (for example, the Pacific coast and the Midwest).
- Wind speeds generally increase with altitude.
- Wind speeds vary spatially on a large scale basis due to factors such as proximity to oceans, mountain ranges and continental weather patterns.
- Local winds may have very different characteristics from the winds generated by large scale systems. In the United States, the very sudden and intense winds from tornados

would pose a serious hazard to trains, but little information was found in the literature search on tornado loading on trains.

- Wind speed is affected by local topography. For example, wind may be funneled along a valley or blocked by mountains. The wind climate may therefore vary along the length of a railway line, and between one line and another.
- "Surface roughness" slows the wind near ground level, and is expressed as a roughness height. Flat, open country has low roughness, while built-up areas have high roughness.
- The large-scale variations within a country may sometimes be obtained from national codes and standards. Alternatively, data from meteorological stations near the line can be used.
- The probability with which the wind blows from any particular direction must be considered. This may be expressed as a "wind rose", or a table of frequency versus angle from north. The angle of the railway line compared with the prevailing wind direction influences the risk assessment.
- Wind speeds may also be correlated with direction. For example, an extreme wind speed may be exceeded less often for one wind direction than for another.

Idealization of Aerodynamic Loads

Crosswinds interact with the train body, inducing drag, lift, side force, rolling moment, pitch and yaw on a train. In severe cases, these interactions, singularly or in combinations, can lead to rollover or wheel climb derailment. In a simple "extended static tipping" idealization (see Figure 22), the aerodynamic loads can be expressed as an aerodynamic moment about the leeward (downwind) rail, M_A. The weight of the vehicle provides a restoring moment, M_R, and in the simplest idealization the critical event for rollover risk is defined by $M_A = M_R$ [116].

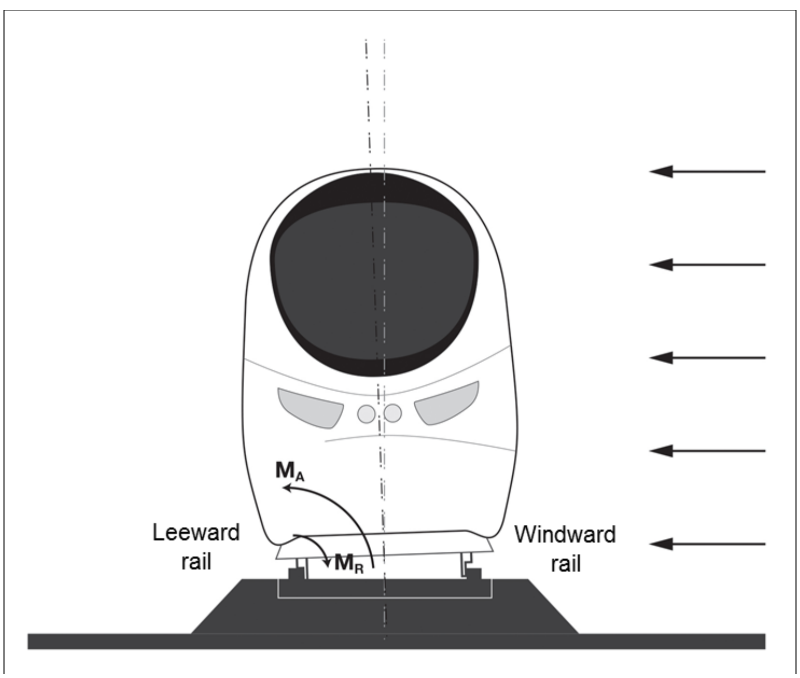

Figure 22. Crosswind action leading to risk of rollover

Wind loading varies in time. Gusts can cause a dynamic response of the moving vehicle, increasing the risk of rollover. Assessment methods for high speed trains typically treat the dynamic response of the vehicle to a wind gust using a multi-body dynamics program.

Force and Moment Coefficients

Aerodynamic loads are normally expressed as non-dimensional force and moment coefficients (C_F representing the Coefficient of Force, C_M representing the Coefficient of Moment). The forces, moments and coefficients are all functions of yaw angle (β).

$$\boldsymbol{c_F(\beta) = \frac{F(\beta)/A}{\frac{1}{2}\rho U^2}} \qquad \textbf{Equation 17}$$

$$\boldsymbol{c_M(\beta) = \frac{M(\beta)/AH}{\frac{1}{2}\rho U^2}} \qquad \textbf{Equation 18}$$

where F is the aerodynamic force, M is the aerodynamic moment (M_A in Figure 22), A and H are the area and height of the side of the vehicle respectively, ρ is the air density, and U is the crosswind speed as defined in Section 5.2.1.

The definitions above are for any consistent unit system, including SI units, the foot-pound-second-poundal system or the foot-slug-second-pound force system. We do not recommend working in non-consistent units. Data should be converted to a consistent unit system before applying the formulae.

The aerodynamic coefficients are found numerically or experimentally for a given vehicle shape at different yaw angles, resulting in coefficients that are functions of yaw angle. Of these coefficients, the side force and roll moment coefficients are presumed to be the most important. Some rollover analysis methods include the lift force while others ignore it [117, 118].

The functions are sometimes idealized as polynomials and fitted to the experimental data, resulting in sets of expressions of the form:

$$\boldsymbol{C(\beta) = C_3\beta^3 + C_2\beta^2 + C_1\beta + C_0} \qquad \textbf{Equation 19}$$

where C_0 through C_3 are constants. This practice is not recommended because all trains have different characteristics that need to be individually expressed. Idealizing as a polynomial results in the loss of some useful data.

Characteristic Wind Curves

In the European definition, Characteristic Wind Curves (CWCs) are curves, lists or tables of the “critical wind speed” that results in 90% unloading of the windward wheel of the most sensitive truck of the most sensitive railcar. The critical wind speeds are functions of train speed, wind angle, and uncompensated lateral acceleration from operating above or below balance speed in a curve.

5.3 Impacts and Mitigation

5.3.1 Impact on Equipment, vehicle, and Freight

Derailment and Overturning

Strong crosswinds are known to cause derailment and overturning of trains. Wind-induced train accidents, some of them fatal, have occurred in many locations including China, Japan, Belgium, Switzerland, France, and Austria. These incidents have prompted multiple research efforts around the world [107, 119, 120].

Passenger trains are potentially becoming more vulnerable to crosswinds. Their speed is increasing, leading to higher aerodynamic loading while their weight is decreasing. Distributed traction (as opposed to traditional locomotives) is becoming more common, making the leading vehicle of the train lighter and more vulnerable to the effects of crosswinds [120].

Crosswinds are a threat not only to high-speed passenger trains, but also to freight trains. Tier I rail vehicles are outside the scope of this report, but it should be noted that unloaded freight railcars can be more vulnerable than passenger cars. Analysis of past wind-induced accidents has shown that the accidents involving empty boxcars tended to happen at wind gusts above 74 mph (33 m/s), while for passenger railcars this number was 98 mph (44 m/s) [119, 121]. High boxcars and double-stacked container cars are especially vulnerable due to their large lateral surface area, bluff shape, and high center of gravity [122, 123].

Incidences of wind-induced train accidents in the US are available from the FRA train accident database [124] beginning in 1992 with two wind-related accident causes ("tornado" and "extreme wind velocity").

From 1992 to 2013, tornadoes accounted for 57 reportable railroad accidents in the US, none of which involved passenger trains. During the same period, extreme wind velocity accounted for 356 reportable accidents, 13 of which involved passenger trains. In none of these 13 cases did the passenger trains derail. In three cases, the damage to the train was caused by catenary wires damaged by high winds. The remainder encompassed carbody damage caused by falling trees and small windblown objects.

Dynamic Envelope Infringement

Crosswind displaces a rail vehicle laterally, possibly exceeding the limits of the dynamic envelope and hence leading to risk of collision with wayside structures, platforms, or other trains.

Infrastructure and Other Impacts

Crosswinds cause lateral loading on the rails, possibly leading to displacement of the track and increased need for maintenance.

A headwind amplifies the nose-passing pressure pulse, and hence amplifies the load generated on other passing trains and on wayside structures. The summary in Chapter 4 (train meeting and passing) describes CFD simulations investigating the effect of headwinds on the pressures generated when a high speed train passed a freight train [5, 55].

Crosswinds also increase aerodynamic drag on trains, leading to higher energy costs. This issue is discussed in Chapter 9 on the Drag Effect.

5.3.2 Mitigation

There are three main ways of preventing crosswind-induced train accidents [125, 126]:

- designing rolling stock such that crosswind effects are minimized, or selecting rolling stock with suitable crosswind stability for the intended route;
- placing restrictions on train speed during the period of high winds, or shutting down train operations altogether; and
- erecting wind barriers along the track.

Rolling Stock Design

Trains with a heavier leading vehicle are less prone to risk of rollover from crosswinds. While this report is not intended to address matters of train design, system operators may desire to understand the Characteristic Wind Curve data related to crosswind-resistance when selecting rolling stock for particular routes.

Speed Restrictions Applied Permanently at Crosswind "Hot Spots"

It may be necessary to set reduced speed limits at locations such as viaducts where wind speeds may be high on a regular basis. The British West Coast Main Line has speed restrictions on some curves due to high wind exposure combined with uncompensated lateral acceleration [127].

Speed Restrictions Applied Temporarily during Strong Winds or when Strong Winds are Forecast

Based on the analysis of past accidents, Chinese researchers recommended not to operate freight trains with empty boxcars when wind gusts exceed 56 mph (25 m/s), and not to operate passenger trains when wind gusts exceed 73 mph (32.7 m/s) [119, 121]. Li et al [128] mention a series of field tests conducted in China on a track section protected by a wind barrier. From the results of the tests, it was concluded that at wind speeds 73 mph (32.6 m/s) and above, train speed should be restricted, and at wind speed above 93 mph (41.5 m/s), trains should not be operated.

Japanese railway operators (conventional and high-speed) have a long history of assessing wind conditions along the railroad and implementing speed restrictions and suspending operations if necessary. Based on analysis of past accidents, they decided to prohibit coupling of lightweight cars when wind gusts reach 45 mph (20 m/s). When wind gusts reach 56 mph (25 m/s) train operations are temporarily suspended. At wind gust speeds of 67 mph (30 m/s) operations are stopped. These standards were later amended to implement a 16 mph (25 km/h) speed restriction at wind gusts of 45 mph (20 m/s). Restrictions are lifted after the wind speed has been under the threshold value for 30 minutes [118, 129].

A number of improvements for this system have since been suggested. Specific values for permissible train speeds as functions of wind direction and speed were calculated based on experimental data and force balance analysis methods (described earlier in this chapter). Criteria for resuming normal train operations were also proposed [107, 108]. An algorithm for making short-term wind speed predictions and implementing speed restrictions before the dangerous wind speeds were reached has been proposed [129]. Since there is spatial variation in wind speed, even at small distances, it was proposed to place anemometers in groups of three and average their readings to give a more accurate assessment of wind speed. It was also proposed that the Detailed Equation (described in Section 5.4.6) with appropriate safety factors be used for determining critical wind speed on individual track sections, taking into account such factors as wayside structures, train type, and train running speed [118]. Studies of using the Doppler radar data to detect and predict wind gusts are being conducted [130].

Similar research efforts are underway in China [117]. Chen et al [131] used quasi-static analysis to derive safe operating speeds for a generic railcar on a tangent track and on a curve. Xiong et al [132] and Shao et al [133] used the same method to derive the safe operating speeds for a CRH2 train running under crosswind in various conditions including sandstorms, rain, tangent track, and curves.

AMTRAK has an internal policy (Electrical Operating Instructions) that governs the operation of electric trains in the Northeast Corridor under severe weather due to the potential damage to the catenary system. Under sustained wind speeds of 50 mph (80 km/h), trains are required to operate at a reduced speed of 60 mph (97 km/h); if wind speeds above 60 mph (97 km/h) are sustained, trains are required to stop at the nearest terminal and wait until wind speed falls below 60 mph (97 km/h).

Automatic Wind Detection and Speed Reduction Systems

Real-time monitoring of wind speeds along the route can be coupled with the signaling systems or automatic train control systems to slow trains when high wind speeds are detected. Gautier et al [79] describe an automatic system for slowing trains when strong winds are detected. The system is used on the TGV Mediterranean high-speed line because it is regularly exposed to strong winds. It incorporates prediction of spatial distribution of wind speed for 4-5 minutes ahead of the present time along continuous sectors of the line, based on measured wind speeds from a network of anemometers. The system is integrated with the signaling system and slows trains automatically in the case of alarm. The mean wind speed for each sector is predicted so that a train can be slowed in time before it enters the relevant sector. This type of system can cause operational difficulties on railways that operate at close to full capacity.

The input to the system is a curve of maximum safe mean wind speeds at which a TGV can run at 186 mph (300 km/h), for all wind angles, and a second similar curve for safe running at 106 mph (170 km/h) also for all wind angles. If the wind speed exceeds the value on the 186 mph (300 km/h) curve, the train speed is reduced to 106 mph (170 km/h). If it exceeds the 106 mph (170 km/h) curve, the train speed is further reduced to 50 mph (80 km/h).

The Chinese Code for Design of High-speed Railway requires that weather monitoring stations are located in the sections of the railroad lines where wind speed may exceed 34 mph (15 m/s). Such stations must be able to detect wind speed and direction, atmospheric pressure, and air temperature. Wind gauges must be installed on catenary masts 13 ft (4 m) above the top of the rail. The average interval between the stations should be 3.1-6.2 mi (5-10 km) in sections with bridges and high embankments, and 0.6-3.1 mi (1-5 km) in sections of mountain crossings, canyons, and valleys [80].

Wind Barriers

The topic of wind barriers has been researched extensively throughout the last two decades, and there are multiple publications discussing and comparing different wind barrier designs. To summarize, barriers 6.6-10 ft (2-3 m) high (including porous noise barriers) are very effective in reducing the aerodynamic loads. Wind barriers should be constructed at locations where the route risk assessment shows an unacceptably high risk of rollover.

On certain Japanese railway lines, wind fences 6.6 to 10 ft (2-3 m) high and made of perforated steel plate or wire cloth (40% porosity) were constructed in locations where crosswinds were especially dangerous, such as embankments and bridges. These fences are reported to reduce the side forces onto trains by about 40%. Noise barriers along some of the Japanese railways also function as wind barriers [107].

Gautier et al [79] state that wind fences were built on the TGV Mediterranean line at locations where safe running at 50 mph (80 km/h) could not be guaranteed based on the 50-year return wind speeds at each location.

The TRANSAERO project [134] concluded that a solid or porous barrier around 6.6 ft (2 m) high was an effective mitigation measure.

Extensive full-scale field tests and wind tunnel tests, conducted in China by Urumqi Railway Administration and China Academy of Railway Sciences, have shown that the optimal wall height is approximately 9.8 ft (3 m). CFD simulations conducted in Central South University in China established a relationship between optimal height of a new ultra-thin wind-break wall and its distance from track centerline. At the same time, the distance of 11.5 ft (3.5 m), which is currently used at Chinese high-speed lines, proved reasonable [128].

Many recent publications describe using CFD methods to find the optimal wind shelter type and geometry [125, 128, 135-142]. The reviewed shelter types include earth embankment walls, various types of fences, and even complex structures covering the trains and the overhead catenary lines. Recommendations for optimal type and dimensions of the structure vary. For a fence, the most common type of wind shelter, the optimal height varied between 6.2 and 16.4 ft (1.9-5m) and the optimal distance to track center varied between 12.8 and 18.7 ft (3.9-5.7 m). Reported efficiencies from these CFD studies varied greatly.

Side-by-side comparisons of some of the studies reveal differences that may be caused by:

- different wind speeds used in the studies (effectiveness of wind barriers can vary with wind speed);
- train and embankment (or bridge) shape differences (they can result in very different flow patterns for the same nominal height of the barrier); and
- location of the wind barrier with respect to wind (windward, leeward, or both) and with respect to train (distance from the track centerline and from train sidewall).

Ballasting the Lead Vehicle

In the UK, weight has been added to one leading vehicle (Class 390) to improve crosswind stability [127].

5.4 Standards

There is a wide variety of national and international standards for crosswind assessment which have many differences both in principles and in details. Summaries of selected standards are given below (with the simpler systems presented first) followed by a discussion about the suitability of the different standards' methods for adoption in the United States. The FRA should choose the type of approach that suits the United States situation best. After selection of type of approach, further work towards the development of standards for the United States can then follow.

5.4.1 British System: Stability Requirement for Conventional Trains

The British crosswind assessment standard pre-dates the European standards and is now used only for trains that are not covered by the European standards. Trains with a maximum operating speed over 140 mph are treated as a special case, with specialist advice required to demonstrate compliance with the standard.

British Railway Group Standard GM/RT2142 [116] requires that the intrinsic rollover wind speed for a vehicle running at its maximum design operating speed on straight and level track shall be not less than 82 mph (36.5 m/s) for vehicles designed to carry people (passengers or crew), and 69 mph (30.8 m/s) for vehicles not designed to carry people. "Intrinsic rollover wind speed" for a vehicle is defined as the wind speed which is just sufficient to cause 100% unloading of the wheels on the windward side when the vehicle is running on straight and level track at its maximum operating speed. The standard defines how "intrinsic rollover wind speed" should be calculated using the Extended Static Tipping method. Note that these are not the actual maximum wind speeds experienced by the trains. The speeds relate to the crosswind stability of rolling stock that experience shows can be operated safely in British wind conditions. For conditions in the United States, the stability requirements are expected to be different.

The aerodynamic rolling moment coefficients may be determined from formulae given in the standard. For vehicles operating outside conventional cant deficiencies or those that do not satisfy the requirements of GM/RT2142 when the formulae are used, the aerodynamic rolling moment coefficient can be determined by wind tunnel tests as described in standard GM/RC2542 [143]. According to the situation, either "uniform profile, low turbulence" tests, or "atmospheric boundary layer with turbulence" tests are prescribed. The standard sets out parameters for wind tunnel testing such as limiting blockage ratio, velocity profile, and turbulence measures, together with the embankment and cant scenarios to be modeled, and requirements for instrumentation and data processing.

5.4.2 British System: Risk Assessment of Tilting Trains

British Railway Group Standard GC/RC5521 [144] defines the method of assessment of proposed permissible speeds for tilting trains on curves, including the effects of crosswinds. The standard includes useful information on calculation of the local maximum wind gust speed at a particular site. Although this standard is intended only for tilting trains, much of the methodology could, in principle, be applied to route risk assessment for any type of train. In summary:

- The "reference wind speed" is the extreme (50 year return) mean hourly wind speed taken from a map given in the standard. The speeds range from 45 mph (20 m/s) to 63 mph (28 m/s) in the most exposed areas.
- The reference wind speed is converted to the local 3-second gust wind speed using the correction factors listed in Table 10 below. Details of how each factor is determined are contained within the standard [26].

Table 10. Correction factors for wind speed in GC/RC5521

Factor for	Explanation
Altitude	Wind speeds are generally higher at altitude.
Direction	The maximum wind speeds occur preferentially in certain directions. Wind directions perpendicular to the track ±30° are considered.
Surface roughness	Four categories of terrain are given with a surface roughness height and factor for each.
Height	Track height compared to surrounding ground.
Topographical	Allows for wind acceleration over embankments.
Time averaging	Converts from 1-hour mean to 3-second gust.
Shelter	Wind fences, etc., offering protection.

The standard is focused on permissible speeds for tilting trains, and therefore considers only curves. The trains do not tilt on tangent track.

For new rolling stock being introduced on an existing route, a comparative assessment based on the same route should be used. Guidance on the factors to be used in the comparative assessment is given in the standard.

The potential of overturning on each curve is calculated based on a number of inputs in addition to crosswind (for example, cant deficiency and the probability of over speeding). The potential of overturning for the route is then calculated as the sum of the potentials for each curve. Guidance is given in the standard on how to incorporate allowances for uncertainties and deviations from the design conditions (for example, the radius and cant angle may vary throughout a curve).

The acceptability criterion for route rollover risk on existing routes is that the risk should be no greater for the proposed operation than for an existing operation on the same route with a history of safe running.

For new routes, a comparative assessment could be used. The comparative assessment should analyze an existing route with similar wind characteristics to the proposed new route. No detailed guidance is given on this method within the standard.

For new routes where a comparative assessment is not possible, for example, when no suitable reference operation can be defined, an absolute risk assessment can be used.

Criteria for use with an absolute risk assessment are:

- The suggested acceptability criterion is a probability of fatality due to overturning of 1×10^{-7} per year for any individual passenger.
- The passenger considered is assumed to take a maximum credible number of journeys on the section of route being assessed. For example, a commuter might make 250 round trip journeys per year, giving 500 total journeys along the route.
- The tolerable probability of overturning is 4×10^{-9} on each occasion that a train passes along a given section of route. That is because 4×10^{-9} times 250 occasions per year results in the target 1×10^{-7}.

- Further, it is required that no curve contributes more than 25% to the overall risk, i.e., the maximum tolerable probability for any curve is 1 x 10^{-9} on each occasion that a train passes.

Overall, the strength of the British system is its simplicity. Unnecessary complications are avoided, and the uncertainties in the different calculation steps are well balanced.

5.4.3 German Guideline Ril 807.04

The German crosswind assessment system (Deutsche Bahn Guidance Note Ril 807.04) is not published in the public domain, but papers describing it in outline are available and have been used for this report [145, 146]. The authors of the papers state that the system offers a complete and consistent approach based on the comparative risks from crosswinds of the train or rail line being assessed compared with existing experience of safe running on the German network. The guideline is mandatory for operations in Germany.

The "first principles" of the guideline are:

- The existing long-term crosswind safety record of rail operations in Germany is acceptable and sufficient, and can therefore act as a baseline for comparisons.
- Future operation should be at least as safe as the existing operation.
- Crosswind safety should be applied to conventional as well as high speed rail.
- Crosswind safety should be controlled and monitored across the whole network.
- To simplify the task of proving safety, analysis and assessment procedures should address separately the crosswind stability of rolling stock and the crosswind exposure of the line.
- The methods should be simple, transparent, and robust, and accessible to a wide range of interested parties.
- The emphasis is on practicality, manageability, consistency, and wide applicability, rather than highly detailed analyses of particular situations.

The logic of the guideline is outlined in Figure 23. Central to the method is the concept of reference to existing operations:

- New vehicles are compliant if their Characteristic Wind Curves are at least as good as the relevant reference CWC (the reference CWC is based on existing rail vehicles with different reference CWCs provided for each class of vehicle)
- New routes are compliant if a vehicle with the reference CWC meets the safety target.

The fact that the method is comparative is an important difference from some other standards. It matters less if certain aspects of the assessment are over-simplified or less accurate because the reference train or line is analyzed with the same assumptions. When the new train or line is compared with the reference situation, the effect of such inaccuracies tends to "cancel out". This is an advantage in crosswind assessment, where the actual situation is very complex and not all of the required information can be known accurately.

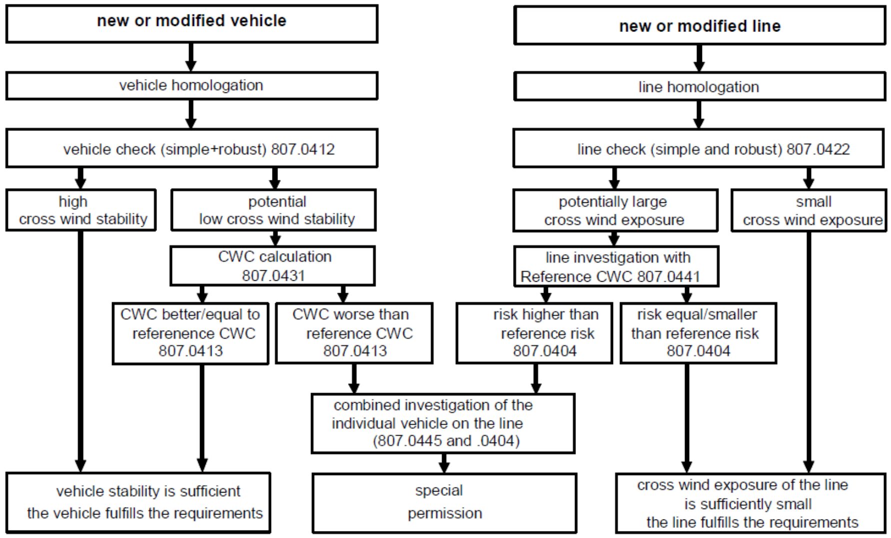

Figure 23. Outline of German guideline Ril 807.04

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Some details of the derivation of CWCs are:

- The aerodynamic coefficients of the vehicle are derived from low-turbulence wind tunnel tests with a flat ground. Although flat ground is not the worst case, it is suitable for *comparative* assessments between one vehicle and another, and is simpler to test.
- The vehicle response is modeled using multi-body simulation (MBS).
- A wind gust model is defined in the guideline (the so-called Chinese Hat idealization whose graph of wind speed over a time duration is similar to the shape of a 19th century Chinese hat, see Figure 24). This model is further defined in EN 14067-Part 6 in which the wind speed varies spatially and the vehicle travels through the wind thus experiencing wind speed that varies with time.
- The safety criterion is 90% unloading of the windward wheel.
- The CWCs are graphs of maximum safe wind speed versus train speed. Each graph applies to a particular combination of yaw angle and uncompensated lateral acceleration.

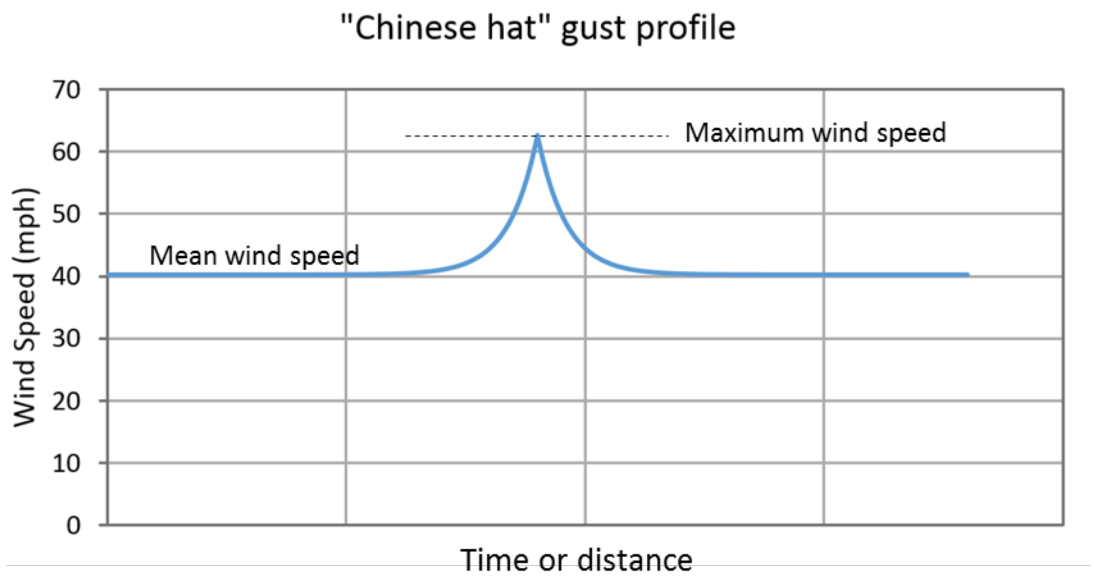

Figure 24. Example of "Chinese Hat" wind gust profile

The steps in the route risk assessment are:

- The line characteristics at points along the route are assessed, including line speed, uncompensated lateral acceleration (from cant deficiency), and wind protection from cuttings.
- Using the CWC curves (either the reference curves, or the curves for a particular vehicle) a new curve of safe wind speed versus distance along the route is produced.
- The probability of exceedance of the safe wind speed at each point along the route is assessed.
- The acceptable exceedance probabilities are defined according to train speed in Ril 807.04.

The probability of exceedance of the safe wind speed is performed by a "Eurocode" method. The Eurocode describes how to calculate the yearly occurrence probability of a mean wind speed by comparison with the 50-year return mean wind speed. The method is similar to that used in Europe for civil engineering applications [114], with these details:

- Geographic areas of the country are grouped into wind zones according to the 10-minute mean wind velocity at 32.8 ft (10 m) height.
- A directional factor accounts for the prevailing wind direction.
- Local ground roughness is considered for both sides of the line.
- A height-dependent speed-up factor is applied for embankments.
- A fixed speed-up factor is applied for bridges.
- A gust factor is applied to transform mean wind velocity into gust velocity.

These factors are then generalized into a calculation of probability of gusts that exceed the safe wind speed.

Figure 25 shows the tolerated rate of CWC exceedance (1.24 mi (2 km), rolling average) in exceedances per year. Note that this does not imply an expected rate of accidents. CWC exceedance is a necessary but not sufficient condition for a crosswind-related rollover to occur. The data includes the effect of mitigation measures in the case of high speed operation. Note the reduction of acceptable rate of exceedance with increasing operating speed, reflecting the increased risk of injury or fatality arising from rollover at high speed.

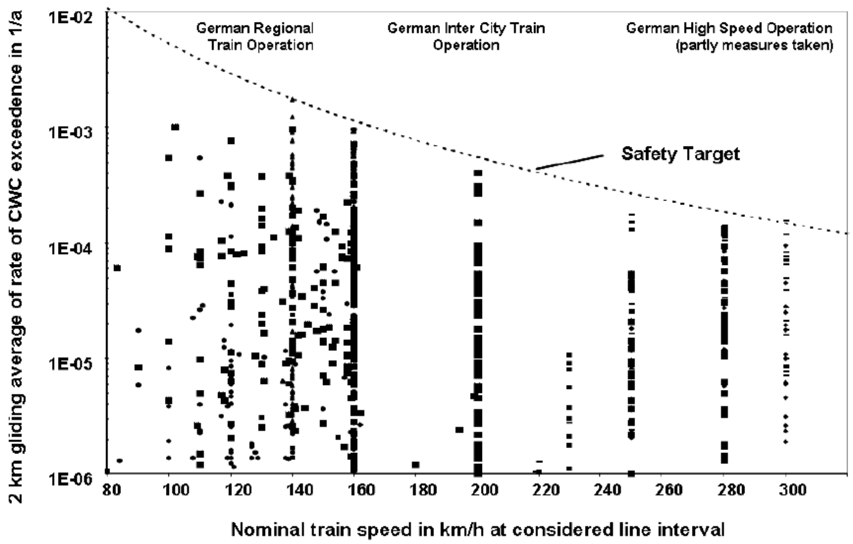

Figure 25. Excerpt from "risk map" as determined by procedures in Ril 807.04
Example only. Not to be used for design; reproduced from [145] by permission of Union Internationale des Chemins de Fer

5.4.4 European Standard EN 14067-6

Aspects of the various European national crosswind assessment systems are carried forward in the European standard EN 14067 Part 6 [147]. The standard is very comprehensive and detailed in some areas, but methods of route risk assessment are lacking due to disagreement between the countries involved. The standard therefore does not provide a complete methodology. The standard applies to passenger vehicles with maximum speed up to 224 mph (360 km/h). At higher speeds, the standard stipulates that compressibility effects shall be taken into account.

The standard gives extensive guidance on the crosswind stability assessment of vehicles. The available methods are summarized in Figure 26 below. The aerodynamic coefficients are evaluated for a ballast and rail scenario only i.e., embankments are not considered.

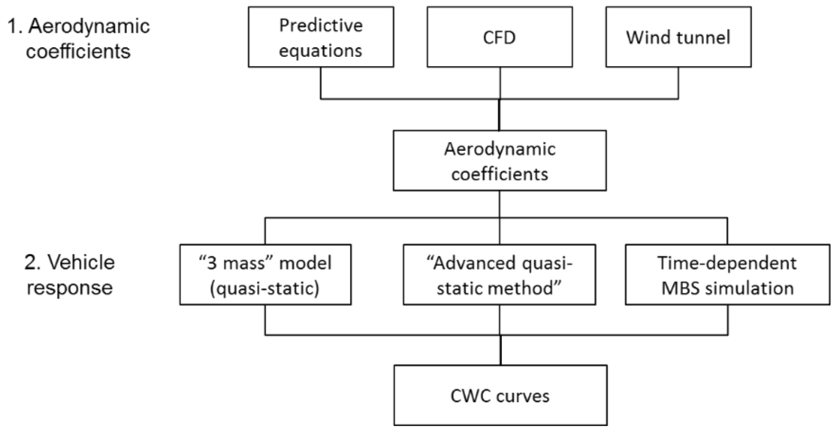

Figure 26. Summary of methods available for rail vehicle CWC evaluation described in EN 14067-6

The "three mass" model is the simplest suitable vehicle model that includes sprung and unsprung masses and, importantly, lateral suspension deformation. This model may be used in quasi-static or dynamic simulations.

Multibody simulation (MBS) is a method of numerical simulation of multibody systems composed of various rigid or elastic bodies. Connections between the bodies can be modeled with force elements such as springs and dampers. Full multi-body simulations (MBS) are preferred by some authors and are required in some standards. The effect of unbalanced lateral acceleration is included as a quasi-static load at the center of gravity of each mass. In the case of MBS it may be included by running the model on a curve. This is discussed in greater detail in Section 5.5.1.

The required format of the CWC curves is given in EN 14067-6 (example in Figure 27). These tables would be provided by the train manufacturer. In each cell, the "safe wind speed" is given. This is the wind speed, $v_{W,}$ at the specified wind angle, $\beta_{W,}$ and uncompensated lateral acceleration, $a_{q,}$ that causes 90% unloading of the windward wheel.

Table 6 — Form for CWC table for passenger vehicles and locomotives in non-tilting mode

Train speed (in km/h)	CWC (in m/s) for angle β_W								
	90°	80°	70°	60°	50°	40°	30°	20°	10°
80									
90									
100									
110									
120									
130									
… (minimum Δv_{tr} = 20 km/h)									
Maximum train speed									
The tables shall be provided for a_q = 0 m/s^2, a_q = 0,5 m/s^2 and a_q = 1 m/s^2									
The values shall be given to one significant decimal.									

Figure 27. Format of CWC curves specified in EN 14067-6 [147].

In Figure 27, the grey cells should be completed as a minimum. Completion of the white cells is desirable. Three such tables are required, for uncompensated lateral accelerations of 0, 0.05 and 0.1 g (0, 0.5 and 1.0 m/s^2) respectively.

The standard provides guidance on collection of data on the route that would form input data for a route risk assessment. The suggested format is shown in Figure 28.

Table 14 — Layout for integrated line database

Connection	Line section	Line-No.	Start-km	End-km	Total length
Train operation mode (normal or active tilting)	Coordinate system used	At the starting line kilometre			
		x-coordinate	y-coordinate	Orientation/north	
Reference of the map		[m]	[m]	[°]	

Line-km	Element length	x coordinate	y coordinate	Radius		Cant		Orientation to north	Track height category: resolution [m]		Track type		Altitude above sea level	Design speed		Wall distance from furthest track centre line		Wall height above top of rail		Remarks on wall design		Roughness (class) Name of classification	
				Radius 1	Radius 2	Cant 1	Cant 2		Left	Right	Left	Right		Forward direction	Backward direction	Left	Right	Left	Right	Left	Right	Left of track	Right of track
[km]	[km]	[m]	[m]	[m]	[m]	[mm]	[mm]	[°]	[m]	[m]			[m]	[km/h]	[km/h]	[m]	[m]	[m]	[m]				

Figure 28. Layout of table of line characteristics, from EN 14067-6 [147].

In Figure 28, features such as embankments and viaducts are noted under “track type”. EN 14067-6 contains further explanation and details for this figure.

Methods to assess wind exposure are outlined briefly in an Annex to the standard, and may be summarized as a choice of “Wind map” approaches or “Transfer” approaches.

Wind map approaches are as described for the British system above (Sections 5.4.1 and 5.4.2). Wind maps or tables from national standards based on long term wind statistics provide the base wind speed. This is then converted to a gust speed at a particular point on the line by applying factors to account for terrain, gust duration, line direction, embankments and viaducts, and other factors. Methods and examples of wind gust speed calculations are given in [144] and [146].

Transfer approaches use long-term wind databases from meteorological stations close to the line. Wind speeds are “transferred” to points along the line between the meteorological stations using numerical modeling methods such as CFD. These models are used to predict the relative wind speeds at the unknown points compared to the meteorological station. The same data may then be used as input to automatic train slow-down systems.

No information is given about how the meteorological data and CWCs should be combined in a risk assessment. Reference CWCs are given only for “Class 1” trains (well streamlined high speed trains with maximum speeds of 155 mph (250 km/h) or more). No information is given about how the acceptability of rollover risk should be determined. The incompleteness of the standard is a major disadvantage.

5.4.5 European Technical Specifications for Interoperability (TSI)

The TSI Rolling Stock Subsystem [14] provides reference CWCs for "Class 1" trains. A rail vehicle complies with the TSI if its CWCs are "superior" to the reference curves, meaning that the characteristic wind speed is greater than the reference value at all points on each curve. Examples of the curves are given in Figure 29 for the case of wind angle β_W =90° and uncompensated lateral acceleration a_q=0. The TSI contains curves at other wind angles and accelerations.

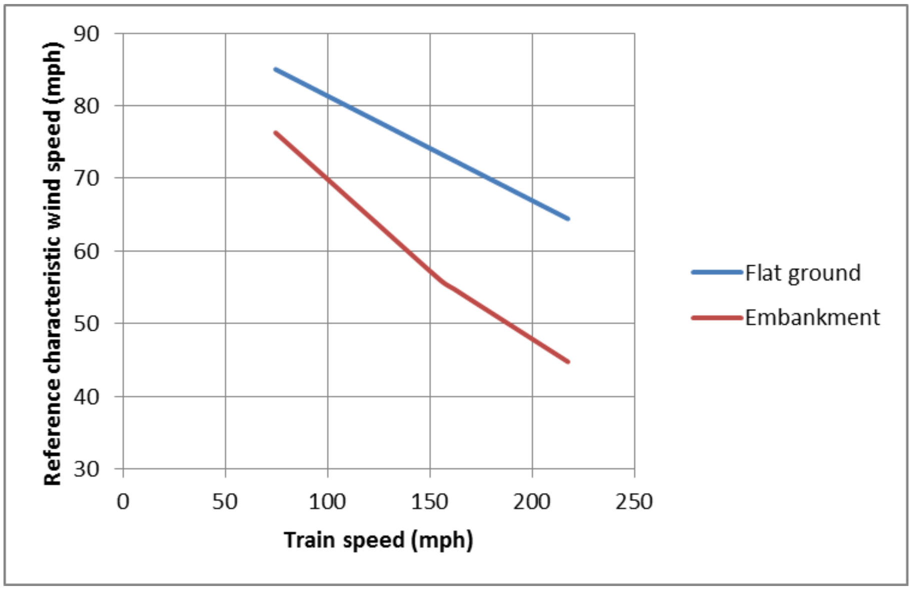

Figure 29. Examples of reference characteristic wind speeds from European TSI (Rolling stock), for wind angle 90°.

Example only - not to be used for design; for full details, refer to the TSI.

Annex G to the Rolling Stock TSI defines how the CWCs for a rail vehicle should be derived. This is more prescriptive than EN 14067-6, permitting only wind tunnel testing for derivation of the aerodynamic coefficients (although future revisions of the standard are expected to permit CFD), and only multi-body simulation for calculation of vehicle response. Within those limitations, the requirements in the TSI for wind tunnel testing and multi-body simulation are similar to that described in EN 14067-6.

The reference CWC curves given in the Rolling Stock TSI [14] may be used for route assessment and for comparison with CWCs for high speed trains when selecting rolling stock. However, the Infrastructure TSI [13] does not define any methods for route risk assessment. It simply requires that a line meets the relevant national crosswind safety standards for an "interoperable train" (as defined by the reference CWCs) under the most critical operating conditions.

European Standards: Methods of Dealing with Embankments and Viaducts

There are major differences in approach to assessing embankments in the different European national standards. The two main types of approach assessments are:

- Calculate CWCs for one standard configuration, usually flat ground. When assessing wind speeds at each site, apply a speed-up factor that accounts for the embankment or viaduct.
- Measure aerodynamic coefficients in different configurations (e.g., embankment heights). The coefficients are then defined based on the upstream wind velocity, i.e., the velocity before amplification by the embankment. CWCs are generated for each configuration. When assessing embankment heights not equal to any of the configurations for which CWCs were calculated, interpolation is used.

The second approach is considered more accurate, but more laborious to apply, and large numbers of CWCs must be generated. For viaducts, the speed-up factor method is generally used.

5.4.6 Japanese System

In Japan, a quasi-static method for determining critical wind velocity (minimum wind velocity that causes 100% wheel unloading on the windward side) based on force and moment balance equations was proposed by Kuneida in 1972 [148] and became known as the Kuneida formula. It was recently modified by Hibino et al [149], who derived the so-called Detailed Equation. It considers a railcar as a 2-dimensional 2-mass system, taking into account such parameters as the truck's mass and location of center of gravity, center of wind force, car body roll angle with respect to truck, and other factors. The end result is a wind unloading ratio on the windward wheels, with ratio of one representing the start of rollover. The formula was verified with full-scale static and field experiments [118].

5.4.7 Assessment of Standards

The following assessment of the above standards is based on applicability to Tier III operations.

Neither the European Standard EN 14067-6 nor the European TSIs are suitable for wholesale adoption in the United States, for the following reasons:

- They do not give a complete method for crosswind safety assessment. The risk assessment methods and acceptability criteria are missing.
- They are unbalanced in that some steps are rather complex while others are inadequately defined.
- A detailed Multi-Body Simulation (MBS) of the train's response to wind gusts is required. MBS methods can be time-consuming to apply. While this approach is widely agreed in Europe, it can be argued that the extra accuracy obtained by MBS over quasi-static methods is small compared to the uncertainties inherent in the aerodynamic coefficients and wind climate data.
- The wind gust to be assumed (Chinese Hat model, see Figure 24) is described in detail and is widely accepted in Europe, but has major deficiencies. The model varies only spatially and not temporally. As the train passes through the gust location, different parts of the train are exposed to the gust, thus achieving a sort of temporal variation. However, this mathematical idealization is not based on the spatial and temporal distributions of real wind gusts.

For these reasons, *it is not recommended to adopt these standards* in the United States. However, some specific aspects of the standards could be useful for the United States:

- The standards contain useful guidance on some aspects of measuring and recording aerodynamic coefficients and Characteristic Wind Curves.
- The concept of separating the vehicle assessment from the route assessment (by use of reference vehicle CWCs) is useful.
- Adoption of the reference CWCs given in the European TSI as an acceptability criterion for Tier III that demonstrate CWCs that are better (higher characteristic wind speeds) than the reference curves.

Overall, a more balanced approach would be desirable including all steps in the process at a level of detail appropriate to the many uncertainties.

The comparative risk assessment method in the German system is reasonable and offers significant advantages for countries where there is an existing record of safe operation of high speed railways. To adapt this method for Tier III operation in the United States would require an existing base of high speed rail services that have been operating safely for many years in the US wind climate. The Northeast Corridor could possibly be used as a reference operation.

The German system shares with EN 14067-6 the same rather complex approach to calculation of the vehicle's response to gusts, but in other respects has useful simplifications. For example, the use of speed-up factors for embankments, and the use of "reference CWCs" to offer the possibility to separate vehicle assessment from route assessment. A further interesting point in the German system is the reduction of acceptable rollover risk with increasing operating speed, reflecting the increased probability of fatalities.

The British system has the advantage of simplicity, and is reasonably well balanced in respect of the details of each step reflecting the uncertainties surrounding the whole process. However, numerous adaptations would be needed if the system were to be adopted in the United States:

- The "stability requirement for conventional trains" is based entirely on British operational experience. Equivalent acceptability criteria would need to be derived for North American rolling stock selected by a long history of safe operation.
- The simple stability requirement would be better expressed as a CWC, enabling the effect of different operating speeds to be accommodated.
- The route assessment method given for tilting trains would have to be adapted to suit all types of trains; primarily, all sections of a route would need to be included, not only curves.
- All the details of the local wind gust speed calculation would need to be revised to suit North American wind conditions.
- Comparative risk assessment for Tier III operations would require a suitable reference operation. The Northeast Corridor may be suitable for this purpose. Meanwhile, any absolute risk assessment would need to be adapted to suit the US approach to acceptability of risk.
- The risk calculation should recognize that the risk of fatalities in overturning accidents depends on the speed of the train.

Overall, no single national or international crosswind assessment system offers a complete approach for the United States. *We recommend developing a new system for the United States based partly on the British system but with details adapted to reflect current best practice and to suit the United States wind environment and risk approach.*

5.5 Data from the Literature Including Measurements, Criteria, and Assessments

5.5.1 Measurement and Analysis

Characterizing the Crosswind

An example of wind characterization is presented in a recent study by Yao et al [119]. These authors describe the method for analyzing 5-year data from 55 meteorological stations along the Lanxin Railway in China. The region was divided into three distinct zones. Seasonal, annual, and daily variations in wind speed in each zone were analyzed. The main parameter of interest was daily extreme wind speed with its probability density functions (PDF) presented using a Weibull distribution. Then a Gumbell distribution was used to calculate the annual maximum daily extreme wind speed. The final outputs were the annual maximum daily extreme wind speeds in three geographic zones for return periods of 2, 5, 10, 20, 50, and 100 years. Such results can be useful to evaluate the long-term risks of crosswind-induced railroad incidents.

Full-Scale Experiments

Due to their high cost, as well as the uncertainty of the wind to blow at the time of the tests and repeatability concerns, full-scale studies are inherently problematic in the case of crosswinds. Nevertheless, they have been conducted, such as during the European TRANSAERO program [150]. The tests involved running a full-size test vehicle equipped with instrumentation to measure wind conditions (speed and yaw angle relative to the train) and wheel-rail contact loads. The results from these experiments were used to inform the European standards governing train stability in crosswinds. The test track section was on a 26 ft (8 m) high embankment, with parts of its length protected by solid walls and porous wind fences. The aerodynamic coefficients of the vehicle could be deduced by comparing the measured loads with the wind velocity relative to the train. The presence of a wind fence appears to generate a constant rolling moment independent of the crosswind due to the creation of a low pressure zone between the train and the fence as the train passes. Thus, it is difficult to quantify the benefit of the wind fence in reducing the moment coefficient due to crosswind. Overall, the rolling moment reduced by a factor of about four for wind speeds of about 22 mph (10 m/s), compared to the case of open track with no barrier.

Reduced Scale (Wind Tunnel) Experiments

Scaled tests are usually conducted on stationary models in wind tunnels. Although the environment is more controlled than in full-scale open environment tests, a number of significant problems arise [57], including:

- The Reynolds number must be reasonably close to that of a full-size vehicle in an open environment. This can be difficult to achieve and puts limitations on the scale of the model.
- For the effects of the ground plane to be fully accounted for, both wind yaw angle relative to the ground and yaw angle relative to the moving train must match those

observed in a full-scale moving train. *This is nearly impossible to achieve with a stationary model*. Even the use of a moving belt does not fully solve the problem when the effects on a bridge, an embankment, or a wind barrier must be investigated.

- The atmospheric boundary layer with its turbulent, unsteady flows is very difficult to simulate in a wind tunnel. In most wind tunnel experiments, only steady, uniform wind is simulated. Nevertheless, attempts to reproduce unsteady conditions have been made using elaborate setups such as flapping airfoils and unsteady cross jets.

These effects are less significant at high train speeds. Even though wind tunnel testing has difficulties and limitations, it represents the best available method at present for evaluating aerodynamic coefficients [110].

Baker [151] used wind tunnel tests to measure the efficacy of noise barriers of different porosities in reducing aerodynamic loads from crosswinds. A solid barrier 10 ft (3 m) high eliminated the rolling moment completely. A 50% porous barrier of the same height reduced rolling moment by a factor of about two. Barriers 6.6 ft (2 m) high were almost as effective as the 10 ft (3 m) high barriers.

Reduced Scale (Moving Model) Experiments

Some moving model rigs are equipped with crosswind generation such as the TRAIN rig in Derby, England [152]. A bank of 16 fans blows air across a section of the track (see Figure 30). The train models are equipped with an array of pressure transducers from which the forces and moments may be calculated.

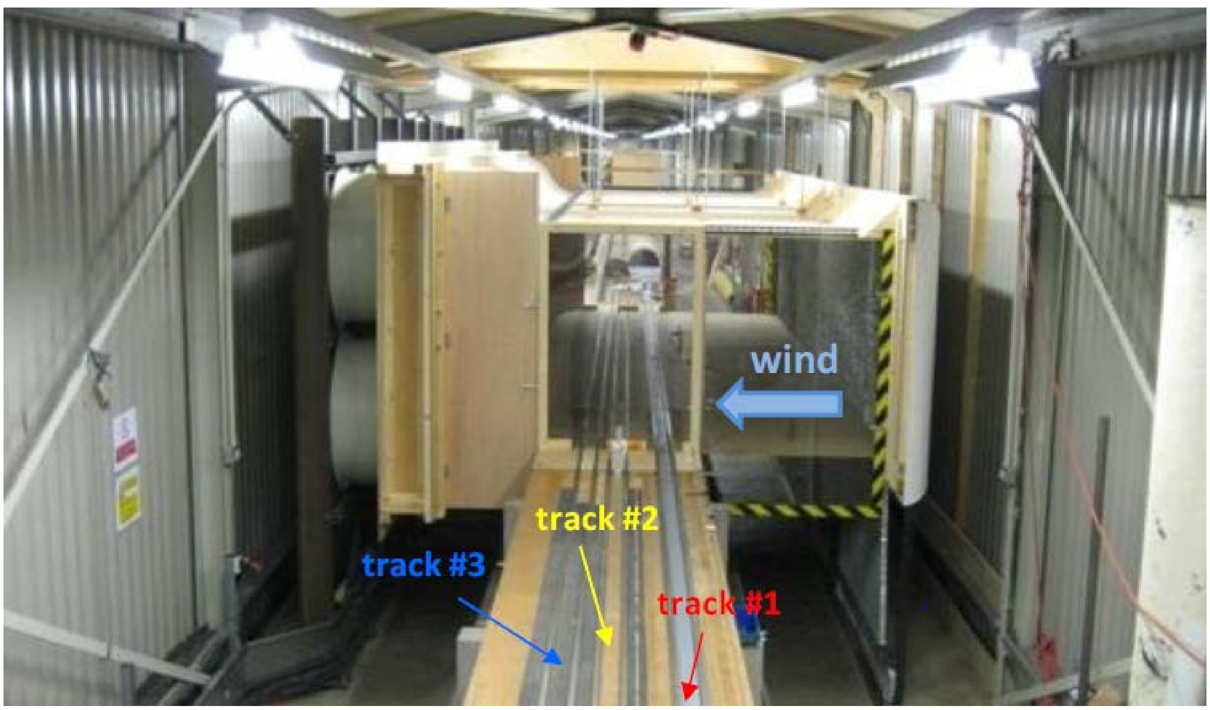

Figure 30. Crosswind generation facility at TRAIN rig in Derby, England
Photo reproduced from Dorigatti [153] by permission of Birmingham Centre for Railway Research and Education.

Numerical Methods (CFD)

Reynolds-averaged Navier-Stokes (RANS) methods can predict static coefficients. It is possible to simulate shear (the reduction of velocity near the ground) but not atmospheric turbulence. Moving ground can be incorporated but this is not often done. Methods such as detached eddy simulation (DES) and large eddy simulation (LES) can simulate unsteady flows, and hence, can be used to model spatial and temporal non-uniformities and investigate loading arising from gusts, but these methods are at an early stage of development.

Typical of steady-state CFD analysis was the research carried out as part of the TRANSAERO project summarized by Matschke [134] in 2002. This research showed that CFD can achieve good agreement with coefficients from physical tests using RANS with a K-epsilon turbulence model provided that care was taken with the grid quality and size. The K-epsilon turbulence model is the most common model used in CFD to simulate turbulent conditions. It is a two equation model that gives a general description of turbulence by means of two transport equations. The first transported variable determines the energy in the turbulence and is called the "turbulent kinetic energy" (k). The second transported variable is the "turbulent dissipation" (ε) that determines the rate of dissipation of the turbulent kinetic energy.

It was concluded that CFD is suitable for parameter variation studies but not for safety-relevant proof of crosswind stability. Since then, developments in CFD modeling methods and computing power have led to improvements in the realism that can be achieved. However, the studies have not been repeated using these developments.

A number of studies have attempted to quantify the significance of the spatial non-uniformities introduced by the atmospheric boundary layer above the ground. Xi et al [154] used a CFD simulation to compare the behavior of a high-speed train running at 217 mph (350 km/h) in a uniform crosswind field versus a non-uniform wind field with a boundary layer-like profile. In the latter case, wind velocity was distributed exponentially in the height direction such that wind speed at height 33 ft (10 m) above ground was the same as wind speed in a uniform crosswind field case. The authors concluded that use of a spatially uniform wind field significantly overestimates the forces onto the train, compared to a non-uniform field. This may be due to the height at which the reference velocity is taken. Alternatively it could be because the flow structures are more coherent for uniform low turbulence flow.

It is important to stress that the study by Xi et al dealt with a spatial distribution of wind speed, and did not take into consideration the temporal distribution (i.e., wind gusts). To-date, very few CFD studies were found that simulate crosswind gusts.

Temporal variations in aerodynamic loads may be studied using large eddy simulation methods, for example, as described by Hemida and Baker [155]. This technique is very CPU-intensive. To keep the computing time within reasonable bounds, slower than real-life speeds are often used in the simulations (i.e., a lower Reynolds number is used in the simulations than the real life situation).

The end result of CFD simulations is typically a pressure distribution on a train surface, which is then integrated to give the aerodynamic force and moment coefficients. It needs to be interpreted in terms of risk of rollover or wheel climb derailment. This can be done either analytically with quasi-static balance equations, or numerically with multi-body dynamics software.

Analysis of Vehicle Response to crosswind Loading Using Formulae

In different countries, different methods tend to be used for crosswind assessment. European studies often use multi-body dynamics simulations, while the majority of Japanese studies use analytical quasi-static methods [149]. Chinese studies use both methods.

Examples of analytical approach for wheel-rail forces, combined with a CFD approach for wind loads, is presented in studies by Fujii et al [107], Gao and Tian [117], and others. The authors used a series of quasi-static force and moment balance equations to derive CWCs for the particular railcars studied.

Numerical Methods (Multi-Body Simulations)

Multi-body simulations (MBS) can include a single vehicle or a series of rigid bodies representing the main masses of the vehicle connected by elements representing the suspension, and with a wheel-rail interface model that typically includes representation of the profiles of the wheel and rail. Example programs offering this type of analysis include SIMPACK® [156], VAMPIRE® [157] and NUCARS® [158][1].

Some multi-body numerical studies use steady or quasi-steady wind speed as an input. For instance, the study by Deng and Xiao [159] simulated a constant wind speed acting over a finite length of track. The distance along which the wind was acting varied between the trials. The authors note the importance of the duration of wind force. The same wind force may or may not lead to derailment, depending on the time that it acts on the train. In their simulations, a rail vehicle traveling at 124 mph (200 km/h) and subjected to a 56 mph (25 m/s) wind for 262 ft (80 m) derailed, while the one subjected to the same wind for 230 ft (70 m) did not derail, although the safety limit for wheel unloading was exceeded.

Typical European multi-body simulations use a standard idealization of a wind gust, in the form of the so-called Chinese hat spatial distribution of wind speed (see Figure 24; details are presented in EN 14067-6).

Multi-body simulations with unsteady aerodynamic loads are reported by Thomas et al [160] who compared two different idealizations of a crosswind wind gust, and a crosswind suddenly applied, at a tunnel exit. The tunnel exit represented the worst case.

Wetzel and Proppe note that *"…due to the stochastic wind excitation and the uncertain parameters of the railway vehicle, it is not possible anymore to get a specific failure boundary and to compute at which critical wind velocity the vehicle will overturn, but it is only possible to derive the probability that the railway vehicle will fail*"[161]. To solve this problem, these authors used multi-body dynamics software in combination with mathematically generated turbulent wind input to obtain the probabilities of train rollover under different wind and terrain conditions.

The effect of unsteady wind loading as opposed to the idealized gust were analyzed by Baker et al [162]. Their conclusion was that quasi-steady specification of wind gust effects is adequate for the time period required for overturning (one to three seconds). In other words, the aerodynamic coefficients may be assumed to remain constant. For behavior that occurs in time

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[1] SIMPACK is a registered trademark of SIMPACK AG (Germany). VAMPIRE® is a registered trademark of Delta Rail, Inc. (UK). NUCARS® is a registered trademark of Transportation Technology Center, Inc. (USA).

periods shorter than about 0.5 seconds, such as pantograph lateral movement, the aerodynamic admittances must be considered such that the aerodynamic forces take a finite time to develop in response to changes of wind speed.

Baker et al [163] showed that the effect of track irregularities can result in wheel unloading of a similar magnitude to that caused by crosswinds. This suggests that the criterion for safe operation in crosswinds should allow for some wheel unloading from sources other than crosswinds. Consequently, this suggests that the acceptability limit for wheel unloading due to crosswinds should be less than 100%.

5.5.2 Criteria

Criteria for the Onset of Rollover

In general, criteria are expressed in terms of wheel unloading and the lateral-to-vertical force ratio to ensure safety against wheel climb derailment. Specific values are prescribed in US regulations and standards regarding rolling stock testing.

The safety criterion for crosswind-induced vehicle rollover most commonly used in Europe is 90% unloading of the windward wheel of the most sensitive truck of the most sensitive vehicle. This criterion can be regarded as a surrogate for additional wheel unloading due to track irregularities.

Assessment methods in Britain and Japan use 100% unloading of the windward wheel.

In the US, there is no crosswind assessment procedure. However, for other purposes, the safety criterion against rollover on high-speed tracks (up to 220 mph, or 354 km/h) is 85% unloading of a single wheel for a continuous 5 ft (1.5 m) of travel [164].

Criteria for Acceptability of Crosswind Stability of Rolling Stock

Reference CWCs are given in the European TSI. High speed trains should have CWCs exceeding the reference CWCs (See Figure 29).

The British system requires that the intrinsic rollover wind speed for a vehicle running at its maximum design operating speed on straight and level track shall be not less than 82 mph (36.5 m/s). This criterion is applied to conventional vehicles for which more detailed assessments are not performed.

Criteria for Acceptability of Rollover Risk for a Route

The German system uses a curve of acceptable CWC exceedance rate per 1.2 miles (2 km) versus train speed (Figure 25). The British system prefers a comparative risk assessment, but permits an absolute assessment based on a passenger who uses the route regularly or the route having a probability of fatality due to rollover of no more than 10^{-7} per year. *Suitable criteria for the United States are lacking and we recommend that they be developed.*

5.5.3 Assessment Methods and Evaluations

The overall purpose of an assessment is to evaluate the risk of crosswind-induced accidents, and to identify where on a route mitigation is required.

According to European methods, which are considered the most comprehensive, evaluation of the crosswind stability of a train consists of tasks that may be broadly summarized as follows:

a) Assessment Method of Crosswind Stability of the Train (Normally Obtained From Train Manufacturer)

- Determine the train's aerodynamic force and moment coefficients, usually by wind tunnel testing on scale models.
- Determine the train's response to the aerodynamic loads. This is done either by a quasi-static tipping calculation (including the effect of suspension deformation) or by a dynamic MBS. The aim of this step is to find the wind speed at which a safety criterion is reached, and to repeat this calculation under different conditions of train speed, yaw angle, and uncompensated lateral acceleration.
- Present the results as CWCs.

b) Assessment Method of Crosswind Risk of the Route-Train Combination

- Identify the wind climate in each sub-section of the route, together with amplifying features such as embankments and viaducts.
- From the line speed profile, use the CWCs to identify the safe wind speed at each sub-section of the route.
- Calculate the probability of the wind speed exceeding the safe wind speed in each subsection of the route.
- Combine the results from each route subsection into an overall risk assessment for the entire route. This may be done as an absolute risk of rollover compared to an acceptable risk.

c) Comparative Assessments Method

- The calculated risk of the proposed vehicle-route operation may be compared like-for-like against a vehicle-route combination with a history of safe operation.
- The vehicle CWCs may be compared against an existing vehicle with a history of safe operation on routes with similar wind exposure. For example, in the UK the "Mark 3 coach" is used as a benchmark vehicle. Aerodynamic coefficients for ICE 3, TGV duplex and ETR 500 are given in EN 14067-6 [147] Annexes C and E.

Derivation of Aerodynamic Coefficients

Aerodynamic coefficients are derived from wind tunnel testing or from CFD analysis. A brief overview of the choices available to derive these coefficients is presented in the remainder of this sub-section.

For both wind tunnel testing and CFD analysis, the simplest "low turbulence" tests involve a stationary model mounted on track, with different yaw angles achieved by rotating the model with respect to the flow. These simulations neglect atmospheric turbulence, wind velocity profile caused by shear from the ground, and the effects of vehicle movement relative to the ground, but are valid for high train speeds. For lower train speeds or stationary vehicles, atmospheric turbulence and ground effect shear must be modeled. A moving ground plane (representing the ground) is desirable, but rarely attempted in wind tunnel testing and is more practical with CFD.

Ground shapes representing flat ground, ballasted track, or embankments may be used. The European standards give the dimensions of standard shapes. The British system requires both super-elevated and flat track when wind tunnel testing is performed. When using aerodynamic coefficients provided by others, it is important to understand to what ground condition the coefficients relate.

The coefficients obtained depend to some extent on the methods used to obtain them, and different values may be obtained from nominally identical tests in different wind tunnels. The coefficients should therefore be regarded as approximate.

The coefficients are constant values that are assumed to hold even for time-varying wind speed. In practice, the forces and moments take time to develop in response to changes of wind speed ("aerodynamic admittance"), but this effect is neglected for purposes of overturning assessment.

Assessment Method for Calculating CWCs

Characteristic Wind Curves (CWCs) are calculated by combining a wind gust model that generates loading according to the aerodynamic coefficients with a model configured to predict the response of the train.

The simplest wind gust model assumes quasi-static loading (i.e., a continuous wind gust of constant speed). The European standards (EN 14067-6 and others) recommend the Chinese Hat idealization (see Figure 24). This idealization is considered unrealistic by some authors. A fully stochastic model of the wind may also be used, in which the wind speed varies in time and space, and multiple simulations are performed.

The evaluations of CWCs are usually made at a range of wind angles and a range of unbalanced lateral accelerations.

It is suggested that simpler methods are more appropriate, given the uncertainties surrounding the aerodynamic coefficients and the wind climate.

Baker [165] has proposed a simplified method to calculate a CWC using a single measured value of the coefficient of rolling moment about the leeward rail at a yaw angle of 40 degrees, and empirical relationships to extrapolate to lower yaw angles. For highly streamlined trains, i.e., the type likely to be used in Tier III operations in the United States, the constant "n" is assumed to be 1.6 and the CWC for tangent track is then defined by Figure 31 and Equation 20.

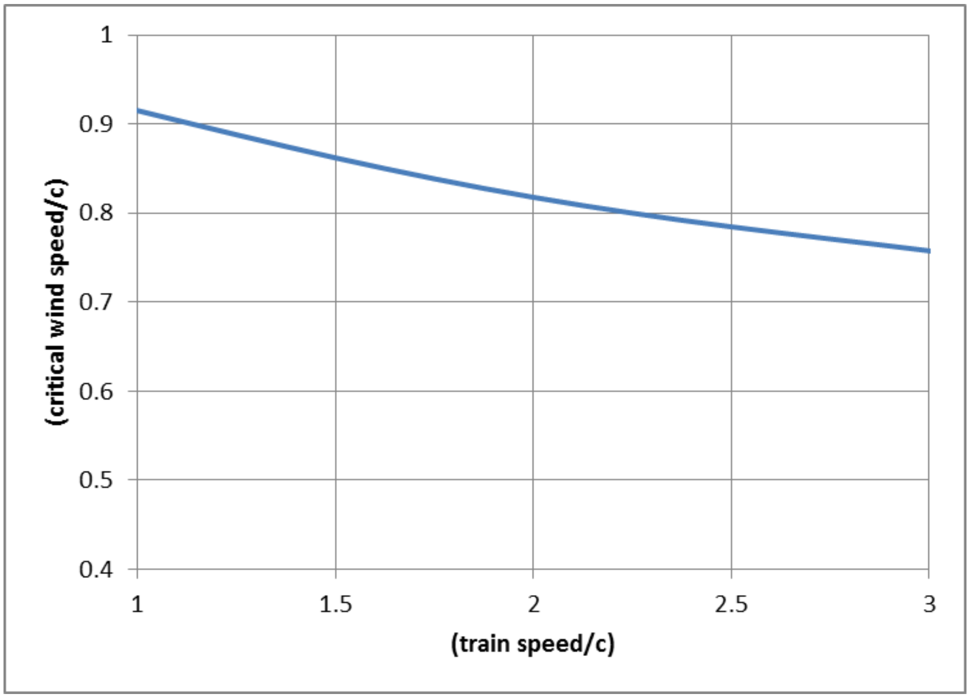

Figure 31. CWC proposed by Baker [165], assuming n=1.6 for well streamlined trains on tangent track; definition of c given below.

In the graph above, the train speed and critical wind speed are non-dimensionalized by c, defined as:

$$\boldsymbol{c^2 = \frac{\gamma M g \theta (sin40°)^n}{0.5\rho C_{RL,40°} A H}} \qquad \textbf{Equation 20}$$

where γ is a parameter that allows for unbalanced lateral acceleration, suspension displacement and a range of other "real" effects (for details of how to calculate γ, see Baker [165]), θ is the track semi-width, M is the vehicle mass, g is the acceleration due to gravity, n is a constant assumed to be 1.6 for well streamlined trains, $C_{RL,40°}$ is the coefficient of rolling moment about the leeward rail with a yaw angle of 40°, and A and H are the area and height used in the definition of C_{RL}. A consistent unit system is assumed.

Route Risk Assessment Method

In principle, the output of the route risk assessment is the probability of a train experiencing a gust that exceeds the critical wind speed, multiplied by the probability that such an exceedance leads to a fatality. The result may be expressed as a dimensionless probability, or in terms of fatalities per year. Acceptability is defined either by comparison against existing operations with good safety records in similar wind climates, or by comparison against other risks on the railway. In common with many other railway risk calculations, the risk from crosswinds has a large uncertainty associated with it. Comparison with existing safe operations is preferred if a suitable reference operation is available.

Baker [165] suggests a formula for calculating the overall risk of a fatality on a particular section of track:

$$\boldsymbol{\Omega = e^{-\left(\frac{u_i}{\lambda}\right)^k} f\left(\frac{v}{v_r}\right)^m \left(\frac{SN}{3600v}\right)} \qquad \textbf{Equation 21}$$

where u_i is the critical wind speed at that section of track, λ and k are parameters of the Weibull distribution for gust wind speeds (which are functions of the mean wind speed and turbulence intensity and where the mean wind speed takes into account local factors such as embankments), f is a constant giving the risk of a fatality being caused by exceedance of the critical wind speed at a reference train speed v_r, v is the vehicle speed, m is a constant, S is the length of the section and N is the number of services per hour. Consistent units are assumed. Analysis is required to assign suitable values for f and m.

The total risk for the route should be summed from the risks for each section. Baker's risk calculation could in principle be used in either absolute or comparative risk assessments. To perform a comparative assessment, the risk would be calculated for the reference operation in the same way as for the proposed new operation.

For the United States, we recommend that the FRA consider the development of a risk assessment method similar to that described by Baker, adapted to include factors relevant to the wind climate in the United States.

5.6 Conclusions and Recommendations

5.6.1 Conclusions

- Crosswinds have major impacts on train operations and safety.
- Aerodynamic concepts are well understood.
- Variability exists in the measurement and reporting of wind properties with a potential for misinterpretation of the data.
- Numerous standards have been developed for rail operations in Europe and Asia along with assessment methods.

5.6.2 Gaps and Issues

Standards and assessment methods need to be developed to accommodate United States rail vehicles and operations. Further details of gaps and issues are included in Section 5.6.3.

5.6.3 Recommendations to Address Gaps and Issues

The following recommendations for establishing United States standards are principally aimed at Tier III operations. In regards to existing methods for rollover risk assessment, none are recommended for wholesale adoption in the United States.

A modified system is recommended with the following characteristics:

- All steps and issues from vehicle aerodynamic properties to total route risk assessment should be included in the standard.
- Unnecessary complexity should be avoided.
- Allowances for uncertainties should be provided.
- Standards should be consistent with the US approaches to risk.

Rail Vehicle Aerodynamic Coefficients

We recommend that the rolling moment coefficient about the leeward rail be derived from wind tunnel testing. Low turbulence testing with flat ground, or standard ballast shoulder geometry representative of North American conditions should be specified.

Rail Vehicle Model

In Europe, MBS is widely held to be the most appropriate method for assessing a train's response to wind gusts. Baker [165] disagrees, on the basis that the additional accuracy offered by MBS over quasi-static methods is small compared to the uncertainties in the aerodynamic coefficients and wind climate.

We recommend that options for methods for assessment include (a) a simple "three mass" model leading to quasi-static assessment of unloading of the windward wheel and (b) Multi Body Simulation. In both methods lateral suspension deformation and unbalanced lateral acceleration must be included. The proposed safety criterion should be 85% unloading, based on existing US practice, and to be confirmed following appropriate analysis.

Wind Gust Model

The so-called Chinese Hat wind gust model is widely used in European methods but is not recommended for the reasons expressed in Section 5.4.7. A simpler approach is considered more appropriate.

We recommend a quasi-static wind load with wind speed equal to the 3-second gust speed.

Calculation of CWCs

The principle of CWCs giving critical wind speed as a function of train speed should be retained. These CWCs are presently derived from the quasi-static three mass model and the aerodynamic coefficients using formulae.

We recommend that a simpler system giving critical wind speed as a function of train speed and unbalanced lateral acceleration be developed.

Meteorological Assessment of Routes

Methods for meteorological assessment of routes are less well defined in the literature. Full details have only been found in the public domain for the British system. However, this subject should be tackled from a North American perspective, based on data available from the National Weather Service, analyzed and adapted for crosswind assessment by wind specialists, and taking into account specific wind climates unique to the United States.

We recommend a system similar to the British system. Factors should be developed and applied to the wind speed to allow for ground roughness and topographical features. Wind specialists should analyze National Weather Service data for routes to provide a profile of 1-second or 3-second gust speed probabilities for the range of possible wind directions.

Special Meteorological Issues for the United States

There is little information on tornado loading on trains. A safety strategy is required with additional research. Issues to be researched include:

- Gust speed and duration, and the effect of tornado gusts on trains.
- Predictability, such as, how to stop trains before a tornado arrives.

We recommend that research be conducted to develop a method as to how tornados could be accounted for in a crosswind assessment or mitigation system.

Risk Assessment of Routes

The data required for route risk assessment are well known and include line speed, cant deficiency, embankment details, and other characteristics at each point along the route.

We recommend the development of a table for the collection of such relevant data.

For route risk assessment, the most complete system found and described in the literature search is the one from Deutsche Bahn. This system relies on comparisons with existing high speed train operating experience to determine the acceptable risk of CWC exceedance.

A comparative system would have the benefit of being less influenced by approximations and uncertainties than a system that attempts to calculate risk on an absolute basis.

We recommend the development of a risk-based assessment method compatible with the US approach to risk. The approach of Baker et al (Section 5.5.3) could be used as a starting point. The use of the Northeast Corridor as a benchmark for comparative assessments should be considered.

6. Test and Analysis Methods

The development of standards, assessment methods, equations, and criteria will require testing and analysis of the test results. There are numerous testing facility types and alternative testing methods available. An understanding of these types and methods will assist in selecting the most appropriate methods to perform the needed work.

6.1 Introduction and Summary

This chapter will examine these testing types and methods and present an assessment of testing requirements, which are predominantly European. The majority of Asian standards, including any relevant test and analysis methods, are not available in the public domain and thus were not accessible during the literature search. This chapter includes:

- standards;
- testing types;
- measurement methods and analyses;
- assessment methods; and
- conclusions and recommendations.

This chapter has the following general conclusions and recommendations:

- International standards for testing have been developed but contain few criteria against which the acceptability of a proposed design may be assessed.
- The most widely used tests and analytical types include:
    - full-scale tests;
    - reduced scale moving model tests;
    - wind tunnel tests, and,
    - computational fluid dynamics (CFD) modeling.
- Standards for testing and assessment for the United States.

6.2 Standards for Testing

6.2.1 EN 14067

The European standard EN 14067 applies to rail aerodynamics, and consists of six (6) parts:

EN 14067 Part 1 [166] defines symbols and units.

EN 14067 Part 2 [23] gives a general introduction to high speed rail aerodynamic phenomena for the open environment.

EN 14067 Part 3 [167] gives a general introduction to high speed rail aerodynamic phenomena for the tunnel environment.

EN 14067 Part 4 [24] is applicable for open environment operations. This section contains detailed descriptions of requirements for full-scale testing and reduced scale testing, and some guidance for CFD. For some of the issues, calculation methods are provided for estimating required air pressures or velocities . *The standard contains no criteria against which the acceptability of a proposed design may be assessed.*

EN 14067 Part 5 [168] is about tunnels. Testing as described in this standard is used to confirm compliance with the nose-entry pressure wave requirements of the Rolling Stock TSI referenced below. Discussions regarding these requirements may be found in Chapter 7.

EN 14067 Part 6 [147] is concerned with crosswind assessment and the associated aerodynamic tests.

6.2.2 European Technical Specifications for Interoperability (TSI)

The European Technical Specifications for Interoperability (TSIs) consist of standards that apply to rolling stock (“Rolling Stock TSI” [14]) and to infrastructure (“Infrastructure TSI” [13]).

The TSIs contain acceptability criteria for certain limited aspects of rolling stock performance and infrastructure design relevant to aerodynamics.

6.3 Data from Literature

6.3.1 Testing Types

Full-Scale Tests

Full-scale testing is used to obtain aerodynamic coefficients for a particular train, or for a particular train/structure combination. These may be used

- in train design development;
- in the assessments of wayside structure designs; and,
- in confirming that the investigated train operation meets the required specification for conformance purposes.

Guidance is given in EN 14067 Part 4 [24], which is applicable only to open environment operations. Points to note are:

- For open track measurements (where the track is not adjacent to platforms and other linear structures) the test site is to be straight, level, and representative in terms of ballast height to those ballast heights existing or planned.
- For platform measurements the site should have a representative platform design and height, and be free of features that might affect the air flow, or shelter the measurement probes from the effects of the train.
- It may be necessary to test different train configurations.
- The ambient temperature, pressure and wind speed, and actual speed of the train should be recorded. Limits of acceptability for wind speed and train speed (to determine whether or not the results of a particular test may be included in the assessment) are given in EN 14067 Part 4, which also provides a formula to correct for small differences between the actual conditions and standard conditions.
- Train speed should be within 5% of the investigated train speed for at least 50% of the runs. Any runs with train speed not within 10% of the investigated speed should be discarded.
- Pressures are measured with Prandtl tubes pointing parallel to the track in the opposite direction to that in which the train is travelling.

- Air velocity is measured with sensors capable of measuring flow in both longitudinal and lateral directions. Results are filtered with a 1-second rolling average.
- Recording of measurements should begin at least one second before arrival of the train and continue at least one second (for pressure measurements) or 10 seconds (for air velocity measurements) after the tail of the train has passed.

For pressure pulse measurements, a minimum of 10 runs is recommended by EN 14067 Part 4 [24], although in practice a smaller number may be used. Test-to-test variability is usually small in the absence of crosswinds. For measurements of slipstream air velocity, test-to-test variability is much greater and therefore a minimum of 20 runs is required. Results are often quoted as a "characteristic" value, defined as the mean of the measured values plus two standard deviations.

Full-scale testing is the benchmark against which other techniques are judged, but it has some disadvantages such as:

- difficulty of organizing access to trains and track together with availability and set-up of measuring equipment;
- scheduling and extent of staffing to conduct the test;
- expense;
- weather uncertainty; and
- measurements may be affected by environmental disturbances such as ambient wind.

Reduced Scale Moving Model Testing

The best known reduced scale moving model test facilities have been developed in Japan (RTRI), Korea, China, Germany (DLR), and the UK. An example is shown in Figure 32. This is the TRAIN (Transient Aerodynamic Investigation) testing rig in Derby, England, operated by the Birmingham Centre for Railway Research and Education, Birmingham University, England. Twenty-fifth scale model trains are propelled down a 492 ft. (150 m) long track by a catapult system. Scale models of platforms, ballast shoulders, tunnels, walls or other structures may be placed next to the track as required. Further description of this facility is given by Baker et al [152].

Other notable moving model setups include a 1/16 to 1/20 scale model facility in China [92] and rotating rail rigs in the UK [169] and at RTRI in Japan. The advantage of the latter is its ability to produce high speeds for extended periods of time.

Figure 32. TRAIN rig reduced scale model testing facility in Derby, England, set up to measure pressure on a short overhead canopy
Photo courtesy of Birmingham Centre for Railway Research and Education

Reduced scale moving model testing is used primarily for open environment conditions but also has been used for studying tunnel aerodynamics such as the design of tunnel entrances to mitigate micro-pressure waves.

It provides a relatively quick and inexpensive method for:

- estimating the air pressure or air velocity coefficients for a particular train;
- verifying the relationships of air pressure or air velocity with distance from the track;
- measuring the air pressures acting on different types of wayside structures, including short structures where transient effects are important.

While reduced scale moving model testing is used for design purposes, EN 14067 specifically precludes its use as proof of conformity to specifications [24]. Full-scale testing proof is required.

Reduced scale moving testing may also be used to assess the air pressure exerted by one train on another train on an adjacent track; but, a full description of the train-passing situation when both trains are moving is difficult to obtain. For practical reasons, the observing train usually remains static during the test. Measurements on moving models are more difficult to record, and the rig must fire both trains at the same time from opposite ends of the track. The facility in Derby, England has this capability but it is rarely used in this mode.

The test facility in Derby has the capability to study effects of crosswinds. It uses large fans to blow air across a section of the track [152]. The difficulties of measuring loads on the moving train model are considerable. On-board balances or pressure transducers that can withstand the high accelerations and decelerations must be used.

In some cases a close level of agreement between full-scale and reduced scale moving model tests has been demonstrated. For example, Baker et al [170] give pressure coefficients measured at reduced scale that are within 5% of the full-scale results, and slipstream velocity coefficients measured at reduced scale that match the full-scale results to within the standard uncertainty of the experiments.

Models of the train should accurately represent the shapes of the nose and tail and have a good representation of the trucks, inter-car gaps and train exterior surface features. Typically, a moving model consists of the leading and trailing vehicle with two or three intermediate cars ("shortened train"). Most testing facilities cannot accommodate models of a full-length train. The effect of using shortened trains on predictions of pressure pulses and air velocities is expected to be small.

The same geometric scale should be applied to the train, any models of structures, the distances between structures and track, and measurement positions relative to the track and ground. Where the measurements are intended to represent air flow above platforms, the platform must be modeled with the correct scaled height and overhang at the platform edge. Likewise, where the measurements are intended to quantify air flow on open track, and where the real-life track is on ballast, the shape and height of the ballast shoulder should be included in the scale model.

For measuring pressure coefficients or velocity coefficients, it is not necessary for the open environment of the model to match the real-life speed of the train. For tunnels, however, the speed of the model should be the same as the real-life speed with adjustments made to the speed to compensate for elevation impacts to the Mach number. Instruments for measuring velocity and pressure are the same as for wind tunnels, but high data capture rates are required (typically of the order of 10,000 samples per second).

To allow for test-to-test variability, a number of nominally identical runs (similar to the requirements for full-scale testing) should be performed. For pressure pulse measurements, a minimum of 10 runs is recommended by EN 14067 Part 4 [24], although a smaller number may be used where the test-to-test variability has already been shown to be small. For measurements of slipstream air velocity, test-to-test variability is much greater and therefore a minimum of 20 runs is required. Results are often quoted as a "characteristic" value, defined as the mean of the measured values plus two standard deviations.

When interpreting reduced scale model results to estimate full-scale results, the following scaling laws apply:

- Pressure coefficients and velocity coefficients are expected to be the same at full-scale as at reduced scale.
- The time axis on graphs of measured responses versus time should be multiplied by the geometric scale to obtain an estimate of the full-scale responses versus time. For example, time measured in a 1/25 scale model should be multiplied by 25.
- Results are first converted to full-scale before applying any required filtering. For air velocity, a rolling 1-second average is applied.

When estimating responses at different train speeds, the following scaling rules apply:

- Because the air pressure coefficient remains constant, the air pressure scales with the train speed squared. For example, the pressure on a certain structure at a train speed of

250 mph is four times the pressure on the same structure relative to a train speed of 125 mph.

- Air velocity scales with train speed. For example, the air velocity experienced by a track worker for a train speed of 250 mph is twice the air velocity experienced by the same track worker for a train with a speed of 125 mph.
- The time axis of graphs of response versus time will scale with the inverse of the train speed. For example, the time gap between the nose pressure pulse and the tail pressure pulse is half as great at 250 mph compared with 125 mph because the train passes twice as quickly.

These rules are frequently taken to apply at all speeds, although EN 14067 Part 4 [24] requires that for speeds above Mach 0.25 (about 185 mph, or 300 km/h) the scale model speed should match the actual train speed. For example, to represent a full-scale train at 250 mph (402 km/h), the scale model train would have to be propelled at 250 mph. In practice, the testing facilities may not be capable of such high speeds. The maximum speed of the TRAIN rig in Derby, England is 140 to 180 mph (225-290 km/h), depending on the weight of the train model. Schetz [57] recommends matching the Mach number of a full-scale vehicle. Schetz also notes that if this number is less than 0.2 and wave propagation phenomena are not considered, simply keeping the Mach number of the scaled model below 0.2 should be sufficient.

Further requirements for reduced scale model testing and processing of results are given in European standard EN 14067 Part 4 Section 5.4 [24].

Wind Tunnel Tests

Wind tunnel testing is used for assessing the pressure pulse in open air or acting on a long fixed structure, and is especially suitable for measuring the crosswind response of leading vehicles. It is not suitable for measuring slipstream air velocity. Measurement of slipstream air velocity requires a full-length train in a wind tunnel moving relative to the ground. This is not feasible in a wind tunnel.

Figure 33 depicts the general configuration of a wind tunnel test for measuring crosswind aerodynamic forces and moment coefficients. A scale model of the train, with a level of detail similar to that described above for moving model tests, is fixed to the ground. Force and moment transducers are used for measuring the aerodynamic loads. *Compared with moving model tests, wind tunnel tests have the disadvantage that effects close to the ground will be less realistic, but the advantage that the effect of crosswinds may be studied by placing the track at an angle to the air flow*.

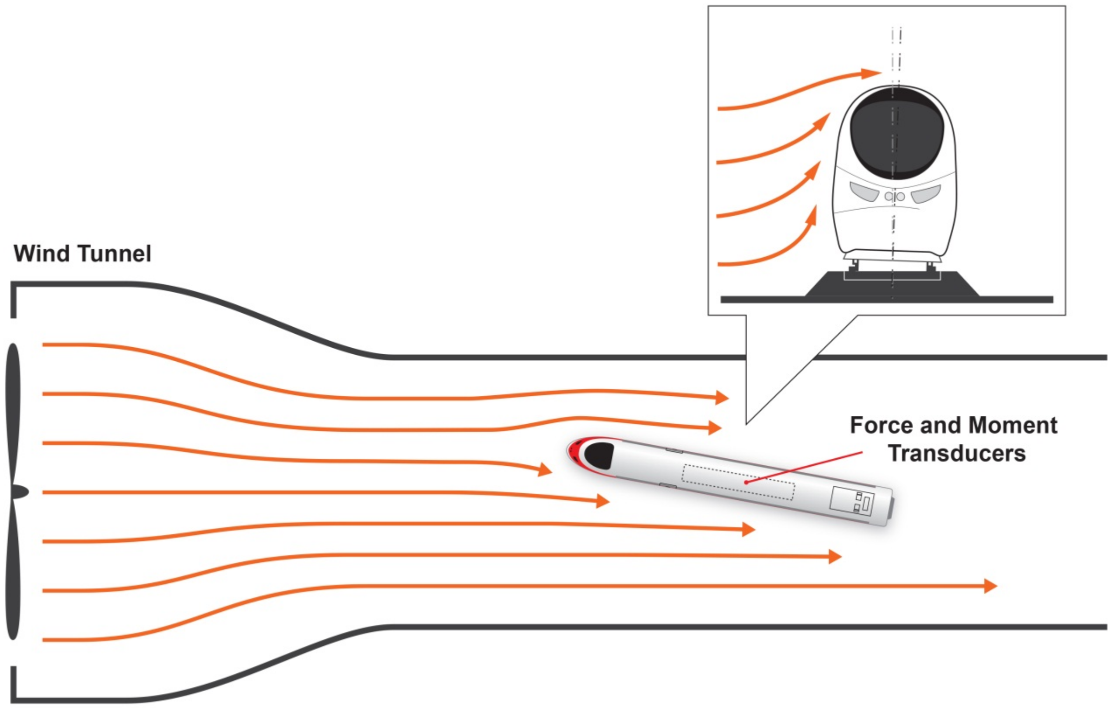

Figure 33. Wind tunnel test for crosswind aerodynamic force and moment coefficients

It is important to note that wind tunnels are designed to simulate laminar, steady air flow. In reality, crosswind is highly non-uniform in a temporal and spatial sense.

Schetz [57] gives an extensive overview of problems associated with wind tunnel testing of trains, as well as some of the proposed solutions. For example, elaborate stationary setups have been created to simulate the atmospheric boundary layer. Moving belt rigs have been built to simulate the train's motion with respect to the ground. Flapping airfoils and unsteady cross-jets have been used to simulate wind gusts. The problem of wind tunnel testing is complex, and there is no single recommended approach. Where the objective is to measure the head pressure pulse, it is usual to model only the leading vehicle.

Wind tunnel tests may be used to assess pressures acting on a long fixed structure, such as a noise barrier, where the pressure pulse reaches a steady state. They cannot be used for short structures or other situations where transient effects are important [24].

Figure 34 depicts the general configuration of a wind tunnel test for measuring pressures on a wayside structure.

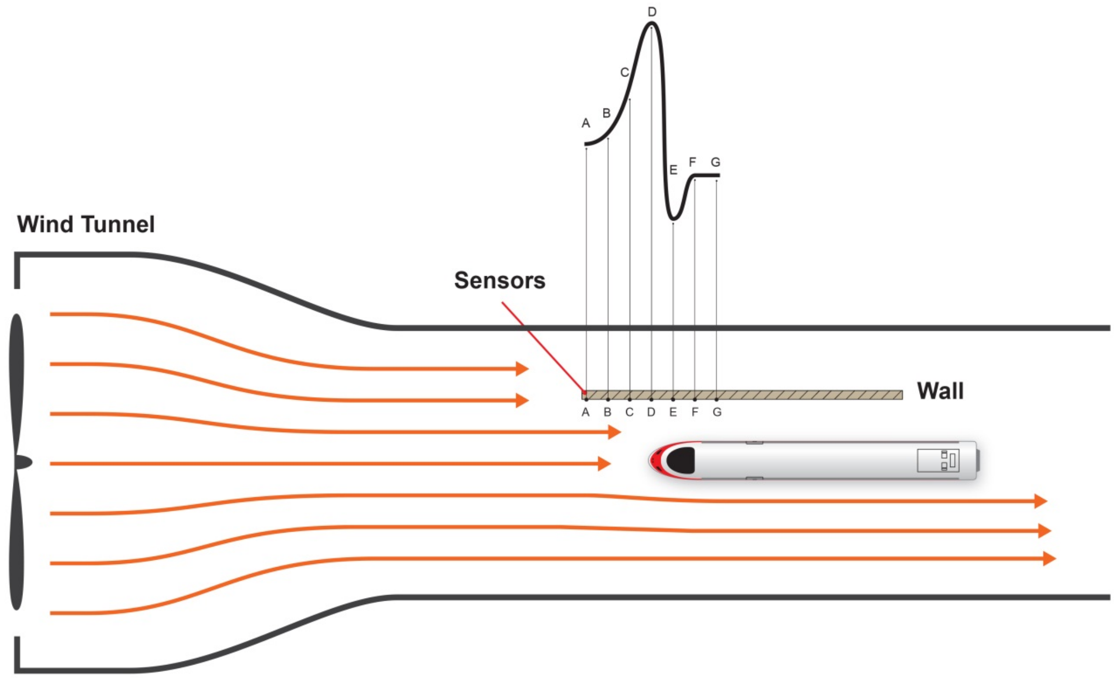

Figure 34. Wind tunnel test for pressures on a wayside structure

In a wind tunnel, the measurements should be taken at many positions down the length of the train. The relationship of pressure versus distance from the train nose in the wind tunnel will then correspond to the pressure versus time in a full-scale test, after applying the transformation "time = distance/speed of train". The graph at the top of Figure 34 shows the pressure distribution along a wall with the nose of the train positioned at Point D.

Ideally, the Reynolds number on a scaled model should be the same as on the full-scale vehicle [57]. In practice, this can rarely be achieved. European Standard EN 14067 Part 4 [24] requires the Reynolds number in wind tunnel tests to be greater than 250,000.

There is no agreement on the optimal scale for wind tunnel testing. Large scale models have realistic Reynolds numbers, but give a poor representation of atmospheric boundary layer and ground effect, and have a large blockage ratio (blockage ratio is calculated by dividing the area of the train face by the area of the wind tunnel). Small scale models, on the other hand, have small Reynolds numbers. As a result, different studies choose radically different approaches. Schetz cautions against using either moving or stationary models on a scale smaller than 1/10 because the results do not accurately represent the full-scale behavior. He cites large differences (10 to 30%) between the experimental results (after extrapolation to full-scale) and the equivalent measurements on full-scale vehicles [57]. In a more recent study, Sakuma and Ido point out the advantages of a 1/5 scale over 1/20 scale when studying train aerodynamics in a large scale wind tunnel [171]. Realistically, studies on train models of such large scale are quite rare.

Computational Fluid Dynamics (CFD)

The assessment of the aerodynamic phenomena by CFD is described extensively in the literature. CFD aids the understanding of the flow around trains and can give clearer insights into this than physical experiments.

6.3.2 Measurement and Assessment Methodology

Use of CFD to Evaluate the Head Pressure Pulse

For a smooth train shape, the head pressure pulse may be calculated with sufficient accuracy using the potential flow assumption (as in a panel method code [67, 172] or by any CFD method that solves the potential flow problem). A turbulence model is optional and not critical to results. For less streamlined shapes, where the flow is distorted or shows separation, a turbulence model is required. In these cases Reynolds Averaged Navier-Stokes (RANS) may be used.

For purposes of calculating the head pressure pulse in open air, the model should include the leading car and ground. The remainder of the train may be omitted. Where pressures on wayside structures or on other trains are simulated, the train model should move past the structure or other train in the simulation. They should start at least one car length behind and finish at least one car length in front of the structure or other train.

Use of CFD to Evaluate Air Velocity for Slipstreams

In studies of slipstreams and crosswind response, the turbulent flow around the train must be calculated. Because the results are highly dependent on turbulence and unsteady flow, assessment of maximum air velocity by CFD analysis is very challenging and cannot be performed using RANS methods. Unsteady flow methods such as Large Eddy Simulation (LES) and Detached Eddy Simulation (DES) are required. Hemida et al [173] described the use of large-eddy simulation (LES) techniques with the open-source program OpenFOAM to predict slipstream air velocities, and obtained good correlation to full-scale test data. The train was kept stationary, while the air, rail, platform and ground were moved. Meshes with 18,000,000 and 12,000,000 nodes were used. The coarser mesh was deemed satisfactory.

An advantage of the LES method is that multiple train passes can be simulated by looking at different time slices. This enables velocity coefficients to be derived from a single simulation, instead of a series of 20 physical measurements.

The LES technique is very CPU-intensive. To keep the computing time within reasonable bounds, slower than real-life speeds are often used in the simulations. Strictly speaking, a lower Reynolds number is used in the simulations than the real life situation. Any results should therefore be used with care, but, these methods show great promise for the future.

Use of CFD for Analysis of Crosswinds

Steady-state CFD RANS methods have been used to evaluate aerodynamic coefficients of trains in crosswinds. LES methods can be used to study unsteady loading from crosswinds.

6.4 Conclusions and Recommendations

6.4.1 Conclusions

Conclusions include:

- international standards for testing exist;
- the testing and associated analysis types most used are:
  - full-scale testing
  - reduced scale moving model testing
  - wind tunnel tests, and
  - computational fluid dynamic analyses;
- the existing European (CEN) Code of Practice describes testing methods in detail and is used widely; and
- new CFD analysis techniques being developed for the study of slipstreams and crosswinds are:
  - Large Eddy Simulations
  - Detached Eddy Simulations**.**

6.4.2 Gaps and Issues

Standards

There currently exist no United States standards for testing for Tier III high speed train operations**.**

6.4.3 Recommendations to Address Gaps and Issues

Standards

It is recommended that existing European standards be used as the foundation on which to develop US standards for aerodynamic testing. Additional testing and assessments to reflect North American type trains will be required.

7. Pressure Wave Effects inside Tunnels

Pressure waves in tunnels impact the aural comfort and safety of passengers and crew, and also the loadings on fixed equipment and train cars. Aural comfort and safety is frequently a major governing factor in determining the cross-sectional area of high speed rail tunnels, and therefore impacts significantly on the construction cost of new tunnels. The associated aerodynamic phenomena are well understood, the impacts on passengers have been measured, and well-established analysis methods are available.

7.1 Introduction and Summary

This chapter examines pressure wave effects in tunnels and the associated analyses performed to determine appropriate cross-sectional areas of the tunnels. It includes:

- basic aerodynamic concepts;
- influencing factors;
- measurement and calculation of pressures and cross-sectional areas;
- known and potential impacts;
- mitigation methods;
- standards and criteria;
- data from literature including measurements, assessments, and evaluation methods; and
- conclusions and recommendations.

This chapter has the following general conclusions and recommendations:

- aerodynamic concepts of trains interacting with air in the tunnels are well understood;
- measurement and analysis methods are well established;
- design and assessment criteria exist internationally but are left mostly to the individual rail operator to adopt to its design and operational procedures;
- criteria determine required tunnel cross-sectional areas and have major cost implications; and
- recommendations for:
    - formal pressure comfort and safety criteria
    - procedures and additional assessments for mitigation design and assessments of fixed equipment, cross-passages, pressure loadings on train cars, and dynamic oscillation of train cars, and
    - additional assessments for policies and procedures for operations.

7.2 Pressure Waves in Tunnels

7.2.1 Basic Aerodynamic Concepts

When a train enters a tunnel at high speed, it generates pressure waves in the air in the tunnel. A compressive pressure wave occurs ahead of the nose, and a rarefaction (negative) pressure wave is caused by entry of the tail of the train. The waves propagate along the tunnel at the speed of sound, reflecting at the portals. At each reflection, the sign of the pressure wave changes so that a compression wave becomes a rarefaction wave, and vice-versa. The pressure at any fixed point within the tunnel changes as the pressure waves (and the train) pass as presented in the upper graph of Figure 35. The pressure waves depicted in Figure 35 through Figure 40 in this section are generalized examples of aerodynamic concepts and are generated by analysis.

The pressure time-histories may be understood using a wave diagram that tracks the movement of the train and the pressure waves through the tunnel. An example is given in the lower graph of Figure 35. The y-axis is distance along the tunnel. The entrance and exit of the tunnel is shown at the top and bottom of the graph respectively. The most uncomfortable pressure changes may be those that occur at entry to or exit from the tunnel.

The blue and red continuous lines indicate the progress of the nose and tail of the train through the tunnel. The dashed lines show the motion of the pressure waves caused by entry of the nose and tail, and the reflections of those waves. As an example of how the diagrams may be used, in Figure 35, the pressure drop that occurs shortly after five seconds (in the rectangle in the upper graph) is caused by the tail-entry wave passing the measurement point (ringed in the wave diagram).

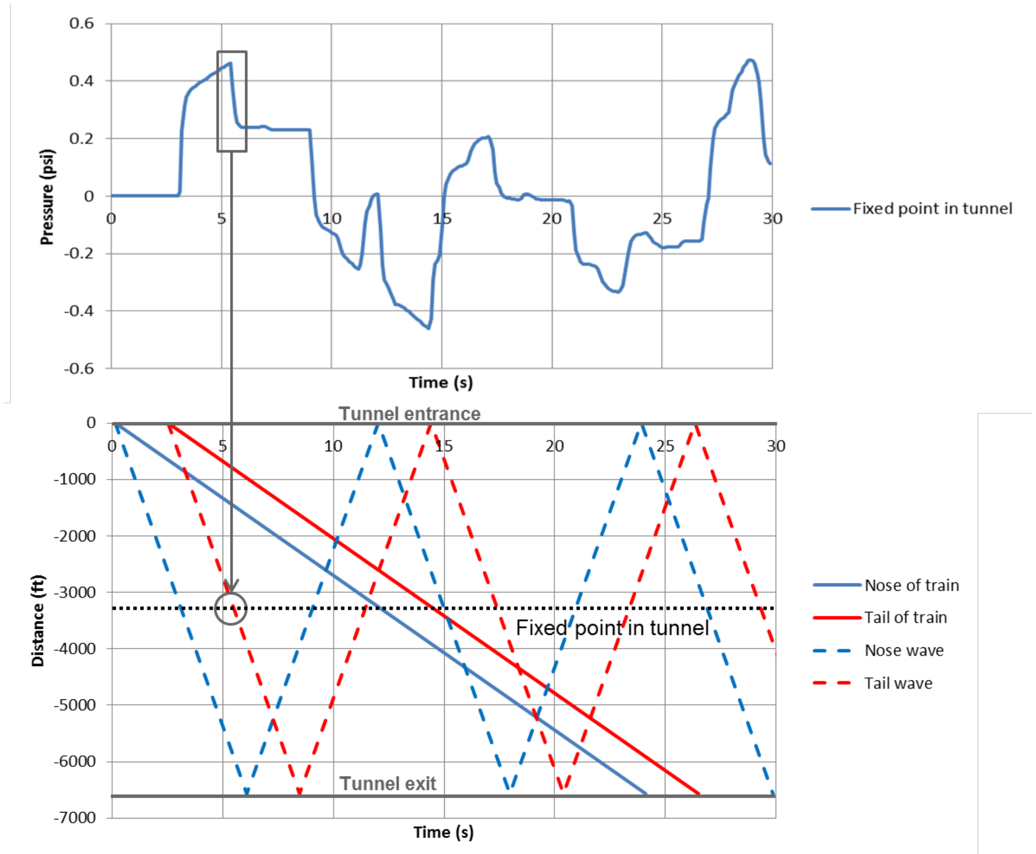

Figure 35. Example wave diagram for pressure at a fixed point within a tunnel

Wave diagrams can also be used to understand the pressures and pressure time histories on a moving train. The blue line in the upper graph of Figure 36 shows the pressure near the front of the train. The progress of the front of the train through the tunnel is given by the continuous blue line in the lower graph. The wave diagram could be used, for example, to deduce that the abrupt drop of pressure that occurs at about 10 seconds (rectangle in the upper graph) is caused by the arrival of the first reflection of the nose wave (ringed in the lower graph).

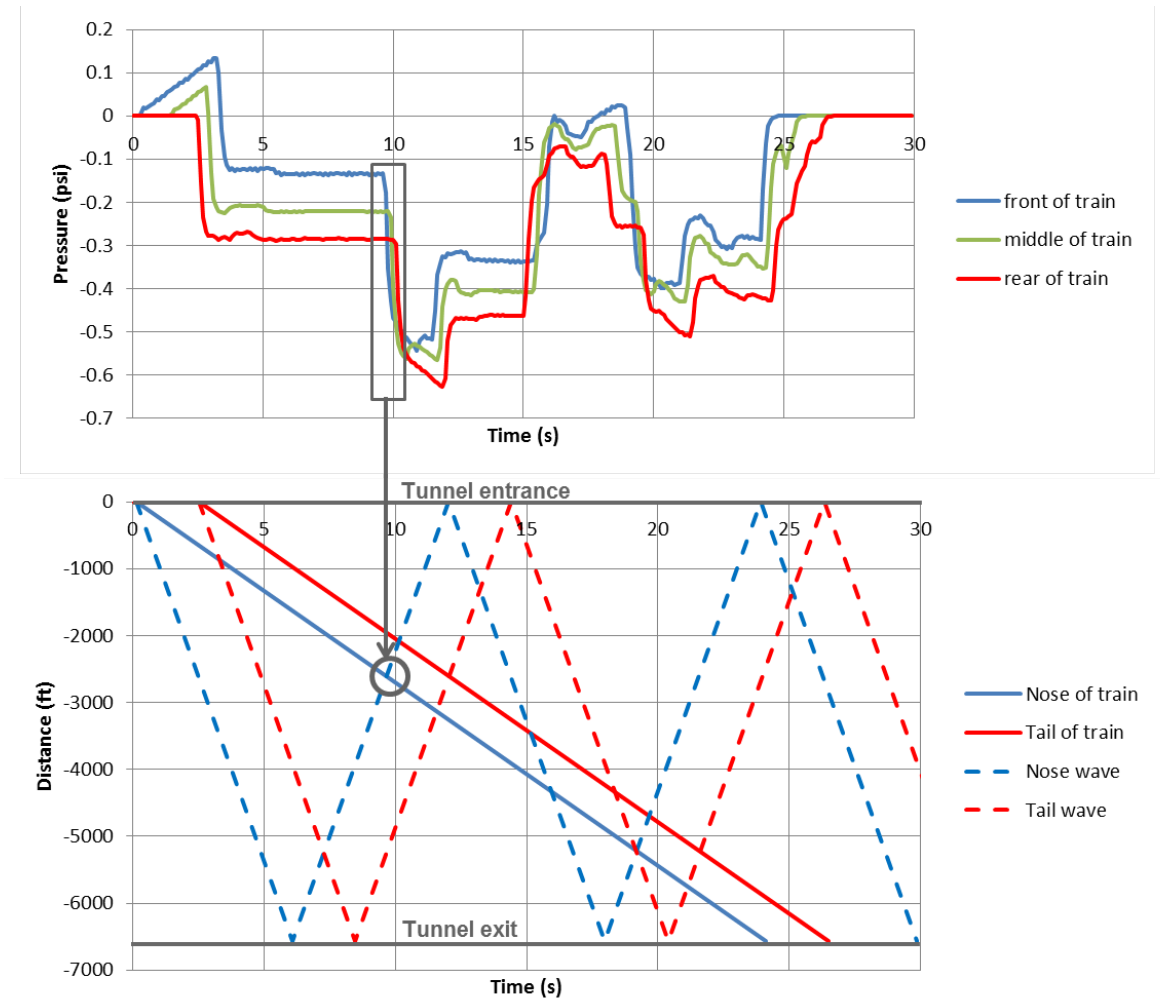

Figure 36. Example wave diagram applied to a point on the moving train

Rapid pressure changes can cause discomfort to passengers, and in extreme cases can damage their ears, due to pressure differences between the air in the middle ear and the external environment causing a net force on the ear drum. Discomfort from pressure changes depends not only on the amplitude of the pressure change, but also on the speed at which the pressure change occurs and on the aural health of the subject. Given sufficient time, the pressure in the middle ear can equalize with the external pressure by venting through the Eustachian tube.

In aircraft, after take-off and before landing, passengers are subjected to pressure changes of around 3-4 psi (20-30 kPa); much greater than the pressure changes in rail tunnels, but spread over about 20-30 minutes making the impact generally tolerable. In rail tunnels, the pressure changes experienced by passengers are usually less than 0.5 psi (3.4 kPa) but occur over seconds rather than minutes. A 0.2 psi (1.4 kPa) pressure change occurring in one second would feel more uncomfortable than the same pressure change spread over 10 seconds. If the train was not sealed, passengers would be directly exposed to the pressure changes (shown in Figure 36) up to 0.4 psi (2.8 kPa) occurring within one second. This pressure change would be very uncomfortable to some passengers.

Modern high speed trains are sealed to protect passengers from pressure changes in the tunnel outside the train, but the sealing systems are not perfect. Air leaks into and out of the railcars in response to external pressure changes, leading to pressure changes inside the railcars that are slower, and often lower in amplitude, than the pressure changes outside the train. An example of the influence of a train sealing system is given in Figure 37.

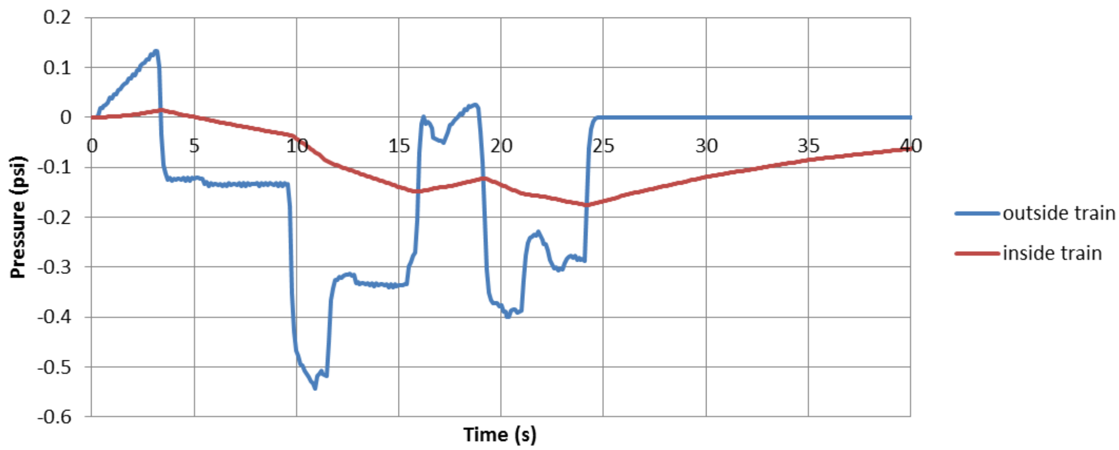

Figure 37. Effect of train sealing system on pressures experienced by passengers

Although the sealing system in this example reduces significantly the amplitudes and rates of pressure change experienced by passengers, it could still be insufficient to meet the desired level of comfort. In that case, a tunnel with larger cross sectional area or other mitigation measures would be required. This is frequently the governing factor in determining the cross sectional area of high speed rail tunnels.

Additional details of pressure histories are illustrated in Figure 38, which shows a snapshot of the pressure distribution in a tunnel at a particular instant in time. Unlike the other graphs in this section, here the x-axis represents position along the tunnel.

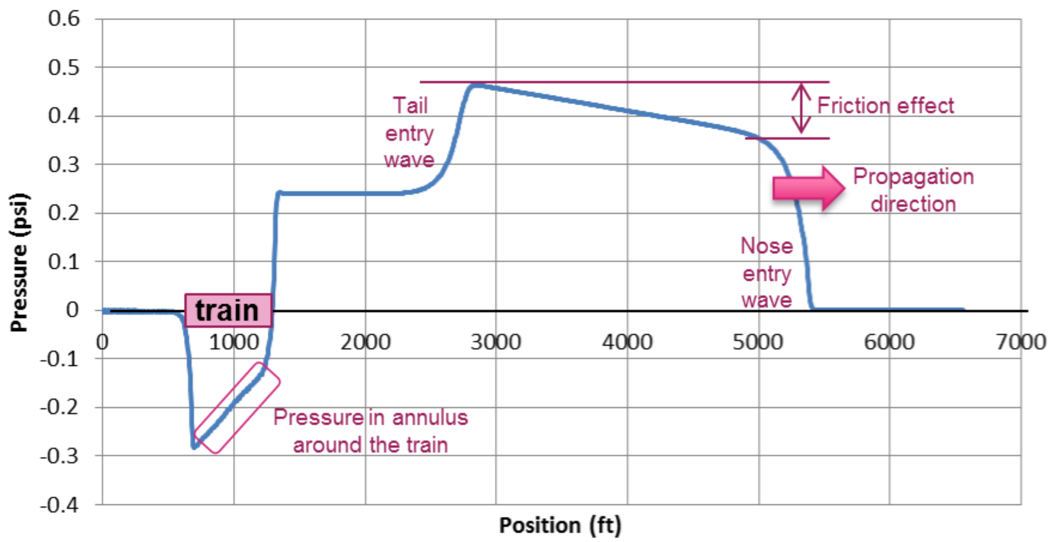

Figure 38. Snapshot of pressure distribution along a tunnel

At this snapshot in time, the nose-entry wave is propagating from left to right, and has not yet reached the far portal. Points to note:

- The train position is travelling from left to right.
- The pressure wave is some distance ahead of the train. Later, it will reflect from the exit portal and pass over the train as a rarefaction wave.
- Between the rise of pressure caused by entry of the train nose and the fall of pressure caused by entry of the tail is a gradual rise of pressure caused by build-up of friction during the time between the entry of the nose and the entry of the tail of the train.
- The pressure in the annulus around the train (which controls the pressure experienced by passengers) is considerably lower than the pressure in the air ahead of and behind the train.

7.2.2 Influencing Factors

Blockage Ratio

The blockage ratio β is a fundamental property of the train-tunnel system, and is defined as follows:

$$\boldsymbol{\beta} = \frac{A_{train}}{A_{tunnel}} \qquad \textbf{Equation 22}$$

where A_{train} and A_{tunnel} are, respectively, the cross-sectional areas of the train and the tunnel.

The greater the blockage ratio, the larger the pressure waves in the tunnel. Very approximately, for small changes of blockage ratio, the pressure is proportional to blockage ratio. Typical high speed rail tunnels have blockage ratios in the range 0.1 to 0.2.

Train Speed

The pressure wave amplitude depends approximately on train speed squared. Due to the complex patterns of superposition of the pressure waves and the effects of train sealing, the pressure changes experienced by passengers and crew do not scale exactly with the amplitudes of the train entry and exit pressure waves, and therefore they also do not scale exactly with train speed squared.

Aerodynamic Design of the Train

The amplitudes of the pressure waves depend partly on the shapes of the nose and tail of the train. A bluff-nosed train creates a bigger pressure wave than a train of the same cross-sectional area with an elongated, streamlined nose. Similarly, the shape of the tail of the train affects the amplitude of the tail entry wave.

Friction on the sides of a train can add significantly to the amplitudes of the pressure changes in a tunnel. Measures that counteract drag in open air, such as covered inter-car gaps, also reduce friction in tunnels.

Train Sealing

Modern high speed trains are designed to be fairly pressure-tight, but no train is perfectly sealed. When the pressure increases outside the train, air leaks in slowly, leading to a gradual increase of pressure inside the train. The sealing of the train is beneficial to passenger comfort by slowing the pressure changes inside the train. HSTs are usually considered as a series of separate cars so that air can leak into and out of each car individually. For cars openly connected the cars are considered as a single unit.

Train sealing performance is usually expressed as a time constant – the longer the time-constant, the better the sealing. The time constant τ is defined such that the rate of change of pressure inside the train (dp_i/dt) is given by:

$$\frac{dp_i}{dt} = (p_o - p_i)/\tau \qquad \textbf{Equation 23}$$

Where p_o is the pressure outside the train, and p_i is the pressure inside the train. Using Equation 23 to assess when a step-change of external pressure occurs (thus creating a pressure difference between the air outside and the air inside the train) the assessment shows that the pressure difference reduces exponentially and leads to a resultant equal to 63% of the external pressure. Typical modern high speed trains such as ICE3 can achieve time constants of about 15-20 seconds or more. Using 63% reduced external pressure as a baseline, Figure 39 shows the pressure time-history inside a train for different sealing times when the external pressure undergoes a step change.

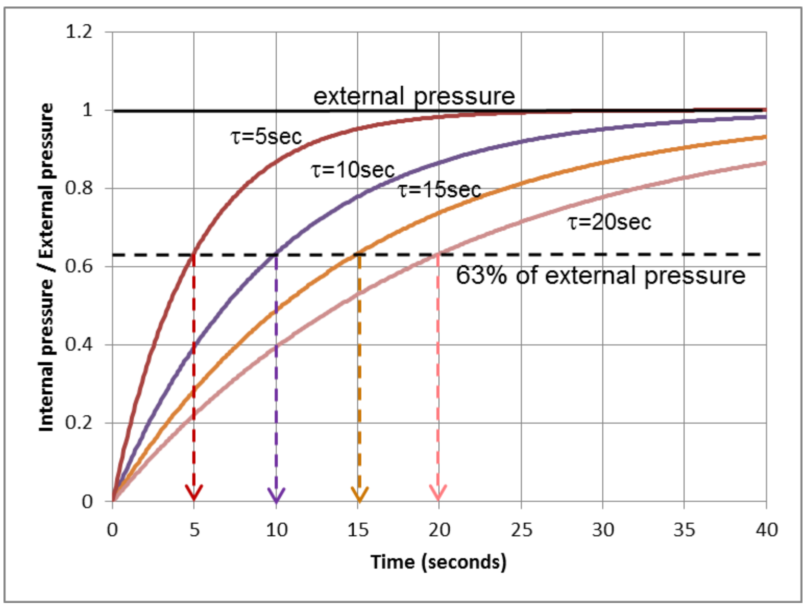

Figure 39. Pressure inside a sealed rigid train: response to step change of external pressure, for time constants 5, 10, 15 and 20 seconds

Sealing performance can be measured in a static test, as specified in UIC leaflet 660 [174], in which a single railcar is evacuated or pressurized and the time taken for the pressure to pass key values is noted. From these measurements, a "static time constant" τ_{stat} may be derived. However, when the train is in motion, the sealing performance described by the dynamic time constant τ_{dyn} may be very different. τ_{stat} may be two to three times higher than τ_{dyn} according to UIC leaflet 779-11 [175]. Furthermore, the time constants for leakage into and out of a railcar may be different from each other.

Train (Car Body Shell) Compressibility

A sealed carbody may be thought of as a slightly compressible, slightly leaky box. A high speed train with openly connected cars can be considered a large carbody. When an external pressure change occurs, not only does air leak through the sealing system, but the walls and roof of the shells of the car bodies also deform slightly. The air inside the carbody is compressed by this movement, and thus a proportion of the external pressure change is experienced immediately inside the railcars. This effect is usually not significant but could become so if the pressure changes in the tunnel outside the train are large, the cars are well sealed, and comfort criterion is selected for short timescales such as one second. Figure 40 shows the effect of compressibility. In the one second period between times 0 and 1, the gold curve (pressure inside a more compressible carbody shell) increases by around 0.28 times the external pressure change, while the red curve (pressure inside a more rigid carbody shell) increases by only 0.1 times the external pressure change.

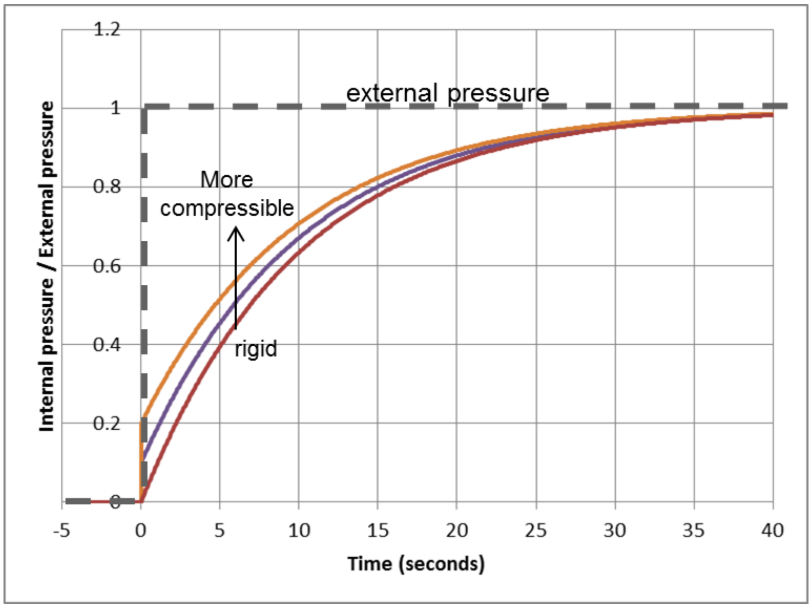

Figure 40. Influence of carbody shell compressibility on response to step change of external pressure

Tunnel Length

Pressure changes in tunnels occur due to pressure waves and their reflections. The length of the tunnel influences the pressure changes in three ways:

1. As shown previously in Figure 36, large pressure changes can occur when the reflected nose wave passes over the train. The timing of this event depends on the length of the tunnel.
2. Coincidences of two waves (for example, the tail entry wave and the reflected nose wave) reaching the train simultaneously can amplify the short term pressure change experienced by passengers. Since the time of arrival of the reflected waves depends on the length of the tunnel, such coincidences of waves occur for certain tunnel lengths.
3. As a pressure wave propagates along a tunnel, its amplitude reduces due to friction effects. Thus, the longer the tunnel, the smaller the reflected waves. The smoothness of the walls of the tunnel and track bed affects propagation of the pressure wave. Higher friction reduces the amplitude of pressure waves as they propagate along the tunnel, and therefore reduces the amplitude of any reflected waves that pass over the train. Ballast

reduces the amplitude of pressure waves and their gradients during propagation along the tunnel.

For these reasons, for any given train speed and blockage ratio, the "worst-case" minimum tunnel length that produces that greatest pressure change in any given time interval is typically three to five times the length of the train. For an unsealed train, the pressure inside the train equals the pressure outside the train and presents the greatest discomfort to passengers. The pressure change maxima that occur at the worst-case tunnel length may be viewed in the graphs in UIC Leaflet 779-11. For sealed trains, due to the protection of the passengers from sudden pressure changes, the worst-case may be multi-mile tunnels [176] in which the pressure changes are smaller but are sustained for a longer time than the tunnel length causing the greatest pressure change outside the train.

Position along the Train

The pressure changes vary along the length of the train. When analyzing pressure changes on a train, several sampling points should be taken at different positions along the train to ensure that a representative worst-case is found. This is often near the front or rear of the train.

Other Trains in the Tunnel

Where a tunnel contains more than one track, the pressure waves from two or more trains occupying the tunnel will be present in the tunnel simultaneously. In general, the pressure changes when two or more trains are present will be greater than if only one train is present.

The timing of entry of the two trains could be such that a coincidence of pressure waves occurs, leading to pressure changes that are especially severe. This has important consequences for the pressure comfort criteria used in the design of twin track tunnels. If the same requirements for mitigating maximum pressure changes were applied using single train passage criteria for tunnels, the tunnel size would need to be much larger.

Air Shafts

Air shafts (see Figure 41) can have a significant influence on pressure comfort. The effect is beneficial in most cases, although the optimum cross-sectional area of a shaft for pressure comfort does not necessarily coincide with the optimum for other purposes, such as ventilation or emergency egress.

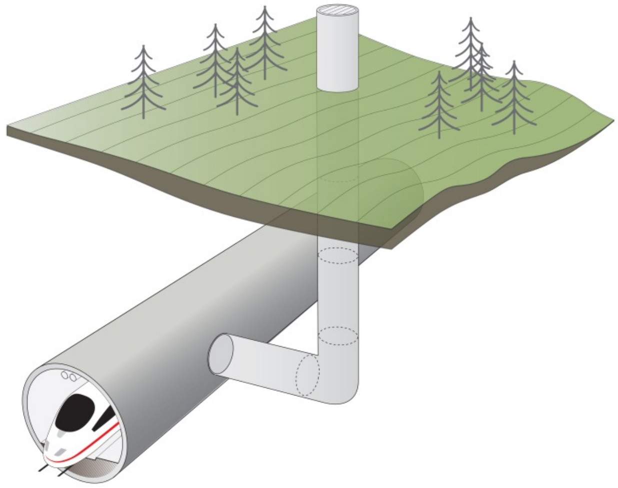

Figure 41. Schematic sketch of an air shaft

Inclination of Tunnel

Pressure changes can occur in a tunnel or in the open environment due to inclination (altitude change). In a tunnel, such pressure changes might add to the pressure changes from the pressure waves and cause a more uncomfortable experience [176].

Fixed Equipment

Equipment in the tunnel experiences aerodynamic loading caused by the same factors that influence the amplitudes and reflections of pressure waves when trains pass. There are several contributing factors:

- **a)** The pressure on the equipment changes when pressure waves pass over the equipment.
- **b)** At the nose and tail of the train, high (positive) and low (negative) pressure zones exist that are similar in principle to those described for the open air case in Chapter 3 (Pressures on Wayside Structures), but have different magnitudes because the air space within the tunnel is enclosed.
- **c)** The pressure immediately ahead of the train is higher than the pressure in the annulus around the train nose as shown in Figure 38. As the nose passes, the pressure drops rapidly. The reverse happens at the tail of the train.
- **d)** The air flows induced by the train act principally in the direction parallel to the tunnel axis. Any equipment (such as signs) offering a surface that impedes this air flow will experience pressure loadings. In the localized “gusts” near the train’s nose and tail, the wind speeds can be as high as the speed of the train.

The same effects cause loading on the trains. The pressure waves (factor “a” from above) apply load to any train in the tunnel, including the train that caused the pressure waves. The remaining factors (b, c and d) apply to trains meeting or passing within the tunnel i.e., the motion of one train causes load to be experienced by the other train.

Dynamic Oscillation of Trains

In tunnels where the track is not positioned centrally (for example, twin track tunnels) vortex shedding may occur predominantly on the side of the train furthest from the tunnel wall. This can cause a net lateral dynamic loading and hence oscillation of the railcars. Where this effect occurs, it tends to increase towards the rear of the train, and may interact with natural swaying frequencies of the suspension. There are recorded instances of this phenomenon in Japan.

7.2.3 Measurement and Calculation

Input Data for Pressure Comfort and Safety Assessment

Calculation of the Train Cross-Sectional Area

For well streamlined trains, a reasonable estimate of the cross-sectional area of a train can be derived from drawings (Figure 42). Vardy and Reinke [177] explain that with older or less streamlined trains, the effective aerodynamic area cannot be deduced accurately from geometrical drawings. For analysis purposes, it is often necessary to calibrate the influence parameters against the results of full-scale tests. For example, the pressure time-history in a tunnel caused by entry of the train might be measured, and the same event can be simulated with one-dimensional analysis software. The input value of aerodynamic area could be adjusted until a reasonable correlation to the test results was attained.

Note that some of the input parameters (loss factors, friction coefficients, and so on) are idealized as constant properties of a train. This allows for analysis of any tunnel; but, in practice these values depend to some extent on the blockage ratio.

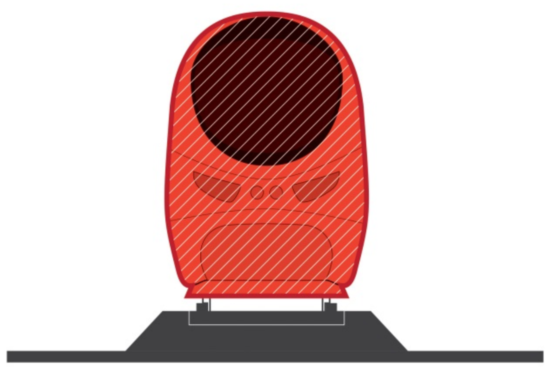

Figure 42. Train cross-sectional area

Calculation of the Tunnel Cross-Sectional Area

The relevant property, sometimes called the “free cross-sectional area”, is the area occupied by air in the absence of trains (Figure 43). Continuous solid objects such as the track-bed, walkways, pipes, wiring, etc., should be excluded from the calculated area. Solid objects that occur infrequently within the tunnel, such as fans and equipment cabinets, may be ignored because the free cross-sectional area is not significantly reduced by the presence of such objects.

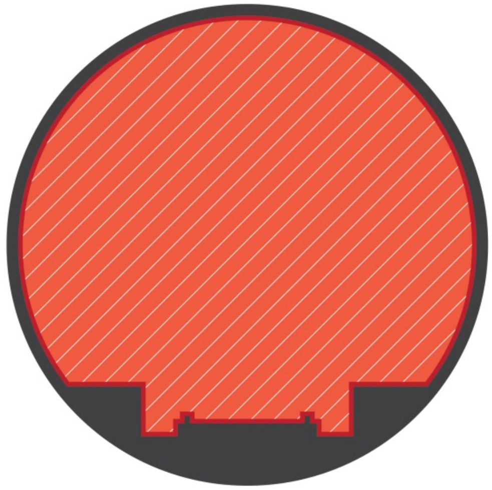

Figure 43. Tunnel free cross-sectional area

Nose Wave Pressure Formula

Two expressions are available for estimating the "nose wave pressure", labeled Δp_N. Ozawa [178] gave the following, which has subsequently been quoted by many authors:

$$\Delta p_N = \frac{1}{2}\rho {V_Z}^2 \frac{1-(1-\beta)^2}{\left(1-\frac{V_Z}{c}\right)\left[\frac{V_Z}{c}+(1-\beta)^2\right]} \qquad \textbf{Equation 24}$$

where β is the blockage ratio, V_Z is the train speed, and c is the speed of sound. This formula has been verified experimentally by several authors, including Gregoire et al [179].

Vardy [180] gives the following alternative:

$$\Delta p_N = \rho c\left(V_z + \frac{c}{\alpha}\left[1 - \sqrt{1+\frac{2\alpha V_z}{c}}\right]\right) \qquad \textbf{Equation 25}$$

where

$$\alpha = \frac{(1+k_N)}{(1-\beta)^2} - 1 \qquad \textbf{Equation 26}$$

and, in this instance, Vz is the speed of the train minus the pre-existing air speed in the tunnel and k_N is the train nose loss factor, usually in the range 0-0.1 for well streamlined high speed trains.

The results given by using Equation 24 and Equation 25 vary typically by a maximum of 10 %. Equation 25, which includes the train nose loss factor, is able to distinguish between well and poorly streamlined trains. Both formulae are approximations and need to be calibrated with experimental data.

Design Curves

UIC leaflet 779-11 includes graphs from which the maximum pressure change outside the train in certain time intervals may be estimated. These are relevant to pressure comfort assessments for unsealed trains. The inputs are:

- Train speed.

- Train type (e.g. streamlined high speed train).
- Tunnel length/train length ratio.
- Train area/tunnel area (blockage ratio, β for these graphs).
- Single train or two train operation.
- Time period of pressure change (1, 4 or 10 seconds).

The predicted pressure change in the selected time interval may then be read off the relevant graph. For the complete set of graphs, refer to UIC 779-11. Figure 44 shows an example. For this example it can be seen that as the blockage ratio (β) increases the maximum pressure change increases, and generally, as the length of the tunnel increases relative to the length of the train, the pressure change decreases.

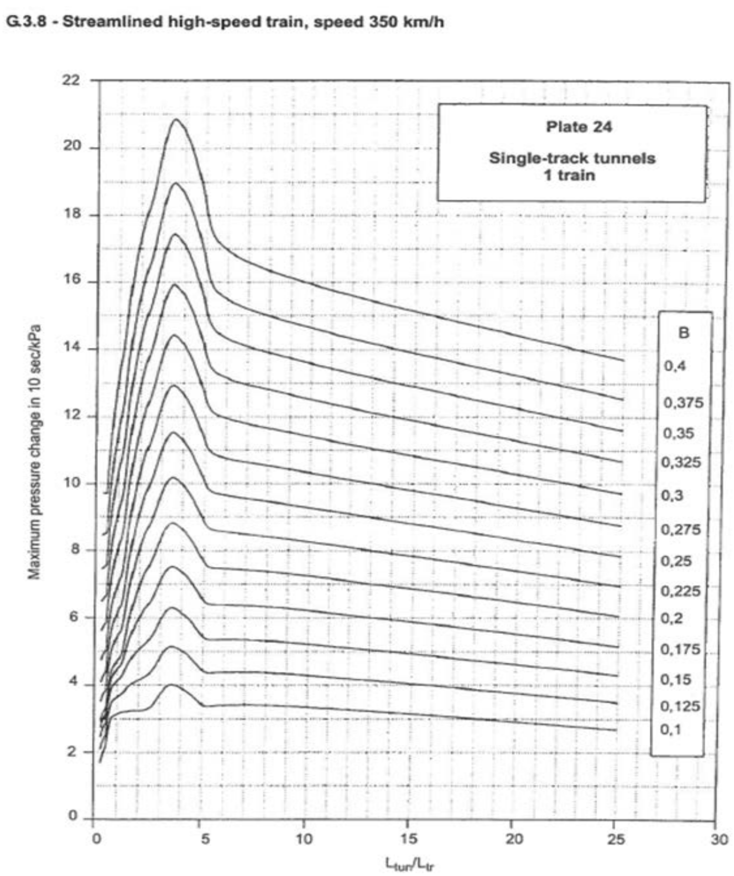

Figure 44. Example graph from UIC Leaflet 779-11 2nd edition 2005 [175]; for streamlined unsealed high speed train, 217 mph (350 km/h), single train operation, pressure change in 10 seconds

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UIC leaflet 779-11 also provides graphs from which the minimum tunnel cross-sectional area required to meet the medical safety criterion (see Section 7.4.1) may be estimated. These are relevant to both sealed and unsealed trains. In this case the inputs are:

- Train speed.
- Train length.
- Tunnel length.

The output is the required blockage ratio, from which the free cross-sectional area of the tunnel may be calculated. An example is given in Section 7.2.4.

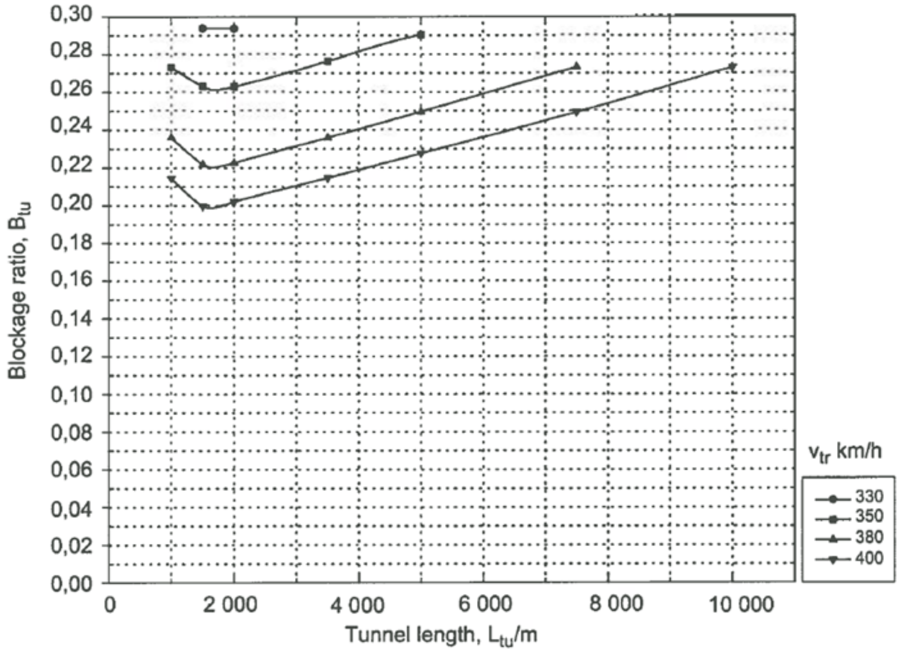

Figure 45. Example graph from UIC Leaflet 779-11 2nd edition 2005 [175] illustrating blockage ratio required to meet medical safety limit, 400 m long train, single train operation

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The curves in Figure 45 give the tunnel blockage ratio considering only the medical safety limit. Generally, the required tunnel size to meet pressure comfort criteria would be larger. No existing document has been found containing design curves for tunnels to meet certain pressure comfort criteria with sealed trains. It would be possible to develop curves in a format similar to Figure 45 to achieve this for a given train sealing time constant. *However, if such guidance is desired to be provided, discussions and coordination with the FRA in development of comfort standards is required in the selection of appropriate comfort criteria.*

7.2.4 Simplified Example

What “free cross-sectional area” is required for a 2.5 mile long tunnel to meet the medical safety limit, assuming a train with 130 ft^2 cross-sectional area and a line speed of 250 mph?

Referencing Figure 45, β = 0.22 for a tunnel length = 4000 m (2.5 miles), and train speed v_{tr} = 400 km/h (250 mph).

Tunnel area = Train area/Blockage ratio = 130/0.22 = 591 ft^2.

Pressure Comfort for Cross-Sectional Area

In regards to determination of the “free cross-sectional area” required to meet pressure comfort criteria with sealed trains, there were no charts found during the literature search equivalent to Figure 45 for determining the required area. This area must be determined using a one-dimensional analysis program capable of predicting the pressure changes inside sealed railcars. The analysis should be re-run with different tunnel areas until the pressure comfort criteria are met.

7.3 Impacts and Mitigation of Pressure Wave

7.3.1 Impacts on Passengers, Train Crews, and Workers

Impacts on Passengers and Workers inside the Trains

The impact of pressure changes on aural safety was studied by the medical expert group C 218 of the European Railway Research Institute [181]. It considered not only people with normal healthy ears but also those with ear problems. It concluded that the risk of irreversible damage was sufficiently low if the peak-to-peak pressure change to which passengers were exposed did not exceed 1.45 psi (10 kPa), within any part of the time taken by the train to pass through a tunnel.

Aural *comfort* is a subjective issue: the same pressure change may be experienced as very uncomfortable by some individuals, but as barely noticeable by others. Studies of the perception of discomfort from pressure changes have been performed using groups of volunteers in pressure chambers [182], and by volunteers assessing comfort on actual rail journeys [183, 184]. These studies have been used to develop the pressure comfort criteria adopted in various countries. Conclusions from some of these studies are summarized under “Data from the Literature“, Section 7.5.

Impacts on Passengers Waiting on Platforms of Underground Stations

Stations in tunnels represent a special case for consideration. The pressure waves caused by trains within the tunnels, and pressure changes caused by trains passing through the stations at high speed, can impact the aural comfort of passengers waiting on the platforms.

Impacts of Lateral Oscillations of Trains on Passenger Comfort

There are recorded instances from Japan of lateral oscillations of trains in tunnels becoming unacceptable for passenger comfort due to general passenger alarm from the swaying motion [185, 186]. The problems occurred with certain designs of Shinkansen trains in twin track tunnels. The gap between the side of the train and the tunnel wall is about 2.3 ft (0.7 m). Train speed and the shape of the train (especially the shape of the tail, where the oscillations were strongest) were considered to be the contributing factors.

7.3.2 Impacts on Trackside Workers

If track workers are permitted to enter tunnels while a railway is in operation, they can be exposed to high pressure changes. Typically, the pressure changes at any fixed point inside the tunnel are greater than those experienced on the train. In the case of sealed rolling stock, the difference is even larger. Therefore a tunnel designed for passenger comfort and safety would not provide the same standard of comfort and safety for track workers. This impact clearly cannot occur where, as with many high speed railway networks, workers are not permitted to enter tunnels during normal operation of the railway.

7.3.3 Impacts of Pressure Changes on Trains

The pressures in tunnels can contribute to fatigue loading of the railcars, especially for sealed rolling stock that must support a large pressure difference between the car interior and the tunnel. However, at current operating speeds no record has been found in the literature search of fatigue problems occurring in practice.

It is unusual for high speed rail tunnels to carry mixed traffic, but such situations do occur over limited rail segments in Europe. In those instances it is possible for pressure waves generated by high speed trains to pass over freight or conventional passenger trains. Potential impacts would include the aural comfort and safety of passengers and crew, the structural integrity of the railcars, and displacement of cargoes. Speed restrictions in tunnels exist in Germany to prevent such impacts. Railway operators have concerns about the use of flexibly-covered wagons when high speed trains pass by in tunnels. *Further research is recommended to determine the effect on conventional trains of pressure waves in tunnels.*

7.3.4 Impacts on Fixed Equipment

Cross-passage doors, equipment cabinets and any other fixed equipment in the tunnel will be exposed to the pressure waves generated by the trains. Where the pressure acts on one side of a surface only (as in the case of enclosed cabinets or cross passage doors), the pressure in the tunnel causes a net force on the surface. Unless designed to support the pressures, fatigue or other forms of failure may result.

Equipment such as signals and signs experience loading due to the air velocity in the tunnel, which can be of the order of 10-20 mph (15-30 km/h) away from the trains, and much higher in short gusts as the train passes, of the order of 50% of train speed according to Busslinger [187]. Equipment should be designed to withstand these gusts.

No record of adverse impacts on fixed equipment at current operating speeds has been found in the literature search, *but this matter is of concern for designers of the equipment and little guidance is available.*

7.3.5 Impacts on Tunnel Design

Impacts on Infrastructure Design and Cost

Since the cross-sectional areas of many high speed rail tunnels are governed by pressure comfort and safety considerations, the impact on construction cost is significant and the economic consequences of faster train speeds must be recognized. A tunnel designed for 250 mph (402 km/h) will require approximately four times the cross-sectional area compared to a tunnel designed for 125 mph (201 km/h). Figure 46 shows an example based on one particular train/tunnel combination. It should be noted that the effect of the train speed on the required tunnel area is expected to remain approximately the same as that shown in Figure 46 for other trainsets.

Choice of pressure comfort criteria also impacts construction cost because stricter criteria require larger tunnels. For example, Klaver and Kassies [188] reported one particular instance in the Netherlands of a 4.5 mile (7.25 km) long single track tunnel with air shafts that was designed for pressure-sealed high speed trains. The area required to achieve the Dutch comfort criteria was 646 ft^2 (60 m^2), while 1020 ft^2 (95 m^2) would have been required to meet the UIC 660 criteria [188], assuming the same air shafts in both cases.

Impacts Related to Cross-Passages

Cross passages represent a component of the tunnel design that presents a particular design challenge with simultaneous requirements for ventilation, drag reduction, smoke control, and avoidance of unacceptable pressure wave effects caused by air movement from one tube to the other when trains pass through both tubes simultaneously. If the passages are completely closed during normal operation then the pressure wave effects can be ignored, other than for passage door structural design.

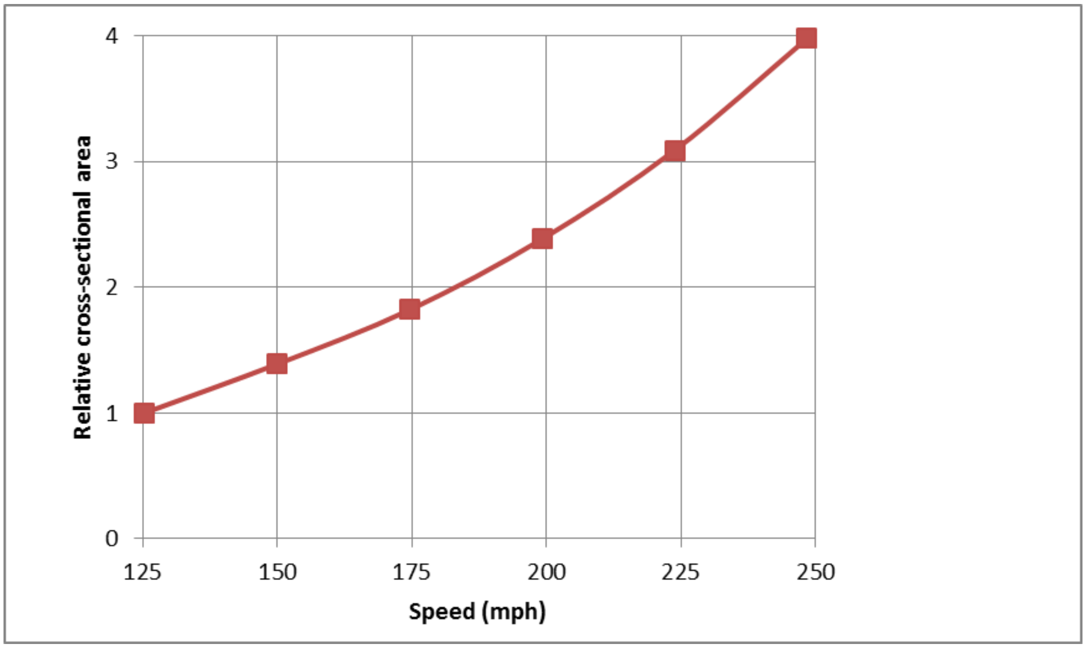

Figure 46. Example for a particular tunnel of the relationship between the required cross-sectional area (to meet comfort criteria) and train speed

7.3.6 Mitigation Methods

Tunnel Cross-Sectional Area

When designing new tunnels for high speed railways, the principal mitigation measure for pressure wave effects is to select the appropriate cross-sectional area for the line speed and traffic type.

Table 11 and Table 12 give examples of cross-sectional areas of high speed train tunnels.

Table 11. Cross-sectional areas of high speed rail tunnels for sealed trains: twin tube (single track) tunnels

Country	Source	Type	Area		Blockage ratio	Speed	
			ft^2	m^2		mph	km/h
Germany	[189]	1-track	646	60	~0.18-0.2	155-186	250-300
China (regulations)	[80]	1-track	753	70		217	350
China (regulations)	[80]	1-track	624	58		155	250
US (proposed)	[190]	1-track	595-795	55-74	0.19-0.25	250	400
US (proposed)	[190]	1-track	555-615	52-57	0.24-0.27	220	355
US (proposed)	[190]	1-track	550	51	0.27	200	320

Table 12. Cross-sectional areas of high speed rail tunnels for sealed trains: single tube (twin track) tunnels

Country	Source	Type	Area		Blockage ratio	Speed	
			ft^2	m^2		mph	km/h
France	[77]	2-track	1076	100	0.11	186	300
Germany	[184] [189]	2-track	990	92	~0.125	174-190	280-305
Japan	[191] [77]	2-track	682	63.4	0.19-0.22	149-186	240-300
Korea	[192]	2-track	1152	107	0.091	186	300
China (regulations)	[80]	2-track	1076	100		217	350
China (regulations)	[80]	2-track	969	90		155	250

The German method is an example of how tunnel design can be simplified by rule-making. For example, twin tube (single track) tunnels for speeds up to 186 mph (300 km/h) must have 646 ft^2 (60 m^2) cross-sectional area per tube.

Table 11 includes tunnel dimensions proposed in 2009 within the framework of the California High-Speed Rail Project [190] based on the medical criterion in UIC 779-11. Apparently, considerations of pressure comfort did not influence the selected cross-sectional areas. The California HSR study noted the expense of tunnels designed for 250 mph and proposed a maximum speed in tunnels of 220 mph which is the current maximum speed for Tier III trainsets.

Apart from cost, disadvantages of larger cross-sectional areas include the need for more powerful ventilation and smoke ejection facilities.

Air Shafts

Air shafts are ducts connecting the tunnel to the outside air. The use of air shafts to relieve pressure transients in rail tunnels has been well established for many decades (Vardy [193], Figura-Hardy [194]). The shafts reduce the amplitude of pressure waves because some of the pressurized air travels up the shaft and out to atmosphere instead of along the tunnel. Typically, air shafts are spaced at 0.1 to 2 miles apart, and (if designed mainly to relieve pressure transients) have a cross-sectional area 10 to 35% of the area of the main tunnel.

Advantages of air shafts can include:

- Mitigation of pressure comfort issues, or permitting a smaller cross-sectional area for the main tunnel while maintaining the same pressure comfort performance.
- Reduced drag on the train, thereby reducing power or fuel consumption or allowing the desired speed to be attained.
- Improved ventilation and control of air temperatures in the tunnel.
- Use for smoke ejection in fires.
- Relatively inexpensive.
- Can share space with emergency evacuation shafts (which are much larger) at small additional cost and land take.

Disadvantages of air shafts include:

- Noise emissions from the shaft portals caused by high air speeds within the shafts and the trains. Noise mitigation treatments within the shafts may be necessary in sensitive areas.
- The need to protect the shaft portals from vandalism, people dropping objects down the shafts, animals or birds entering the shafts, etc. These are sometimes achieved by enclosing the shaft portal in a purpose designed building [195]. The shaft may exhaust through the roof of the building.
- Micro pressure waves resulting in audible noises could be emitted from the shaft portals if pressure waves with high gradients are present within the tunnel, or could be caused by the train passing the shaft within the tunnel.
- May not be feasible where the overburden is high or where a tunnel runs below an urban area.

Air shafts are extensively described in the literature. Where the effects of shafts on pressure changes experienced by passengers are described, most of the sources refer to pressure changes in unsealed trains. Conclusions about optimum shaft sizes and configurations may be different for sealed trains. Such conclusions also depend on tunnel length, traffic type (single or crossing trains) and other factors.

Vardy [193] gives a theoretical result for the optimum position of a single shaft to mitigate pressure changes from a single train passing through a tunnel based on Mach number. He states that the cross-sectional area of short air shafts in short tunnels should not exceed 35% of the cross-sectional area of the tunnel, and that for the tunnel/train combination studied, the optimum area for a single shaft was 14% of the tunnel area, reducing pressure change by up to 38%. Two such shafts gave reductions of 40%, while additional shafts offered no further benefit. The conditions studied were a 0.62 mile long tunnel (1.0 km), train speed of 112 mph (180 km/h), unsealed trains, and both single passages and crossing train scenarios.

Burri and Zumsteg [196] give similar conclusions for Swiss Rail tunnels. Thirteen tunnels were considered, all were twin track (single tube) and with lengths ranging from 0.07 to 2.8 miles (120 to 4690 m). The trains were unsealed. Single train passages and crossing train cases were analyzed, with train speeds up to 155 mph (250 km/h). The conclusions were:

- Optimal shaft cross-sectional area was around 15% of the cross-sectional area of the main tunnel.
- There was little benefit in increasing the number of shafts above three, and in many cases two shafts gave almost the same benefit as three.
- The presence of shafts reduced the maximum pressure changes over four seconds by about 40 to 50%.

Hagenah et al [197] report measurements made on the 1-mile long (1.6 km) double-track Emmequerung tunnel, which has cross-sectional area of 818 ft^2 (76 m^2) and two air shafts, each of cross-sectional area 129 ft^2 (12 m^2) or 16% of the tunnel area. They showed by one dimensional analysis that had the shafts been absent and the tunnel retained the same cross-sectional area, the pressure changes during a single train passage at 137 mph (220 km/h) would have been more than double compared to the existing design with shafts. To meet the pressure comfort criterion without air shafts for a single train passing through the tunnel, an area of 1130 ft^2 (105 m^2) would have been required.

The same sets of measurements at Emmequerung are described and evaluated by Vardy and Hagenah [198], and were made publically available [199]. Measured air flows in the shafts reached a maximum of about 50 mph (80 km/h).

Temple [195] described a study on raising speeds to 140 mph (225 km/h) on the UK West Coast Main Line. Two existing twin track tunnels required modification to meet the pressure comfort criteria for meeting trains scenarios. The 0.28 mile (449 m) long Stowe Hill tunnel was located 66 ft (20 m) below ground, with open fields above and therefore little restriction on adding air shafts. Four shafts were constructed. However, the 0.2 mile (319 m) long Northchurch tunnel ran under a residential development, offering limited opportunities for shafts. Cross passages and a third bore with openings to both existing bores were considered, but when combinations of trains in the two bores were considered, the worst case pressure changes with the mitigation were greater than for the pre-mitigation tunnel. The remaining solution was to construct a single air shaft within the residential development, with the outlet disguised within a building similar to the surrounding houses. Since construction, complaints have been received concerning noise from the shaft.

Proposals for small bore frequently spaced shafts have been made. For example, Henson and Pope [200] analyzed the effects of 3.3 to 6.6 ft. (1 to 2 m) diameter shafts spaced at 66 to 328 ft. (20 to 100 m) centers for two trains meeting in a 3,740 ft (1140 m) long tunnel with cross-sectional area 880 ft^2 (82 m^2). Pressure changes over four seconds were predicted to be reduced by up to 58% depending on shaft configuration.

Finally, a number of assessments of varying spaced and sized shafts were analyzed by Figura-Hardy [194] who performed 132,000 runs with the software ThermoTun. Her runs generated data showing the pressure reductions achievable with different numbers of air shafts, train types, (unsealed and sealed), blockage ratios, tunnel lengths, and train lengths.

Cross-Passages

Cross-passages link the two tubes of a twin-tube tunnel. They are normally required in twin-tube tunnels for safety reasons. Typically, the passages contain doors that are closed during normal operation, but it is possible to reduce pressure wave effects by allowing a percentage of the cross-sectional area to remain open. This is a relatively inexpensive countermeasure, but has some disadvantages:

- Instead of being able to design each tube in aerodynamic isolation, the two tubes are now linked, so pressure wave combinations from trains in each tube must be considered.
- It is possible, although rare, for a "worst-case" combination of trains in the two tubes to give a more severe result than the case where the cross-passages are completely closed [195].
- It can cause side wind on trains.
- There is a need to provide dampers such that the passages can be closed automatically in the event of a fire to prevent smoke reaching the unaffected tube.
- It is difficult to satisfy all the requirements of pressure wave mitigation, smoke control, ventilation and drag reduction simultaneously.

Portal Design

Porous tunnel entrances (tunnel entrances with holes) can be used as mitigation for micro-pressure waves. These entrances also have some beneficial effect on pressure comfort by slowing the build-up of the pressure wave as the train enters the tunnel. The benefit is likely to be greater for unsealed or less well sealed trains, in which rapid pressure rises are the dominant events for the comfort of passengers.

Cone-shaped flared portals designed specifically for pressure comfort have been proposed, but the entrance region needs to be long. Pope et al [201] describe a 19 mile long tunnel with unsealed trains running at 218 mph (350 km/h) and states that flared regions 0.5 mile long at each end would permit the cross-sectional area of the main tunnel area to be 33% smaller. According to Pope et al, the savings from reduced cross-sectional area of the main tunnel more than offset the extra cost of the flared regions. Flared regions are more difficult to construct in bored tunnels due to a two (2) stage construction process but would be easier to incorporate into mined tunnels.

Train Properties

Benefits for pressure comfort may be obtained by:

- Adopting trains with improved sealing performance (large benefit for pressure comfort, no benefit for the medical safety criterion, which intentionally does not recognize the effect of the train sealing system).

- Adopting trains with reduced cross-sectional area (small benefit for both pressure comfort and medical safety criterion).

Active Pressure Control in Trains

Kobayashi et al [202] describe an active pressurization system inside Japanese railcars. In a tunnel, the main duct through which air enters or leaves the railcar is closed by a valve. A series of up to four ducts of different sizes bypass the valve. Each bypass duct contains a choke that can be activated by a control system reacting to changes of pressure inside and outside the railcar. By setting the pressure levels at which each choke is activated, pressure changes inside the railcars can be prevented from exceeding the comfort limits.

Train Speed

Reducing the speed of trains is a highly effective mitigation measure because pressures increases with speed squared. It is necessary to reduce the train speed only at the tunnel entrance and exit (and possibly when passing air shafts or discontinuities of cross-sectional area within the tunnel) because these are where the pressure waves are generated.

Tunnels for Mixed Traffic

If tunnels are to be used by a mix of high speed and conventional traffic, the limiting factor that determines the tunnel cross-sectional area or the maximum train speed will likely be the train type that is most vulnerable to pressure wave effects. For example, if conventional unsealed passenger trains are to run alongside sealed high speed trains, then pressure comfort in the unsealed passenger trains will most likely be the limiting factor and dictate the required tunnel area and the acceptable speed of the high speed train.

This situation rarely arises in Europe where high speed lines and tunnels are usually purpose-built and dedicated to high speed services only. However, there are examples such as Loetschberg Base Tunnel in the Swiss Alps (Busslinger et al [187]). In operation since 2007, the twin-tube tunnel is 22 miles (35 km) long and carries mixed traffic (passenger trains, shuttle trains, and freight trains). Due to the cost of boring long tunnels under mountains, a free cross-sectional area of only 484 ft^2 (45 m^2) was selected, and the speed of traffic was restricted to avoid unacceptable aerodynamic impacts: 155 mph (250 km/h) for passenger trains and 100 mph (160 km/h) for freight.

Current Tier II lines in Northeast Corridor have tunnels with mixed traffic, but in all cases except one, speeds through tunnels are limited by switches, curves, stations, and grades, and therefore cannot be increased. If a speed increase is proposed in the tunnel, where the current limit is 120 mph, or if new Tier II routes with tunnels are planned, the effect of pressure waves on the aural comfort of passengers and crew and potential impacts on freight cars should be considered, especially for the case of trains meeting inside the tunnel.

Considerations when Line Speed is Increased in Existing Tunnels

If analysis shows that the increased line speed will result in unacceptable pressure wave effects, some possible mitigation measures are:

- Adopting trains with improved sealing performance or reduced train cross-sectional area.

- Maintaining the previous line speed when passing the tunnel entrance and exit even though increasing speed within the tunnel.
- Addition of air shafts.
- Increasing the tunnel cross-sectional area to some extent by excavating the floor to a lower level.

Mitigation of Loading on Fixed Equipment

Equipment must be designed to withstand the loading caused by passing trains. Aerodynamic specialists may be asked to estimate maximum and minimum pressure loads as part of a study that includes analysis of pressure comfort and safety. *There are no published methods of doing this* and *this is an area recommended for further study.*

Mitigation of Lateral Oscillation of Trains in Tunnels

Problematic oscillations occur predominantly with certain combinations of train shape, tunnel dimensions, and train speed. One example is the Shinkhansen 300 series on the Sanyo Line. One mitigation measure is to avoid trains that are known to experience this problem.

Diedrichs et al [186] report results from Suzuki suggesting that the problem is less likely to occur if the train to wall gap is at least 2.6 ft (0.8 m). For single track tunnels, positioning the track centrally within the tunnel is likely to be an effective mitigation measure.

7.4 Standards and Criteria

7.4.1 Passengers' in Train, Train Crews', and Workers' Comfort and Safety

UIC Leaflet 779-11

UIC Leaflet 779-11 [175] is the main European standard. It provides a guide to selecting the cross-sectional area of tunnels for pressure comfort and safety. The standard includes:

- Guidance on calculating the train and tunnel cross-sectional areas.
- Graphs from which the pressure changes in 1-second, 4-seconds and 10-second periods may be estimated for various train types, speeds, and blockage ratios. For unsealed trains, these graphs allow the cross-sectional area of simple tunnels to be selected (see Section 7.2.4).
- Notes on the 10 kPa medical health criterion which is the upper limit on pressure change in the air outside the train.
- "Medical health limit curves". Graphs indicating the blockage ratio at which the maximum pressure change will equal the 1.45 psi (10 kPa) medical health limit, as a function of tunnel length, for various train speeds. These are relevant to both sealed and unsealed trains.
- Guidance for using the graphs.
- Description and applicability of design tools developed under the auspices of the European Rail Research Institute Committee C 218, namely SEALTUN, TRENDSHAFT and DE-SHAFT. However, these are now considered obsolete and are no longer recommended for use.

- Notes on pressure tightness of trains.
- Discussion about pressure comfort criteria, lists of criteria used internationally, and ERRI's recommended "baseline pressure comfort criteria".

UIC Leaflet 660

UIC Leaflet 660 [174] sets out further pressure comfort criteria for sealed trains and describes pressure tightness tests for trains.

Medical Health (Safety) Criterion

The European Infrastructure TSI [13] imposes a mandatory upper limit of 1.45 psi (10 kPa) on the pressure changes in unlimited time that may be experienced by passengers and crew in tunnels, for medical safety reasons. The limit must be respected even in the extreme case of the train sealing system failing (for example, due to window breakage). At each point on the train, excluding any effect of the sealing system, the maximum variation of pressure (i.e., the difference between the maximum and minimum pressures occurring at any time during transit through the tunnel at that point on the train) must be less than 1.45 psi (10 kPa).

Pressure Comfort Criteria

A range of different pressure comfort criteria are adopted internationally. None of these are mandatory and are adopted as a commercial choice of the carrier. The sections below describe the various criteria.

Pressure Comfort criteria for Unsealed Trains

The criteria for unsealed trains described herein generally pre-date the introduction of pressure-sealed rolling stock and represent a much lower standard of comfort than would be expected for high speed rail passengers today. They are not relevant to Tier III operations in the United States if sealed trains are used and are given here only for completeness.

Gawthorpe [203] proposed pressure limits for unsealed trains, with different criteria applying according to the frequency of tunnels on the route (Type A has less than 10% of the route in tunnels, Type B is for inter-city services with greater than 10% in tunnels), and distinguishing between "every time" pressure changes occurring when a single train passes through the tunnel, versus "rare" events caused by trains meeting. Lower limits are appropriate for more frequent events. These are presented in Table 13 together with the percentage of the population predicted to be made uncomfortable by those pressure changes. This percentage was developed according to the data from Johnson et al [204] and the logistic regression model from Schwanitz et al [205]. (A logistic regression model calculates the probability of a result that has two possible outcomes whereas a regular regression model predicts the value of a continuous variable). The Schwanitz model distinguishes between pressure increases and pressure decreases. Therefore, Table 13 shows these separately.

Table 13. Pressure comfort criteria for unsealed trains, Johnson et al

Route type	Event type	Pressure change in 4 s psi	Pressure change in 4 s kPa	% uncomfortable (Johnson et al [204])	% uncomfortable (Schwanitz et al [205]) increase	% uncomfortable (Schwanitz et al [205]) decrease
A	Every time	0.36	2.5	16%	40%	14%
	Rare meeting	0.58	4.0	33%	88%	58%
B	Every time	0.29	2.0	10%	23%	7%
	Rare meeting	0.44	3.0	20%	59%	25%

The comfort assessments from Johnson are reasonably consistent with those from Schwanitz et al for pressure decreases, but not for pressure increases. The Schwanitz data suggest that pressure increases of these magnitudes would feel uncomfortable to a much greater proportion of the population.

An early criterion from British Rail suggested limiting pressure change inside a passenger railcar to 0.145 psi (1 kPa) and limiting the pressure change rate to 0.029 psi/s (200 Pa/s). In 1991, British Rail adopted a series of pressure limits, which depended on route and railcar types. These limits range from 0.102 psi (700 Pa) in four seconds for urban routes (such as subways with many tunnels) to 0.363 psi (2,500 Pa) in four seconds for unsealed trains on intercity routes with few tunnels [10]. These limits are based on the research by Gawthorpe and Johnson reported above.

In the United States, the Subway Environmental Design Handbook [21] recommends limiting the maximum pressure change rate in subway cars to 0.06 psi/sec (414 Pa/sec), (applicable to pressure changes above 0.10 psi (690 Pa)) based on the recommendations by Carstens and Kresge [206]. Due to the high frequency of tunnels in subway systems, more stringent criteria are appropriate than for high speed railways with few tunnels.

Pressure Comfort Criteria for Sealed Trains

Pressure-sealing of rolling stock offers operators an opportunity to provide a more comfortable travel experience. It is therefore appropriate to set lower limits on pressure changes for sealed trains than for unsealed trains.

Typically, the pressure criteria have multiple components. For example, the maximum pressure change in any 1-second period, the maximum pressure change in any 3-second period, and the maximum pressure change in any 10-second period, may be specified.

Criteria for sealed trains are compared in Table 14 and Figure 47 and described in the following paragraphs.

Table 14. Pressure comfort criteria

	Time period (seconds)				
	1	3	4	10	Unlimited
	psi kPa	psi kPa	psi kPa	psi kPa	psi kPa
UIC 660[174]	0.072 0.5	0.12 0.8	-	0.15 1.0	
UIC 779-11 “baseline comfort” [175]	0.15 1.0	-	0.23 1.6	0.29 2.0	
Netherlands (single train) (*) [188]	0.072 0.5		0.123 0.85	0.203 1.4	
Netherlands (meeting trains) (*) [188]	0.123 0.85		0.196 1.35	0.305 2.1	
Italy [175]	0.072 0.5				0.218 1.5
Japan [175]	0.058 0.4 (+)				0.144 1.0

(*) For the Netherlands, further pressure criteria in 20, 30, 40, and 50 seconds are given.

(+) Reported values vary – the actual criteria are not published.

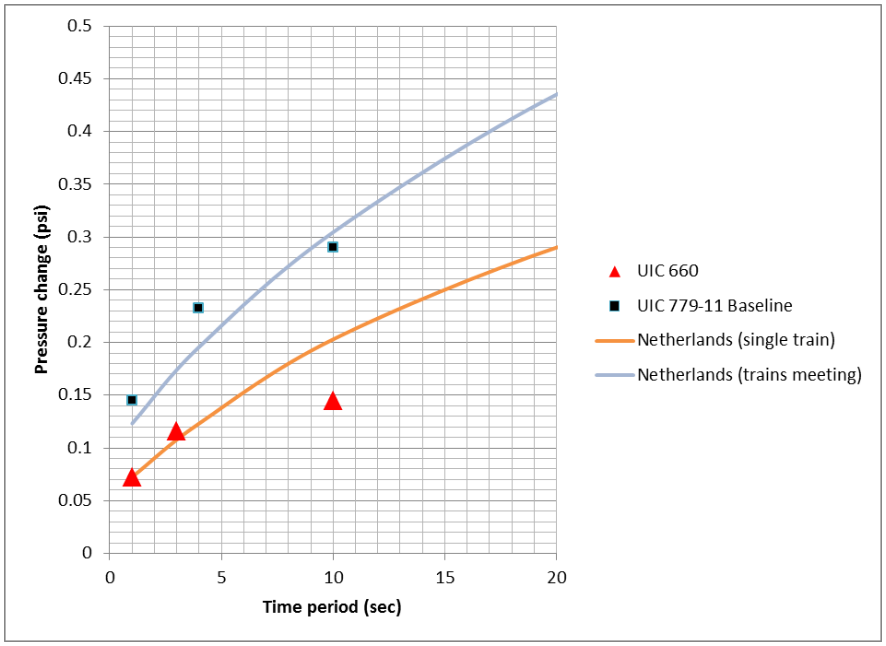

Figure 47. Pressure comfort criteria

UIC 779-11 Criteria for Sealed Trains

“Baseline comfort” criteria are given in UIC leaflet 779-11 for sealed trains (Table 14). The background to these criteria is described by Gawthorpe [207]. UIC have stipulated that these should be non-mandatory because it should be the prerogative of the operator to decide on matters of comfort, based on commercial considerations. The criteria are intended to form a lenient baseline to be applied in all cases, including rare events of trains meeting in tunnels. Operators may choose to adopt more stringent criteria.

UIC 660 Criteria for Sealed Trains

The UIC 660 criteria were developed first by Deutsche Bahn for their own internal use and were later deemed suitable for international use and published by UIC. The criteria were based on experiments by Glöckle et al [183, 184] reported above. They have been used extensively in Europe to design tunnels, primarily single-tube tunnels containing two high-speed tracks. Typically, the resulting tunnels have cross-sectional area of around 1,000 ft^2 (90-100 m^2) for 185 mph (300 km/h) line speed. With this tunnel size, the criteria are met for single trains passing through the tunnel but may not be met for train meeting events. The research by Glöckle showed that these rare events do not determine passengers' overall impression of comfort.

Until recently, most European tunnels were constructed as single tube (twin track) on the basis of cost; however, most new tunnels are being designed as twin tube for fire safety reasons. To meet the UIC 660 comfort criteria with a twin tube tunnel, each tube would need a cross-sectional area around 1,000 ft^2, which is felt to be unnecessarily conservative. European tunnel design is presently moving away from strict adherence to the UIC 660 criteria and in particular the criterion that requires no more than 0.15 psi (1.0 kPa) in 10 seconds. The 10-second component was based on research using trains that were poorly sealed by modern standards, and may not be appropriate to modern, better-sealed trains.

Netherlands Criteria for Sealed Trains

Different criteria apply to single train passages and to trains meeting. These criteria are strikingly similar to the lines giving 5% (for single passages) and 10% (for trains meeting) of passengers experiencing discomfort, predicted from the logistic regression model of Schwanitz et al. These criteria may form a suitable starting point for future criteria for the United States.

Europe

For countries having high speed railways with sealed trains and do not follow the UIC recommendations, data are given in Table 14.

Japan

Japanese pressure comfort criteria are not published but believed to be 0.06 psi (0.4 kPa) in one second, and 0.145 psi (1.0 kPa) for the whole passage through the tunnel. However, reports vary.

United States

There are currently no formal criteria for pressure comfort in sealed trains in the United States.

In 2009, the California High-Speed Rail Authority recommended using the medical safety criterion from UIC 779-11 to design the tunnels for California HSR [190]. No pressure comfort criteria were recommended or used in the design of the tunnels.

Pressure Comfort Summary Comparisons

Figure 48 compares comfort criteria with research results on the comfort ratings found in human subject experiments. The data points in the figure are:

- "Gawthorpe/Johnson": 10% of people uncomfortable with 0.29 psi (2 kPa) in four seconds, from pressure chamber tests. While this result appears anomalous compared to the results of the other researchers additional analysis of the data would be needed to confirm test results.
- "Berlitz": with a mean comfort rating of 2.5 from full-scale tests in sealed trains. (See Section 7.5.1 for details on comfort rating value of 2.5).
- "Schwanitz PC 5% (or 10%)": pressure increases making 5% (or 10%) of people uncomfortable, from a logistic regression model derived from pressure chamber test results.
- "UIC 660": Criteria for sealed trains.
- "UIC 779-11 Baseline": Criteria for sealed trains.

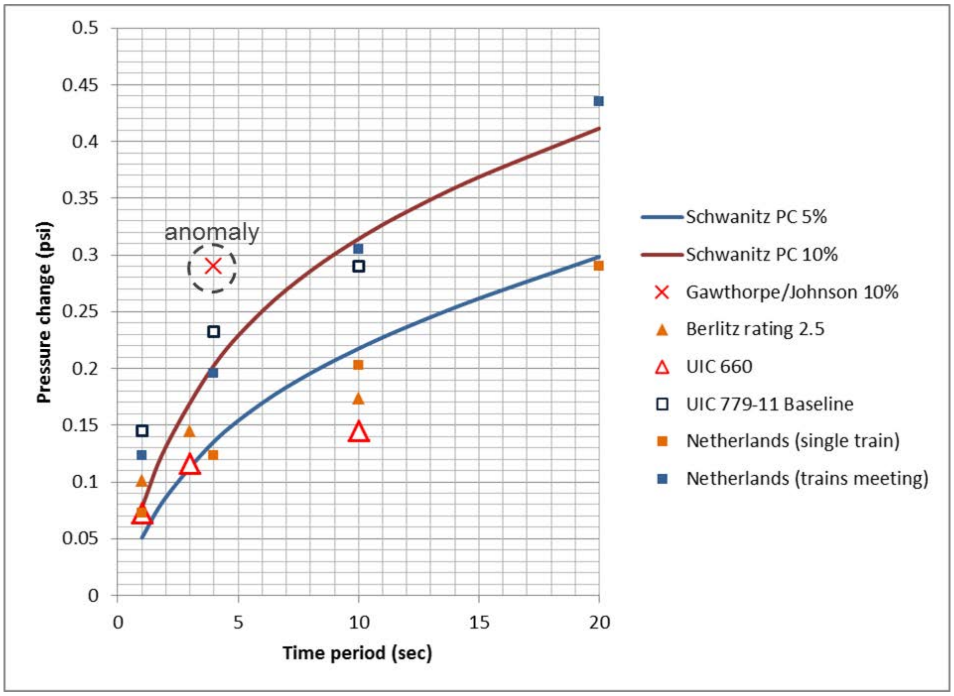

Figure 48. Pressure comfort standards and comfort research results

7.4.2 Criteria for Pressure Comfort and Safety of Track Workers in Tunnels and Passengers on Underground Stations

Gawthorpe et al [208] quote a British Rail criterion for track workers in tunnels. They should not be exposed to pressure changes greater than 1.0 psi (7 kPa) in four seconds. No other criteria have been found for pressure changes to which track workers are exposed in high speed rail tunnels. There are arguments for different criteria to apply to track workers compared with passengers inside trains:

- Track workers are exposed to the pressure changes on a very regular basis and therefore may require lower pressure change limits than passengers who are exposed to pressure changes only occasionally.
- Comfort expectations for track workers may fall below those of passengers, therefore higher pressure change limits may be appropriate.

For Tier III operations, because passengers will be protected from pressure changes by the train sealing system and track workers will not, the track workers will inevitably be exposed to higher pressure changes. If protection of track workers became the governing case for design of the tunnels, it might be concluded that track workers should not be present in the tunnels during operation of a high speed railway, or that speed restrictions should be imposed when workers are present.

In the United States, fire safety standards NFPA 130 and NFPA 502 [209, 210] limit the maximum air velocity in rail tunnels to 2200 fpm (25 mph or 11 m/s) so that fire ventilation systems do not impede evacuation of people through tunnels. Los Angeles County Metropolitan Transportation Authority adopted this criterion as a limit for air velocity in tunnels when workers are present. This may restrict train speeds when workers are present.

For passengers on platforms of underground stations, the evidence found in the literature search is that the same safety and pressure comfort criteria are used as for passengers inside trains. The passengers face the additional impact of air velocity due to both slipstreams of passing trains and air pushed along the tunnels by the trains.

7.4.3 Criteria for Pressure Loading on Fixed Equipment in Tunnels

Criteria for pressure loading on fixed equipment such as cross passage doors are rarely published. This is a specification gap that should be filled.

Busslinger et al [187] give ±1.6 psi (±11 kPa) as the design criterion for such equipment in Loetschberg Base tunnel. Maximum load on plane surfaces (signs, etc.) due to air velocity in the tunnel was set at 1 psi (7 kPa). These criteria are not proposed for general use. This tunnel represents an extreme case due to the small free cross-sectional area and large blockage ratios. It was preferable economically to increase the robustness of the equipment where necessary, rather than bore a larger tunnel through 22 miles of mountain.

In general, the loading is expressed in terms of pressure. For very large surfaces the pressure may not be uniformly applied and so the total net force and the maximum pressure would both need to be specified.

7.4.4 Criteria for Train Pressure Loading and Lateral Oscillation

No criteria relative to the structural integrity or fatigue loading on the trains have been found for acceptable limits on train pressure loadings to which high speed trains are exposed in tunnels. Standards governing rolling stock (for example, British Railway Group Standard GM/RT2100 [211] and European standard EN 12663-1 [212]) typically state that trains must be designed to resist the aerodynamic loading in tunnels, but do not state what loading should be assumed in design or considered acceptable. Train manufacturers use their own internal criteria for the design of their cars [15].

There are, however, studies which evaluate the effects of specific pressures on the integrity of specific train bodies [213], and that methodology could potentially be used to develop assessment criteria for pressures.

Additionally, there are regulations for fatigue resistance of train side windows to pressure loading (see Section 4.5.5).

Novak and Koinig [93] state that sudden pressure changes of 0.22 psi (1.5 kPa) are withstood structurally by normal freight trains. The study focused on pressures from the nose wave of a passing high speed train, but sudden pressure changes could also arise from the pressure waves propagating along the tunnel and passing over the freight train. *If tunnels with a mix of high speed and freight or other conventional traffic are to be considered in the United States, criteria suitable for North American rail vehicles do not currently exist and will be required.*

Lateral acceleration comfort criteria are adopted by many operators, but these are not useful for design in the context of oscillations caused by vortex shedding in tunnels because the oscillation amplitude cannot be predicted reliably. *Basic research must be performed to establish comfort limits and potential minimum clearance distances between the side of a train and the tunnel wall.*

7.4.5 Criteria for Train Performance in Tunnels

European Technical Specifications for Interoperability (Rolling Stock) [14] sets mandatory requirements for interoperable trains (See Figure 49). The pressure wave generated when a train enters a tunnel with cross-sectional area 678 ft^2 (63 m^2) at 155 mph (250 km/h) must satisfy the limits shown. (Δp_N is nose wave pressure, Δp_F is friction pressure, Δp_T is tail wave pressure). These requirements are intended to enforce a level of aerodynamic design of the rolling stock.

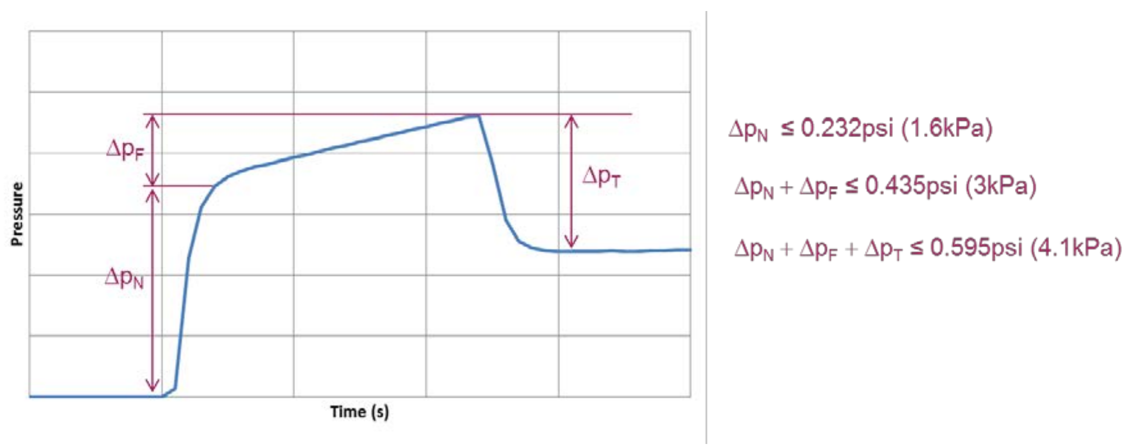

Figure 49. European TSI requirements for interoperable train entering a tunnel

7.5 Data from Literature

7.5.1 Measurement, Assessment, and Evaluation Methodology

Pressure Change Symptomatology: Literature Survey by Cartsens and Kresge

Lee [10] summarized the findings of the survey of medical literature performed by Cartsens and Kresge in 1965 [206]. The following symptoms might be experienced by passengers if the pressure change occurs too rapidly to be equalized by venting through the Eustachian tubes, or if the Eustachian tubes are blocked:

- At pressures 0.06-0.10 psi (0.4-0.67 kPa) passengers experience a feeling of fullness in the ears.
- At pressures 0.19-0.29 psi (1.33-3 kPa) passengers experience stronger feelings of fullness, as well as a decrease in sound intensity.
- At pressures 0.29-0.58 psi (2-4 kPa) passengers may experience tinnitus and, in some cases, ear pain and mild vertigo.
- At pressures above 0.58 psi (4 kPa), the symptoms (pain, tinnitus, vertigo) become more severe.
- At pressures above 1.93 psi (13.3 kPa), the tympanic membrane may rupture.

Pressure Comfort Experiments: Full-Scale Tests, Glöckle and Berlitz

In 1991, Glöckle et al [183, 184] performed tests with 192 volunteers (64 on each of three successive days) riding the Würzburg to Fulda line, which has 20 tunnels. The route was subdivided into 15 sections, and railcars with two different levels of sealing were used. The subjects rated each subsection for pressure comfort on a scale 1-7, with 7 being the most uncomfortable. The results were analyzed to derive the pressure changes that would achieve a mean rating of 2.5, the desired comfort target for Deutsche Bahn.

Berlitz [176] performed regression analysis on the same data in 2003, and concluded that higher pressure changes than those derived by Glöckle would achieve the desired mean rating of 2.5 (See Table 15).

Table 15. Pressure changes giving comfort rating 2.5, from Glöckle and Berlitz

Time period (sec)	Pressure change to give mean rating 2.5: Glöckle (1991)		Pressure change to give mean rating 2.5: Berlitz (2003)	
	psi	**kPa**	**psi**	**kPa**
1	0.07	0.5Pa	0.10	0.7Pa
3	0.12	0.8Pa	0.15	1.0kPa
10	0.15	1.0kPa	0.17	1.2kPa
30, 45, 60			No correlation	
Whole tunnel			No correlation	

Figure 50 shows the Berlitz data for three second time periods.

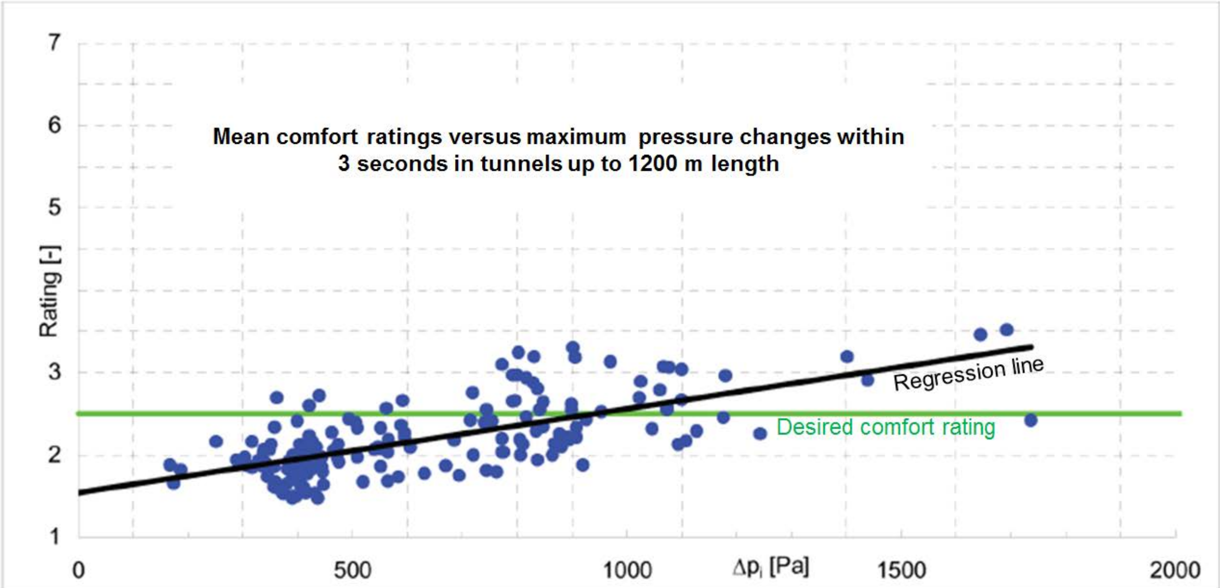

Figure 50. Comfort rating versus pressure change in 3 seconds from Berlitz, 2003 [176]
Reproduced by permission of Union Internationale des Chemins de Fer

The Berlitz re-analysis could be assumed to supersede the conclusions of Glöckle. However, Glöckle's pressure changes had already been adopted by Deutsche Bahn and later published in UIC leaflet 660 as acceptability criteria for the pressure changes inside sealed trains. It should be noted that due to the low sealing performance of the trains used in the experiments, the 10-second limits derived by both authors may be over-conservative if applied to better-sealed trains. For poorly sealed trains, the feelings of discomfort may have been influenced by the pressure changes occurring over shorter timescales within the 10-second periods considered.

No correlation was found in this study between comfort rating and pressure change over 30 seconds or longer time intervals, suggesting that, in the test conditions, pressure changes over shorter time intervals dominated the impact on passenger comfort. This may have been due to the sealing performance of the trains used in the tests, which had relatively low time constants. Pressure changes over 0.29 psi (2 kPa) occurred in these longer time periods without apparently giving rise to discomfort. The limit at which discomfort would arise for these long time periods was not encountered during the tests.

Pressure Comfort Experiments Using Pressure Chamber: Gawthorpe, Johnson Studies

Johnson et al [204] presented a statistical analysis of the comfort ratings given to pressure changes in a four second period from previous studies involving volunteers in pressure chambers, such as those by Gawthorpe in 1985 [182]. Taking a rating of 3.5 or higher (on a scale of 1 to 7) as "uncomfortable", the analysis showed that 10% of the population would regard a 0.29 psi (2 kPa) pressure change in four seconds as uncomfortable. This result contrasts markedly with the Glöckle results, which concluded that pressure changes greater than 0.17 psi (1.2 kPa) in three seconds would make 32% or more of people uncomfortable. Possibly, the subjects in Gawthorpe's tests were more tolerant of pressure changes (for example, due to their previous experience of railway journeys) or perhaps their subjective interpretation of "uncomfortable" was different. Whatever the reason, Gawthorpe's data seems to represent an anomaly among the other research and should likely not be considered a suitable basis for future pressure comfort criteria.

For the case of trains meeting within a tunnel, Johnson gives a probabilistic method that combines the likelihood of a certain meeting scenario with the pressure comfort rating predicted from the 4-second pressure changes. The method combines the effects of relatively rare train crossings (low probability of occurrence but with a high probability of discomfort) with more common transit of a tunnel in which no train crossings occur (high probability of occurrence with low probability of discomfort). This method suggests that smaller free cross-sectional areas could be used where the probability of trains crossing is low.

Pressure Comfort – Effect of Repeated Pressure Changes

Vardy and Haerter [214] questioned the common assumption that level of comfort can be determined by analyzing the largest pressure change event in a journey on the basis that frequency of occurrence of pressure changes also influences comfort. Subway systems typically set lower pressure change limits because the tunnels are so frequent. For the situation of increasing occurrences, the pressure change causing a certain level of perceived discomfort was shown to be reduced by about 20 to 30% if the pressure changes are repeated at one minute intervals, and by about 60 to 70% if repeated at ten second intervals. Repeated pressure changes can occur not only when there are many tunnels, but also if the tunnels contain air shafts or other discontinuities. In summary, different pressure criteria are required in cases where pressure changes occur at high frequency.

Pressure Comfort Experiments: Schwanitz Studies

Schwanitz et al [205] performed pressure chamber tests with 31 volunteers, who were subjected to 30 pressure increases and 30 decreases in different timescales (see Table 16).

Table 16. Pressure changes (indicated by checkmarks) tested during time periods in pressure chamber, Schwanitz et al

Time period (seconds)	Pressure change psi (kPa)						
	0.0145 (0.1)	0.029 (0.2)	0.0725 (0.5)	0.145 (1.0)	0.363 (2.5)	0.725 (5.0)	1.45 (10.0)
1	✓	✓	✓	✓			
2	✓	✓	✓	✓	✓		
5		✓	✓	✓	✓	✓	
10		✓	✓	✓	✓	✓	
25			✓	✓	✓	✓	
50				✓	✓	✓	✓
100					✓	✓	✓

The volunteers gave subjective ratings for each pressure change on a 7-point scale, with 0 being "not at all uncomfortable" to 6 being "extremely uncomfortable". The authors provide the mean and standard deviation of the ratings for each pressure change, and a logistic regression model that predicts the proportion of the general population who would feel uncomfortable if subjected to any given pressure change (described by its gradient, amplitude, timescale, and whether an increase or a decrease). In the logistic regression model, "uncomfortable" is defined as a rating of 4 ("fairly uncomfortable") or above.

The regression model has been used to derive the data in the graphs (See Figure 51) predicting what pressure changes are experienced as uncomfortable by a given percentage of the population.

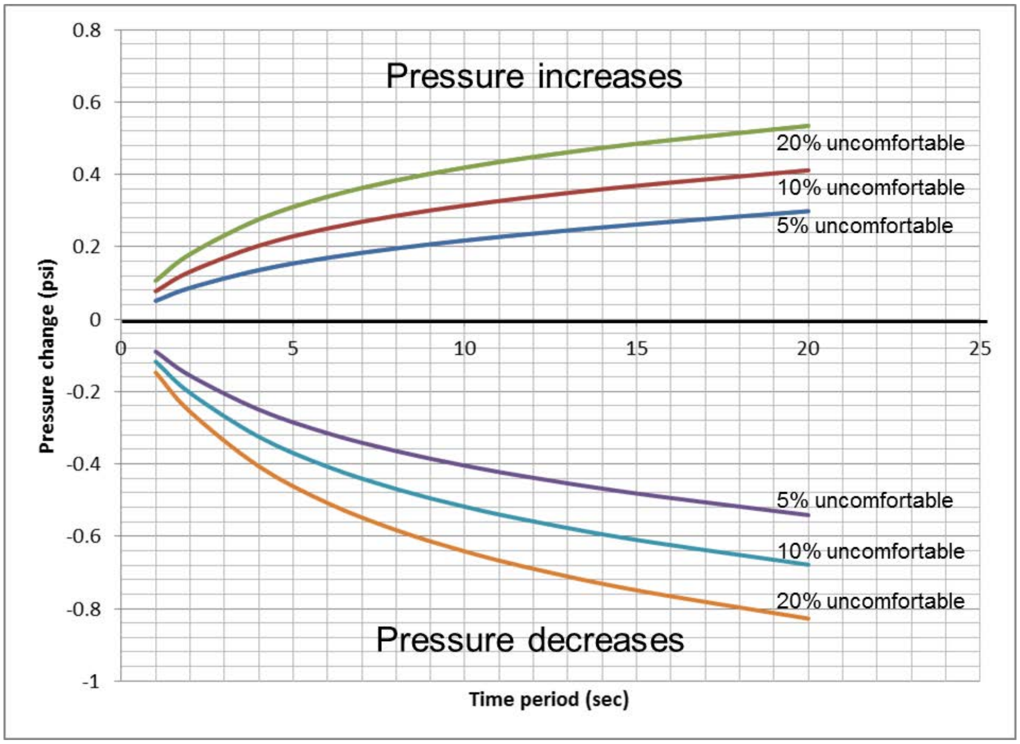

Figure 51. Iso-comfort contours, pressure change versus time-period, from logistic regression model by Schwanitz et al

Points to note:

- Pressure increases are more uncomfortable than pressure decreases of the same amplitude over the same time. For example, 0.4 psi (2.8 kPa) in 10 seconds is predicted to make about 20% of passengers uncomfortable if applied as a pressure increase, but only 5% if applied as a pressure decrease. This is because the middle ear is usually ventilated automatically in the case of an external pressure decrease, while for a pressure increase the pressure in the middle ear may have to be equalized actively by yawning or swallowing.
- The pressure changes applied in the pressure chamber were in the form of a constant gradient over the stated duration. In tunnels, the pressure does not change in that manner.

- The 31 volunteers were all healthy. The logistic regression model makes no allowance for people, for example, with damaged ear drums or whose Eustachian tubes are blocked due to illness or injury.
- Passengers' perception of discomfort is likely to be greater when several tunnels follow in quick succession, compared to a single pressure change [214]. In the experiments, the 60 different pressure changes were applied sequentially, separated by breaks of 30 seconds – loosely resembling a real-life situation with several tunnels.
- The subjects in the experiments were highly focussed on pressure changes, which may have affected the perception of discomfort compared to typical passengers on trains.

The same 31 subjects experienced a real-life railway journey on the Cologne-Frankfurt line (Schwanitz et al [215]), where trains pass through 22 tunnels within 40 minutes. The subjects were equipped with sliders to record continuously the level of discomfort. The pressure inside the railcar was recorded simultaneously with the slider outputs from the subjects. Subsequently, the recorded pressure time-histories were replayed to the same subjects in the same pressure chamber used for the simpler tests described above. The pressure chamber results correlated closely with the railway journey results.

Evaluation Methodology: Pressure Comfort and Safety

There are two common methods of assessing pressure comfort and safety:

- By reference to design curves such as those given in UIC leaflet 779-11.
- By specialized one-dimensional analysis programs. The programs simulate the unsteady flow of the air in a tunnel as the trains pass through, and output (among other data) the pressure time-histories and pressure changes relevant to the selected pressure comfort criteria.

Formulae can be used to calculate the amplitude of the initial nose entry pressure wave. Wave diagrams can then be used to estimate the times at which the waves pass over the train. This is useful for checking and understanding test or analysis results. However, evaluation of pressure comfort by formulae is not a practical option and would take much longer than analysis by a suitable one-dimensional analysis program. It would be necessary not only to calculate the amplitude of the initial nose entry and tail entry waves and to track all the waves and their reflections, but also to calculate at each point in time the pressure distribution in the annulus around the train (which is different to the pressure in the tunnel ahead of and behind the train because the air accelerates over the nose and tail). Additionally, it would be necessary to identify the consequent pressure changes at each of several points along the train, and then to calculate the effect of the train's sealing system. Therefore we suggest pressure comfort should be evaluated either by design curves such as those in UIC-779, or by one-dimensional analysis programs.

Evaluation by three-dimensional (or two-dimensional) CFD is similarly not efficient for plain tunnels. The analyses would take much longer to set up and run than analyses using one-dimensional programs, and would produce little increase in meaningful accuracy.

CFD may be useful for estimating certain input data for one-dimensional analysis, such as loss coefficients for new train designs. However, such data are rarely of primary importance for this scope. CFD is more appropriate for situations such as pressure comfort for passengers waiting on platforms of underground stations, where the geometry and air flow effects cannot always be represented using one-dimensional approximations. Vardy et al [216] explored the limitations of one-dimensional analysis for these cases.

Assessment of Pressure Comfort and Safety Using One-Dimensional Analysis

One-dimensional analysis using a specialized program is the key assessment method. The programs simulate the unsteady flow of the air in the tunnel as the trains pass through. Typically, the programs are based on the "Method of Characteristics". This numerical technique is described extensively in the literature, for example by Fox and Vardy [217] and Shultz and Sockel [218]. The required inputs include:

- Simple geometrical data for the tunnel (length, cross-sectional area).
- Simple geometrical data for the train (length, cross-sectional area, starting position, speed).
- Data such as friction factors and local loss factors that may be estimated from the literature or other sources.
- Train sealing time constant.
- Atmospheric conditions.
- Positions of the trains within the tunnel at which pressures should be monitored.

Examples of one-dimensional analysis programs include:

- ThermoTun, commercially available from Dundee Tunnel Research [106], and available for use over the Internet [219].
- In-house programs developed by national rail carriers and research centers such as Deutsche Bahn's DB-TUNNEL.
- SEALTUN, TRENDSHAFT and DE-SHAFT, developed by European Rail Research Institute these are mentioned in the literature and described in UIC leaflet 779-11, but are now considered obsolete and have been withdrawn by UIC.

Many authors demonstrate the accuracy of one-dimensional analysis methods by validating the predicted pressure changes against full-scale experiments. For example, Wormstall-Reitschuster et al [220] and Berlitz [176] used the program DB-TUNNEL, and Glöckle and Pfretschner [184] and Hagenah et al [197] used ThermoTun.

Schultz and Sockel [218] show that the accuracy of one-dimensional analysis of trains in short, simple tunnels can be improved by modeling the nose and tail of the train with an artificially-elongated tapered shape, calibrated against test data or suitable 3D analyses. This may be because the train pushes stagnant air ahead of it, which behaves like a long tapering extension on the train nose in so far as it influences the air flow over the train.

Assessment method by Gawthorpe

The following procedure was recommended by Gawthorpe [207] for determining the required cross-sectional area for a tunnel:

1. Identify input data:
    - Tunnel length, single or double track, with or without air shafts.

    - Train cross-sectional area, length, speed, type, pressure sealing time constant.
    - Pressure comfort criterion (selected by the operator).
    - Single or multiple train operation.
2. For plain tunnels and unsealed trains, use graphs in UIC leaflet 779-11.
3. For sealed trains and tunnels with air shafts, analysis must be performed at this time. Gawthorpe explained the use of SEALTUN, TRENDSHAFT and DE-SHAFT. However, these are now considered to be outdated and the newer validated one-dimensional software such as ThermoTun could be used instead.
4. Check compliance with medical safety limit and comfort criteria.
5. Check suitability and robustness of design for future developments:
    - Higher speeds.
    - Different train types and sizes.

Effect of Gradients (Tunnel Inclination)

Atmospheric pressure decreases with increasing altitude. The pressure outside a train changes as it passes through an inclined tunnel irrespective of any pressure waves. The pressure change in a tunnel due to change of altitude is of course no greater than would occur if the railway were not enclosed by a tunnel. However, such pressure changes add to the pressure changes caused by pressure waves, resulting in a larger overall pressure change than in a non-inclined tunnel. As explained by Montenegro-Palmero and Vardy [221], in long inclined tunnels this can cause difficulty with meeting the TSI medical safety limit which requires that the pressure changes during passage through the tunnel should not exceed 1.45 psi (10 kPa) irrespective of the duration over which the pressure changes occurs. This is a characteristic of the way the criterion is defined and data from the literature search suggests that most agencies do not consider this a real safety concern but rather more an anomaly of the criteria. The criteria should be modified to reduce the overly conservative estimates of pressure effects and reflect the actual pressures encountered in an inclined tunnel.

Assessment by Reduced Scale Moving Model Testing

Reduced scale model testing has been used to generate data from which:

- one-dimensional analysis tools can be validated;
- an understanding of the fundamental aspects of the behavior of pressure waves in tunnels can be attained (e.g. Da Costa et al [222]); and
- the efficacy of air shafts can be evaluated (e.g. Kim [223]).

Because of the complex speed-dependent interactions of pressure waves, the model trains must be fired at actual line speed [57].

Assessment by Full-Scale Tests

Full-scale tests have been used extensively to:

- understand the fundamental aspects of the behavior of pressure waves in tunnels,
- measure pressure wave effects in existing tunnels or develop targets for future tunnels,
- confirm that pressure comfort and safety objectives have been achieved,
- obtain data for the validation of one-dimensional analysis, and

- obtain data from which input data for analysis may be derived.

Examples are given in the literature references, e.g. Kim and Kwon [192], Vardy [198], and Busslinger et al [187].

Pressure transducers may be fixed to the inside of tunnels or to trains. Busslinger et al illustrate micro-pressure transducers integrated into plates fixed to the exterior of trains with mobile data acquisition systems inside the trains.

The train speed, ambient temperature, and wind speed in the tunnel before arrival of the train should be recorded.

Assessment of Loading on Fixed Equipment

No published methods were found for assessing aerodynamic loading of equipment in tunnels caused by passing trains. The contributing pressure changes and air velocity effects are listed in Sections 7.2 and 7.4. In the case of cross-passage doors and enclosed cabinets where only one side or surface is exposed, the maximum pressure difference between the exposed and unexposed surfaces must be considered as a fatigue load. Where the equipment is wholly immersed in the air inside the tunnel (for example, signs) there is no net force arising from the pressure changes, but pressure caused by air flow along the tunnel must be considered, including “gusts” at the nose and rear of the train. This pressure could be evaluated from a three dimensional analysis.

Assessment of Lateral Oscillation of Trains in Tunnels

No published methods were found for predicting whether problematic oscillations will occur. Further assessment should be conducted.

7.6 Conclusions and Recommendations

7.6.1 Conclusions

- Aerodynamic concepts of pressure waves in tunnels are well established.
- Measurement and analysis methods are well established.
- Mitigation methods are well known consisting primarily of:
    - increasing tunnel cross-sectional area
    - increasing size and number of air shafts
    - requirements for better sealing of trains.

7.6.2 Gaps and Issues

Safety and Pressure Comfort Criteria

There currently exist no formal medical safety or pressure comfort criteria for tunnel operations in the United States. Criteria are needed to limit pressure differences across the ear drum that could potentially cause hearing damage.

Loadings on Fixed Equipment

Aerodynamic loading on fixed equipment in tunnels can be very significant. No guidelines were found for estimating such loading pressures.

Loadings on Trains

Train manufacturers design railcars assuming certain train pressure loadings relative to structural integrity and fatigue. The proprietary numerical values vary from manufacturer to manufacturer. However, for organizations engaged in design of tunnels for HST, there are no criteria or guidelines as to what pressures on the train should be considered acceptable.

Dynamic Oscillation of HST Caused by Asymmetrical Vortex Shedding within Tunnels

This phenomenon is not well understood at present. Existing assessment methods do not provide reliable predictions of physical and operational conditions that lead to dynamic oscillations, such as when the track is not positioned centrally within the tunnel.

Policies and Procedures for Operations

Standardized policies and procedures for operations are not established in the United States that dictate the types of tunnel construction, i.e., twin tube versus single tube tunnels, worker safety requirements, mixed traffic constraints, and other vehicle design requirements.

7.6.3 Recommendations to Address Gaps and Issues

Safety and Pressure Comfort Criteria

A safety criterion should be mandatory. The 1.45 psi (10 kPa) “medical safety limit” used internationally is proposed for this purpose incorporating adjustments for inclined tunnels.

In regards to pressure comfort criteria it would not be unreasonable to leave the choice of particular comfort criteria to the carrier, although *we recommend that the FRA provide guidance on this issue*. We recommend that the guidance should have the following characteristics:

- Multi-component, i.e., the criteria will consist of maximum pressure changes in each of several time intervals, for example 1-second, 3-second, 10-second, and 20-seconds.
- A strategy for designing twin track tunnels. If the same criteria were used for all situations, including trains meeting, the tunnel size would be controlled by crossing events that occur only rarely, and extra money will be spent on construction with little benefit to passengers. Possible strategies include:
    - A set of criteria is applied to single train passages. Meeting events are not considered for comfort, but they must still be considered for safety. Provided that the criteria are sufficiently stringent, the rarely-occurring meeting events may cause high pressure changes, but will not be intolerable.
    - One set of criteria is applied to single train passages, and another (less onerous) to meeting events, similar to the Netherlands criteria.
    - The frequency of occurrence of meeting events could determine the criteria to be applied. For example, the single passage criteria may be exceeded by up to X% for Y% of train passages.
- Multi-level criteria may be desirable. Different comfort levels could be selected according to the situation. For example:
    - More stringent limits where tunnels are more frequent.
    - Less stringent limits for trains meeting in tunnels.

- Choice of more stringent or less stringent limits according to the trade-off desired by the operator between luxury and construction cost.

The details of the criteria (numerical values of maximum pressure changes in defined time intervals) should be developed in future work after discussion with the FRA. The Netherlands criteria might form a reasonable starting point.

Loading on Fixed Equipment

The literature search identified no published methods for assessments of aerodynamic loadings. Additional studies and assessments should be conducted to develop a standardized methodology for quantifying the loadings.

Loading on Trains

Additional studies and assessments utilizing current research and operational experience should be conducted. The results of these studies and assessments would establish pressure loading guidelines that would be used in the design of vehicles and in the development of mitigation factors for occurrences of trains meeting and passing in tunnels.

Dynamic Oscillation Loading of HST Caused by Asymmetrical Vortex Shedding within Tunnels

Further research is needed regarding this subject. Criteria should be developed and standardized to quantify and assess the impacts of the increased frequencies and oscillations. Resulting rules could take the form of a minimum distance between the tunnel wall and the side of the trains.

Policies and Procedures for Operations

Based on discussions with the FRA, it is currently anticipated that Tier III operations and beyond (125-250 mph) will have dedicated new-build lines carrying only high speed trains. These high speed trains will not interact aerodynamically with conventional trains in tunnels and issues of mixed traffic in the tunnels on these lines will not arise.

Standardization of policies and procedures for operations should be adopted so that criteria for rules and guidelines for tunnel designers can be developed. Questions and issues to be considered by the FRA include:

- Will twin track tunnels be permitted in the United States, and if so up to what length? In Europe, twin track (single tube) tunnels are no longer favored, for fire safety reasons. Analysis will assess the increased costs of twin tube tunnels versus safety and comfort criteria.
- Will track workers be permitted inside the tunnels during normal operation?

It is recommended that these issues be studied and assessed in the next phase of this project for establishing aerodynamic assessments and mitigation guidelines.

In the event mixed traffic conditions occur then the selection of safety and pressure comfort criteria for Tier II mixed operations is recommended along with the assessment of operating conditions as described above.

8. Micro-Pressure Waves Emitted From Tunnels

Micro-pressure waves (MPWs) emitting from tunnel portals can cause noise and vibration in the environment and sometimes generate localized "sonic booms". The phenomenon is well-understood, methods are available to assess it, and there are known mitigation measures to control it. However, the boundaries of acceptability for MPWs are not quantified and this presents uncertainty for the design of tunnels especially in the conceptual design phase.

8.1 Introduction and Summary

This chapter examines these micro-pressure waves and the resultant effects. It includes:

- basic aerodynamic concepts;
- influencing factors;
- measurements and calculation methods;
- known and potential impacts;
- mitigation methods;
- standards including acceptability criteria;
- data from literature including MPWs measured in practice and assessment methods; and
- conclusions and recommendations including methods for establishing acceptability.

This chapter has the following general conclusions and recommendations:

- MPWs must be assessed in the design of high speed railway tunnels. MPW amplitude scales with train speed cubed (and in some cases more), and so the problem becomes at least eight times greater at 250 mph (402 km/h) than at 125 mph (201 km/h). The train speed has an even stronger effect on MPWs than it does on pressure comfort.
- MPW assessment and acceptability criteria do not currently exist for the United States. They should be developed building upon the existing standards and criteria of Europe and Japan.
- Additional studies and assessments should be conducted to develop more cost effective mitigation assessments and methods.

8.2 Micro-Pressure Wave

8.2.1 Basic Aerodynamic Concept

A micro-pressure wave (MPW) is a pulse of air pressure that is emitted from a tunnel portal into the environment whenever any pressure wave inside a tunnel is reflected at the portal. Every railway tunnel in the world emits MPWs. These are generally at frequencies below the audible range and of such small amplitude that they are rarely noticed. However, MPWs can take the form of "sonic booms" and can be very loud. These were first experienced in Japan in 1974 during running tests on the Okayama-Hakata extension of the Sanyo Shinkhansen line. Booming noises were heard at tunnel exits and residents complained of rattling windows and shutters. The impact is principally one of annoyance for people near the tunnel exit.

The strongest (and most noticeable) MPWs generally arise from the "nose entry wave", i.e., the pressure wave caused by the train entering the tunnel. In long tunnels these can occur at the tunnel exit long before the train itself arrives (e.g., roughly 16 seconds for each mile of tunnel). The influence of the effect on people is amplified because there is no prior warning of the disturbance.

The phenomenon is extensively described in the literature by Vardy [180]. When considering aerodynamic effects in tunnels, such as aural comfort of passengers, the property of the pressure wave that is of primary interest is its magnitude. However, for MPWs it is *the pressure gradient that matters most.* The amplitude of the MPW experienced outside the tunnel is proportional to the gradient of the pressure wave inside the tunnel as it approaches the tunnel exit. Hieke et al [189] suggest that pressure gradients greater than about 5.8 psi/sec (40 kPa/sec) at the tunnel exit can result in MPWs with strong audible frequency components.

The generation and transmission of MPWs take place in four phases (see Figure 52):

- Generation of a pressure wave inside a tunnel, typically caused by the nose of the train entering the tunnel.
- As the pressure wave propagates down the tunnel at the speed of sound (approximately 762 mph) the gradient of the pressure wave may increase ("steepening") especially in long slab-track tunnels. In ballasted tunnels the gradient may decrease.
- When the wave reflects from the tunnel exit, a proportion of the energy is radiated into the surrounding environment as an MPW.
- The MPW wave propagates through the air to receptors such as windows and human ears.

These phases are described in more detail in Section 8.2.2.

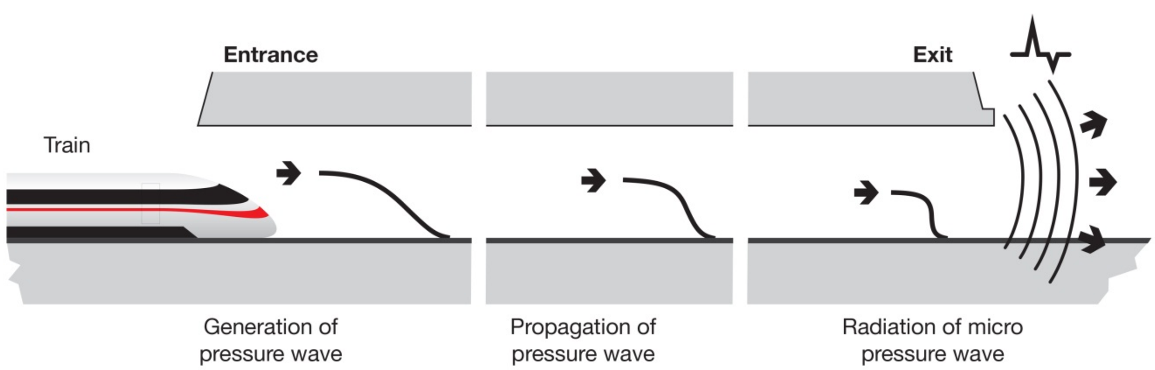

Figure 52. Micro-pressure wave generation, propagation and emission

8.2.2 Influencing Factors

Generation of Pressure Wave

As the train enters the tunnel, the nose of the train compresses the air in front of it, setting up a pressure wave. This is a three dimensional process and it takes a finite time to occur, leading to a pressure wave with a finite maximum gradient (not a shock wave, which would have close to infinite gradient). While the pressure wave magnitude is proportional to train speed squared, the gradient is proportional to train speed cubed. For this reason, even relatively modest increases in train speed can result in MPWs becoming a problem, although at the lower speed they were unnoticeable. The pressure gradient can be reduced by measures that reduce the pressure wave magnitude, such as increasing the cross-sectional area of the tunnel, decreasing the train speed, modifying the train nose shape or by increasing the time taken for the pressure wave to build up to its full magnitude, through modifications to the geometry of the entry portal.

Wave Propagation

The pressure wave propagates along the tunnel at the speed of sound, in an essentially one-dimensional process. The pressure gradient changes during propagation down the tunnel. It is the pressure gradient at the exit of the tunnel that determines the amplitude of the MPW emitted. Severe cases of MPWs causing loud bangs occur when the pressure wave has become almost infinitely steep, i.e., the back of the wave has completely caught up with the front, and the wave becomes a shock wave. The pressure gradient changes due to the following competing effects, all of which become more significant for longer tunnels:

- "Inertial steepening" tends to increase the gradient. This occurs because the front of the wave propagates through stationary air, while the back of the wave propagates through air that is moving in the same direction as the wave (and hence the speed of the back of the wave relative to the tunnel is greater). Additionally, the speed of sound in the pressurized air at the back of the wave is slightly greater than in the unpressurized air at the front. For these two reasons, the back of the wave tends to catch up with the front, and the pressure wave becomes spatially shorter, and hence steeper.
- Friction resists or damps the flow of air down the tunnel, and tends to reduce the pressure gradient. Friction may be increased by discontinuities in the surfaces of the walls and track form.
- The presence of ballast tends to reduce the pressure gradient ("ballast effect"). This is thought to be due to air being lost from the pressure wave front as it passes into the air spaces between the ballast particles, resulting in the wave being spread over a greater distance.
- Worker access tunnels or other side passages tend to reduce the pressure gradient.

In slab-track tunnels, the inertial steepening process dominates. The pressure wave becomes steeper as it propagates (Figure 53). The longer the tunnel, the more time is available for this process to occur, the greater is the pressure gradient at the tunnel exit, and the greater is the amplitude of MPW emitted.

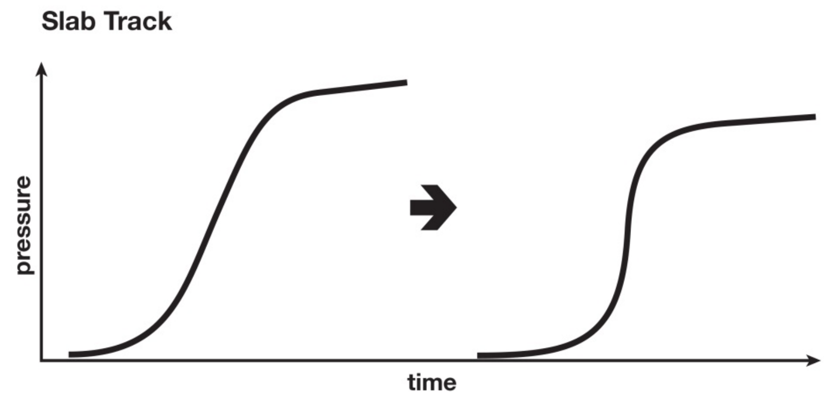

Figure 53. Pressure gradient increasing during propagation, typical of slab-track tunnels

The rate of wave steepening increases with the magnitude of the pressure wave. More steepening occurs as train speed increases, or as the blockage ratio (train area divided by tunnel area) decreases. Therefore, while the gradient of the initial nose-entry pressure wave varies with train speed cubed, after the gradient is amplified by wave steepening, the gradient at the tunnel exit varies even more than the train speed cubed.

In long, ballasted track tunnels, the ballast effect usually dominates. The pressure gradient reduction rate due to the ballast effect more than cancels out the inertial steepening. The gradient of the pressure wave reduces as it propagates (Figure 54). This is why MPW problems have not been typically reported in long ballast-track tunnels. However, it should not be assumed that a tunnel containing ballast will not produce unacceptable MPWs. This point is explained later.

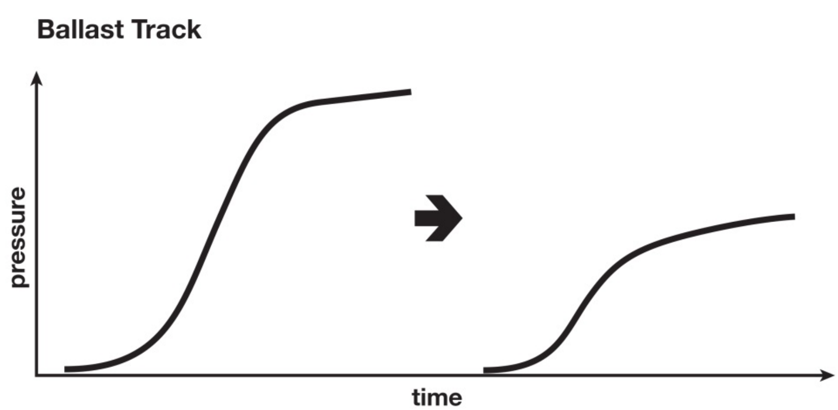

Figure 54. Pressure gradient decreasing during propagation, typical of ballast-track tunnels

MPW Emission

When the pressure wave reflects at the exit portal, a proportion of the energy is radiated out into the environment as an MPW (see Figure 55). When the velocity of the air at the tunnel portal changes (due to arrival and reflection of the pressure wave), the portal acts like a loudspeaker. The amplitude of the MPW is proportional to the gradient of the pressure wave inside the tunnel. It is also proportional to the cross-sectional area of the tunnel. A larger tunnel acts like a larger loudspeaker. This effect partially cancels out the benefit of the larger tunnel in terms of reduced pressure wave gradient.

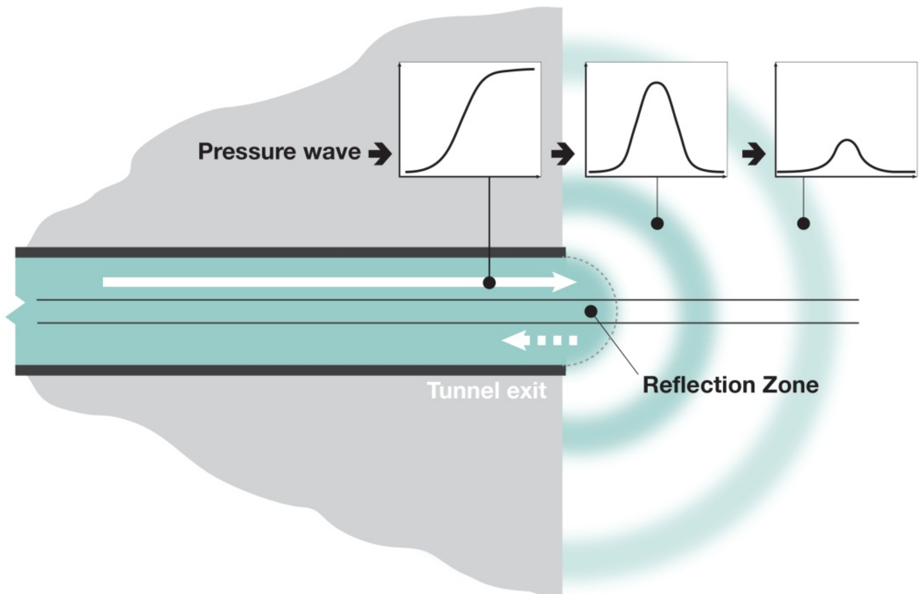

Figure 55. Pressure wave reflection and micro-pressure wave emission

MPW Transmission

When the MPW is emitted from the tunnel, it radiates out into the environment. A simple assumption is that the MPW amplitude reduces in proportion to the inverse of distance from the portal. Thus, an observer at 200 ft (60 m) from the portal would experience half the amplitude compared with an observer at 100 ft (30 m) from the portal. The MPW amplitude is also dependent on the shape of the terrain around the tunnel exit. An MPW emitted from a tunnel in a large vertical cliff-face will be concentrated into a quarter-sphere bounded by the horizontal ground plane and the vertical cliff-face, while the MPW emitted from a tunnel emerging into almost-flat ground may be spread over almost a half-sphere. Further, cuttings or other local topography may funnel the MPW preferentially in certain directions. It is thought that MPWs are little affected by noise barriers or other objects intervening between the tunnel portal and the receptor because they typically consist of low frequencies and long wavelengths.

MPW from Other Causes

The literature focusses on “classic” MPWs emitted from tunnel exits caused by reflection of the nose-entry pressure wave after propagation down the tunnel. MPWs may also be caused by any other event that leads to a steep pressure wave or rapid change of air velocity at an entrance or exit of the tunnel. For example, pressure relief shafts (or other air shafts connecting the tunnel to the open air) may have a beneficial effect on the “classic” MPW caused by a nose entry wave transmitted down the tunnel. There is also possibility of adverse impacts:

- MPWs can be emitted from the shaft portals due to wave reflections within the shafts, just as they are from the main tunnel portals. These could have unacceptable impacts in the environment around shaft portals.

Pressure waves are generated when a train passes a shaft inside a tunnel. Saito et al [224] describe this phenomenon and provide a theoretical treatment. Such pressure waves cause MPWs at the main tunnel portals and at the shaft portal. These could have unacceptable impacts, although no such examples have been found in the literature at current operating speeds (less than 250 mph). The MPW amplitude arising from trains passing shafts is likely to be greater for higher train speeds and for larger diameter shafts. *There is a lack of assessment methods for MPWs from this source.*

Iida et al [225] discuss MPWs emitted directly from the portals as the train nose or tail enters or leaves the tunnel ("entry/exit waves"). Because the waves that cause these MPWs have not been transmitted down the tunnel, there is no chance for steepening to occur. These MPWs will be infrasound (low and often inaudible frequencies less than 20 Hz). In all cases reported to date, these waves are weaker than the "classic" MPWs. For example, Iida et al measured these waves outside a 1.1 mile long (1.8 km) Shinkansen tunnel without entrance hoods and found their amplitudes to be no more than half the amplitude of the "classic" MPWs. (See Section 8.3.2 for detailed discussion regarding hoods). Scale model experiments indicated that the waves were strongly directional, with much of the energy being directed into the tunnel rather than out into the environment. *Therefore," entry/exit" waves are unlikely to require assessment or mitigation if the "classic" MPWs have already been determined to be acceptable. However, if mitigation measures are developed that reduce the "classic" MPWs but not the "entry/exit" waves, there remains a possibility of the "entry/exit" waves becoming the critical case for adverse impacts and further assessment would then be required.*

No railway currently runs through tunnels at speeds as high as 250 mph. At such speeds, all potential sources of MPWs should be considered. *No assessment methods for this type of MPW were found in the literature search. Further, there is an absence of published information on whether the mitigation measures effective in suppressing "classic" MPW also work for these directly-emitted waves.*

8.2.3 Measurements and Related Issues

If sufficient steepening has occurred during transmission along the tunnel for the pressure wave to become almost a shockwave (in which the pressure gradient becomes close to infinite), the MPW may be heard as a loud bang and is likely to be audible over a large distance. If a shockwave has not developed, the MPW will consist of lower frequency noises or infrasound. MPWs with significant power at frequencies up to about 100 Hz have been reported, but other cases show most of the power in the 1-10 Hz range (infrasound).

MPWs are most likely to be a problem under the following circumstances:

- High train speed
- Long tunnels (especially if slab-track)
- Residential or other sensitive areas near the tunnel exit
- Terrain that funnels the emitted sound towards sensitive areas
- Tight tunnels (high blockage ratio), especially for long tunnels

Unacceptable MPWs are sometimes considered to be a problem unique to long slab-track tunnels, but they can occur in short tunnels, including ballast-track as well as slab-track.

In practice, unacceptable MPWs have been experienced at speeds above about 125 mph (201 km/h). For a short tunnel and a given train, the amplitude of the MPW is proportional to V_z^3 (where V_z is the speed at which the train enters the tunnel). In longer slab-track tunnels there is an even greater impact from V_z relative to a ballast-track tunnel. Therefore the difficulty of designing tunnels to prevent unacceptable MPWs and the expense of constructing the tunnels to mitigate MPWs both become much greater as speeds increase from 125 mph (201 km/h) towards 250 mph (402 km/h). The same holds as slab-track tunnels become longer. When considering an increase of speed on existing lines with tunnels, the possibility of unacceptable MPWs must be considered even if no MPW problem was experienced at the lower speed.

Unacceptable MPWs were found in the literature only for long slab track tunnels. Hieke et al [189] report that unacceptable MPWs occurred at the 4.8 mile (7.7 km) long Euerwang Tunnel in Germany, after the originally-planned ballast track was changed during the design process to slab track. Ozawa et al [178] give examples of full-scale test measurements of MPWs from four tunnels without mitigation measures. The left graph of Figure 56 shows the results. The tunnels are:

- Short slab track tunnel (1 mile (1.6 km) long, white circles in Figure 56)
- Short ballast track tunnel (0.4 mile (0.7 km) long, white triangles)
- Long slab track tunnel (4.2 mile (6.8 km) long, black circles)
- Long ballast track tunnel (2.5 mile (4 km) long, black triangles)

The two short tunnels show the same V_z^3 relationship with train entry speed, indicating that track type has little effect on MPW amplitude for short tunnels. The MPWs from these tunnels are described in the paper as inaudible. The long ballast track tunnel shows lower MPW amplitude than would be indicated by the V_z^3 relationship. This is because the pressure wave lengthens during propagation due to the action of ballast. Meanwhile the long slab track tunnel emitted MPWs with greater amplitude than indicated by the V_z^3 relationship, and these were audible and unacceptable. During propagation, the pressure wave became shorter due to inertial steepening.

At Ohirayama (another slab-track tunnel), fitting an entrance hood reduced the MPW amplitude by a factor of almost 10 (right-hand graph, Figure 56). The hood for this tunnel is shown in Figure 63 [226]. Note that the entry speeds here were 124-155 mph (200-250 km/h). The same hood would not necessarily be equally effective for higher entry speeds, nor for longer tunnels. Hoods must be designed on a case-by-case basis.

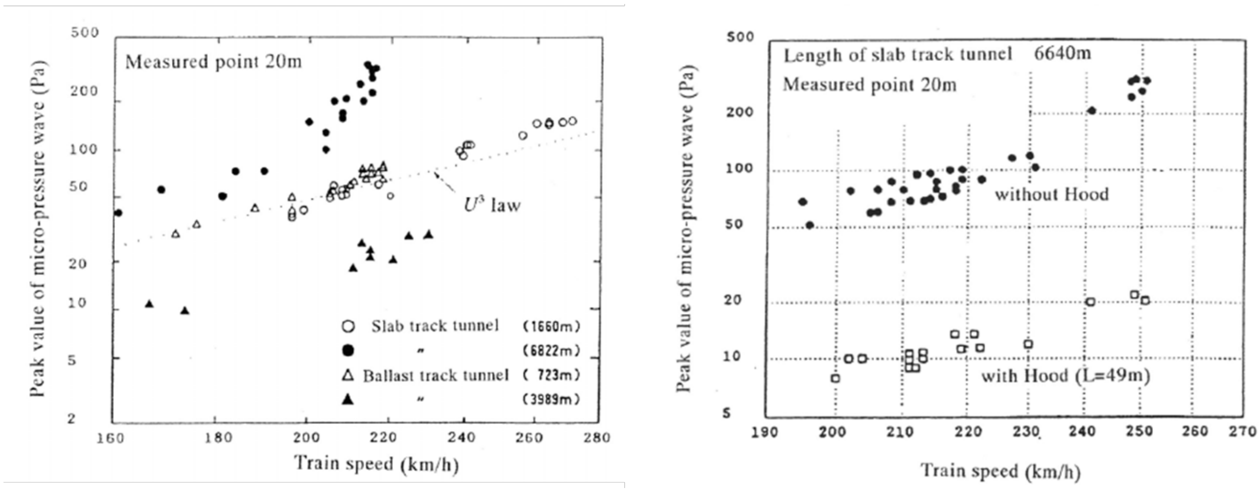

Figure 56. Measured micro-pressure waves at Japanese tunnels, from Maeda et al [226]
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There is no record from the literature search of unacceptable MPWs occurring in short tunnels, nor in long tunnels equipped with ballast track. Ballast counteracts the steepening process and is effective as a mitigation measure in long tunnels. However, in theory, unacceptable MPWs could occur even in short and long tunnels with ballasted track:

- In a short tunnel, there is little time for the pressure gradient to change. The pressure gradient at the tunnel exit will be almost the same as at the tunnel entrance, whether the tunnel has ballasted track or slab track. The pressure gradient due to train nose entry may be sufficient to cause an MPW problem if the train speed is high and insufficient mitigation measures are provided.
- In a long ballasted track tunnel, if the pressure wave amplitude is high, the inertial steepening rate might be too large to be overcome by the ballast effect.

The implication is that at least an initial MPW assessment should be carried out for all new tunnels during design, whether slab-track or ballast-track.

Assessment and Calculation Methodologies Summary

The four phases of MPW generation and transmission are generally evaluated in a sequence chain, with the output from one phase becoming the input for the next. Often, different methods are applied to each of the four phases. In summary, the methods available are:

- Simple formulae suitable for spreadsheet-based assessments.
- One-dimensional analysis, using specialized software such as ThermoTun [106].
- Three-dimensional solutions developed by Howe [227-230].
- Three-dimensional CFD.
- Scale model testing.

The applicability of the methods to the phases of MPW generation and transmission are given in Table 17 below:

Table 17. Assessment methods for micro-pressure waves

Methodology	Wave generation	Wave transmission	MPW emission	MPW transmission
Simple formulae (calculator/spreadsheet)	✓	✓	✓	✓
One-dimensional analysis		✓		
Three-dimensional closed form	✓			
Three-dimensional CFD	✓	✓(*)	✓(*)	✓(*)
Scale model testing	✓	✓(+)	✓	✓(++)

(*) – Possible, but not usually done in practice

(+) – Possible, but only for tunnels short enough to fit within the test facility

(++) – Possible, but limited by the space available: requires absence of reflections such as from walls or ceiling.

As an example of combining methods in a chain, Hieke et al [231] describe well-validated methods for MPW prediction using CFD for analyzing pressure wave generation, then one-dimensional software for wave transmission, then simple formulae for calculating MPW emission and transmission.

The methods are described in more detail below and in Section 8.5 relative to assessment method theory.

Accuracy of Measurements and Calculations

It is usually possible to make conservative assessments of the MPW amplitude that will be emitted from a given tunnel. Because of the conservatism, there will be a tendency to over-design mitigation potentially leading to unnecessary expense. The two main obstacles to more accurate (i.e., less conservative) assessments are:

- The tunnel entry phase requires investment in 3D analysis methods. This is especially important for short tunnels.
- In long tunnels, the wave propagation phase is subject to damping and dissipation effects that are difficult to predict. When the tunnel geometry is complex (not a constant prismatic shape), large uncertainties exist.

Simplified (Spreadsheet-Based) Assessment Method (from Vardy [180])

Vardy [180] has summarized an evaluation method that can be carried out using a calculator or spreadsheet for simple cases (plain tunnels without pressure relief shafts). The method is appropriate as an initial assessment to determine whether more detailed consideration is necessary. The assessment covers the four phases (pressure wave generation, wave steepening, MPW emission, and transmission) using theoretically-derived equations with some empirical constants. The equations shown below give approximations with further definition described in the original references. Note also that this simplified method estimates only the amplitude of the

MPW. Other properties such as the frequency content may influence the audibility and impact of the MPW but are not included in this assessment method.

The parameters and symbols used in the equations are given in Table 18.

Table 18. Symbols and variables for equations used in assessment method by Vardy

Symbol	Meaning	Units assumed in the equations	Conversion from English units
Δp	Amplitude of pressure wave caused by train nose entry	N/m^2 (= Pa)	$= 6900\Delta p_{psi}$
p_a	Atmospheric pressure	Pa	$= 6900 p_{a,psi}$
T_a	Ambient temperature in the tunnel	Degrees Celsius	$= 0.56(T_{a,Fahrenheit} - 32)$
ρ	Density of air	kg/m^3	$= 16.0\rho_{lb/ft}3$
c	Speed of sound in air	m/s	$= 0.447c_{mph}$
V_z	Speed of train	m/s	$= 0.447V_{z,\ mph}$
k_N	Nose loss coefficient (aerodynamic property of the train)	Dimensionless	same
A_z	Cross-sectional area of train	m^2	$=0.0929A_{z,sq\ ft.}$
A_T	Cross-sectional area of tunnel	m^2	$=0.0929A_{T,sq\ ft.}$
β	Blockage ratio = A_z/A_T	Dimensionless	same
D_T	Effective diameter of tunnel = $\sqrt{}(4A_T/\pi)$, where $\sqrt{}$ equals square root and effective diameter means the diameter of the circle that has the same area as the tunnel (even if the tunnel is non-circular).	m	$=0.305D_{T,feet}$
Δt_{wave}	Pressure wave rise time, explained in below	Seconds	same
L_E	Tunnel “entry length”, explained below	m	$=0.305L_{E,feet}$
Φ	Empirical coefficient for entry length	Dimensionless	same
dp/dt	Maximum temporal gradient of pressure wave	Pa/s	$=6900(dp/dt)_{psi/sec}$
η_H	Efficiency of entrance hood	Dimensionless	same
L_H	Length of tunnel entrance hood	m	$=0.305L_{H,feet}$
L_T	Length of tunnel	m	$=0.305L_{T,feet}$
Ω	Solid angle associated with MPW emission	Steradians	same
r	Distance of receptor from tunnel portal	m	$=0.305r_{,feet}$
p_{MPW}	Acoustic pressure of Micro-Pressure Wave	Pa	$=6900p_{MPW,psi}$

Units

The published formulae all assume consistent units. When using Imperial units, the following process is recommended:

- Convert input data to SI units using factors in the table above
- Apply the formulae in SI units
- Convert the output back to Imperial units.

Simplified Methodology for Assessing Wave Generation

For this step, the aim is to estimate the maximum gradient of the pressure wave near the tunnel entry. The salient properties of the nose entry wave are idealized as shown in Figure 57.

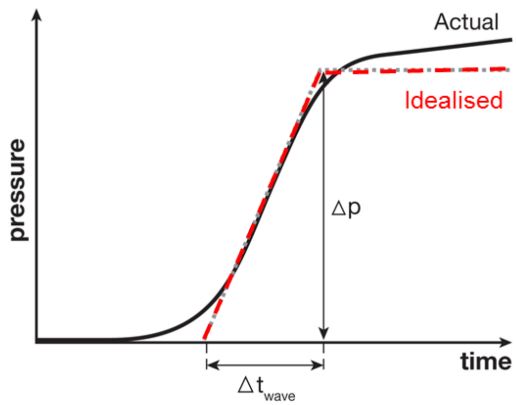


Figure 57. Nose entry wave, actual and idealized

Step 1: Calculate the expected pressure rise caused by the nose entering the tunnel, Δp:

$$\Delta p = \rho c \left\{ V_z + \frac{c}{\alpha}\left[1 - \sqrt{1 + \frac{2\alpha V_z}{c}}\right]\right\} \qquad \textbf{Equation 27}$$

where

$$\alpha = \frac{1 + k_N}{(1 - \beta)^2} - 1 \qquad \textbf{Equation 28}$$

The density ρ and speed of sound c may be calculated from the atmospheric pressure and temperature as follows (atmospheric pressure in Pa, temperature in degrees Celsius):

$$\rho = \frac{p_a}{287(T_a + 273)} \qquad \textbf{Equation 29}$$

$$c = \sqrt{1.4 \times 287 \times (T_a + 273)} \qquad \textbf{Equation 30}$$

Step 2: Calculate the "effective entry length" L_E, which may be thought of as the physical distance at the entrance to the tunnel over which the idealized pressure wave develops. As an initial estimate, the following formula may be used for a plain tunnel without an entrance hood:

$$L_E = \emptyset D_T \qquad \textbf{Equation 31}$$

For a flat-fronted train, ϕ is likely to lie in the range 0.75 to 1.5. For the elongated noses that are typical of high speed trains, the appropriate value of ϕ is likely to be greater than 1.0. Often, a suitable value of ϕ for a particular train/tunnel combination may be derived from the tabulated data provided by Vardy and Brown [232]. When this is not possible, values might need to be determined from scale model testing or from three-dimensional analysis methods such as CFD.

When assessing the potential influence of an entrance hood on MPWs, the effective train entry length becomes:

$$\boldsymbol{L_E = \eta_H L_H} \qquad \textbf{Equation 32}$$

where η_H = the efficiency of the hood, typically 0.5 to 0.8 for a well-designed hood, and L_H = the length of the hood.

Step 3: Calculate the effective rise-time of the pressure wave, Δt_{wave}:

$$\Delta \boldsymbol{t_{wave} = L_E \left(\frac{1}{V_Z} - \frac{1}{c}\right)} \qquad \textbf{Equation 33}$$

Step 4: The maximum pressure gradient near the tunnel entrance is given by:

$$\frac{\boldsymbol{dp_{entry}}}{\boldsymbol{dt}} = \frac{\Delta \boldsymbol{p}}{\Delta \boldsymbol{t_{wave}}} \qquad \textbf{Equation 34}$$

It should be recognized that wave formation during train nose entry is a three-dimensional process affected by parameters such as the shape of the tunnel and train nose. These complex behaviors cannot be assessed accurately using such simple methods, therefore the formulae above represent a rough guide only.

Simplified Method for Assessing Wave Propagation (Steepening or Shortening)

It is helpful to think of the steepening of the pressure wave as a reduction of its spatial length while its pressure amplitude remains unchanged. In other words, the wave shortens as it moves down the tunnel. This occurs primarily because the front of the wave is travelling through stationary air, while the rear of the wave is travelling within air moving down the tunnel with velocity $\Delta p/\rho c$. In addition, the speed of sound in the compressed air at the rear of the wave is larger. Therefore, the rear of the wave catches up with the front. This process of shortening of the wave is known as "inertial steepening", and may be estimated as follows (reference parameters and symbols, Table 18, for definition of variables).

$$\Delta \boldsymbol{t_{steepening}} = \frac{\boldsymbol{1.2\Delta p L_T}}{\boldsymbol{\rho c^3}} \qquad \textbf{Equation 35}$$

If the above formula indicates shortening by more than the initial length of the wave, i.e., $\Delta t_{steepening} > \Delta t_{wave}$, then a shock is predicted within the tunnel and the MPW is very likely to be unacceptable. If not, then continue to calculate the pressure gradient at the tunnel exit:

$$\frac{\boldsymbol{dp_{exit}}}{\boldsymbol{dt}} = \frac{\Delta \boldsymbol{p}}{\Delta \boldsymbol{t_{wave}} - \Delta \boldsymbol{t_{steepening}}} \qquad \textbf{Equation 36}$$

Counteracting the inertial steepening process, friction may reduce the rate of shortening. Friction is sometimes described as having "steady" and "unsteady" components. The former is a shear stress proportional to the air velocity, while the latter represents shear stresses that depend on the rate of change of air velocity. The "unsteady" component in particular is difficult to quantify without experimental data and varies with tunnel construction details, but it is likely to be very small. As a conservative first assumption, *all* friction effects may be ignored (i.e., steady as well as unsteady).

Ballast is known to counteract (and, in long tunnels, to overcome and even reverse) the inertial steepening process, but no simple assessment methods were found to allow for it. In principle, the ballast effect can be ignored for short tunnels because there is insufficient time for it to have a significant influence. It should be noted that there is little guidance available as to the definition of "short" in this context. It is likely that the influence of ballast depends primarily on the steepness of the wavefront. If so, the "shortness" of a tunnel will depend upon the train speed and the tunnel entrance configuration. As a rough guide, it may be inferred from early measurements on the Shinkansen in Japan that ballast does not have a decisive influence in tunnels up to about 1 mile (1 – 2 km) long even when the portals are unmodified. F*urther research assessment into this area will be helpful.*

Simplified Method for Assessing MPW Emission and Transmission

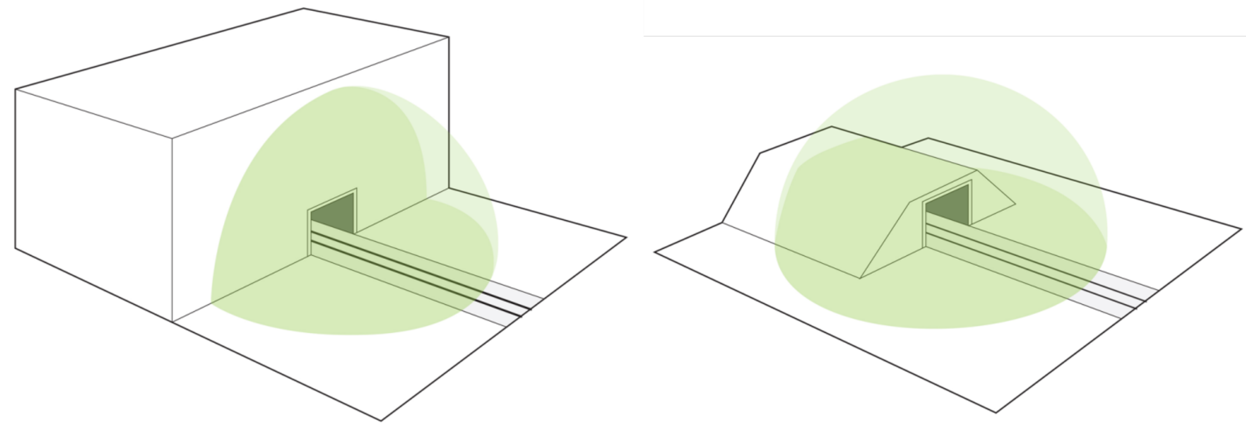
The amplitude of the MPW is estimated from a solution for the acoustic pressure (p_{mpw}) caused by a vibrating piston in an infinite baffle, valid for the far field (more than one tunnel diameter outside the portal plane of the entrance) and low frequency range (less than 20 Hz):

$$p_{MPW} = \frac{2A_T}{\Omega rc}\frac{dp_{exit}}{dt} \qquad \textbf{Equation 37}$$

(reference the parameters and symbols, Table 18, for definition of variables).

The formula includes transmission to a distance r from the portal and it assumes that the "solid angle" Ω is uniform throughout the flow field.

The solid angle may be regarded as an empirical factor describing the local topography. Theoretical values for simple geometries range from π (for the quarter-sphere between a flat ground plane and large vertical cliff face, see Figure 58(a)) to 2π (for a featureless flat ground plane, see Figure 58(b)), but experimental measurements of MPWs suggest that the values vary widely according to measurement position even at the same tunnel portal. In the absence of better information, values in steradians around 3 to 4 may be used, with smaller values being more conservative and resulting in larger predicted MPW amplitudes. In the case of tracks emerging from a tunnel into a semi-confined space such as a cut, the solid angle may be as low as 1 to 2 steradians.



(a) Tunnel exit is in a vertical cliff. Quarter-sphere available for MPW emission (solid angle = π)

(b) Tunnel exit is in flat topography. Half-sphere available for MPW emission (solid angle ≈ 2π)

Figure 58. Spherical influence of solid angle for vertical cliff face and flat topography

Refinements to this formula are available for more detailed assessments, and are given in Section 8.5.

Assessing the Acceptability of Calculation Results

MPW acceptability criteria are discussed below. The simpler criteria are in the form of a certain amplitude and distance combination, for example, 0.003 psi at 66 ft (20 Pa at 20 m) from the tunnel. To assess acceptability one can compare the calculated p_{MPW} with the limit using the appropriate distance for 'r'. If no criterion is provided, then 0.003 psi at 66 ft might be used as a conservative guide. If the predicted MPW amplitude is less than 0.003 psi at a distance of 66 ft from the tunnel, it is unlikely that mitigation measures will be required. However, this criterion may be over-conservative in many cases.

The impact of MPWs depends on their frequency content and other factors as well as their amplitude. The simple assessment methods consider only amplitude. This is sufficient for a conservative check to determine the need for further work, but does not enable the actual full impact of MPWs to be estimated.

In addition, the simplified assessment methods cannot be used with the more sophisticated noise-based acceptability criteria described in Section 8.5.

Assessing MPWs from Sources Other Than "Classic" Nose Entry Wave MPWs

No published assessment methods were found for MPWs arising directly from train entry and exit at the portals, nor for MPWs arising from a train passing a pressure relief shaft within a tunnel. Such MPWs typically have lower amplitudes than "classic" MPWs and are not on record as having caused any adverse impacts. However, when considering speeds up to 250 mph, the potential impacts of MPWs from these other sources should be considered, and *development of an assessment method is therefore recommended.*

Examples – Not to be Used for Design

An example of calculation of the MPW amplitude by the simple assessment method is shown in Figure 59.

Input Quantity	Input data (imperial units) Value	Units	Derived data in SI units Value	Units
Train speed	150	mph	67.1	m/s
Train cross-sectional area	120	ft^2	11.1	m^2
Train nose loss factor	0.05	none	0.05	none
Tunnel length	10000	ft	3048	m
Tunnel cross-sectional area	720	ft^2	66.9	m^2
Entrance ϕ factor	1.2	none	1.2	none
Ambient pressure	14.7	psi	101357	Pa
Ambient temperature	55	deg-F	12.8	deg-C
Entrance hood length	0	ft	0	m
Hood efficiency	0.7	none	0.7	none
Tunnel exit solid angle	4	steradians	4	steradians
Distance at which MPW is measured	66	ft	20.1	m
Derived input data:	**Value**	**units**	**Equation**	
Air density	1.24	kg/m^3	29	
Air sound speed	339	m/s	30	
Blockage ratio	0.167			
Effective tunnel diameter	9.23	m/s		
Calculation:	**Value**	**units**	**Equation**	
α	0.512		28	
Δp	1294	Pa	27	
L_E	11.1	m	31 or 32	
Δt_{wave}	0.132	sec	33	
dp_{entry}/dt	9769	Pa/s	34	
$\Delta t_{steepening}$	0.0984	sec	35	
dp_{exit}/dt	38021	Pa/s	36	
p_{MPW}	187	Pa	37	
Convert result to psi:				
$p_{MPW,psi}$	**0.0271**	**psi**		

Figure 59. Example of simple MPW assessment

Examples Figure 60 shows graphical examples of the influence of tunnel length and train speed on the MPW amplitude at 66 ft. (20 m) from the tunnel (calculated by the simple assessment method). Two tunnel cross-sectional areas are considered: 720 ft^2 (67 m^2) as per the above example (solid lines) and 900 ft^2 (84 m^2) (dashed lines). In both cases the train cross-sectional area is 120 ft^2 (11 m^2), giving blockage ratios of 0.17 and 0.13, respectively. All other input data and assumptions are the same as in the example above. No entrance hood or other MPW mitigation measures are included. Note that in all cases the predicted MPW amplitude exceeds the commonly-assumed "Japanese MPW criterion" of 0.003 psi at 66 ft. (20 Pa at 20 m), but this does not necessarily mean that the MPW would have unacceptable impacts.

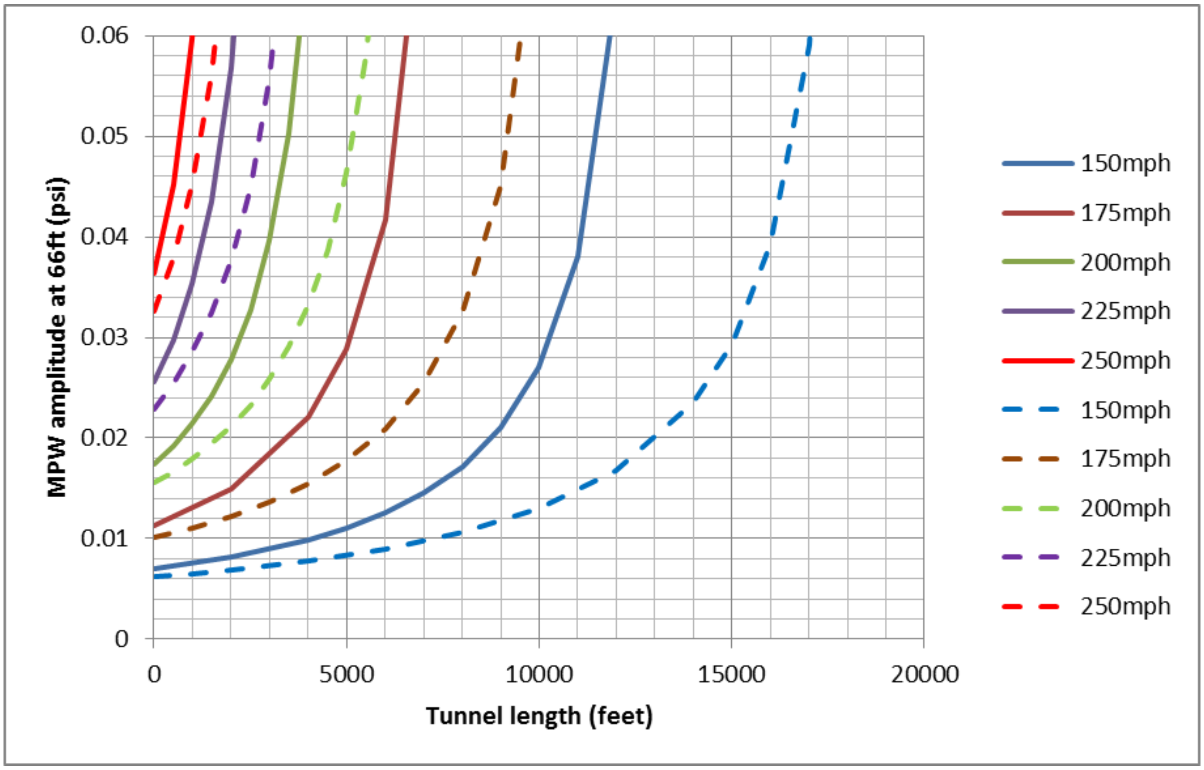


Figure 60. MPW amplitude at 66 ft from exit portal of tunnel without entrance hood; solid lines: 720 ft^2 tunnel; dashed lines: 900 ft^2 tunnel

Figure 61 shows examples of the influence of entrance hood length on MPW amplitude for a particular train-tunnel combination of 20,000 ft (7 km) long tunnel with 900 ft^2 (84 m^2) cross-sectional area and train cross-sectional area 120 ft^2 (11 m^2). It is assumed that the hood design is 70% efficient. Other input data and assumptions are the same as in the example above.

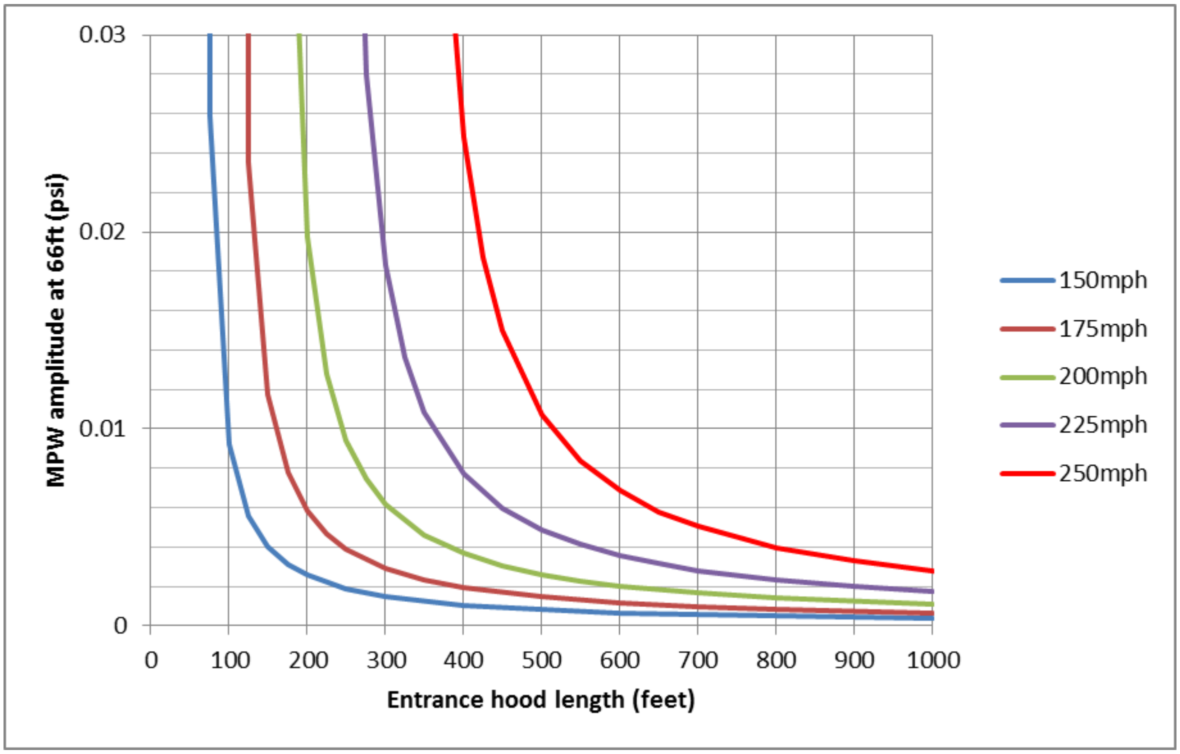


Figure 61. MPW amplitude at 66 ft., effect of entrance hood length (20,000 ft long tunnel; 900 ft^2 tunnel area, 70% hood efficiency)

These example data can be re-arranged to indicate the required entrance hood length to achieve a given MPW amplitude criterion. As with all the examples in this section, the data should not be used for design as they are intended only to show the type of information that could be developed during initial design. Here, two possible criteria are illustrated: 0.003 psi at 66 ft, and 0.0073 psi at 66 ft. (Figure 62). Both criteria are mentioned in the literature, but it should not be inferred that either of these criteria is suitable for general application in the United States. The graphs are given here only as examples of how the simple assessment calculations can be used.

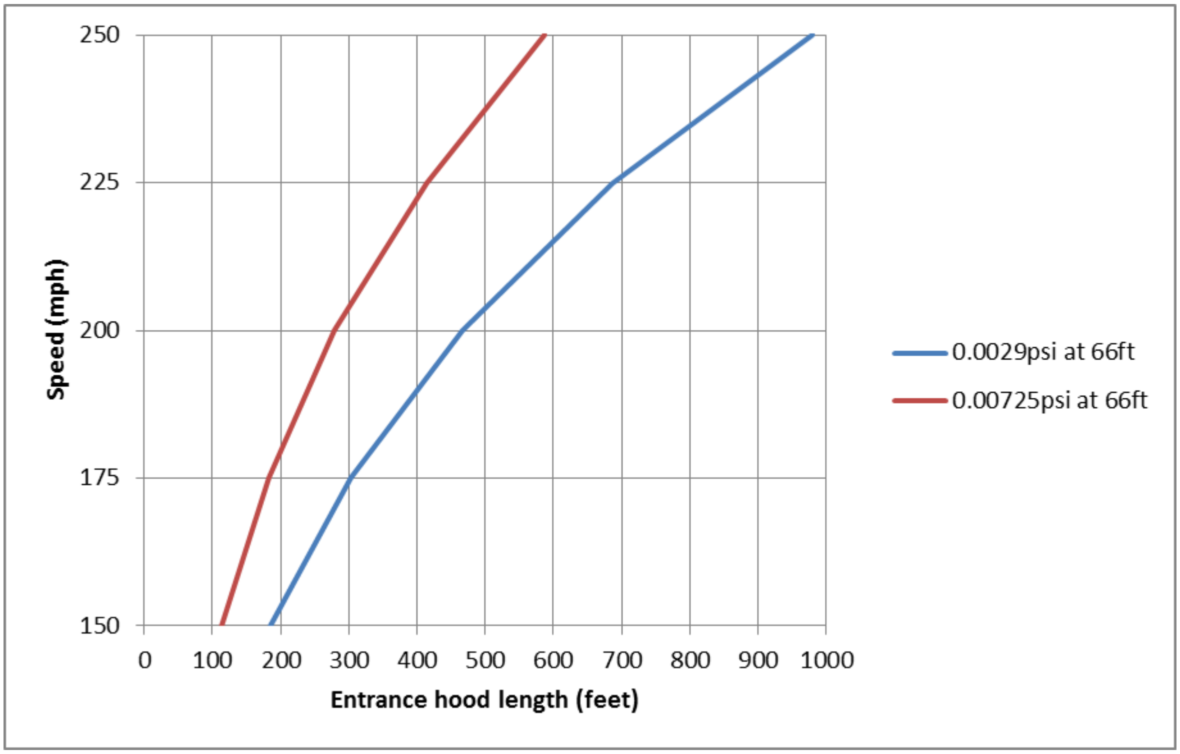


Figure 62. Entrance hood length required to meet certain MPW amplitude criteria for an example tunnel and train combination

8.3 Impacts and Mitigation

8.3.1 Impacts

Micro-pressure waves have impacts as follows:

- People near a tunnel exit may hear an unpleasant or frightening noise, such as a loud bang or a low booming noise. The impacts on people are similar to other noise impacts.
- Doors and windows or other parts of buildings near the tunnel exit may rattle or vibrate, causing annoyance to residents.
- No records were found in the literature of structural damage to buildings due to MPWs.
- Similar impacts may occur near the portals of pressure relief shafts.
- If pressure waves with high gradients are present within the tunnel, when these pass over trains within the tunnel, passengers and crew may be subjected to unpleasant noises [233].

8.3.2 Mitigation Methods

Tunnel Entrance Hoods

The most commonly adopted mitigation measure is to fit the tunnel with an entrance hood designed to reduce the gradient of the pressure wave generated when the train enters the tunnel. Typical hoods in use today (for tunnels with train entry speeds up to about 185 mph, or 300 km/h) are between 60 and 250 ft (18 to 75 m) long, and have a uniform cross-sectional area between 1.3 and 1.5 times the cross-sectional area of the main tunnel. The required length of hood for a given tunnel increases strongly with train speed, assuming that the acceptability criterion and all other conditions remain the same.

Alternatively, but less common in practice, hoods may be funnel-shaped, with the cross-sectional area being larger at the entry portal, tapering down towards the main tunnel. For such hoods, it can be advantageous for the taper to lead to a smooth match with the cross-sectional area of the main tunnel. In both cases the hoods will usually have holes or slots in either the roof or walls or both, enabling air to escape during the initial build-up of pressure.

The efficacy of hoods in eliminating audible MPWs is well-established. For example, Ozawa and Maeda et al [178, 226] report the case of Ohirayama tunnel that was emitting an unacceptable audible MPW of amplitude 0.044 psi (300 Pa) at 66 ft (20 m) from the portal for 155 mph (250 km/h) train entry speed. After fitting the tunnel with a 160 ft (50 m) long entrance hood, the MPW was no longer audible and the amplitude reduced to about 0.003 psi (20 Pa) at 66 ft (20 m) – see Figure 56.

Hoods are constructed of concrete or steel. A Japanese steel hood is shown in Figure 63.

Figure 63. Japanese tunnel entrance hood (steel) – retro-fitted to Ohirayama tunnel, from Maeda et al [226]
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Hieke et al [234] describe 164 ft (50 m) long hoods at the new Katzenberg tunnel with a line speed of 155 mph (250 km/h). The hoods have slot-shaped holes and are covered with soil and grass, leaving only the rims of the holes protruding (Figure 64). The design of the hoods and optimum size of holes were established using CFD analysis. An interesting feature of these hoods is that the holes through which air exits from the tunnel were intentionally built larger than the expected optimum size, and covered by sliding plates so that final optimization of the hole size could be achieved by full-scale testing on the finished tunnel.

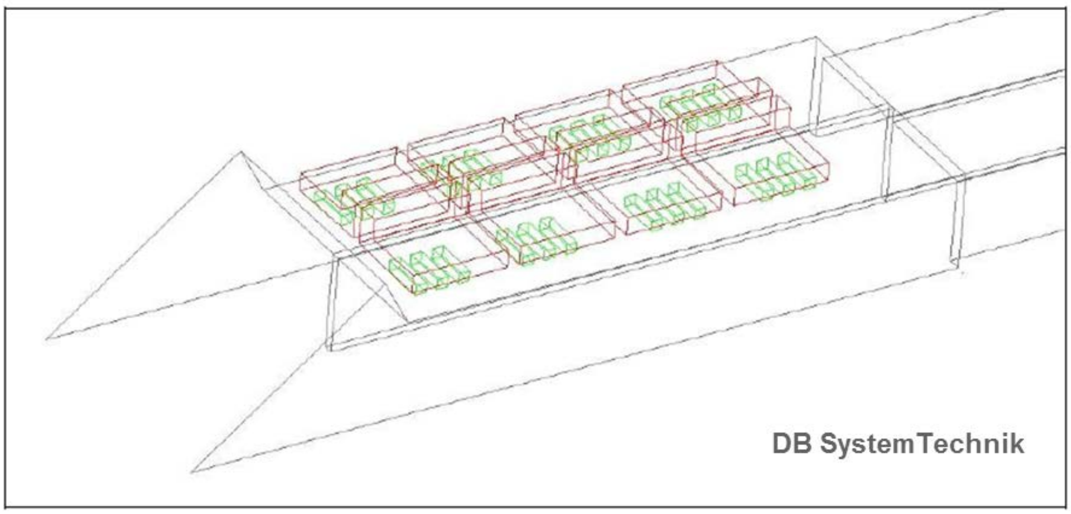

Figure 64. Katzenberg tunnel entrance hood, from Hieke et al [234]
Photo reproduced with permission of DB Projektbau; schematic drawing with permission of DB SystemTechnik

The distribution and size of holes can be chosen using aerodynamic analysis or scale model testing to obtain the greatest reduction of pressure gradient. Rety and Gregoire [235] analyzed seven different combinations of hole size and hole distribution for a 66 ft (20 m) long hood and 170 mph (275 km/h) train speed, obtaining pressure gradient reductions from 38% to 58%. Figure 65 shows schematic examples of pressure gradient time-histories generated by optimal and non-optimal designs.

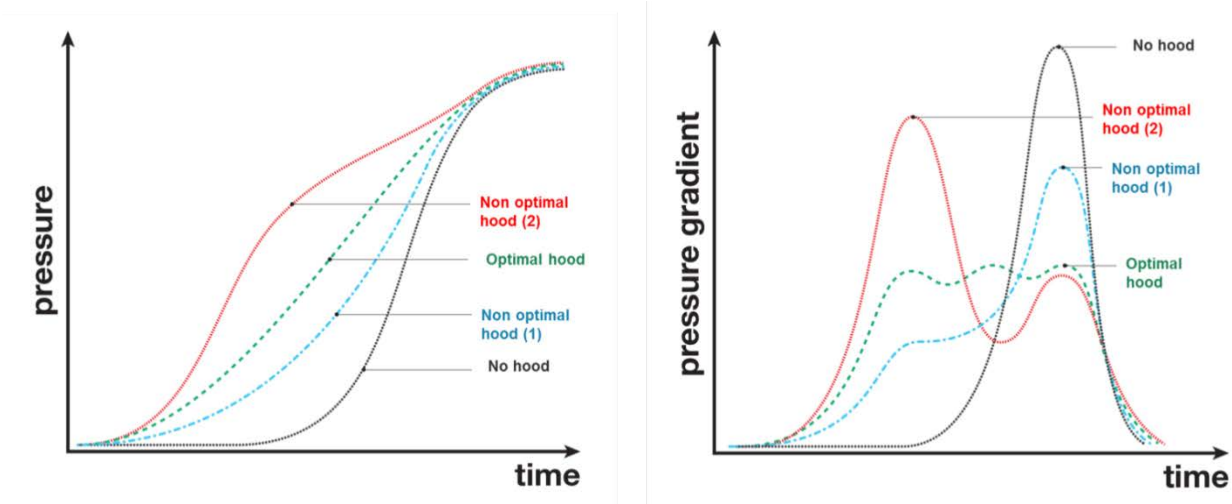

Figure 65. Pressure and pressure gradient waveforms with optimal and non-optimal hoods – general form of graphs – after Rety and Gregoire [235]

Hoods have been added to existing tunnels in Japan as a retro-fit mitigation measure, to allow an increase of train speed. Sakurai et al [236] report a lightweight steel construction that can be erected quickly and economically. Fatigue loading from the pressures generated by trains was considered in the design of these steel hoods.

Tunnel Portal Shape

A small reduction of pressure wave gradient may be obtained by sloping the entrance portal. This type of entrance is sometimes referred to as a scarfed portal or as a "penne pasta" portal shape, and is shown in Figure 66. The portal plane is inclined at 45 to 60 degrees to the vertical. Rety and Gregoire [235] quote a 17 % reduction of pressure wave gradient owing to the portal shape compared to a vertical portal plane for a blockage ratio of 0.16 and speed of 170 mph (275 km/h). Similar reductions are reported by other authors. Such small reductions of pressure gradient are unlikely to suffice as the sole mitigation measure for unacceptable MPWs, but might form part of a package of mitigation measures. Also, such portals can have visual advantages.

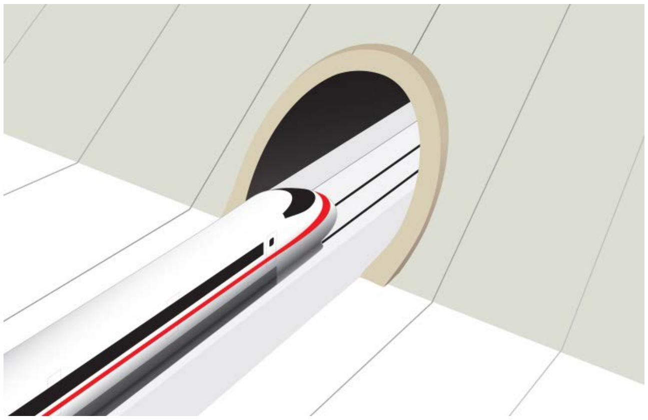

Figure 66. Sloping portal shape

Train Nose Design

The duration of the nose-entry period can alternatively (or additionally) be increased thus reducing the pressure gradient using a long tapering nose region on the train. Some Japanese Shinkhansen trains (see Figure 67) have tapering noses over 40 ft (12 m) long. The purpose of these is in part to allow trains to run at higher speeds without modifying the existing tunnels and without causing unacceptable MPWs. Some of the research behind this, including the search for optimal nose shapes, is described by Kurita et al [237]. Proposed nose designs were assessed by scale model testing and CFD.

Figure 67. Nose of Shinkhansen E5

Assessment methods are similar to those for tunnel entrance hoods. The nose entry pressure wave (including its maximum gradient) may be estimated for a particular train/tunnel combination by scale-model testing, from Howe's closed form solutions, or by CFD analysis.

Train Cross-Sectional Area

If reducing the train area is under consideration for economic or other reasons, the reduction also benefits MPW performance because the pressure in the tunnel is reduced, thus reducing both the initial pressure gradient and the rate at which the pressure wave steepens. For example, a 10% reduction of train cross-sectional area could reduce MPW amplitude by around 15% or more depending on the length of the tunnel.

Closed Side Branches

Closed side branches are short blind tunnels perpendicular to the main tunnel (shown schematically in Figure 68). These help to reduce the gradient of the pressure wave as it propagates along the tunnel because some of the pressurized air at the front of the wave passes into the side branches, thus delaying the build-up of pressure downstream.

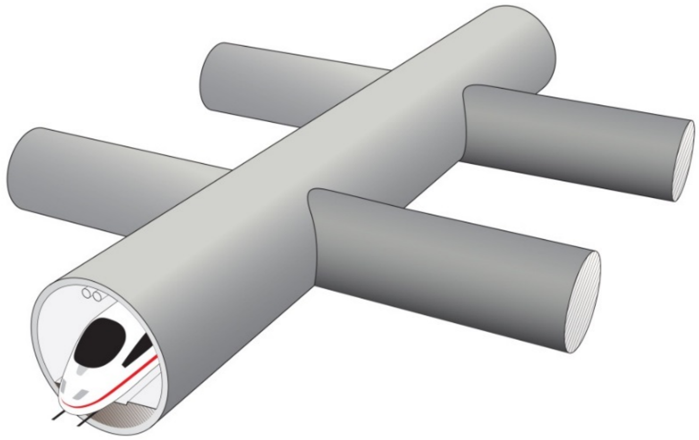

Figure 68. Schematic sketch showing closed side passages

Fukuda et al [191] describe a 16 mi (26 km) long Shinkhansen slab-track tunnel in which side passages are used to give an effect similar to ballast by reducing the steepness of the wave during transmission down the tunnel. The tunnel has a total of 83 side passages and five long inclined shafts, with the maximum spacing between passages being about 0.3 mi (0.5 km). In Figure 69, the pressure gradient exhibits a saw-tooth profile, falling abruptly when the pressure wave reaches a side branch or an inclined shaft, then rising again until the next branch or shaft.

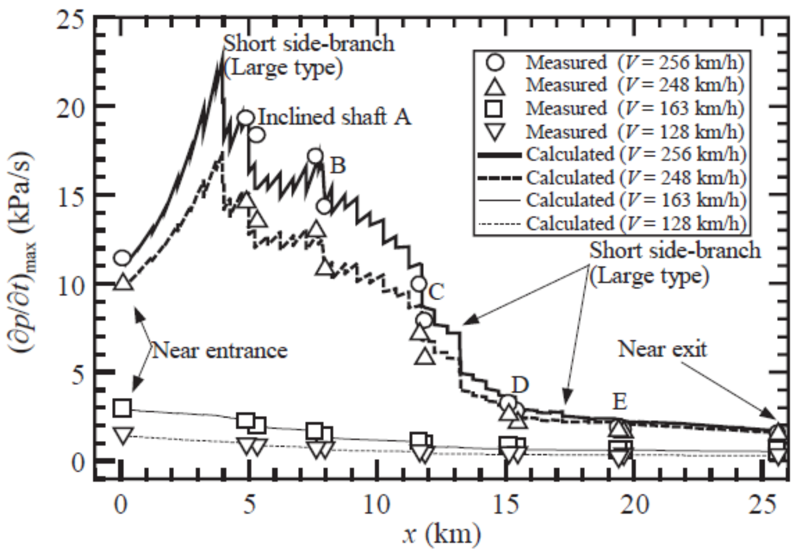

Figure 69. Pressure gradient reduction in slab track tunnel with side passages and inclined shafts - from Fukuda et al [191]

Reproduced by permission of RTRI

For side branches no design guidance or assessment methods were found in the literature.

Air Shafts

Air shafts can attenuate pressure waves and thereby reduce their gradient. Shafts can therefore be an effective mitigation measure for the “classic” MPWs caused by the initial entry of the nose of the train into the tunnel. However, shafts can themselves cause unacceptable MPWs, if not properly designed.

Tunnel Cross-Passages

For twin-bore tunnels, it may be possible to use cross-passages or additional ducts between the bores (shown schematically in Figure 70) to mitigate MPWs. Although the doors leading from the tunnel to the cross-passages would normally be closed, holes could be provided to allow a controlled flow of air from one bore to the other.

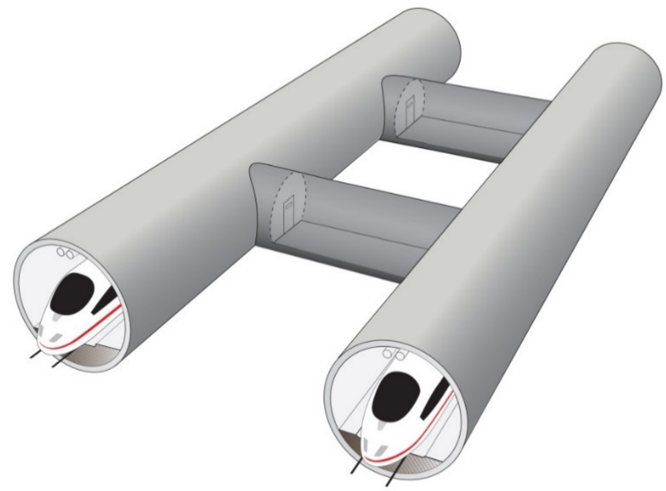

Figure 70. Schematic sketch showing cross passages

Such measures are mentioned as a possibility in the literature [238]. *No design guidance or assessment methods were found.* Research would be needed to establish whether this method has the potential to form a mitigation measure for MPWs in practice. It would also be necessary to consider the presence of a train in the other bore. This adds considerable complexity to the calculations, due to the need to consider a range of starting positions of the second train relative to the first. There may be combinations of train arrival times for which the results with the mitigation measure become worse than the results without mitigation, and this would need to be determined by analysis.

Acoustic Absorbers

The Euerwang tunnel in Germany suffered sonic booms, and was retro-fitted with acoustical track absorbers [239]. The absorbers are a commercial product designed to reduce vibration from trains, but also have the effect of attenuating the wave steepening within the tunnel. The absorbers consist of plates of expanded clay six inches (15 cm) thick, glued to the slab. The total cross-sectional area of the plates (width x thickness) for the twin-track tunnel is 6 ft^2 (0.6 m^2). The properties quoted are: porosity 25%, density 5,000 lb/ft^3 (1,027 kg/m^3), and a flow resistance of 0.13 psi/sec-ft^2 (9,540 Pa/(sec-m^2)).

The MPW emitted by the tunnel was measured before fitting the absorbers at a position 213 ft (65 m) from the portal and 52 ft (16 m) from the track (the nearest public access). A pre-installation sound exposure level of 113 dB(C) was recorded (corrected for impulsive noise effect). After installation, the sound exposure level fell to 102 dB(C), which is comparable to train pass-by noise of 108 dB(C) at the same location.

Nakao et al [240] report scale model experiments with porous resin occupying 7-21% of the tunnel cross-sectional area (resin blocks placed on the floor and later on the wall), or perforated steel plates separating 13-24% of the tunnel area. The porous material at 7% of tunnel cross-sectional area prevented wave steepening and gave an effect similar to that measured at full-scale in a ballast-track tunnel. With around 20% of the cross-sectional area occupied by the porous material, the pressure wave gradient reduced by a factor of 10-20 in a tunnel of length 600 times the diameter. The steel plate models were generally less effective at reducing the pressure gradient than the resin models. Depending on the initial pressure gradient, the plates were not always capable of preventing the pressure gradient from increasing.

Ballast

The beneficial effect of ballast, especially in long tunnels, has been well documented. Selecting a ballast-track system is therefore a mitigation measure for MPWs in long tunnels. Even if the tunnel employs a slab-track system, it may be possible to place some ballast within the tunnel. However, *there is no reliable method available to calculate the amount of ballast required.* Furthermore, the free cross-sectional area of the tunnel will be reduced by the presence of the ballast, slightly reducing that benefit and possibly leading to marginally poorer pressure comfort performance.

Ballast-Effect Air Spaces

In long slab-track tunnels, it may be possible to replicate the effect of ballast by providing air chambers connected to the main tunnel air space via small holes. One aspect of this mitigation strategy is explored theoretically by Sugitomo [241]. Potentially, this mitigation method could be more economical and less intrusive than long entrance hoods. The air-spaces could be provided within the existing tunnel cross-section, for example, in the space under walkways or within the trackbed. *Research could validate this mitigation method and develop design guidance*

Speed Restrictions

A very effective method of reducing MPWs is to reduce the speed of entry of the train into the tunnel. The speed could increase once the train is inside the tunnel. This mitigation measure has the obvious advantage of having no incremental construction cost, but the disadvantage of an impact on journey time.

Other Mitigation Measures

Ozawa et al [178] mention the use of water sprays in side branches of tunnels, and an active control method in which the MPW is partially cancelled by “anti-sound” played through a loudspeaker. Reduced scale model trials of this system were apparently successful. Advantages of active methods of attenuation include low cost, on-going adaptability, and suitability for retro-fitting. Disadvantages include the consequential need for on-going maintenance and the potential for performance issues if any of the mechanical or electrical systems fail.

8.4 Standards

8.4.1 Japanese MPW Acceptability Criterion

Japan was the first country to experience MPW problems and develop mitigation measures. However, a confirmation of Japanese MPW acceptability criterion for design of new tunnels was not found in the literature search.

The criterion seems to be based on a limit of 0.003 psi (20 Pa) on the amplitude of the MPW, but reports differ as to the distance from the tunnel at which this should be measured. The distance is a critical aspect of the acceptability criterion because the MPW amplitude reduces in approximate proportion to the inverse of the distance from the tunnel.

Many authors assume that the Japanese acceptability criterion is <u>0.003 psi (20 Pa) at 66 ft (20 m)</u> from the center of the portal. Most Japanese field measurements of MPW reported in the literature are taken at 66 ft (20 m) from the portal. The empirical experience was that, when the MPW amplitude was reduced by mitigation measures to 0.003 psi at 66 ft, the adverse impacts disappeared [178]. But no published data were found suggesting that lesser mitigation measures would not have worked also.

Pesava and Sockel [242] report that the limit in Japan is <u>0.003 psi (20 Pa) at 164 ft (50 m)</u> (or equivalently, <u>0.0073 psi (50 Pa) at 66 ft (20 m)</u>) from the portal.

Johnson [243] suggests that MPWs become audible only when their amplitudes are higher than about <u>0.006 psi (40 Pa) at 66 ft (20 m)</u> from the tunnel portal.

Hieke et al [189] report that the Japanese have found a limiting value of <u>0.003 psi (20 Pa) at the closest building</u> to be sufficient to avoid rattling of windows and doors.

Until recently the "Japanese" MPW amplitude-based criterion was the only available guidance on MPW acceptability. It has the advantage of being simple to apply when assessing a potential tunnel design, but has several limitations including being overly conservative and not distinguishing between signals of different frequencies. These limitations are discussed more fully in the following two paragraphs.

There are many tunnels on existing high speed railways where the MPW amplitude is greater than 0.003 psi at 66 ft (20 Pa at 20 m), but where this does not cause any perceived impacts or problems. Therefore it would be overly conservative to use 0.003 psi at 66 ft. as a design criterion for all new tunnels, and would result in money being spent unnecessarily on mitigation measures. The choice of an appropriate distance at which the 0.003 psi limit should be applied as a design criterion requires knowledge of the impacts of MPWs of different amplitudes. *Such knowledge is lacking* based on the literature search.

A criterion based on MPW amplitude does not distinguish between signals of different frequencies. A 0.003 psi (20 Pa) sound pressure at 1000 Hz would have a Sound Peak Level (SPL) of 120 dB (a very loud noise) while 0.003 psi at 1 Hz would be inaudible. The impacts of MPWs on humans and on buildings vary with frequency. Empirical evidence in Japan suggests that meeting the 0.003 psi criterion tends to ensure that the MPW does not cause adverse impacts. Therefore, the higher-frequency components of the MPW are assumed to be sufficiently suppressed, but the criterion itself does not guarantee that. *The criterion is not based on a rational analysis of how the impacts are caused.*

8.4.2 Korean Acceptability Criteria

While it might be necessary to apply strict MPW criteria for tunnel portals in residential or other sensitive areas, to apply the same criteria to all tunnels would in many cases be overly conservative and result in unnecessary expense. In Korea, the 0.003 psi (20 Pa) limit is applied at the distance of the "nearest observer", which could be interpreted as a building or highway or other point of public access. This results in MPW acceptability criteria being different for each tunnel. Higher MPW amplitudes could be tolerated from a tunnel portal that is several miles away from any buildings, highways, or towns, compared to a tunnel portal in a residential area. Even in these cases some upper limit may be required to avoid adverse effects on people walking nearby and wildlife. Stricter criteria are sometimes used for MPWs affecting residential buildings compared with MPWs affecting places where people may be walking in open air, for whom the adverse impacts of noises are less severe.

8.4.3 Deutsche Bahn Noise-based MPW Acceptability Criteria

Many of the limitations are addressed in MPW acceptability criteria recently adopted by Deutsche Bahn and described by Hieke et al [234, 244]. The requirements are:

- At the nearest dwelling (or other sensitive building such as a school or hospital), the C-weighted Sound Exposure Level should not exceed 70 dB(C). Higher limits apply to garden plots (85 dB(C)) and industrial areas (95 dB (C)).
- At 82 ft (25 m) from the tunnel portal, the C-weighted SPL should not exceed 115 dB(C).
- Independent of the acoustic assessment of MPWs, the A-weighted Sound Exposure Level (SEL) must be in accordance with German traffic noise regulations.

To check for conformance to these criteria, the MPW is measured with a suitable sound meter. The C-weighted Sound Exposure Level (SEL) and Sound Peak Levels (SPL) are checked at the relevant positions. When assessing the MPWs using analysis, the MPW pressure time-history is passed through a C-weighting filter. Then the SPL and SEL are calculated according to the equations in ISO 3095:2001 [245].

The rationale behind these limits is as follows:

- The C-weighting filter has been chosen in place of the A-weighting more usually associated with noise assessments. While A-weighting reflects the typical human perception of the loudness of sounds of different frequencies, C-weighting is more often used to assess impulsive and low-frequency sounds and hence is more appropriate for MPWs. The frequency response of A and C weighting functions are shown in Figure 71.
- The 115 dB(C) limit is intended to protect people near the portal from dangerous sound levels. For comparison, the lower exposure action value in the European directive 2003/10/EC [246] is 135 dB(C). It is unlikely that 135 dB(C) will be exceeded even very close to the portal, provided that the 115 dB limit at 82 ft (25 m) is satisfied.
- The 70 dB(C) Sound Exposure Level was chosen to be well below the 80 dB(C) upper limit for single sound incidents in residential areas at night according to German gun noise management directive [247]. Experience has shown that MPWs with SEL below 73 dB(C) are hardly audible.

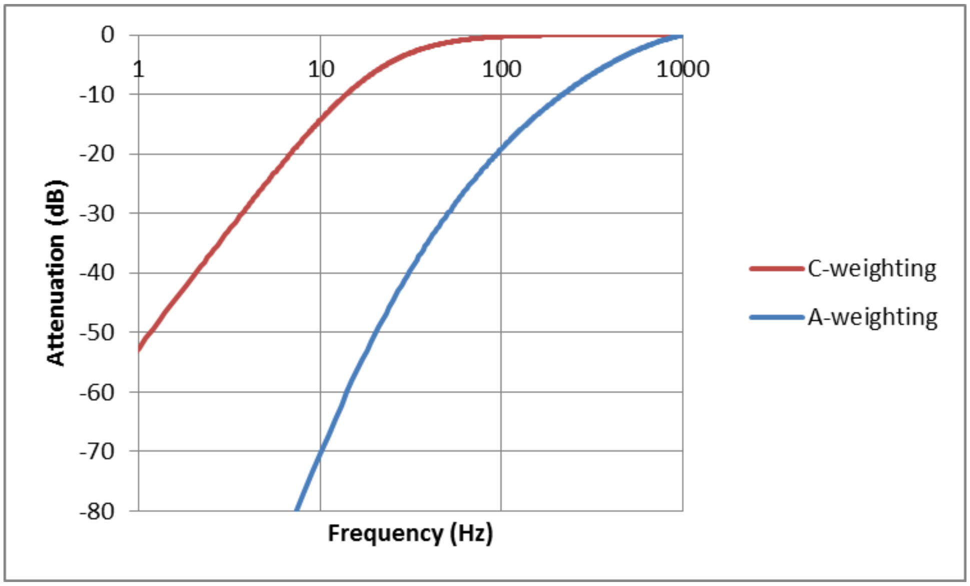

Figure 71. A- and C-weighting functions

These limits form a rational basis for assessing the direct impact of MPWs on human hearing. *It is not known whether these limits can also be expected to deal adequately with the potential impacts of rattling doors and windows. Further research is necessary to confirm them.*

Note that receptors near the tunnel portal will also hear noise from the train when it passes by. The 70 dB(C) SEL limit at the nearest receptor is much lower than the likely pass-by noise from the train. It is not usual to apply C-weighting to train pass-by noise, but if this were done, the SEL for train pass-by would likely be at least 95 dB(C) for a receptor 330 ft (100 m) from the track and a high speed train passing at 185 mph (300 km/h). It may seem counter-intuitive that more stringent criteria are applied to one noise phenomenon (MPWs) than to another (train pass-by). However, this may allow for the fact that MPWs can take observers by surprise, being emitted suddenly from the tunnel some time before the train itself can be heard.

Full-scale measurements to test compliance with the Deutsche Bahn criteria are easily achieved using a sound meter. The criteria are much more difficult to apply during predictive assessments. Both the amplitude and frequency content of MPW must be predicted. This is difficult for short tunnels, and even with a 3D analysis, high accuracy cannot be expected. For long tunnels, the uncertainties around wave propagation make accurate prediction even more difficult.

There is a lack of published methods for assessing MPWs during the design of tunnels that can predict the frequency content. More research is needed in this area to determine whether it might be possible to develop such methods.

8.4.4 MPW Acceptability Criteria: European Technical Specifications for Interoperability (TSI)

There are no clauses related to MPWs in the current versions of the European TSIs but it is thought that future versions of the Infrastructure TSI may set limits on the pressure gradient inside the tunnel (an indirect method of limiting MPW amplitude).

8.5 Data from Literature

8.5.1 Measurement and Assessment Methods

Detailed Assessment Methods for the Pressure Wave Generation Phase

The available assessment methods for predicting the maximum pressure gradient (or full time-history of pressure gradient) at the tunnel entry are as follows.

- Howe et al [229, 230] have published closed-form analytical methods of predicting the pressure-time history when a train enters a tunnel, including the effect of entrance hoods. Although based on complex mathematics that may be inaccessible to many engineers, the analysis can potentially be executed by a computer very rapidly to generate the full pressure wave time-history. Vardy and Howe [227] demonstrate that the solution method can give results that match scale model experiments even for relatively complex tunnel entrance hood designs.
- Vardy and Brown [232] have used the methods of Howe to tabulate results enabling the gradient of the pressure wave to be calculated, for the case of a simple portal without a hood, but allowing for the influence of the length and shape of the train's tapered nose region.
- Unsteady CFD analysis may be used to predict the nose-entry pressure wave. For example, Hieke et al [189] used the commercial CFD software ANSYS-CFX to simulate pressure wave generation. The tunnel, portals, and surrounding environment were modeled with a stationary sub-domain, while the air around the train was represented in a moving sub-domain. The sub-domains were connected via fixed domain interfaces.
- Scale model testing using a moving model of the train is described under "Assessment using scale model tests" in Section 8.5.1.

Pressure wave generation is a strongly three dimensional phenomenon, and cannot be analyzed accurately using one-dimensional methods alone. However, if one of the above methods can be used to provide a base case against which the one-dimensional analysis can be calibrated, it may be possible to use the one-dimensional analysis to predict results for other similar situations. For example, Vardy and Howe [227] show how the one-dimensional method may be adapted to obtain similar results to the three-dimensional calculation, and indicate some of the limitations experienced in attempting to predict results for more complex tunnel entrance designs with one-dimensional methods.

Detailed Assessment Methods for Analysis of the Wave Propagation Phase

Wave propagation is essentially a one-dimensional phenomenon, and is generally analyzed using one-dimensional methods:

- For a conservative estimate of the maximum pressure gradient at the tunnel exit, ignoring any effects of friction or ballast, the simplified spreadsheet-based formulae are sufficient.
- When the full pressure gradient time-history is required, or to take account of simple "steady" friction where this can be estimated, a well-validated one-dimensional software package may be used (as described by Vardy [180]). Care should be taken that empirical parameters such as the numerical mesh have no significant influence on the results.

- Some one-dimensional software packages have the capability to predict the effects of "unsteady" friction, which can slightly attenuate wave shortening even in slab-track tunnels. They may also be able to approximate the effects of ballast to some degree, but the relevant input parameters must be validated against measurements of pressure wave transmission in full-scale tunnels [231]. The parameters are likely to depend on details affecting the effective roughness of the tunnel, such as refuge niches, details of the track formation, and equipment in the tunnel. Therefore, the measurements need to be made in a tunnel with the same construction type and design details as the tunnel being analyzed.
- Scale model testing has been used to investigate certain aspects of wave propagation, but cannot accurately reproduce wave steepening (or gradient attenuation) properties of full-scale tunnels.

Detailed Assessment Methods for Analysis of the MPW Emission Phase

It is common practice to use simple formulae for analysis of the MPW emission and transmission phases. Detailed assessment methods are not often used. However, there are variations on the formulae.

The most commonly-used formula to calculate the MPW emission and transmission is:

$$\boldsymbol{p_{MPW}} = \frac{\boldsymbol{2A_T}}{\boldsymbol{\Omega rc}} \frac{\boldsymbol{dp_{exit}}}{\boldsymbol{dt}} \qquad \text{(See Section 8.2.3)}$$

This formula is suitable for initial assessment and for low frequency MPW emissions. To extend the validity to the full frequency range, the following methods are available:

- Matsuo et al [248] give an "end correction" that takes into account the three-dimensional nature of the wave reflection process and the finite distance required for reflection to take place. The reflection distance is geometry-dependent, and is typically $0.4D_T$ to $0.5D_T$, where D_T is the effective tunnel diameter and L_{wave} is the spatial length of the pressure wave (the "reflection zone" is shown diagrammatically in Figure 55). Pressure waves with a spatial length of the same order as the reflection distance or less will generate an MPW of lower amplitude than predicted by the simple formula. There are two ways to account for this:
    - Vardy [180] suggests that the pressure gradient to be used in the above formula should be averaged over a time interval $2\Delta l/c$ where Δl is the reflection distance and c is the speed of sound.
    - A correction factor $k_{reflection}$ may be applied to the MPW amplitude, given by:

$$\boldsymbol{k_{reflection}} = \left(\frac{\boldsymbol{L_{wave}}}{\boldsymbol{\pi k D_T}}\right) \boldsymbol{atan}\left(\frac{\boldsymbol{\pi k D_T}}{\boldsymbol{L_{wave}}}\right) \qquad \textbf{Equation 38}$$

where k is typically 0.4 to 0.5 [248]. The correction becomes significant when the spatial length of the pressure wave is less than about two tunnel diameters.

- Hieke [231] uses a convolution integral formula derived by Ozawa [249] that extends the aeroacoustic vibrating piston solution across the full frequency range.

Directionality of MPWs should also be considered. Differing opinions on this are expressed in the literature. For example, *no accepted formulae were found expressing to what extent MPW amplitude is affected by the surrounding topography, how it varies with the angle between the* *track and the line from portal to receptor, and to what extent MPWs would be attenuated for a receptor hidden from the portal by intervening slopes, cuttings, or other topographical features*. In theory, these issues are dealt with by setting a value of solid angle Ω appropriate to the environment around a particular tunnel portal and the measurement position. The directionality of the MPW (and hence the appropriate value of Ω to use in assessments) is poorly understood in practice, and this has to be accepted as a limitation of the assessment process.

Hieke et al [189] measured the MPW amplitudes at different locations near tunnel portals and the pressure gradients inside the tunnel, for many train passages at different speeds (and hence pressure waves with a range of different gradients). Their results showed that the appropriate value of Ω to use in the formula varied not only with measurement position, but also with pressure gradient inside the tunnel. Lower pressure gradients inside the tunnel required higher values of Ω in order for the formula to predict the MPW amplitude correctly. For example, to obtain the measured results at the southern portal of the Euerwang tunnel from the formula, Ω must be set to about 3 when the pressure gradient in the tunnel is greater than 1.7 psi/s (12 kPa/s); Ω must be set to about 4 when the pressure gradient is 0.7 psi/s (5 kPa/s). Directionality may be more marked for higher frequency MPWs, and with their shorter wavelengths they could be more affected by topographical features.

Detailed Assessment Methods for Analysis for the MPW Transmission Phase

Most authors assume that the MPW amplitude decays in proportion to the inverse of distance from the tunnel portal, for distances beyond about one or two tunnel diameters. Validation of this assumption from experimental data is given by Matsuo et al [248], who also found that the amplitude was insensitive to direction in his experiments. The same is not necessarily true for all tunnels. In practice, wave transmission and attenuation may vary with frequency. For example, obstacles such as noise barriers are effective for audible noise but ineffective for low frequency infrasound, due to the relative size of the barrier compared to the wavelength. There may also be variations in the rate of attenuation with distance.

Gerbig and Hieke [244] give an empirically validated formula for calculation of propagation loss ΔL in decibels (dB) as a function of distance from the center of the portal plane (r), i.e., the reduction of amplitude with distance:

$\Delta L = 13.5 \log(r/r_2)\text{dB}$ for $(r_1 \le r \le r_3)$ r_1=33 ft (10 m); r_2=82 ft (25 m); r_3=164 ft (50 m)

$\Delta L = [4 + 16.5 \log(r/r_3)]\text{dB}$ for $(r_3 \le r \le r_4)$ r_3=164 ft (50 m); r_4=656 ft (200 m)

$\Delta L = [14 + 20 \log(r/r_4)]\text{dB}$ for $(r_4 < r)$

Results are plotted in Figure 72. This formula suggests that within 660 ft (200 m) of the tunnel, MPW amplitude decays at a lesser rate than predicted by the simple formula.

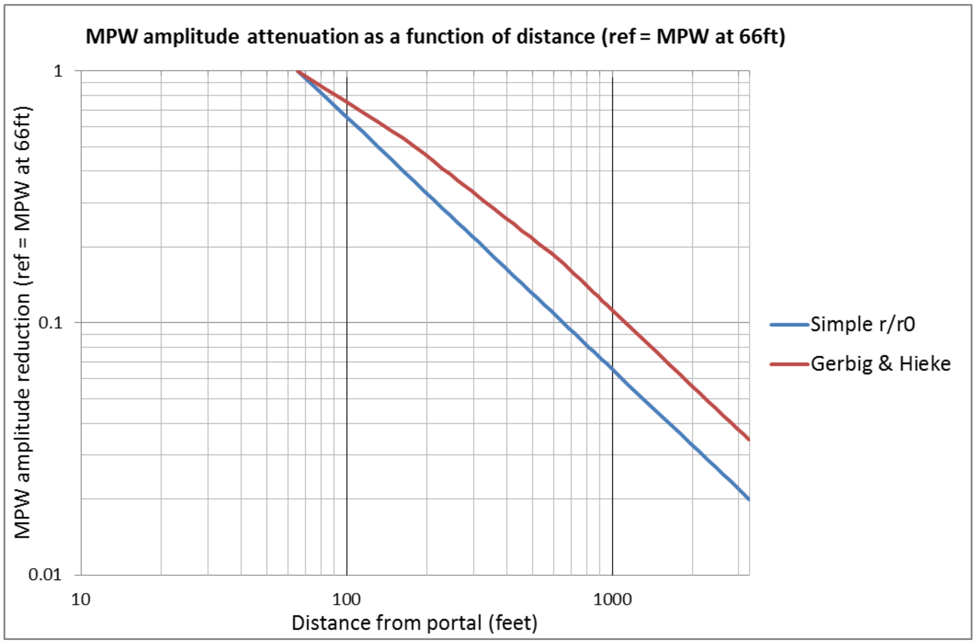

Figure 72. MPW attenuation as a function of distance from portal

Assessment Using Scale Model Tests

Reduced scale moving model tests can be used to assess train entry pressure waves. The 1/61 scale model rig at RTRI in Japan has been used by many authors [236, 237] to investigate the effects on the nose entry wave of different countermeasures. The rig has a circular tunnel and axially-symmetric train model, capable of being fired at speeds up to and beyond 250 mph (402 km/h). Johnson and Dalley [250], Hieke et al [234] and others describe use of the TRAIN rig (TRansient Aerodynamic INvestigations) at Derby, England, in which a detailed 1/25 scale model of a train can be propelled through a scale model of a tunnel at up to 165 mph using a catapult system. Because accurate scale models of the actual train and tunnel can be used, this type of facility can be used to predict the pressure gradient for a particular train/tunnel combination. Gregoire et al [179] describe a 1/70 scale model test facility using an enclosed system filled with low sound velocity gas mixtures, enabling Mach numbers up to 0.35 to be tested.

Reduced scale models have also been used to study wave transmission. For example, Nakao et al [240] used scale modeling to demonstrate the ability of porous materials to attenuate wave steepening.

8.5.2 Assessment of Impacts

While there are means of predicting the amplitude of a MPW or the noise generated by it, *there are no validated methods of assessing the impact of those quantities on the surrounding environment*, such as the level of annoyance caused to people nearby. Rather, tunnels are designed to meet certain acceptability criteria in respect of MPW, and if the criteria are met, it is assumed that the impacts are acceptable.

Comparisons between the Deutsche Bahn MPW noise criteria and noise from other sources were given in the previous Section 8.4 of this report.

8.6 Conclusions and Recommendations

8.6.1 Conclusions

The following conclusions have been determined through the review of the literature:

- Aerodynamic concepts are well understood.
- MPW amplitude increases by a factor of the train speed cubed or more.
- Mitigation measures exist and have been employed internationally.
- International standards, assessment methods, and acceptability criteria exist in Europe and Asia but with significant limitations.

8.6.2 Gaps and Issues

The following gaps in information and criteria and associated issues have been identified:

- There exist no criteria or standards for the United States for assessment of MPWs.
- International criteria have various limitations, including:
  - The criteria being insufficiently relevant to human perception of MPWs; and
  - Difficulty of application of criteria to assessment of new tunnel designs.
- Gaps exist in current knowledge to allow for a more comprehensive assessment of tunnel designs including the effects of ballast, “entry and exit” MPW, the effects of air shafts, and MPW directional impacts.

8.6.3 Recommendations to Address Gaps and issues

Assessment Criteria and Standards

The criteria to be developed for the United States should consist of a set of noise-based limits for detailed assessments and field measurements of MPWs, and simpler limits suitable for initial design and assessment. These are more fully discussed below.

Acceptability Criteria for Detailed Assessments and Field Measurements

We recommend that additional research is conducted to define noise-based MPW acceptability criteria for the United States, taking into account public expectation of the noise environment, vulnerability of typical North American buildings to rattling doors and windows, and other factors to be determined. We recommend using the Deutsche Bahn noise-based MPW acceptability criteria as an initial basis.

Acceptability Criteria for Initial Design and Assessment

While the Japanese-type criteria do not relate directly to the impacts caused by MPWs, they are useful for initial assessments, and therefore a criterion similar to these should be developed for the United States. Note that Japanese experience of MPWs causing doors and windows to rattle in the 1970’s and 1980s’ may not be relevant to current North American buildings. We recommend including a criterion for the minimum acceptable duration of the MPW as well as a criterion for its maximum acceptable amplitude. This will help ensure that the dominant frequencies of the MPWs are below the range audible to humans.

An initial action would be to measure the micro-pressure waves from tunnels on high speed lines, including those at which MPWs are not perceived to be a problem. Choice of data to be measured and detailed specifications for tests should be developed as part of this work. The measured data will provide subjective experiences at the measurement position and expectations for those nearby. This information can then be used to assist with the development of acceptability parameters.

The criteria to be developed might consist of a set of noise-based limits for detailed assessments, and a set of limits based on simpler criteria suitable for initial design and assessment. It will be desirable to include consideration of frequency content.

Graphs should be developed similar to the above examples that can be used for initial design to meet a new United States acceptability criterion.

Gaps in Current Knowledge

To address gaps in current knowledge we recommend the following:

- Develop methods of assessing wave propagation for ballast-track. This might require a program of full-scale tests and analysis.
- Develop assessment methods for “entry and exit” MPWs (waves emitted from tunnel portals as the train enters or exits, without first being propagated down the tunnel) and investigate mitigation measures for these.
- Develop assessment methods for MPWs caused by trains passing shafts within tunnels, based on full-scale testing (or reduced scale-model testing) and analysis. Investigate mitigation measures for these.
- Investigate the directionality of MPWs by full-scale test measurements and determine how directionality could be included in MPW assessments.
- Research “ballast-effect air-spaces” as mitigation measure for long slab-track tunnels and develop design guidance.
- Research “closed side-passages” as a mitigation measure for MPWs.

9. Drag Effect

Aerodynamic drag is the principal source of resistance for high speed trains. It is proportional to the square of train speed and dictates much of the power requirement for a given high speed operation. For example, almost twice the power is required to run a train at 250 mph compared to the same train at 200 mph. In planning speeds, energy operating costs and availability of sufficient electrical power need to be assessed.

9.1 Introduction and Summary

This chapter examines drag and its resultant impacts including:

- basic aerodynamic concepts;
- measurements and calculations;
- impacts;
- mitigations,
- standards including criteria;
- data from the literature review including experimental methods; and,
- conclusions and recommendations.

This chapter has the following general conclusions and recommendations :

- basic aerodynamic concepts are well understood,
- drag effects can be calculated using Davis Equation coefficients that the train manufacturers possess.

9.2 Drag

9.2.1 Basic Aerodynamic Concepts

Drag is the force that opposes train motion. It can be divided into aerodynamic drag, caused by the interaction between the train and air, and mechanical drag, caused by the wheel-rail interactions and friction in the bearings. Both are well understood.

Aerodynamic drag is proportional to the square of train speed, while mechanical drag is idealized as being constant or linearly dependent on speed. Because the aerodynamic contribution to total drag increases significantly with speed, understanding it is especially important in the context of high-speed rail operations [57, 58].

The total aerodynamic drag consists of the sum of the forces that are normal to the train surface (known as *pressure drag*), and forces that are tangential to the train surface (known as skin drag, *friction drag*, skin friction, or viscous drag).

Pressure drag is caused by the pressure difference between the high-pressure stagnation region at the nose of the train and the low-pressure region behind the tail of the train. The more abrupt the changes in the train's cross-sectional area (i.e., the more blunt the nose and tail are), the larger the pressure drag. Structures such as pantographs, trucks, and car-to-car connections also contribute to pressure drag.

Friction drag is the sum of the shear forces acting along the surface of the train, resulting from the air velocity gradient in the boundary layer surrounding the train. Friction drag is proportional to the air viscosity and to the boundary layer velocity gradient. The latter is a function of the train shape (especially car-to-car connections, pantographs, and underbody equipment), roughness of train surface, train speed, and the surrounding environment [251]. For well streamlined high speed trains, the majority of the total drag is friction.

The total drag force is often thought of as having a component arising from the nose and tail (typically on the order of 10 to 15% of the total drag for a well streamlined high speed train) and a component arising from features along the length of the train (typically on the order of 85 to 90% of the total drag). The total drag force also depends strongly on the length of the train because this increases the total skin friction area.

Estimates of the proportions of the aerodynamic drag caused by the different features of the train may be found in the literature, for example Peters [252], Schetz [57], Guihew [253], and Maeda [58, 98].

Aerodynamic drag is increased by crosswinds, and the aerodynamic effects of tunnels.

9.2.2 Measurements and Calculations

The Davis Equation

The Davis equation, proposed in 1926 [254] and still widely used, gives the total drag (mechanical and aerodynamic) on the train as a function of train velocity and the Davis coefficients [57, 58, 255]. Its general form for level track at constant speed with no wind is given as:

$$\boldsymbol{R = A + BV + CV^2} \qquad \textbf{Equation 39}$$

where R is total drag force, V is train speed and A, B, and C are the Davis coefficients specific to a particular train, which are usually measured by train manufacturers. A and B are the coefficients associated with mechanical drag, while C is associated with aerodynamic resistance. There is no evidence to suggest that the Davis equation, or the coefficients for a particular train, would become invalid at speeds up to 250 mph (402 km/h).

More specifically in regards to the Davis coefficients:

- A is associated with rolling resistance.
- B is derived from two variables, namely
  - B_1 due to mechanical resistance components such as transmission losses, and
  - B_2 associated with ingesting air for cooling and air conditioning [57, 70].
- C is associated with aerodynamic drag and can be further expressed as:

  $$\boldsymbol{C = \frac{1}{2}\rho S C_D} \qquad \textbf{Equation 40}$$

  where ρ is air density, S is cross-sectional area of the train, and C_D is the aerodynamic drag coefficient for a particular train.

  - It may be also desirable to express the drag coefficient in a form that enables analysis of the influence of train length. C_D can be approximated as:

  $$\boldsymbol{C_D = C_{dp} + \frac{\lambda}{d} l} \qquad \textbf{Equation 41}$$

where C_{dp} is the pressure drag coefficient (typically around 0.15-0.20 for high speed trains), λ is the friction coefficient, d is the hydraulic diameter of the train, and l is the train length [58, 256].

Davis coefficients, including the term associated with aerodynamic drag, are generally estimated by fitting to the results of full-scale tests. Other experimental methods involve full-scale or scaled track experiments, as well as wind tunnel, water tunnel, and towing tank tests [57]. Since the drag is dependent on the design and length of the train, the coefficients must be determined separately for each train configuration.

In practice, where Davis coefficients are required for the purpose of infrastructure design, it is recommended that they be provided by the train manufacturer and not be estimated from data in the literature. However, the published data are available and may be of interest for comparison [58, 61, 70, 257]. It is worth noting that as aerodynamic design has substantially improved in recent years, the figures given for older designs are poorly representative of current train design practice. Also, because of intellectual property issues the coefficients for many modern high speed trains are not available in the public domain.

In any analysis of drag, *care should be taken to account for the uncertainties* in drag coefficients relative to operating conditions and ambient winds. It may be preferable to run many simulations with the input parameters subject to random variation within the expected range of uncertainty.

Davis Equation with Ambient Wind

In the presence of ambient wind, the drag coefficient can be modified according to the following approximate formulae (valid for yaw angles below 30 degrees): [57, 258]

$$\boldsymbol{R = A + B_1 V_G + B_2 V_A + C(\beta) V_A^2} \qquad \textbf{Equation 42}$$

$$\boldsymbol{C(\beta) = C_{\beta=0}(1 + a\beta)} \qquad \textbf{Equation 43}$$

where V_G is the ground speed (speed of the train relative to the ground) and V_A is the air speed (speed of the train relative to the moving air), $C_{\beta=0}$ is the value of C in the absence of a crosswind, β is the yaw angle (in degrees) and a is a constant of the order of 0.01 to 0.02. The B coefficient consists of two terms: (1) B_1 which is the speed relative to the ground, and (2) B_2 which is the speed relative to the air. The C coefficient is an aerodynamic variable which measures the air speed only. In the absence of wind, the ground speed and the air speed are identical.

It is estimated that on a calm day, wind increases aerodynamic drag on a train by about 10%. Under strong crosswind at unfavorable angle, the drag increase can be as much as 50 to 60% [57, 252, 259]. Calculations of energy consumption for a route should take into account the prevailing wind direction and speed in the estimation of drag for each section of the route.

Analysis of Drag in Tunnels

In tunnels, the aerodynamic drag is increased for the two reasons described by Schetz [57]:

- The pressure drag is greater because the train pressurizes the air ahead of the nose (piston effect);
- The air flows over the train in the direction from nose to tail, thus the velocity of the train relative to the air is increased compared to the open air case.

Each of these effects varies [177, 260] and depends on blockage ratio, tunnel length, the roughness of the tunnel walls, and other parameters.

As a very rough approximation, a simple tunnel factor "T_f" is applied to the aerodynamic resistance:

$$\boldsymbol{R = A + BV + T_f CV^2} \qquad \textbf{Equation 44}$$

The tunnel factor, T_f, varies for each tunnel and is a function of blockage ratio, tunnel length and train length, and is typically in the range 1 to 2 for well streamlined high speed trains. A theoretical derivation of T_f is given by Sockel [261]. Further information can be obtained from train manufacturers for particular trains.

Specialized one-dimensional analysis software, such as ThermoTun [106], can predict the drag force time-history during transit through a tunnel. The results can be used to inform a suitable choice of T_f for each tunnel for later use in simpler route-wide calculations, and as part of a more detailed study of maximum and average power consumption for trips through each tunnel.

Examples

An example calculation is given here for a train with the following Davis coefficients:

A = 2 kN = 450 lbf

B = 0.1 kNs/m = 10 lbf/mph

C = 0.010 kNs^2/m^2 = 0.45 lbf/mph^2

The resistance force at 250 mph is:

$$\text{Force} = \text{A} + \text{BV} + \text{CV}^2 = 450 + 10 \times 250 + 0.45 \times 250^2 = 31{,}000\ \text{lbf}$$

The energy consumption in Btu over a one mile distance is:

$$\begin{aligned}\text{Energy} &= \text{Force} \times \text{distance} \times \text{Unit conversion}\\ &= 31{,}000\frac{\text{lbf}}{\text{mile}} \times 1\ \text{mile} \times 6.8\frac{\text{Btu}}{\text{lbf mile}}\\ &= 210{,}000\ \text{Btu/mile}\end{aligned}$$

The power consumption is:

$$\begin{aligned}\text{Power} &= \text{Force} \times \text{speed} \times \text{unit conversion}\\ &= 31{,}000\ \text{lbf} \times 250\text{mph} \times 0.0027\ \frac{\text{hp}}{\text{lbf mph}}\\ &= 21{,}000\ \text{hp}\end{aligned}$$

Converting the power consumption into metric units (kilowatt or Megawatt):

21,000 hp x 0.746 kW/hp = 15,666 kW = 15.666 MW

Graphs of resistance force, energy consumption per mile, and power requirement are shown as functions of speed in Figure 73, Figure 74, and Figure 75 (blue lines), while the aerodynamic contribution to the total drag (CV^2 term) is shown as a red line in the same figures. It is clear that aerodynamic resistance dominates at higher speeds. At 250 mph, the power requirement to overcome drag is about eight times as great as at 125 mph for the same train.

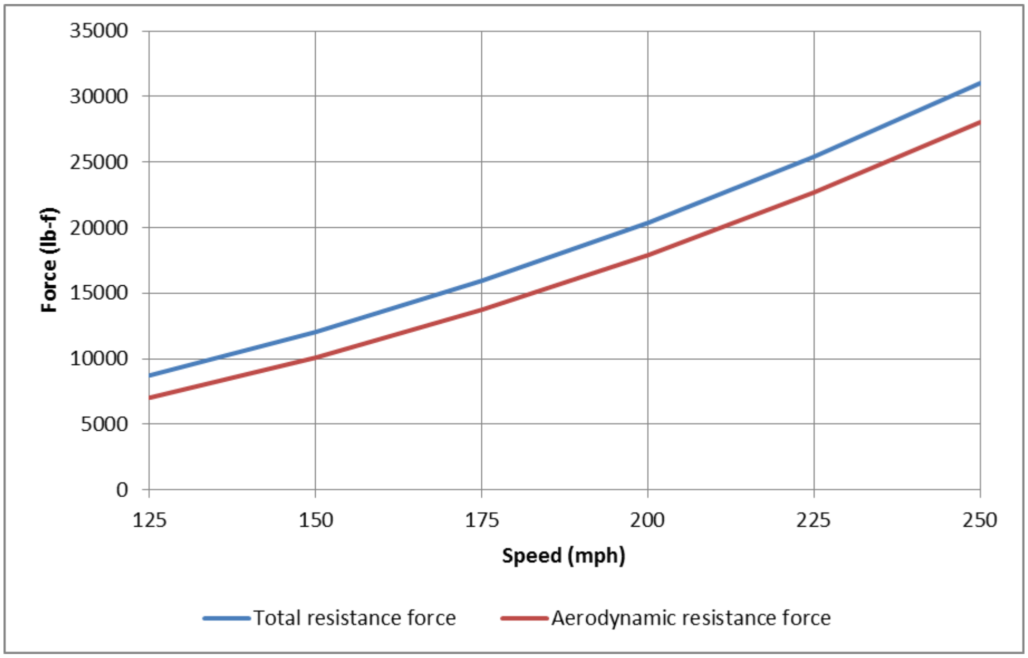

Figure 73. Example of variation of drag (resistance) force with speed

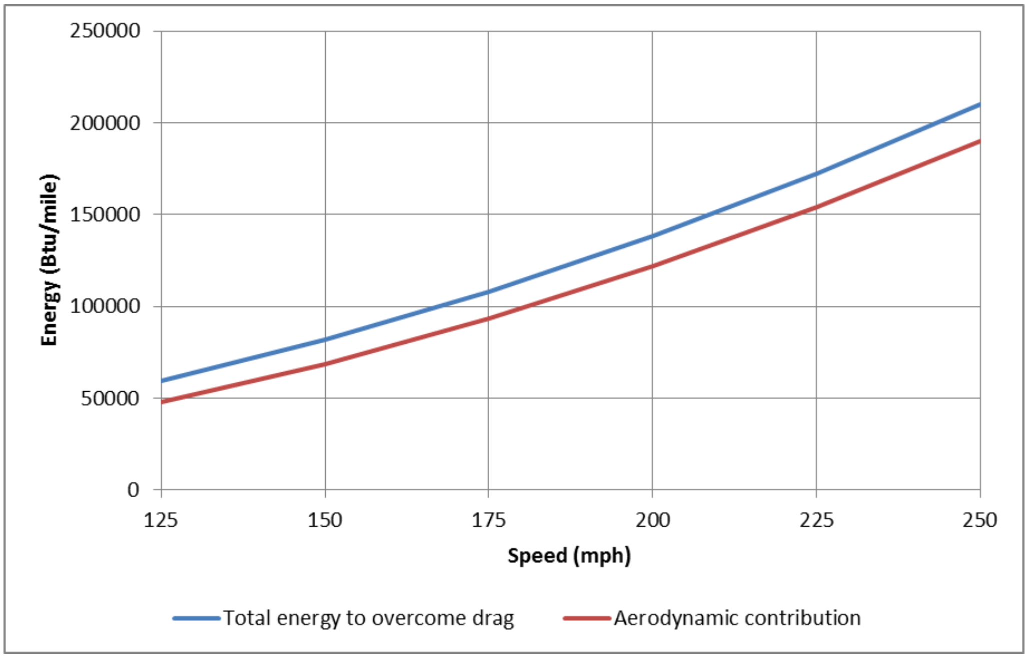

Figure 74. Example of variation of energy usage per mile with speed

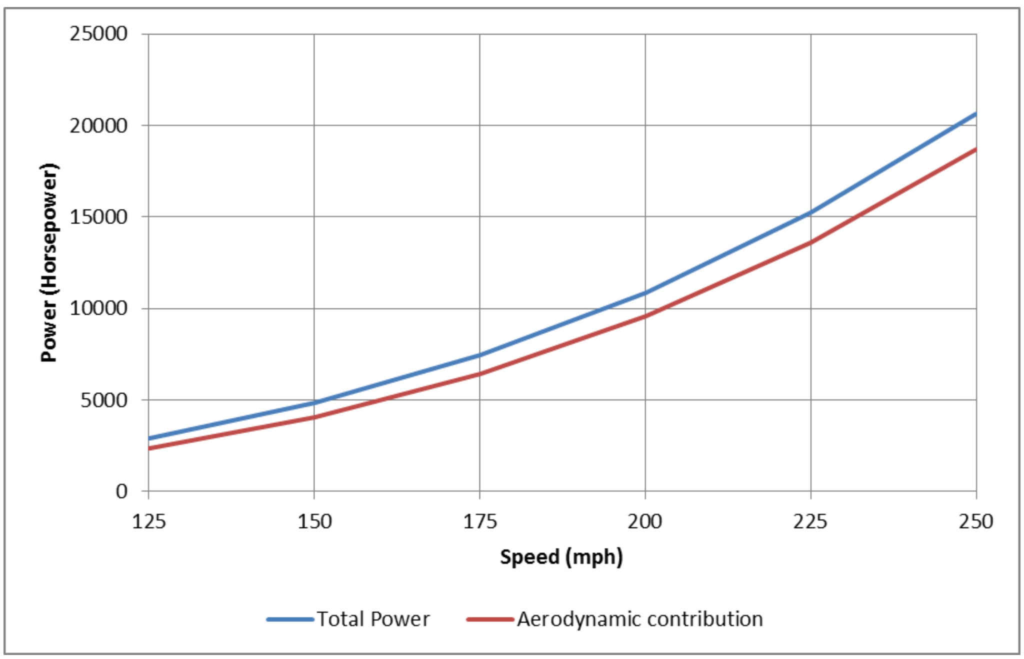

Figure 75. Example of variation of power consumption with speed

9.3 Impacts and Mitigation

9.3.1 Impact on Operations and Planning

The impacts of aerodynamic drag are principally financial, environmental, and operational.

Aerodynamic drag is responsible for at least 70% of energy consumption by a high speed train running at constant speed [57, 58, 70, 251]. The drag force is proportional to the square of train speed and the power required to overcome the aerodynamic drag is proportional to the cube of the train speed. Higher speeds therefore have a dramatic impact on energy consumption and on costs.

Drag is increased when in tunnels. If speeds are reduced to mitigate costs, this could impact journey times if tunnels form a significant percentage of the route.

British publications [76, 262] provide the following normalized values for energy consumption and power requirements of trains of the same shape traveling at different speeds (Table 19):

Table 19. Normalized values for trains' energy consumption and power requirements [76, 262]

Speed, mph (km/h)	100 (160)	125 (200)	140 (225)	168 (270)	186 (300)	205 (330)	280 (450)
Energy consumption	0.64	1	1.27	1.82	2.25	2.72	5.06
Power requirement	0.51	1	1.42	2.46	3.38	4.49	11.39

Formulae are available [263] for estimating operating costs, including the cost of electrical energy, as functions of average train speed. Nevertheless, higher speed does not necessarily mean total higher operational cost, since the latter is influenced by many factors of which energy consumption is one.

9.3.2 Impact on Infrastructure Design

Impacts of aerodynamic drag on infrastructure design and construction cost of high speed railways affect mostly the electrical system and the design of tunnels.

The electrical supply system (including substation numbers and locations) must be designed to accommodate the power consumption of the trains. Increased train speeds require more power, in turn requiring more expensive power supply equipment and associated infrastructure. Additionally, the power consumed by the train heats the air in tunnels. Ventilation and cooling systems must be designed to accommodate this. If this is not done, high temperatures in the tunnel could have impacts on comfort, and in extreme cases on safety of passengers and crew.

In regards to infrastructure design, it may be necessary to provide a larger cross-sectional area for a tunnel, or provide pressure relief shafts, to reduce aerodynamic drag to acceptable levels that allow the desired speed to be maintained.

9.3.3 Mitigation

Mitigation measures to reduce aerodynamic drag can include the reduction of train speeds and the procurement of trains with low Davis equation coefficients.

Train manufacturers can reduce aerodynamic drag for a given train by changing the shape and design details. For high speed trains, roughness along the length of the train should be minimized. Actions to achieve this include covering gaps between cars, adding fairings around pantographs, and installing skin panels underneath the train to cover under-floor equipment.

Drag in tunnels can be reduced by tunnel ventilation modes such as pressure relief shafts [264]. Cross-passages linking the tubes of a twin tube tunnel are effective, but keeping the passages open during normal operation may conflict with fire safety strategies.

9.4 Standards and Criteria

9.4.1 Assessment Criteria

There are currently no formal criteria for "acceptable" values of aerodynamic drag for high-speed trains. Greater aerodynamic drag requires higher power consumption and greater operating costs. Any criteria would be a business driven assessment of acceptable operating costs.

9.5 Data from Literature

9.5.1 Full-Scale Experiments

There are a number of full-scale testing methods for measuring aerodynamic drag. The most common method is a "coasting" or "run-down" test [57, 255, 265, 266]. The train is run up to a certain speed and then, immediately before entering a straight, level test section of track, all tractive effort and sources of magnetic resistance are stopped and the train is allowed to coast. Train speed is measured as a function of time, and the deceleration is measured directly with accelerometers. Instantaneous resistance force R is evaluated from the measured deceleration a and the train mass m modified by a factor k_{RM} that accounts for energy stored in rotating masses:

$$\boldsymbol{R = k_{RM} m a} \qquad \textbf{Equation 45}$$

European Standard EN14067 Part 4 [24] contains some requirements and guidance for performing coasting tests and interpreting their results.

The measured data are expressed as a series of points on a graph of resistance force versus train speed. The Davis coefficients A, B and C that provide the best fit to the measured data are found by regression analysis.

As an alternative to coasting tests, a dynamometer car with an instrumented coupler can be incorporated into the train [57, 70], but the measured force (dependent on the specific setup) excludes the drag on the part of the train ahead of or behind the dynamometer car. It is also possible to estimate the total resistance of the train by carefully monitoring the power consumption of the traction motors.

The problems with the above methods include the difficulty of separating mechanical drag from aerodynamic drag, high cost, and lack of control over important experimental conditions such as grades and crosswinds [57, 58, 255]. To address these problems, an interesting method has been proposed in Japan [267]. It relies on the measurement of pressure rise on the train surface as it enters a tunnel. This technique allows separating not only aerodynamic drag from mechanical drag, but also pressure drag from friction drag.

9.5.2 Full-Scale Experiments in Tunnels

Vardy and Reinke [177] describe a method by which measurements of pressure and air velocity in tunnels can be used to infer the resistance coefficients of the trains passing through the tunnel.

An iterative process using one-dimensional simulations is used to obtain values such as the train skin friction coefficients.

9.5.3 Scaled Experiments

Experiments in a controlled environment (wind tunnel, water tunnel, or towing tank) are also conducted. No current facilities can accommodate a full-size train, and very few can accommodate even one locomotive or railcar, so most of the testing is done on scaled models. This creates a number of challenges. It can be difficult to obtain the same Reynolds and Mach numbers on a test model and on a full-size vehicle. Trains have a number of small-scale but important surface features such as pantographs that are difficult to incorporate accurately into scale models. In a typical wind tunnel setup, a train is stationary with respect to the ground, so the flow patterns are different from those seen on a track. Special measures, such as placing the train model on a moving belt, can somewhat mitigate this problem [57]. Nevertheless, wind tunnel testing is a useful tool during design development for comparing drag coefficients of different candidate designs.

Estimates of accuracy of scaled testing in wind tunnels vary. Various sources report up to 30% differences in aerodynamic drag between scaled models and full-scale vehicles, depending on scale and test method [57]. One must keep in mind that while drag measurements can be used to evaluate the performance of the design, drag measurements alone give no information about the flow patterns and therefore cannot inform design changes likely to reduce drag. More sophisticated measurement and flow visualization techniques must be used for this purpose, such as particle image velocimetry (PIV) and pressure sensitive paint (PSP) [268].

9.5.4 Numerical Methods

The advantages of numerical methods are that flow patterns and drag coefficients can be calculated and visualized, easily informing what design changes are likely to reduce drag. Various methods, such as Reynolds-Averaged Navier-Stokes (RANS), Unsteady Reynolds-Averaged Navier-Stokes (URANS), Large Eddy Simulation (LES), Detached Eddy simulation (DES), Direct Numerical Simulation (DNS), spectral methods, cortex methods, and Lattice-Boltzmann methods have all been used to evaluate the aerodynamics of trains [269]. The length of trains compared to the cross-sectional dimensions and the grid size required for accuracy leads to very heavy demands on computing resources, especially for the more advanced methods such as LES.

In general, the methods mentioned above (wind tunnel testing, full-scale testing, and numerical analysis) can be and are used in tandem [270].

An approach by NASA was successfully used for the Heavy Vehicle Drag Reduction program [271]. This program addressed road trucks rather than trains, but the same principles could be used for trains:

- Small-scale wind tunnels were used for concept screening.
- Large-scale wind tunnel experiments were used for higher accuracy and to evaluate the effects of different Reynolds numbers.
- Full-scale open environment tests were performed for full demonstration.

9.6 Conclusions and Recommendations

Concepts and methods are well understood.

For new Tier III operations, we recommend using Davis Equation coefficients from train manufacturers for calculating power requirements and operating speeds to optimize energy consumption.

When designing tunnels for Tier III operations, we recommend that operators and designers estimate the increased drag in tunnels and consider whether it is necessary to provide pressure relief shafts or other mitigations.

10. Ballast Flight

Ballast flight constitutes a complex aerodynamic issue that can limit the operating speeds of high speed trains and has the potential to prevent speeds up to 250 mph (402 km/h) in certain situations. The phenomenon has been studied extensively, but is not yet fully understood.

10.1 Introduction and Summary

This chapter examines ballast flight and the resultant impacts including:

- basic aerodynamic concepts;
- influencing factors;
- measurements and calculations;
- known and potential impacts;
- mitigation methods;
- standards;
- data from the literature review including measurement and assessment methods; and,
- conclusions and recommendations for additional studies.

This chapter has the following general conclusions and recommendations :

- ballast flight constitutes a significant issue for high speed trains;
- theoretical concepts are not fully understood;
- impacts include reported damage to vehicles and equipment with the potential for injuries to passengers and workers;
- mitigation measures include reduction of train speeds and restrictions on placement heights of ballast relative to the ties; and
- recommendations for testing and assessments.

10.2 Ballast Flight Nature and Influencing Factors

10.2.1 Basic Aerodynamic Concept

"Ballast flight" describes the movement of ballast under the influence of aerodynamic effects from passing trains. The phenomenon has been extensively researched *but is not yet fully understood*. Fall of ice from trains has been known for many years to initiate ballast flight, even for trains with relatively low speeds. However, such "winter conditions ballast flight" is not primarily an aerodynamic problem and is not included in the scope of this research. With the advent of high speed trains in Europe, instances of ballast flight occurring under normal weather conditions have increased and it is not obvious how the movement of ballast is initiated in these cases. Mechanisms that have been postulated include:

- vibration of the track, especially the ties, caused by passing trains;
- the negative pressure peaks at the front and rear of the train; and
- shear caused by air velocity under the train.

Pieces of ballast lying on top of the ties are much more likely to become projected than ballast pieces between the ties. Once airborne, the ballast particles can be propelled by the turbulent air flow under the train.

10.2.2 Influencing Factors

Ballast flight was encountered during proving tests on the ICE 3 high speed train in Belgium and France [272]. Three ballast projection incidents were recorded at train speeds up to 185 mph (298 km/h). The incidents consisted of multiple ballast particles striking the underside of the train resulting in substantial repair costs. No similar incidents had occurred previously with the same train in Germany, nor with TGV trains in Belgium or France, even at higher train speeds. Further incidents occurred during test runs of the ETR 500 train at 185 mph in Italy. The mechanism is thought to be a chain-reaction, as described by Johnson:

- Ballast particles start to move, perhaps due to aerodynamic pressures or track vibration.
- The moving particles are accelerated by the air flow under the train.
- Some particles hit obstacles and are projected upwards.
- Some of these particles impact the moving train and rebound at a greater speed.
- These particles then strike the ballast, projecting further particles.

Tests performed on the Korean railways [273] showed that:

- In a wind tunnel setting, for ballast on top of a tie, the critical wind velocity (airflow velocity at which ballast starts to move) is 45 mph (20 m/s). For ballast stacked between the ties on a track the critical wind velocity is 74 mph (33 m/s).
- Airflow velocity 0.79 in (20 mm) above the tie surface is 56 mph (25 m/s) for the test train traveling at 185 mph (300 km/h) and is enough to initiate ballast flight.
- Airflow (and, therefore, the probability of ballast flight) is strongest near the track center.
- Critical wind velocity is lower for smaller ballast particles than for larger particles. It is also lower for rounded particles than for flat particles.
- Ballast flight is primarily caused by the turbulent boundary layer and the disturbances due to the train's underbody shape (trucks, inter-car spaces).
- Effect of train nose shape onto ballast flight is negligible.
- Ties are very effective in blocking the airflow between them; therefore, lowering the ballast profile is an effective countermeasure against ballast flight.
- Probability of ballast flight is quite sensitive to train speed. At 217 mph (350 km/h), the risk of ballast flight is two times higher than at 186 mph (300 km/h).

Ballast flight risk is increased with ballast bed vibration. It has been observed that the risk is higher on bridges, due to increased vibration of the track and due to stronger winds [274].

Quinn et al [275] report full-scale test measurements of the air pressure and velocity under passing high-speed trains, and of the vibrations of the ties and rails. The measurements indicated air velocity immediately above the tie surface of 0.3 to 0.5 times the train speed, consistent with the Kwon and Park study [273]. Analysis of the data suggests that neither aerodynamic forces nor vibrations of the ties in isolation would be sufficient to initiate ballast flight, but a combination of the two effects may be responsible.

Research on ballast flight has recently been conducted in Europe (AeroTRAIN Project [272, 276]). To date, little data from this project have been published, but some of the key findings are:

- Ballast flight is associated with train speeds over 155 mph (250 km/h);
- The underbody design of the train is a significant parameter, with cavities or high roughness contributing to the likelihood of ballast flight, especially if the clearances between the underside of the train and the ballast are low.
- A smooth train underbody helps to prevent ballast flight.
- Ballast levels above the ties make ballast flight more likely.

Based on data from several HST operators worldwide, Jacobini et al [277] conclude:

- Speed of 162 mph (260 km/h) may be considered a threshold value at which the possibility of ballast flight sharply increases.
- In some environments threshold speed values can be much lower than 162 mph (260 km/h). For example, there were reported cases of sign post damage consistent with ballast flight in tunnels with posted speed limits of only 87 mph (140 km/h).
- Train crossing can be an additional risk factor. There were recorded instances in the US of ballast projection during train meeting at speeds below 100 mph (160 km/h).
- High winds could create more favorable conditions for ballast flight by altering the arrangements of the particles on the surface of the trackbed.
- Train length plays a major role in the initial displacement of the ballast particles. It has been shown that 16-car trains are more prone to generate ballast flight than 8-car trains. This may be due to the greater chance of initiating a chain reaction.

Ballast flight could constitute a significant issue for operations at speeds up to 250 mph (402 km/h), which are beyond current worldwide experience of regular high speed train operations.

10.2.3 Measurements and Calculations

Kwon and Park [273] introduced the concept of a ballast-flying probability factor (BFPF), which can be calculated from maximum and minimum airflow velocities at which ballast moves, and from the average airflow velocity just above the track. Airflow velocities were measured in the field using a Kiel probe array comprised of small tubular sensors arranged in a multi-directional configuration where the direction of wind flow is unknown or varies with operating conditions. In addition, Kwon and Park conducted tests in a wind tunnel using a full-scale ballast and tie model. These test results were discussed in Section 10.2.2 of this report.

Jing et al [274] derived a simplified formula for the prediction of ballast flight based on particle mass, wind load effective area, wind pressure coefficient, ballast vibration acceleration, and ballast interlocking force. These factors have to be determined experimentally from train speed and ballast properties. Jing specifically described a method for measuring ballast interlocking ability using a spring dynamometer. Values for these properties are not published.

10.3 Impacts and Mitigation

10.3.1 Passenger and Worker Impacts

The literature survey revealed no publications discussing the impact of aerodynamically-induced scattering of ballast on passengers and track workers. Nevertheless, reported cases of broken windows and other damage to structures due to ballast flight [273] suggest that such dangers are present.

10.3.2 Vehicle, Equipment, and Freight impacts

If ballast particles become scattered on top of the rail, damage to train wheels and rail head ("ballast pitting") may result. The impacts are increased maintenance of rail grinding and wheel cutting, and shorter life before replacement.

In addition, projected ballast can impact train body and line-side structures. Where a chain-reaction occurs, damage to the underside of trains can be substantial. Cost impacts can also occur during introduction of new trains. The ICE 3 train underbody had to be modified to allow it to operate on the affected track [272]. In severe cases, ballast flight can destabilize the ballast layer and lead to track perturbations, which would increase vertical and lateral wheel-rail forces and decrease ride quality [273, 274].

10.3.3 Mitigation Methods

Reduction of speed is an effective mitigation measure.

The UIC report on high speed track maintenance [278] recommends the following strategy to mitigate the risk of ballast flight:

- Maintain low ballast profile (top of the ballast surface 1.6 in (4 cm) or lower from top of the tie);
- Ensure that no ballast particles are on top of the ties; and
- If other strategies fail, implement a speed restriction.

Jing et al [274] also propose a number of strategies:

- Maintaining low ballast profile and compacting its top layer;
- Attenuating the vibration of ballast bed by altering bed depth and using ballast mats;
- Using bonding material to increase ballast interlocking ability; however, this presents problems for maintenance;
- Using higher density ballast materials (e.g., basalt instead of granite);
- Removal of ballast from the top of the ties;
- Implementing strict ballast condition monitoring and restricting train speed on bridges;
- Using steel or plastic screens to stabilize the ballast. Again, maintenance of the ballast becomes more difficult.

Several European countries adopted the strategy of lowering the ballast profile by 0.8-1.2 in (2-3 cm) to mitigate the risk of ballast flight. Lowering the ballast creates voids between the bottom of the rail and the top of the ballast. During train passage, air can escape through these voids, thereby reducing the aerodynamic pressure. While this solution proved very effective, in France it caused an increase in tamping frequency, presumably by lowering the lateral resistance of the trackbed [277].

On certain Japanese high-speed lines, special screens are laid on top of the ballast to prevent ballast scattering due to fall of ice from trains [279-281]. Another similar solution currently being tested in Japan is enclosing the ballast in bags made of coarse mesh. This method retains all functions of the ballast, but complicates track maintenance [277].

While replacing ballasted track with slab track to mitigate ballast flight may be too costly on the existing lines, it should be considered during the planning of new HST lines [277].

A new type of railroad tie has been developed in Spain and installed on a portion of the Madrid-Barcelona HST line. The tie has been shown to decrease aerodynamic loads on a trackbed by 21% [277].

A number of patents have been published on improvements to the train body shape specifically to minimize turbulence underneath the train to prevent ballast pickup [282]. No studies were found evaluating their efficacy.

Although not mentioned in any publication explicitly, it is likely that measures that reduce aerodynamic drag from trucks and other structures underneath the train body may also reduce the risk of ballast flight.

10.4 Standards

The European TSI (Rolling Stock) [14] indicates that ballast flight should be considered in the design of new trains, but the method for doing this is not specified.

The Chinese Code for Design of High-speed Railway [80] requires a ballast density of no less than 109 lbm/ft^3 (1.75 g/cm^3) and requires the ballast top surface to be 1.6 in (4 cm) lower than the tie's supporting surface and no higher than the tie's top surface in the middle of the tie.

10.5 Data from Literature

10.5.1 Measurement and Assessment

No evidence was found in the literature search of attempts during design of new high speed railway infrastructure to predict whether ballast flight will be a problem nor are there any current international standards for an assessment method. Rather, research is currently directed towards acceptability criteria for trains and limiting operating speeds for a given train.

Saussine et al [283] present a risk assessment method for ballast flight. They conclude that ballast flight is a sporadic phenomenon that is difficult to predict or characterize under real conditions, and a probabilistic assessment method is therefore preferred. The method implicitly assumes that shear stresses due to air flow under the train are the principal mechanism driving ballast flight. It can be used to assess the increased risk of ballast flight associated with speed increases on existing lines.

The method may be summarized as follows:

- An array of 20 Pitot tubes at pre-defined ground-based positions (Figure 76) measures air velocity under the train.

- The “signal power” (time-averaged value of velocity squared, equivalent to the square of the RMS velocity) is calculated for the set of Pitot tubes.
- Numerical simulations of the contact dynamics of irregular polyhedral particles were used to develop statistical relationships between signal power, the percentage of grains displaced more than four inches (10 cm), and the number of grains ejected (Figure 77).
- The mean and standard deviation of signal power is evaluated from many train passes at a constant speed. These are considered as aerodynamic properties of the particular train type and track form (Figure 78).
- The risk of ejection of a certain threshold number of grains is evaluated from the convolution of the two Gaussian distributions (i.e., the combined risk of a certain signal power occurring coupled with the risk that signal power can eject the threshold number of grains).

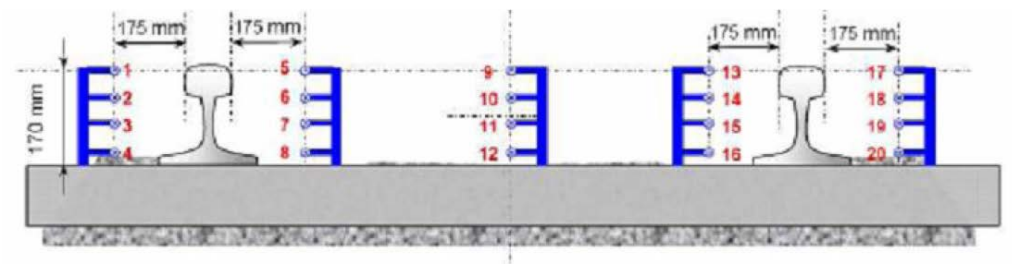

Figure 76. Array of Pitot tubes
Reproduced from [283] by permission of Union Internationale des Chemins de Fer

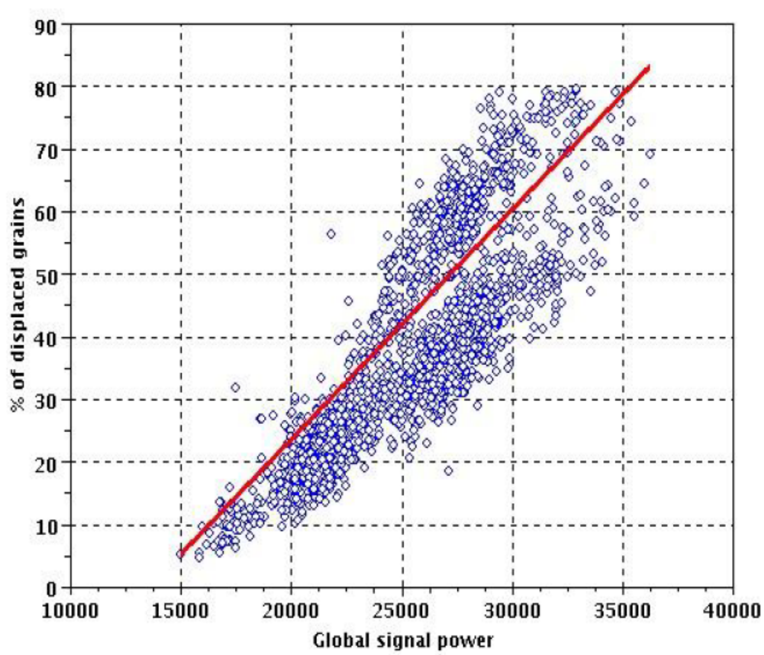

Figure 77. Relationship of signal power to percentage of displaced grains
Reproduced from [283] by permission of Union Internationale des Chemins de Fer

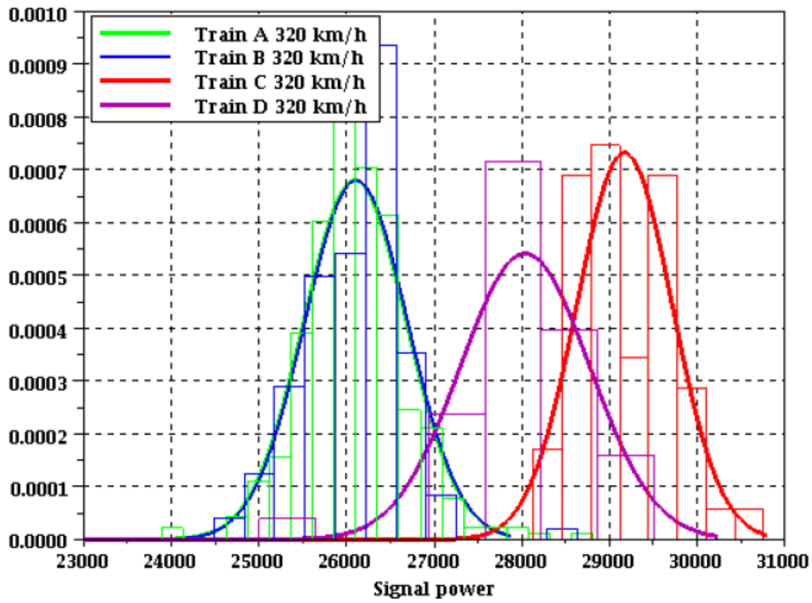

Figure 78. Signal Power Gaussian distributions for four train types at 199 mph (320 km/h)

Reproduced from [283] by permission of Union Internationale des Chemins de Fer

An outline of a ballast flight assessment method based on air velocity under the train has been developed in the AeroTRAIN project. Details were not yet published at the time of the literature review, but the results may underpin an acceptance test for new trains. The criterion may then eventually be adopted by the European TSIs.

It is believed that the existing single-parameter criterion that does not account for the possibility of ballast flight initiation by mechanisms such as track vibration or the suction associated with the nose pressure pulses of trains is unlikely to cover all high speed rail operations adequately. *There is further research needed in this area.*

10.6 Conclusions and Recommendations

10.6.1 Conclusions

The following conclusions, based on a review of the results of the literature search, include:

- Ballast flight constitutes a potentially significant issue for high speed trains at speeds greater than the current international high speed trains' operating speeds.
- Concepts to understand ballast flight caused by the aerodynamic effects of HST are not fully developed.
- Impacts include reported damage to vehicles and equipment with the potential for injuries to passengers and workers.
- Mitigation measures include reduction of train speeds and restrictions on placement heights of ballast relative to the ties.

10.6.2 Gaps and Issues

Apart from short test runs, there is no international experience of operating at speeds as high as 250 mph on ballasted track. There are no internationally-agreed methods of assessment for ballast flight.

No current standard has been adopted by the United States for the placement of ballast along the track bed to mitigate ballast flight.

10.6.3 Recommendations to Address Gaps and Issues

A standard for ballast placement could be adopted based on the Chinese Code of Design of High-Speed Railway with modifications to accommodate North American vehicles and maintenance procedures. On-going research in Europe, Japan, and South Korea should be assessed for potential use in the development of such a standard.

Research into ballast flight is recommended for North American track design, maintenance procedures, and vehicles.

11. Conclusions and Recommendations Including Next Steps

11.1 Summary

The review, selection, designation of pertinent information, and assessment of information from the literature search regarding HST's aerodynamic factors and issues have been presented in Chapters 2 through 10. Substantial progress has been achieved in compiling into this single document those aerodynamic factors and issues relative to HSTs.

Much of the information, however, was found to be limited in scope and not readily transferrable to the development of an aerodynamic assessment and mitigation design guidance manual that allows for maximum flexibility of type of vehicles, operations, and right-of-way considerations.

The primary reasons for this lack of transferability were that the information:

- presented experiments or analysis relating to a defined situation but lacked the means of generalizing the results;
- provided calculation methods without any guidance as to what results should be considered acceptable;
- provided assessment methods and acceptability criteria that are based on or restrict the type and size of the vehicles ;
- was restrictive and not available in the public domain; and
- contained gaps in information and basic understanding.

This chapter presents recommendations and a way forward to address these information gaps so that a guidance manual allowing substantial design flexibility can be developed. It includes:

- discussion of the structure of the guidance manual;
- summary of types of information gaps and methods to ascertain the information to fill the gaps; and
- specific recommendations for addressing individual information gaps.

General conclusions and recommendations of this chapter include:

- recommendations for a guidance manual with a two part approach to design assessment and mitigation;
- specific development steps for production of the guidance manual;
- a table of specific recommendations for establishing the information necessary to address individual gaps in information; and
- a summary of next steps for the way forward.

11.2 Structure of the Design Guidance Manual with a Two Part Approach to Aerodynamic Assessment and Development of Mitigation Measures

Aerodynamic criteria and look-up tables for design assessments and selection of mitigation measures exist internationally but only for certain limited train types and operational arrangements. An example of a limited operational arrangement within the existing standards is that the literature search produced very little information and no guidance or assessment methods relating to aerodynamic impacts from HSTs on freight trains.

An Aerodynamic Assessment and Mitigation Design Guidance Manual for the U.S. should be flexible to accommodate varying train types and operational conditions.

To develop a design guidance manual both expeditiously and cost effectively, a two part approach for the structure of the guidance manual is proposed.

Part One would include aerodynamic assessments and selection of mitigation measures based on existing international standards, but with current limitations such as:

- maximum train dimensions and body types;
- train types that comply with established aerodynamic tests;
- speeds limited to 200 mph; and
- no sufficiently close adjacent operations with freight rail.

Part Two would include aerodynamic assessments and development of mitigation measures allowing for maximum flexibility in both train type and operations. This Part would apply to Tier III and to Tier II operations that are different or exceed the limitations imposed by the existing international standards. Part Two would accommodate:

- larger train dimensions;
- trains whose aerodynamic performance are outside the defined existing parameters;
- speeds above 200 mph; and
- joint operations with close freight rail track.

The advantages of such a two part approach structure will be:

- Part One will allow for immediate guidance from international standards being available, but with understood limitations.
- Part Two will allow for:
    - phased development and implementation of standards reflecting the anticipated types of trains and operating conditions for the U.S.;
    - phased research and development efforts and cost; and
    - flexibility in implementation of Part Two assessment and mitigation measures.

11.3 Types of Information Gaps and Methods to Fill Gaps

As discussed throughout Chapters 2 through 10, there are numerous gaps of information in both theory and practice for assessment of aerodynamic forces, impacts, and development of flexible mitigation measures. The following sections describe the types of gaps and the methods needed to fill them.

11.3.1 Extending Existing Criteria and Methods to Different Train Types

The literature search and subsequent assessment of findings showed formulae and criteria exist relative to some aerodynamic impacts and mitigation measures. However, these formulae and criteria are limited for use to certain train types or sizes. For example, the formulae for pressures on wayside structures assume European-size trains with a defined standard of streamlining. For Part Two of the Guidance Manual, the formulae need to be adapted for a wider range of train types. This task could be achieved using scale model testing.

11.3.2 Speeds Above 200 mph

Certain aerodynamic phenomena found during the literature search are not considered problematic at operating speeds up to 200 mph but could become problematic at higher speeds. Some of these (such as ballast flight) are not well understood and need further research. Others are well understood in principle but assessment methods and criteria are lacking. Many of the gaps identified in this study relate to the need to encompass speeds up to 250 mph.

The development of “correction factors” similar to the Mach number correction factor discussed in Chapter 3 may be needed for certain criteria and assessments. Dependent on the nature of these criteria and assessments, verification of the appropriateness of the correction factor may require full-scale or reduced scale moving model testing.

11.3.3 Shared Corridors

There are large gaps in the knowledge of HST effects on other traffic types because shared corridors are not commonly encountered internationally. While measurements have been made on Northeast corridor it would be difficult to develop guidance criteria for all shared corridors from a generalization of these measurements. Field research, computational analyses, full-scale, and reduced scale moving model testing will be required.

11.3.4 Developing New Criteria or Assessment Methods

Published criteria suitable for use in a Design Guidance Manual are lacking for several HST aerodynamic phenomena. Examples include micro-pressure waves emitted from tunnels (Chapter 8) and crosswind route risk assessment (Chapter 5). Research and assessment methods will range from measurements taken during full-scale testing to computational analyses.

11.3.5 Improvement of Existing Criteria and Standards

The literature search found instances where criteria and assessment methods exist internationally, but they are either dated or could be enhanced using today’s advances in testing methods, computational analysis techniques, and equipment.

In these cases, discussion with the FRA is recommended to decide whether to adopt the existing criteria and methods, whether better criteria and methods should be developed, and how a program should be developed and managed to accomplish what is decided as the best approach.

11.4 Specific Recommendations for Addressing Individual Information Gaps

Specific recommendations to address information gaps are discussed in detail in Chapters 2 through 10 and are summarized in Table 20 and Table 21. Both tables contain a prioritization of the efforts to accommodate phasing of effort and cost. The ultimate priorities will require coordination and concurrence from the FRA.

The priority rating is defined as follows:

- Priority 1 - issues that (in the opinion of the authors) must be resolved to enable definition of the most essential elements of guidance for Part One of the Design Guidance Manual.
- Priority 2 - secondary issues for Part One of the Manual and essential elements of Part Two of the Manual.

- Priority 3 - issues that are thought to be less problematic even at speeds up to 250 mph, and secondary issues for Part Two of the Manual.

Table 20. Information gaps and recommended actions prioritized for Part One of Design Guidance Manual using existing international standards

Issue	Issue or Gap	Action or comment	Priority
Slipstreams (Chapter 2)	Safety criteria for safe distances for platforms and track workers in the United States.	Select from existing international criteria.	1
	Speed limits for tracks alongside platforms.	Select from existing international practice.	1
	Existing safety criteria do not relate to risk of falling accidents by nearby passengers or track workers.	Research to improve criteria.	3
	Safety criteria for child strollers on platforms are lacking.	Research to develop criteria.	2
Pressures on Wayside Structures (Chapter 3)	Formulae for calculating pressures.	Agree on use of existing formulae.	1
	Lack of data on tolerance to pressures of typical existing wayside structures.	Agree to assumptions regarding closeness of passage to structures.	1
	Improvement of existing formulae may be desirable.	Testing and development of better formulae.	3
	Lack of information about the effect of pressure pulses on track workers.	Agree to assumptions about limited operating speeds.	1
Trains Meeting and Passing Each Other (Chapter 4)	Guidance on track spacing for HST in the United States (or, maximum speed for given track spacing).	Select from existing international guidelines.	1
Crosswinds (Chapter 5)	Assessment methods for rail vehicles exist but are rather complex.	Develop and validate simplified system.	1
	Meteorological route assessment method suitable for the United States is lacking.	Develop method based on data from U.S. National Weather Service.	1
	Safety strategy for tornados is required.	Research and develop guidance.	2
	Route risk assessment method (vehicles plus route) suitable for the United States is lacking.	Develop and validate methods for assessments.	1
	Data for North American “reference operations” with history of safe operation is required.	Gather wind data and measure crosswind characteristics of rail vehicles.	1
Test and Analysis Methods (Chapter 6)	Standards for aerodynamic tests needed for the United States.	Agree to use of existing international standards.	1

Issue	Issue or Gap	Action or comment	Priority
Pressure Wave Effects Inside Tunnels (Chapter 7)	Methods for calculating pressure wave effects.	Agree to use of existing specialist software.	1
	Safety criterion for the United States is lacking.	Propose to adopt international "medical safety criterion".	1
	Pressure comfort criteria for the United States are lacking.	Select from existing criteria (sealed trains only).	1
	Lack of published methods of assessing pressure loads on fixed equipment.	Develop guidance and validate by testing.	2
Micro-Pressure Waves Emitted from Tunnels (Chapter 8)	Assessment and calculation methods suitable for use in initial design.	Agree to use of existing approximate methods.	1
	Lack of published criteria or standards for MPWs suitable for use in initial design.	Select simple criterion based on existing international practice.	1
	Simple criteria do not relate to audibility or other impacts.	Research to improve criteria.	2
	Noise-based criteria for assessing impacts from existing tunnels.	Criteria exist internationally, but testing and research is needed to calibrate for U.S. expectations.	2
	Lack of assessment methods for "secondary" MPWs.	Agree to use of limited speeds.	3
	Lack of information on directionality of emission of MPWs.	Agree to use existing approximation methods for assessments.	3
	Lack of assessment methods for effect of ballast on wave propagation (and hence on MPWs).	Research needed.	3
	Lack of assessment methods for potential mitigation methods for side passages and in-tunnel air spaces.	Research needed.	3
Drag Effect (Chapter 9)	Data for specific trains to be used with Davis Equation held by train manufacturer.	Agree to use of existing assessment methods.	1
Ballast Flight (Chapter 10)	Lack of United States standard on ballast placement to avoid ballast flight.	Develop standard similar to Chinese standard.	1
	Lack of knowledge and assessment methods for ballast flight. Research currently under way internationally.	Assess results of current research and incorporate pertinent findings.	3

Table 21. Additional information gaps and recommended actions prioritized for Part Two of Design Guidance Manual based on phased development efforts

Issue	Issue or Gap	Action or Comment	Priority
Slipstreams (Chapter 2)	Safe distances for track workers lacking for speeds above 185 mph.	Testing to derive speed/distance trade-off.	2
	Unknown effect of non-standard train dimensions.	Testing to derive rules to account for train dimensions.	2
	Assessment of safe distance for less aerodynamic trains.	Testing to derive guidelines and criteria.	2
	Inability to compare existing measurements from Northeast Corridor with international equivalents.	Repeat measurements to international standards.	2
	Possible impacts of slipstreams on other trains especially freight.	Research to investigate further.	3
Pressures on Wayside Structures (Chapter 3)	Unknown effect of train dimensions and types in existing formulae.	Testing to extend formulae to a wider range of train dimensions and types.	2
	Determination if formulae require a Mach number correction for 200-250 mph.	Testing to check.	3
	Lack of guidance on minimum distance of wayside structures from the track.	Testing and develop guidelines.	3
	Lack of data on tolerance to pressures of typical existing wayside structures.	Measure pressures on existing structures (NE corridor or other lines).	2
	Lack of criteria for vibrations of buildings near the track caused by pressure pulses from HSTs.	Research and conduct measurements to develop criteria.	3
	Lack of information about the effect of pressure pulses on track workers.	Research on human tolerance to very short duration pressure pulses.	3
Trains Meeting/Passing Each Other (Chapter 4)	Lack of guidance on track spacing (or, maximum speed for given track spacing) for HSTs of non-European dimensions or types.	Develop guidance based on comparative analysis method.	2
	Lack of data to support track spacing (or, maximum speed for given track spacing) for HSTs of non-European dimensions or types.	Testing; obtain factors for different train types; extend formulae to account for train dimensions; and develop guidelines.	2

Issue	Issue or Gap	Action or Comment	Priority
	Lack of guidance on track spacing between HST and conventional lines in the United States.	Measure pressures on trains on conventional lines and develop guidance.	2
	Determine requirement for a Mach number correction factor for 200-250 mph.	Testing and assessment needed for determination.	3
	Lack of data on tolerance to pressures of freight and older North American rolling stock.	Measure pressures on trains on conventional lines and develop guidance.	2
	Lack of assessment methods and criteria on trains passing and meeting in tunnels.	Research and develop guidelines.	2
Crosswinds (Chapter 5)	Assessment methods for "non-standard European" rail vehicles.	Assess applicability of existing methods from Part One.	2
	Route meteorological and risk assessment methods	Assess applicability of existing methods from Part One.	2
	Data for North American "reference operations" with history of safe operation is required.	Research existing operations.	2
Test and Analysis Methods (Chapter 6)	Standards for aerodynamic tests needed for the United States.	Assess applicability of existing methods from Part One.	2
Pressure Wave Effects Inside Tunnels (Chapter 7)	Analysis methods.	Assess applicability of existing methods from Part One.	2
	Safety criterion and pressure comfort criteria for passengers and crew, with guidance for unsealed as well as sealed trains.	Develop guidance based on existing international practice.	2
	Lack of information on tolerable pressures for all train types in tunnels.	Research and develop guidance.	2
	Lack of assessment methods for dynamic oscillation caused by vortex shedding at 200-250 mph.	Research and develop assessment methods.	3
Micro-Pressure Waves Emitted from Tunnels (Chapter 8)	Develop assessment methods and criteria	Assess applicability of existing methods and criteria from Part One.	2
	Lack of assessment methods for "secondary" MPWs.	Research and develop guidance.	2

Issue	Issue or Gap	Action or Comment	Priority
	Lack of assessment methods for effect of ballast on wave propagation (and hence on MPWs).	Research and develop guidance.	3
	Lack of assessment methods for some potential mitigation methods for side passages and in-tunnel air spaces..	Research and develop guidance.	3
Drag Effect (Chapter 9)	Formula (Davis Equation) already exists. Data for specific trains to be obtained from train manufacturer, or measured if not available.	Some operators may wish to measure drag data as this affects operating costs.	3
Ballast flight (Chapter 10)	Lack of United States standard on ballast placement to avoid ballast flight.	Assess applicability of existing standard from Part One.	2
	Lack of knowledge and assessment methods for ballast flight (research currently under way internationally).	Assess results of international research and supplement if needed.	2

11.5 Summary of Next Steps (Way Forward)

In regards to the next steps for the way forward for development of an Aerodynamic Assessment and Mitigation Design Guidance Manual we recommend the steps shown below. All of these steps are to be performed in close coordination and concurrence with the FRA.

- Establish scoping and review meetings with the FRA.
- Agree to the structure of the Guidance Manual.
- Modify priorities as determined from scoping meetings.
- Establish phasing schedules and cost budgets.
- Agree to train types for which existing criteria can be applied.
- Prepare an Interim Guidance Manual with the information available to date.
- Prepare draft detailed assessment methods with list of tests and assessments needed to fill knowledge gaps.
- Develop, confirm, and deliver a program to fill the knowledge gaps.
- Perform testing and assessments as planned and fill the gaps in existing assessment methods.
- Perform further testing to verify the draft assessment methods and complete agreed to tasks
- Prepare the updated Guidance Manual that can be followed without the need for specialist aerodynamic knowledge.

Additionally, integral to the next phase of the way forward, we recommend the formation of a team of professional and specialty talent for performance of research, testing, analysis and assessment tasks. All team members will be selected in consultation and with concurrence of the FRA.

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Abbreviations and Acronyms

AAR	Association of American Railroads
ADA	Americans with Disabilities Act
APT	Advanced Passenger Train
AREMA	American Railway Engineering and Maintenance-of-Way Association
BFPF	Ballast Flying Probability Factor
CEN	Comité Européen de Normalisation (European Committee for Standardization)
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CHSRA	California High Speed Rail Authority
CPU	Central Processing Unit
CU	Customs Union of Belarus, Kazakhstan, and Russia
CWC	Characteristic Wind Curve
DB	Deutsche Bahn (German Railroads)
DES	Detached Eddy Simulation
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DNS	Direct Numerical Simulation
EMU	Electric Multiple Unit
EN	European Norm
ERRI	European Railway Research Institute
ETR	ElettroTreno Rapido (Fast Electric Train)
FRA	Federal Railroad Administration
HSNEL	High-Speed Non-Electric Locomotive
HSR	High-Speed Rail
HST	High-Speed Train
ICE	InterCity Express
ISO	International Organization for Standardization
KTX	Korea Train Express
LES	Large Eddy Simulation
MBS	Multi-Body Simulation

MPW	Micro-Pressure Wave
NEC	Northeast Corridor
PDF	Probability Density Function
PIV	Particle Image Velocimetry
PSP	Pressure Sensitive Paint
RANS	Reynolds-Averaged Navier-Stokes
RSSB	Rail Safety and Standards Board
RTRI	Railway Technical Research Institute
RWT	Rails with Trails
RZD	Rossiyskie Zheleznye Dorogi (Russian Railways)
SCADA	Supervisory Control and Data Acquisition
SEL	Sound Exposure Level
SNCF	Société Nationale des Chemins de Fer Français (National Society of French Railways)
SPL	Sound Peak Level
TGV	Train à Grande Vitesse (High Speed Train)
TRAIN	Transient Railway Aerodynamics Investigation
TRANSAERO	Transient Aerodynamics for Railway System Optimization
TSI	Technical Specifications for Interoperability
TTC	Transportation Technology Center
TTCI	Transportation Technology Center, Inc.
UIC	Union Internationale des Chemins de Fer (International Union of Railways)
UK	United Kingdom
URANS	Unsteady Reynolds-Averaged Navier-Stokes
WMATA	Washington Metropolitan Area Transit Authority