U. S. Department
of Transportation

**Federal Railroad
Administration**

ASSESSMENT OF POTENTIAL AERODYNAMIC EFFECTS ON PERSONNEL AND EQUIPMENT IN PROXIMITY TO HIGH-SPEED TRAIN OPERATIONS

Office of Research
and Development
Washington, D.C. 20590

Safety of High-Speed Ground Transportation Systems

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13. ABSTRACT (Maximum 200 words)

Amtrak is planning to provide high-speed passenger train service at speeds significantly higher than their current top speed of 125 mph, and with these higher speeds, there are concerns with safety from the aerodynamic effects created by a passing train. Trains operating at high speeds will pass other trains on adjacent tracks, passengers on station platforms, and other equipment and workers along the wayside. The aerodynamic effects created by a passing train include both pressure and induced airflow which can be a potential hazard to equipment and people in proximity to the passing train.

This report assesses the potential hazards created from the aerodynamic effects of passing high-speed trains at speeds of 150 mph. It will specifically address the hazards to window glazing on passenger trains and to people on station platforms. A literature review was conducted and many of the data obtained served as a basis for this study. A description associated with passing trains and data on aerodynamic force levels produced from a passing train are presented first. Data on structural load limits for glazing and tolerance levels for human comfort which provide criteria for hazard assessment are also presented. Second, computations are performed to assess the potential hazards of passing high-speed trains to train window glazing and to people.

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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

METRIC TO ENGLISH

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)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
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)

TEMPERATURE (EXACT)

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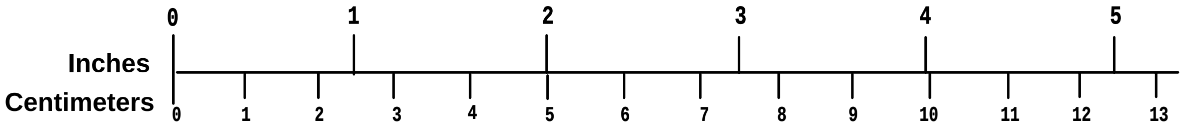
QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°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

This report examines the effects of aerodynamic forces created by a train traveling at speeds up to 150 mph as it passes other trains on adjacent tracks, people on station platforms, and structures in proximity to the train. Information and test data in this report were obtained from the literature that was identified through international literature surveys on aerodynamic effects produced by high-speed trains.

Aerodynamic forces created by a passing train are influenced by three factors: train speed, distance from the train, and the geometry of the train. Train speed in particular has a great impact on the aerodynamic force since these forces increase with the square of the train speed. The aerodynamic forces also increase with proximity to the passing train. Finally, the aerodynamic forces caused by the head perturbation are greatly affected by the geometry of the train nose – a slender nose produces weaker aerodynamic force than a bluff nose.

Two aerodynamic effects are created by the passage of a train. One effect is the pressure pulse that is produced by the passage of the head of the train, and another, generally weaker pulse, at the tail. During the passage of the train nose, a pressure pulse is produced where pressure rises, followed by a rapid pressure drop, with the entire event occurring in a very short duration. A second effect is the airflow induced by a passing train. The moving train creates a boundary layer along the length of the train, and a wake behind the train. This results in an airflow in the general direction of the moving train, while at the wake behind the train, the airflow is accompanied by turbulent fluctuations.

The magnitude of the aerodynamic forces expected when trains pass at high speeds can be determined from data gathered in the literature review. The data on aerodynamic forces display a range of values at a given train speed. Train geometry, particularly the shape of the train nose, has a significant influence on the strength of the aerodynamic forces. There are sufficient variations in the strength of the aerodynamic forces due to a train's design, such that a streamlined train with a slender nose, traveling at 150 mph, creates aerodynamic forces that are no more severe than a train with a bluff nose traveling at a speed of 110 mph. If a train proposed for high-speed operation has a streamlined body design with a slender nose at the head and tail ends, it is possible that its favorable aerodynamic characteristics can offset the higher aerodynamic forces that would otherwise be created by its increase in speed.

This report focuses on the effects of aerodynamic forces on window glazing as a train passes another train on an adjacent track, and on the effects of pressure and airflow on people on station platforms.

Passenger Car Window Glazing

A moving train passing another train (either stationary or approaching) on an adjacent track generates a moving pressure wave onto the other train. When a train is passing another train at a speed of 150 mph, the maximum suction pressure is 0.107 psi for a slender-nose train, and 0.213 psi for a bluff-nose train.

Based on ¼-in. safety plate glass, the estimated breaking pressure for Amfleet-1 car window size is 3.8 psi, and for MBB single level commuter coaches and Kawasaki bi-level commuter cars, it is 1.9 psi. These estimated breaking pressures on the window glazings are about a factor of ten above the computed static loading. Although these are static loading comparisons, the breaking pressure is sufficiently high that the stress developed from the dynamic response is not expected to be a problem.

Platform Safety

Three different effects were considered in evaluating the safety of people on platforms at non-stop stations as high-speed trains pass through.

First is the effect that the pressure generated by the nose of the passing train has on a person's eardrums. Based on a maximum peak-to-peak pressure limit of 0.2 psi, a train passing at a speed up to 150 mph generates a pressure differential that is within this limiting value. With a person situated at a distance of 3.3 ft or greater from a passing train, whatever sensation is felt in the eardrums is not likely to be significant.

Second is the effect that the pressure wave from the nose of the passing train has on a person's sense of balance. The pressure wave generated by the head of a TGV-001 train passing at 143 mph can produce a force of 16.9 lb. on a person 2.4 ft from the side of the train. For a person weighing 165 lb., this force would produce an acceleration of 0.1 g, about the level of acceleration that would be experienced by a person on a rapid transit train during acceleration. Because the force acts for a very short duration, a momentary imbalance might occur to a person, depending on the person's reaction to the sudden blast of air.

Finally, the effect of the induced airflow from a passing train on people on station platforms is evaluated for trains with high, and low induced airflows. Permissible passing train speeds were computed based on wind strength criteria suggested by British Rail of 24 mph for members of the public, and 38 mph for railroad personnel (corresponding to Beaufort numbers 5 and 7 respectively). For a person 6.6 ft away from the side of a passing train, the criteria would limit the passing train speed to a range between 61 to 91 mph for the public, and between 97 to 144 mph for railroad personnel. At the same distance of 6.6 ft from the train, a train passing at a speed of 150 mph would generate airflow speeds of 40 to 59 mph. These results indicate that a train passing at a speed of 150 mph can produce significant airflow. This airflow and the wake effect of the train with its turbulent fluctuations and buffeting in the air, along with any dust and debris that is blown or propelled, is a serious issue impacting the comfort and safety of people on the platform.

1. INTRODUCTION

As train speed increases, the effects of a train's aerodynamic forces on its surroundings increase. These forces can have an adverse effect on adjacent properties and might jeopardize the safety and comfort of people near the track. These effects consist of pressure variations resulting from the moving train's flow field interacting with another nearby train or structure, and of wind produced by the air being carried along with the train. These effects are consistent with the operation of high-speed trains, and they create the issues of aerodynamic forces on adjacent trains, wayside equipment, and on people on station platforms.

Aerodynamic effects arising from a moving train include pressure distribution, both positive and negative, around the train. These pressures can vary sharply in a brief period of time as the train's airflow interacts with nearby objects such as passing trains, wayside structures, or tunnels. At high speeds, time duration as well as the magnitude of the pressure change are critical in evaluating effects on a structure.

Due to the viscosity of air, a moving train drags the surrounding air with it, resulting in an airflow that, relative to stationary objects, is felt as wind. This induced airflow arises from two locations - the boundary layer formed along the side of the moving train and the wake at the rear of the train. Since the air at the surface is moving at the same speed as the train, a train traveling at high speed can induce high airflows near the train. In addition, the strong, turbulent airflow created at the wake can stir up debris around the track and propel it onto station platforms. Therefore, objects or people close to a train passing at high speed can experience high wind forces.

This study was conducted to assess the potential aerodynamic effects on people and equipment in proximity to train passages at speeds up to 150 mph. A literature search was conducted to identify relevant sources of information on this subject. The results obtained have been supplemented with calculations to provide an understanding of the potential aerodynamic effects from passing high-speed trains.

2. DESCRIPTION OF TRAIN PASSING EVENT

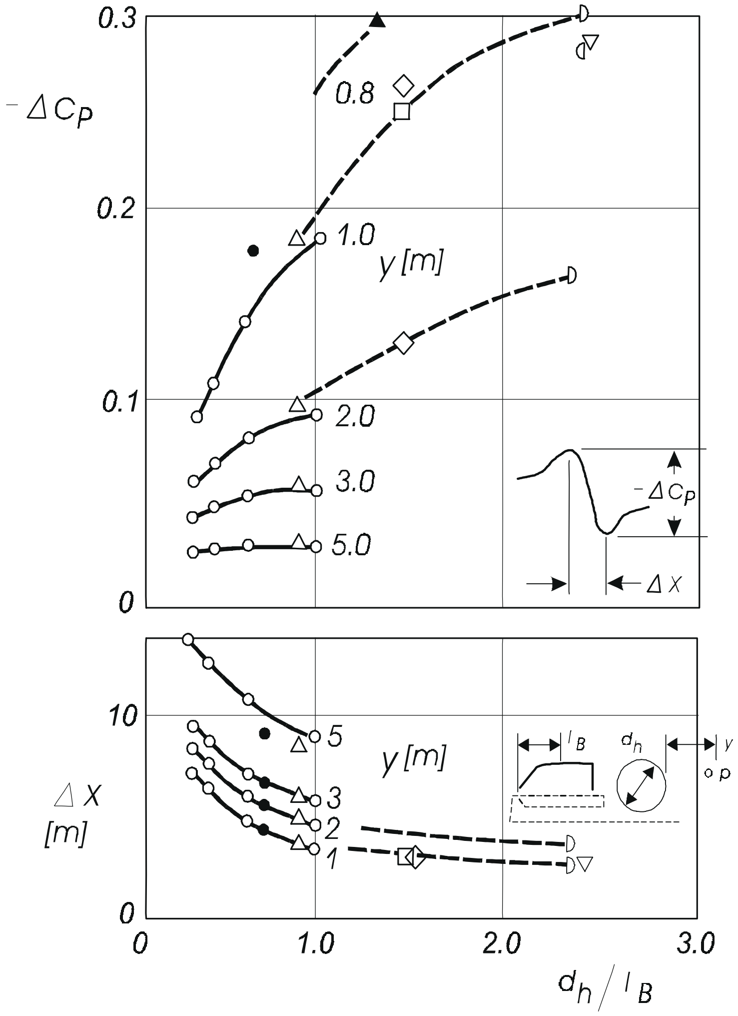
A literature search was conducted to assess the potential aerodynamic effects on people and equipment in the proximity of high-speed train operations. The information obtained indicates that the issues associated with the aerodynamic effects of train passage have been recognized, and both theoretical and experimental studies have been performed to measure these effects.

Data obtained from all sources can be divided into four categories: aerodynamic pressures generated from passing trains, airflow induced by a passing train, structural loading due to aerodynamic pressures, and human comfort tolerance levels. Some references provide a comprehensive discussion on various aspects of the aerodynamic effects of passing trains, while others focus on a particular aspect of the topic. Hammitt,[1] Sockel,[2] Gawthorpe,[3,4] Neppert,[5] and Marty[6] provide a broad treatment on the subject of the aerodynamic effects of train passages that includes theoretical and experimental data, and the potential effects associated with the event.

2.1 Aerodynamic Pressures Generated from Passing Trains

A moving train creates a pressure distribution from the flow field surrounding it. A passing train produces a pressure variation in its proximity that rises to a positive peak followed by a drop in pressure to a negative peak, all occurring in a short period of time as the head of the train passes. The pressure is generally near ambient along the length of the train, until the tail of the train is reached, where the pressure rapidly drops and then rises. The difference between the maximum positive pressure and the minimum negative pressure (differential pressure), and the time interval between which the maximum and minimum pressure difference occurs, are the two relevant parameters of interest, because this pressure pulse will act as a shock on structures such as windows.[2]

The five parameters affecting the magnitude of the pressure wave due to the passage of the head of a train are train speed, train cross-sectional area, distance from a passing train, or the lateral clearance between trains, ground clearance, and nose length.[3] Figure 1 presents theoretical and experimental differential pressure coefficients at different aspect ratios of the train nose and distances from the train[5] (see Appendix for definition of aerodynamic force coefficients). The duration of the pressure pulse is inversely proportional to the relative speeds between the observer and the passing train. For a slender nose train, the duration of the pressure pulse caused by the head perturbation is about the time it takes the nose to pass, which for an APT-E (British Rail's experimental Advanced Passenger Train that reached a speed of 152 mph in 1975) with nose length of 11.5 ft is about 0.05 psi at a passing speed of 155 mph.[3]



Theory	Symbol	Nose Shape	Height Position, (m)
Theory	○	Ellipsoil	1.7 m above train floor
	△	P1	1.4 m above train floor
Model	○	Ellipsoil	1.7 m above train floor
	△	P1	1.4 m above train floor
	●	AVF/PP1	1.4 m above train floor
	◇	DB locomotive 103	2.5 m above top edge of rails
	▽	DB locomotive 110	2.5 m above top edge of rails
	◗	DB locomotive 112	2.5 m above top edge of rails
Actual Readings	□	DB locomotive 103	2.5 m above top edge of rails
	◖	DB locomotive 112	2.5 m above top edge of rails
	▲	RAB De 8/16	2.2 m above top edge of rails

Figure 1. Lateral aerodynamic differential pressure coefficients from passage of nose wave in unrestricted flow without side winds and distance intervals of pressure pulse.[5]

Kikuchi[7] performed a numerical analysis on the pressure variation from the passage of a train and compared the results with test measurements. His analysis used a three-dimensional boundary element method, and assumed an incompressible and inviscid flow field. A comparison between the numerical and measured results shows good agreement in the positive pressure peak at the head, but the negative pressure peak that follows drops more in the measured values than in the numerical results. This was attributed to the frequency response of the measuring device. In the tail, the measured pressure variations are smaller than the computed values because of flow separation.

Kikuchi also presented countermeasure techniques to reduce the pressure variations along the wayside from the passage of a train. One approach is to design an elongated train nose to reduce the pressure gradient from the head perturbation, and to use a wedge-like nose configuration so that more of the air is displaced upward instead of sideways. Another technique to reduce the pressure variations on the wayside is to erect a wall along the track. Results showed that the greatest pressure attenuation occurs in the vicinity of the wall, but the attenuation is less farther away from the wall.

When two trains pass each other, the train being passed (observing train) undergoes a pressure change similar to the pressure change that occurs when a single train passes by a given point in open air, except that the pressure levels are higher for two passing trains. The effect is a traveling pressure wave (positive peak to negative peak) that sweeps along the length of the observing train, followed by a similar opposite pulse (negative peak to positive peak) at the passage of the tail of the train.[3]

One interesting aspect concerns the relationship between the speed of the two trains and its effect on the pressure. The amplitude of the pressure wave induced by the passing train onto the observing train during passing is dependent only on the speed of the passing train, its nose shape, and the spacing between the two trains, but not on the speed of the observing train.[9] This can be explained as follows:

> “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.” [3]

While the amplitude of the pressure pulse generated by the passing train is theoretically unaffected by the motion of the observing train, measurements conducted by the French and Germans showed that there is a 30 to 40 percent increase in differential pressure coefficients when both the observing and passing trains are moving at the same speed.[4] Gawthorpe attributes this effect to the interaction of the boundary layers between the two trains, and the interaction of the leeward slipstream from one train to the other during windy days.

Experimental measurements have been made to measure the aerodynamic pressures generated between two passing trains. When a moving train passes a stationary train, the aerodynamic pressures exerted on the stationary train are more severe than those on a moving train. Because the higher forces appear on the stationary train, along with its simpler instrumentation, measurements are frequently made on the stationary train in model and full-scale experiments.[2] Figure 2 presents the differential pressure coefficients from both theory and experiments for the passages of two trains where both trains are moving in opposite directions at the same speed, and where one train is moving and the other is stationary.

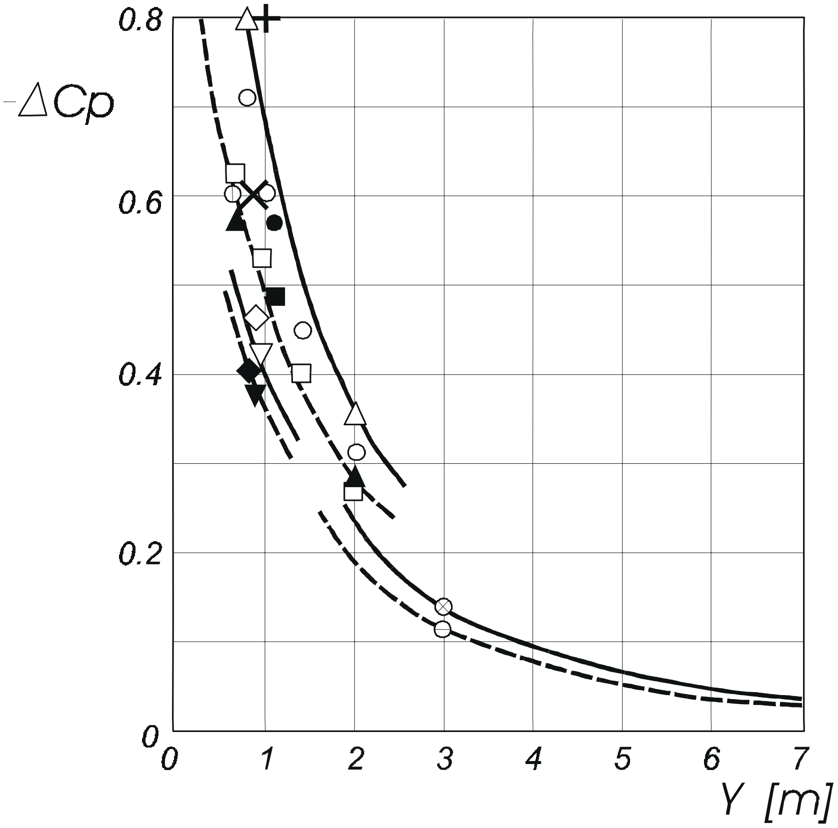
The effect of train nose geometry on pressures generated at the head of the train is illustrated from full-scale test.[4] A comparison of pressures can be made between slender-nose locomotives having nose shape ratios (ratio of nose length to body width) of 0.8 to 1.25, and bluff-nose locomotives whose nose shape ratios range from 0.1 to 0.5. Measurements showed that the slender-nose shapes of the APT train produced pressure effects that are half those of bluff-nose trains, and therefore, a slender-nose train can travel at a 40 percent higher speed for the same effect as a bluff-nose train. Tests performed with container trains generated pressure pulses that are up to 20 percent higher than those of bluff-nose trains.

A theoretical solution on the aerodynamic interaction between two passing trains was computed based on the assumptions of incompressibility and two-dimensional inviscid flow.[2] It is expected that the assumption of incompressible flow is reasonable for speeds up to 223 mph, but a solution that limits the flow in two dimensions will produce pressures that will be higher than for three-dimensional flow. The trains were modeled as two-dimensional, semi-infinitely long bodies of unit width, with circular noses, and with a centerline-to-centerline distance between trains of 1.3 (distance is larger than train width by a factor of 1.3). Results were obtained for three different train-passing cases: (1) pressures on a moving train being passed by a train traveling in the opposite direction at the same speed; (2) pressures on a moving train as it passes a stationary train; and (3) pressures on a stationary train being passed by a moving train.

Pressures were computed as a function of approach distances at several locations on the train. A comparison can be made on the effects that relative train motion has in pressure response by plotting the pressure history on the car body side (location P-1) for all three train passing cases taken together as shown in Figure 3.

During the late 1960s, the Federal Railroad Administration tested rail vehicles for the High-Speed Ground Transportation Program. The testing program conducted by Melpar, Inc.,[8] made measurements to determine the effects of aerodynamic interactions as two trains pass each other in opposite directions. The cars used for the test were “Silverliners” - self-propelled, multiple-unit cars built by the Budd Company.

In one run, the instrumented train**,** traveling at 128 mph**,** was met by another train traveling in the opposite direction at 100 mph, producing peak lateral differential pressures of 345 Pa (0.05 psi) positive**,** followed by 138 Pa (0.02 psi) negative. In another run, the instrumented train**,** traveling at 100 mph**,** was met by a train traveling in the opposite direction at 138 mph, producing peak lateral differential pressures of 352 Pa (0.051 psi) positive**,** followed by 469 Pa (0.068 psi) negative, with the internal pressure deviating by about 41.4 Pa (0.006 psi).



	Symbol	V Test train / V incoming train	Nose Shape	Pressure At
Theory	—▽—	1	TGV	TGV
	—▼—	0	TGV	TGV
	—△—	1	Paraboloid	Wall
	—▲—	0	Paraboloid	Wall
Model Wiko	□	0	DB locomotive 103	Test Wall
	○	0	DB locomotive 112	Test Wall
	—⊖—	0	P1	Train Silhouette
	—⊗—	1	AVF/PPI	Train Model
Waka	■	0	DB locomotive 103	Test Car
Actual Readings	●	0	DB locomotive 112	Test Car
	⦶	0	RAB De 8/16	Test Car
	◇	1	TGV	Test Train
	◆	0	TGV	Test Train
	+	1	DB locomotive 103	Test Train
	×	0	DB locomotive 112	Test Train

Figure 2. **Peak aerodynamic differential pressure coefficients for the passage of two trains with each train traveling in opposite directions and with a moving train passing a stationary train.**[5]

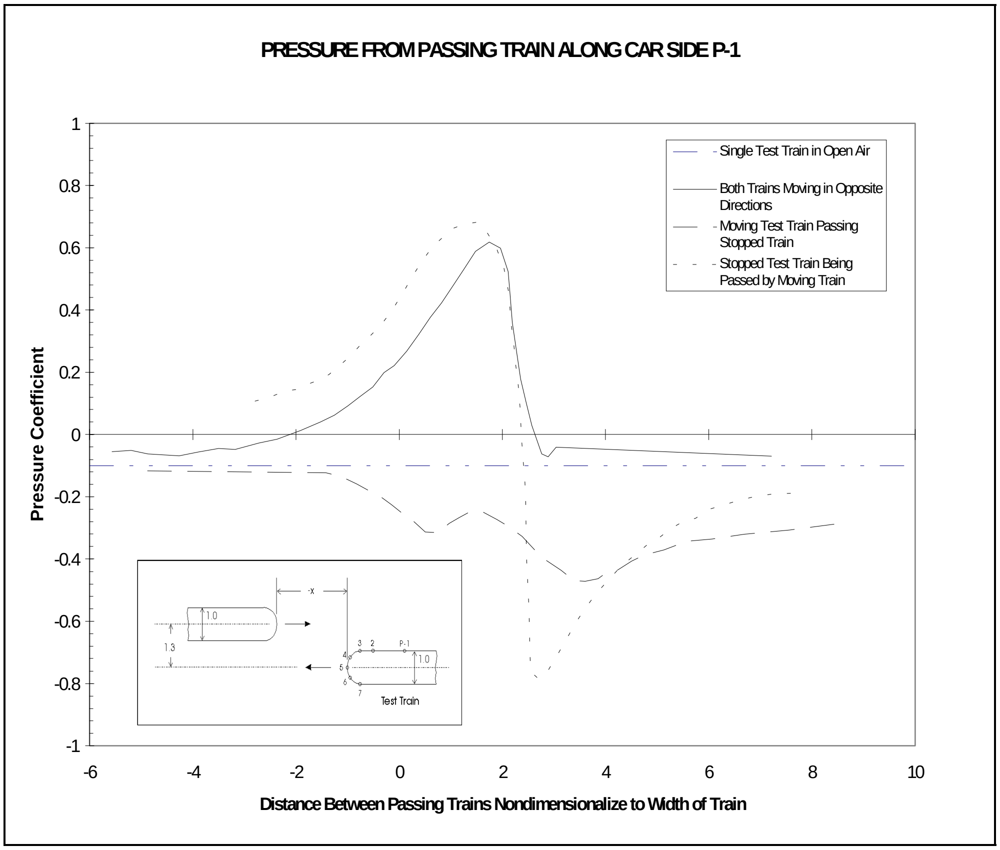


Figure 3. Pressure coefficients at location P-1 for the three train passing cases and a single train in open air from two-dimensional inviscid flow theory.[2]

Table 1 shows the data from these two runs, along with pressure coefficients that were computed based on these data. The results indicate that the pressure coefficients for the two runs differ significantly when comparing their peak values, but the differential pressure coefficients are about the same.

A research program conducted in France by the French National Railway (SNCF), obtained both theoretical and experimental results for a variety of conditions, including the passage of a single train in open air and its effect on wayside objects**;** two trains passing each other in open air**;** a train entering a tunnel; and two trains passing in a tunnel.[6] SNCF obtained results from two- and three-dimensional mathematical models and compared them with experimental measurements using the prototype train**,** TGV 001. Pressures were computed and measured for different positions on the surface of the locomotive body. In the test of two passing trains with distances of 11.5 ft between the two tracks, a TGV 001 train traveling at speeds of 113 mph to 195 mph passed a stationary model of a TGV train, producing a maximum pressure coefficient on the stationary train of about 0.2 to -0.2 at the first peak and second pressure peaks respectively**.** SNCF also made measurements on a stationary train being passed by locomotives with different head geometries (Type 6500, TGV, and RTG locomotives) which showed that a well-streamlined TGV nose produced the lowest pressure variation of the three locomotives.

In a scale model test, Colin[9] measured the aerodynamic pressures on a stationary train as a moving train with various nose geometries passed it. He performed the test using 1:40 scale models on a pendulum-style apparatus, with the moving model mounted to the end of the radial arm that swings past a stationary model at the bottom of the arc where it reached a maximum speed of 39.4 ft/s. Colin applied these measurements for full-scale spacing of 1.64 ft between trains (clearance between trains on the Belgian railways system). In one of the measurements, the pressure coefficients rose to a first peak of 0.2, followed by a drop to -0.4, resulting in a differential pressure coefficient of -0.6. He then conducted a test in a wind tunnel, using 1:10 scale models that showed agreement with the moving model test. Other results and conclusions from this test are as follows:

- A comparison between the differential pressure coefficient and the rate of pressure change shows the corresponding trend where large differential pressures also produce large rates of pressure change.

- Streamlining in the vertical plane was most effective in reducing the amplitude of the pressure wave.

- A car behind the locomotive can produce additional pressure transients as strong as the pressures produced by the locomotive. This was the case when there was a gap between the car and locomotive, and when the car was taller than the locomotive.

Table 1. Data measured from Melpar test with computed pressure coefficients.[8]

Instrumented Train Speed	Passing Train Speed	First Peak Pressure and Coefficient (Cp)		Second Peak Pressure and Coefficient (Cp)		Differential Pressure and Coefficient (Cp)	
km/h (mph)	km/h (mph)	Pa (psi)	Cp	Pa (psi)	Cp	Pa (psi)	Cp
206 (128)	161 (100)	345 (0.05)	0.28	-138 (-0.02)	-0.11	-483 (-0.07)	-0.39
161 (100)	222 (138)	352 (0.051)	0.15	-469 (-0.068)	-0.20	-827 (-0.12)	-0.35

To address the vehicle passing issue on the highway, Beauvais[10] conducted a scale model experiment to measure the aerodynamic forces and moments generated by a bus passing a car parked on the side of the road. Although the bus and car configurations differ from that of a train, the test used a moving model technique that could be useful for scale model train testing. This 1:10 scale model test used a catapult arrangement in which an elastic shock cord propelled a bus down a track, passing a parked car that was instrumented for force measurements.

The European Rail Research Institute (ERRI)[11] conducted a study to determine the aerodynamic loads acting on structures in the vicinity of passing trains. These results are for application in the design of structures erected along the track, such as anti-noise barriers, platform canopies, catenary canopies, and scaffoldings that are exposed to the aerodynamic loads of train passages. ERRI obtained results from theoretical simulations and experimental measurements for passing trains with locomotives of different head shapes. The measurements showed that the passage of the head of a train produced overpressures followed by underpressures (suction), then another underpressure toward the rear of the train followed by overpressures at the passage of the tail. These pressures were of lower levels than those at the head of the train. The study measured both overpressures and underpressures, but only the largest pressure peaks (positive or negative) were presented as pressure coefficients. Effects of natural wind were also measured, and showed that for anti-noise screens at their usual distances from the track, aerodynamic loading on the screens from a passing train with side wind had a greater effect than with head wind.

Trains passing each other in confined environments such as the presence of vertical wall embankments or in a tunnel can create pressures that are more severe than in open air. Based on theoretical and experimental results, pressure changes are most critical when two trains pass in a tunnel (from SNCF document).[5]

The aerodynamics of trains passing each other in a tunnel are more complex than in open air. This is due to waves reflected back from each end of the tunnel whose magnitude of the pressures depends on additional factors such as tunnel length, cross-sectional area, location of passing, and ventilating ducts.

In 1927, Tollmien[12] analyzed a graphical solution using two-dimensional flow for two trains passing in a tunnel. British Rail also conducted a full-scale test on the tunnel-passing problem at the double track Milford tunnel that is 0.486 miles long with a cross-sectional area of 479 ft^2. Pressure changes at the middle of the train during passing in the tunnel, compared to open air, were about three times larger with blocked air shafts, and about twice as large with opened air shafts.[3] Tests conducted by SNCF on two oncoming trains with type BB16000 locomotives, traveling at 89 mph and passing at the middle of the tunnel show the generation of abrupt pressure variations of 0.06 atmospheres or 6,080 Pa (0.882 psi) due to the interaction of the wave fronts.[6]

The presence of tunnels can also affect structures along the wayside outside the tunnels. In a review by Maeda,[13] it was shown in Japan that Shinkansen trains entering a tunnel at high speeds generate a compression wave (called micro-pressure wave) that travels down the tunnel and radiates at the other end. This creates a tunnel sonic boom that can rattle the windows and doors of houses along the wayside. The effect of the wave is stronger for long tunnels with slab track, because the longer tunnels allow the pressure gradient to steepen as the wave propagates through the tunnel, and the attenuation of the wave is less with slab tracks.

The problem of tunnel sonic boom has been mitigated by constructing hoods at the tunnel portal and by designing a more slender train nose geometry to reduce the pressure wave. In a study done by Iida[14] on nose geometry, it was found that a paraboloid of revolution produces one of the smallest pressure gradients of the compression wave**,** and that a longer train nose results in smaller maximum pressure gradients. Using a nonlinear optimization technique, Iida determined an optimum nose shape that produces an even smaller maximum pressure gradient than the paraboloid of revolution.

2.2 Airflow Induced by a Passing Train

In addition to the pressure variations created by the inviscid flow field, there is a viscous effect where the train drags along air, producing a boundary layer that grows outward down the length of the train. The effect of this phenomenon, along with the wake created behind the train, induces an airflow to the surroundings that can be best described as follows:

> "…viscous flow effect **…** involves the action of the train boundary layer which grows in width down the length of the train and in which, the velocity is varying continuously from train speed in the region immediately adjacent to the train down to a very small virtually zero velocity at its outside edge. The effect of the boundary layer is that of a draught moving along the trackside parallel to the train, and imparting a force on an object situated in it due to the consequent pressure field set up around it.
>
> "Behind it, the train leaves a turbulent wake which, due to its mixing with the surrounding air, rapidly spreads out behind, and in so doing dissipates its energy. The effect of this at the trackside is to cause a buffeting which is at a maximum just after the train passes and then reduces in strength as the train proceeds on its way. As the wake consists of a complex vortex field where the flow is highly turbulent and circulatory in motion, an object enveloped in the wake may be subjected to violent force changes which could act in virtually any direction. It is generally felt that the wake produces effects which are the most destabilizing to trackside objects." [3]

People or objects situated close to a train passing at high speeds can experience these high airflow forces. In addition, the wake induces airflow at the rear of the train that can stir up debris around the track which, in turn, can be propelled toward people on station platforms.

Induced airflow speeds have been obtained from both theoretical computation and from test measurements. Theoretical values of the speed of induced airflow can be computed at various lateral distances away from a passing train. Using a 1/7-power law velocity distribution, Figure 4 shows the airflow speeds computed for parameters of vehicle cross-sectional geometry and drag coefficient**,** based on frontal area.[1] Three airflow strengths are computed (high, medium, and low), the severity of which depends on the vehicle parameters.

Figure 5 presents induced airflow data measured from a number of different trains for different lateral distance**s** away from the passing trains.[5] The theoretical airflow values (from Figure 4) also are shown on the graph as a comparison with the measured data. The strength of the induced airflow is dependent on train speed, clearance from the side of the train, ambient wind speed and direction, and nose shape and surface roughness of the train.[4] The external profile of the train can have an important effect on the induced airflow. Measurements indicate that the

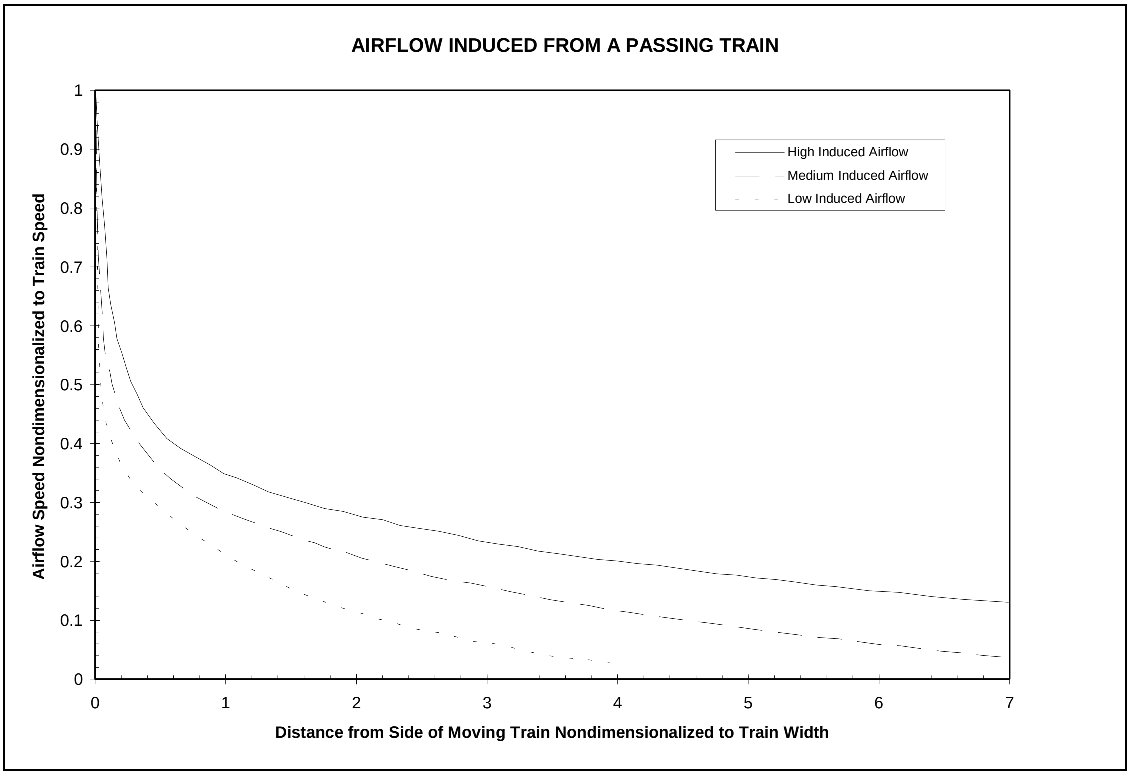


Figure 4. Induced airflow speed from a passing train as a function of lateral distance from side of train.[1]

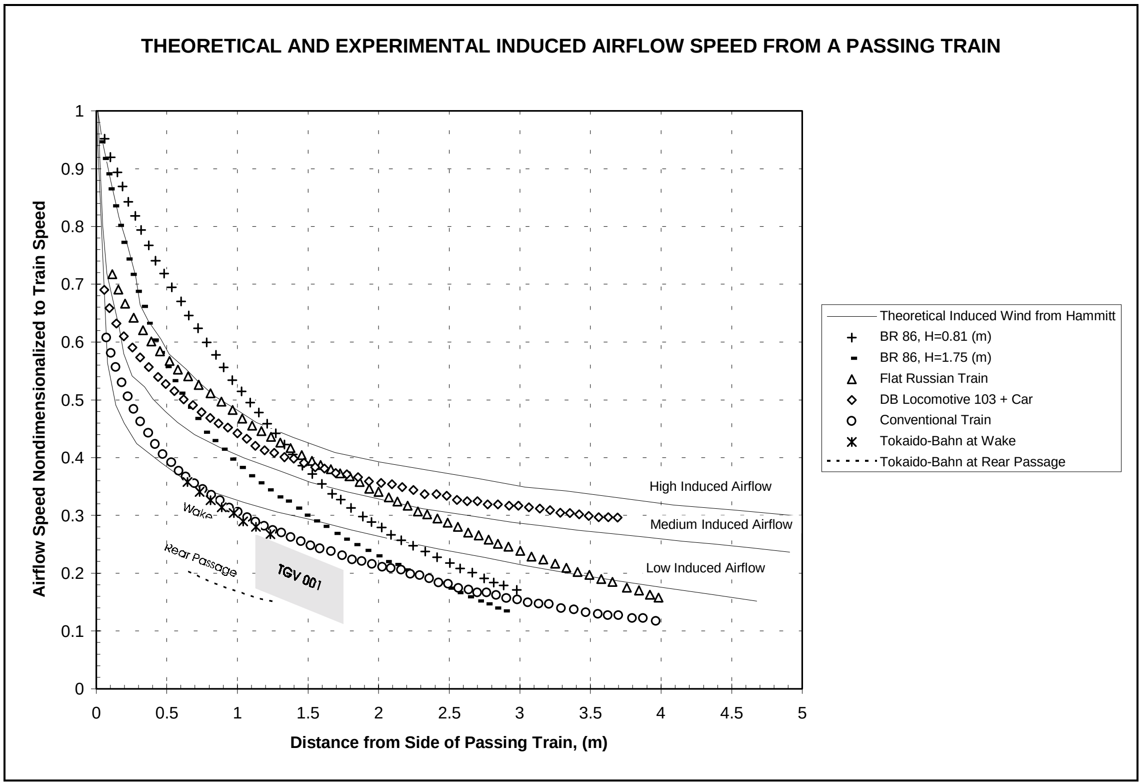


Figure 5. Measured induced airflow at various lateral distance from the train.[5]

induced airflow speed of a slender-nose APT train is 0.78 times lower than for a bluff-nose train, while for freight trains, it can be 1.9 to 3.5 times higher than for a bluff-nose train. Therefore, the APT train can travel at 25 to 30 percent faster than a bluff-nose train and still produce the same maximum flow disturbance.

Wind forces created by passing trains are the subject of an experimental study reported by Andersson.[15] Two bodies were installed along the side of the track to simulate people standing on a station platform at two different distances from the track. The bodies had a projected surface area of 7.86 ft^2 perpendicular to the track, and 3.88 ft^2 parallel to the track, and were located at distances of 10.5 ft and 14.1 ft from the center of the track. Andersson measured wind forces for 32 train passes from three different types of trains: freight trains, IC trains (Swedish express train), and X2 trains (Swedish high-speed train now called the X2000). These measurements were intended to be a comparison of forces from the three types of trains and were not to be considered absolute values regarding the effects of people on platforms.

Table 2 shows some of the test results in terms of average values. The maximum resultant forces are shown for both bodies at 10.5 ft and 14.1 ft away from the center of the track. The force measurement listed in the table for the body at 10.5 ft away is referred to as a compressive and drag force that was interpreted as an overpressure and suction force respectively. In several cases, the wind force levels at 14.1 ft from the track center are less than half the levels at 10.5 ft away. The results also indicated that X2 trains caused high wind force levels at speeds above 155 mph. It was found that, with one exception, forces from freight trains did not produce high force levels. The exception was the passage of one freight train at 57 mph that had wind force levels approximately the same as the highest force levels from an X2 train. There were a number of varying conditions in the test that included variations within each type of train - particularly in freight trains - variations in train speeds, and wind conditions.

Table 2. Measured wind forces from passing trains.[15]

	Arithmetic Mean of Maximum Resultant Forces			
	Inter-City Train	Freight Train	X2 Train (Under 200 km/h)	X2 Train (Over 200 km/h)
Body at 4.3 m (14.1 ft) from Center of Track*	62 N (14 lb)	96 N (22 lb)	59 N (13 lb)	114 N (26 lb)
Body at 3.2 m (10.5 ft) from Center of Track**	139 N (31 lb)	154 N (35 lb)	103 N (23 lb)	261 N (59 lb)
Maximum Drag (Suction) Force at 3.2 m (10.5 ft) from Center of Track**	88 N 20 lb)	65 N (15 lb)	90 N (20 lb)	126 N (28 lb)
Maximum Compressive (Overpressure) Force at 3.2 m (10.5 ft) from Center of Track**	101 N (23 lb)	101 N (23 lb)	88 N (20 lb)	208 N (47 lb)

*4.3 m (14.1 ft) from the center of the track corresponds to 2.76 m (9.06 ft from the side of an X2 train.

**3.2 m (10.5 ft) from the center of the track corresponds to 1.66 m (5.45 ft) from the side an X2 train.

A study by SNCF, obtained wind forces on an object simulating a person in proximity to a passing train.[6] SNCF made both theoretical calculations and experimental measurements to determine the forces on a cylindrical object from the induced airflow generated by the head of a passing TGV 001 train. Although the cylindrical object used for the experimental measurement was of a smaller size than in the theoretical calculations, it was found that the differences in the results between measurement and theory were consistent with the difference in the size of the object used. The theoretical results were computed for the object at two different distances from the track (measured from the rail) at a train passing speed of 143 mph. With the body situated at a distance of 4.49 ft from the track, the passing train produced a peak force on the object of about 16.9 lb., while at 6.14 ft away from the track, the peak force drops to about 11.2 lb. (A distance of 4.49 ft from the track corresponds to 2.36 ft from the side of the train, and a distance of 6.14 ft from the track corresponds to 4.0 ft from the side of the train.) The duration of the peak forces was about 0.03 s, which is about the time required for the nose pressure wave to pass.

2.3 Structural Loading from Aerodynamic Pressures

Fixtures on trains, buildings, and other structures alongside the track must be capable of withstanding the aerodynamic pressures produced by passing train**s** at high speeds. The issue of structural fatigue can be important due to the frequent exposure to the pressure pulses. In his study of the aerodynamic problems of high-speed trains, Gawthorpe states, “Although the peak-to-peak pressure changes due to passing on open ground are small compared to the tunnel pressure transients, … because the number of occurrences is large, thereby significantly affecting structural fatigue life, and the problems of passenger discomfort on other trains, window life, etc.” [3]

One of the issues is the ability of window glazing to maintain its structural integrity on passenger cars during passage of another train at high speed. The possibilities of failure include either the glazing cracking**,** or the glazing being dislodged from the window mount. Kalkbrenner[16] discusses structural strength testing on windows using a vibration machine that simulates the loading conditions on glazing caused by a passing train. From results obtained from another test [M. Mani], Figure 6 shows the stress levels on the window glazing from measurements on the horizontal surface bending stress in the center of windows.[2] Some tests on window glazing suggest that the stresses are highest around the window edges, and are more than an order of magnitude lower than the manufacturer’s design limit.[4]

Passenger cars operating in the United States must meet the requirements specified in Code of Federal Regulations (49 CFR 223)**,** where the side-facing window glazing must meet the test of a 24 lb. cinder block impacting at 12 ft/sec (see Appendix for text of the requirements). While no information has been obtained on the properties or construction details on specific passenger car window glazing, Table 3 shows the magnitude of pressures required to cause breakage to 1/4-in. laminated safety glass which is similar to that used in railway passenger and Pullman cars.[17]

Table 3. Pressure test for 6.35 mm (1/4-in.) safety plate glass.[17]

Glass Specimen	Method of Glazing	Average Breaking Pressure		
		Glass Size: 305X305 mm (12X12 in.)	Glass Size: 457X457 mm (18X18 in.)	Glass Size: 610X610 mm (24X24 in.)
6.35 mm (1/4-in.) safety plate (2.78 mm glass, 0.381 mm plastic, 2.78 mm glass) (7/64-in. glass, 0.015-in. plastic, 7/64-in. glass)	Clamped at margin with gaskets	75,800 Pa (11 psi)	41,400 Pa (6 psi)	24,100 Pa (3.5 psi)

Temperature of test specimens, 297 K (75°F); pressure loading, 34,500 Pa/min (5 psi/min)

2.4 Human Comfort Tolerance Levels

Trains operating at high speeds can produce variations in air pressure that affect the comfort of people both on the wayside and inside the train. Carstens[18] conducted a literature survey that included the effect of pressure changes on human comfort, as it applies to high-speed transportation. Changes in pressure are felt by the body cavities that normally contain gas, such as the middle ear, sinuses, lungs, intestinal track, and occasionally, teeth. Measurements of pressure changes must consider both the rate of pressure change and the maximum pressure differential. Table 4 shows the effect that different levels of pressure changes have on the human ear. An advisable limit that can be considered the instantaneous pressure change from a physiologic standpoint is 414 Pa (0.06 psi).

Pressure variations below a frequency of 20 Hz, which is below the audible range of the human ear, are referred to as infrasonic. There are no standards established for human exposure limits because there is insufficient understanding about human exposure to infrasound and its effect on hearing loss.[19] A suggested maximum sound pressure level for infrasound exposure is 150 dB, regardless of how short the exposure time.[20] This maximum pressure level is lowered for an exposure of longer duration.

One aspect of pressure change related to the aerodynamics of high-speed train operations is that the people on station platforms situated too close to a passing train can experience the effects of pressure transients as sensation in their ear passages. In terms of these produced pressures, "…the perturbation to the air caused by the head of the train as it passes is transmitted through the surrounding air for some distance before it dies away. Any object, or even the eardrum of a line-side worker or waiting passenger, which is situated near the train, will experience the effect of the pressure change as a pressure difference across it." [3] For trains passing at speeds up to 186 mph, however, the physiological effects of pressure change on the eardrums of bystanders, while noticeable, will not cause discomfort.[3]

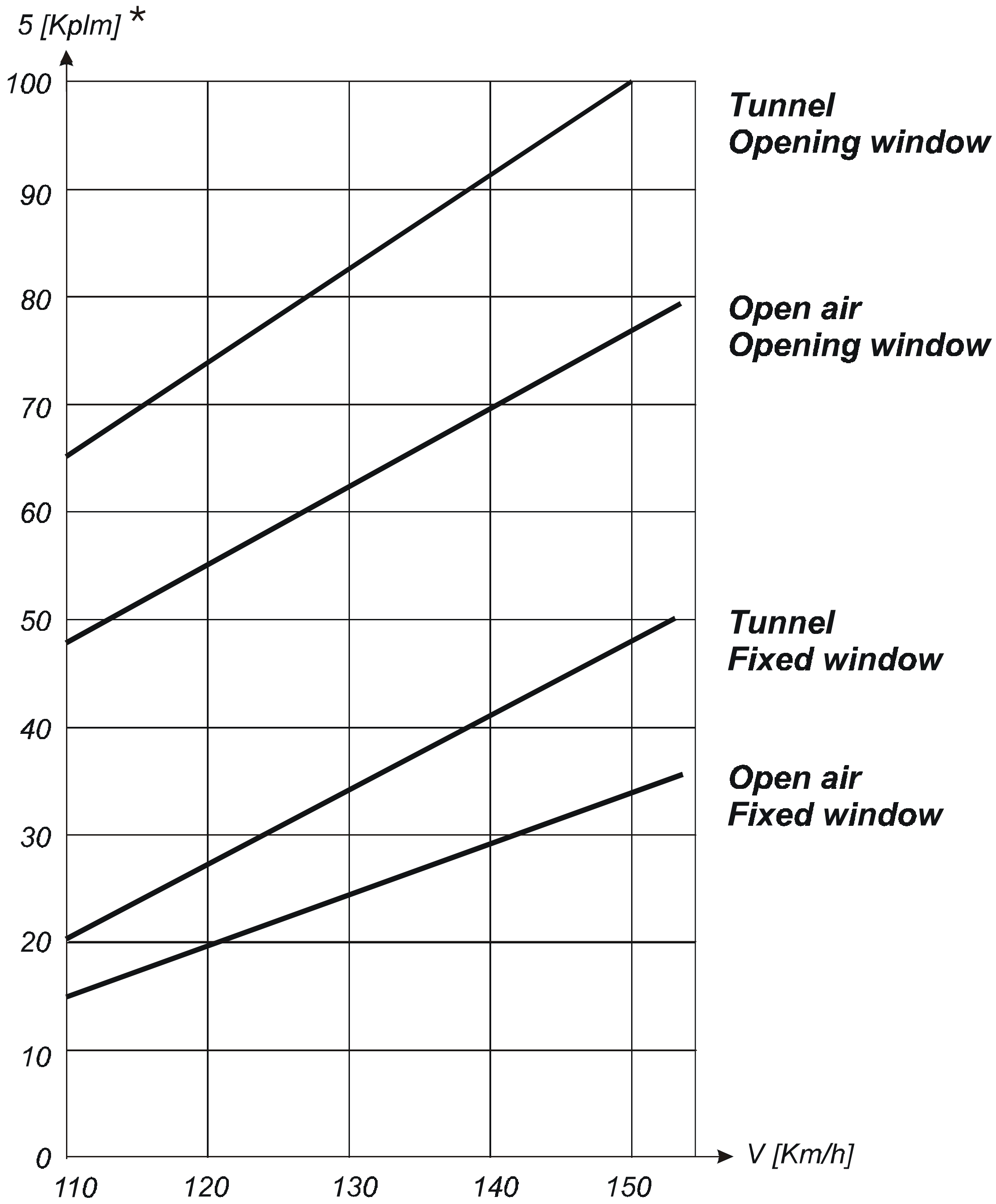


Figure 6. Horizontal surface bending stress in the center of window glazing [M. Mani].[2]
***(KP: kilopond: 1 KP=9.807 N)**

Table 4. Ear symptoms at varying levels of pressure change.[18]

Relative Pressure Higher In Middle Ear (Decrease In Ambient Pressure)			Symptomatology
(mm Hg)	(psi)	(Pa)	
3 to 5	0.06 to 0.10	400 to 667	Perceptible feeling of fullness in the ear.
10 to 15	0.19 to 0.29	1,333 to 2,000	Distinct feeling of fullness. Lessened sound intensity.
15 to 30	0.29 to 0.58	2,000 to 4,000	Increasing discomfort with ear ringing (tinnitus) of a hissing, roaring, crackling, or snapping character; may be pain and mild vertigo. (Pressure of 15 mm Hg is normally sufficient if no pathology present - to force the eustachian valve and equalize the pressure - produces an annoying "click" which is heard and felt in the ear.)
30 or more	0.58 or more	4,000 or more	Increasing pain, tinnitus, and vertigo.
100 to 500	1.93 to 9.65	13,332 to 66,661	Tympanic membrane ruptures if eustachian tube completely and firmly blocked.
Relative Pressure Lower In Middle Ear (Increase In Ambient Pressure)			**Symptomatology**
(mm Hg)	(psi)	(Pa)	
-3 to -5	-0.06 to -0.10	-400 to -667	(same as above)
-10 to -15	-0.19 to -0.29	-1,333 to -2,000	(same as above)
-15 to -30	-0.29 to -0.58	-2,000 to -4,000	(same as above)
-60	-1.16	-7,999	Severe ear pain, marked tinnitus, and beginning nausea.
-60 to -80	-1.16 to -1.54	-7,999 to -10,666	Severe ear pain radiates to temporal region, parotid gland, and the cheek; deafness is marked; vertigo and tinnitus, usually increase but tinnitus may disappear.
-100 to -500	-1.93 to -9.65	-13,332 to -66,661	Tympanic membrane ruptures.

Another issue in high-speed train operation is in tunnels where during tunnel entry, or possibly where two trains are passing each other in a tunnel, pressure variations to the train interior may occur causing discomfort to passengers' eardrums. In an earlier criterion by British Rail on the internal pressure transients in a passenger car, a suggested limit on the rate of pressure change is 0.029 psi/sec and a limit on the pressure differential is 0.145 psi.[3] Suzuki[21] reviewed the research performed in Europe and Japan on human comfort levels from pressure variations to railroads passenger car interiors. In 1991, British Rail adopted different allowable limits of pressure changes whose criterion depends on the route and the types of cars, with pressure limits as low as 0.102 psi in 4 seconds for rapid transit in mostly tunnel operation, to 0.363 psi in 4 seconds for unsealed Inter-City train with few tunnels. Limits above these values are permitted for extreme cases. Japan has proposed a provisional guideline to limit the allowable pressure change in their train interiors to 0.29 psi or less in 4 seconds.

ERRI[22] conducted a study on reactions to pressure variations from both an on-line test during an actual train journey, and from a pressure chamber test. These tests were to determine acceptable internal pressure variations on passenger trains passing through tunnels at high speed. The study found that the influence of pressure difference was greater than the rate of change of pressure; below 0.109 psi/sec, discomfort diminishes significantly. These tests suggested that in terms of comfort criteria, values should be applied as a dissatisfaction percentage, so that a minimum number of passengers are dissatisfied, instead of defining threshold values that should not be exceeded.

Another issue related to pressure variations is noise. While the subject of noise is beyond the scope of this study, the aero-acoustic noise generated by the airflow over a train (as opposed to noise from propulsion and structural/mechanical sources) can be significant. At speeds of 155 mph or greater, the aero-acoustic noise radiating sound in the frequency range of 250 Hz to 500 Hz can be a dominant noise level, depending on the significance of the mechanical and structural noise.[23] As part of the research program by Japan on their 300X EMU Shinkansen test train, principal aero-acoustic noise sources derive from the current-collecting pantograph, and from the train nose.[24] Their study found that pantograph noise can be reduced by the use of pantograph covers, and noise generated by the train nose can be reduced by nose shapes such as the "round-wedge" or the "cusp" configurations.

Finally, there is a possibility that when a high-speed train passes a platform, people situated in the proximity of a passing train will be exposed to both forces from the induced airflow, along with blowing debris, such as gravel or dust, which can cause discomfort and perhaps injury. A measure of the effects that airflow creates can be seen from the Beaufort Scale shown in Table 5, relating the wind speed to the effects it exerts on people and objects. In terms of the level of induced airflow exposure for people on station platforms, British Rail suggested a limit for line-side workers of 38 mph which corresponds to the upper end of the Beaufort Scale Number 7.[3] For members of the public, the suggested limit is 25 mph, which corresponds to the upper end of Beaufort Scale Number 5.[3] British Rail recommended that for trains passing through stations up to 125 mph, the public should keep back 4.9 ft from the edge of the platform, and that railroad personnel working along the tracks should keep back 6.6 ft from the running rail during train passage.[4]

Table 5. Beaufort Scale[25]

Beaufort Number	Name	Wind Speed		Description
		(km/h)	(mph)	
0	calm	less than 2	less than I	calm; smoke rises vertically
1	light air	-5	1-3	direction of wind shown by smoke but not by wind vanes
2	light breeze	6-11	4-7	wind felt on face; leaves rustle; ordinary vane moved by wind
3	gentle breeze	12-19	8-12	leaves and small twigs in constant motion; wind extends light flag
4	moderate breeze	20-29	13-18	raises dust and loose paper; small branches are moved
5	fresh breeze	30-39	19-24	small trees in leaf begin to sway; crested wavelets form on inland waters
6	strong breeze	40-50	25-31	large branches in motion; telegraph wires whistle; umbrellas used with difficulty
7	moderate gale (or near gale)	51-61	32-38	whole trees in motion; inconvenience in walking against wind
8	fresh gale (or gale)	62-74	39-46	breaks twigs off trees; generally impedes progress
9	strong gale	75-87	47-54	slight structural damage occurs; chimney pots and slates removed
10	whole gale (or storm)	88-101	55-63	trees uprooted; considerable structural damage occurs
11	storm (or violent storm)	102-120	64-72	very rarely experienced; accompanied by widespread damage
12	hurricane	above 120	73- 136	devastation occurs

3. EFFECTS OF PASSING TRAIN AERODYNAMICS ON TRAIN WINDOW GLAZING AND ON PEOPLE ON STATION PLATFORMS

The magnitude of the aerodynamic forces expected when trains pass at high speeds can be determined from data provided by the literature review. The results focus on the effects of aerodynamic forces on window glazing during train passages, and on the effects of pressure and airflow on people on station platforms. These results apply to trains operating in open air with no natural wind components present. Figure 7 illustrates the aerodynamics of pressure and airflow around a moving train.

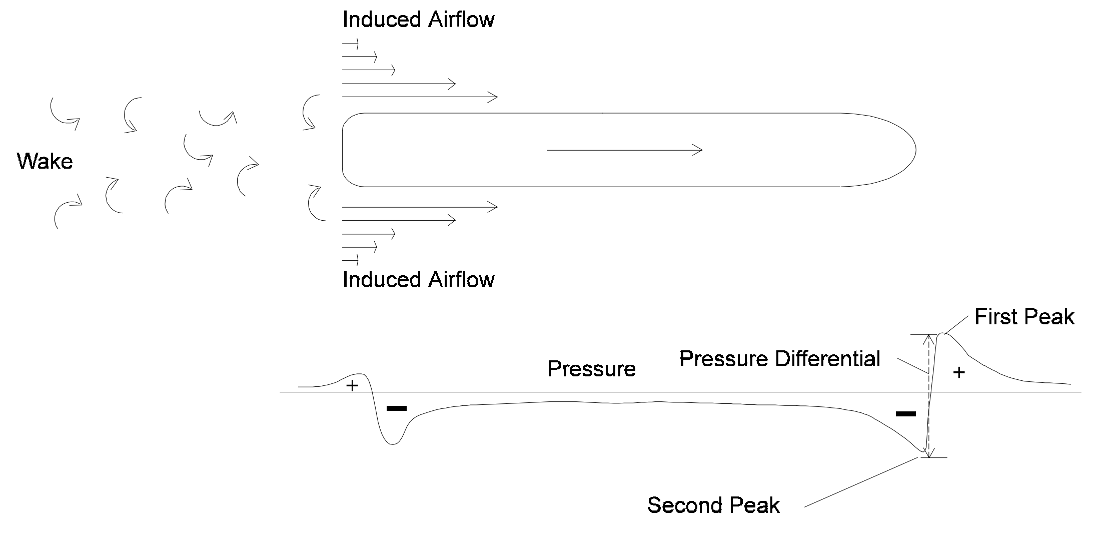


Figure 7. Pressure and airflow around a moving train.

3.1 Pressure Loading on Passenger Car Windows

One of the issues in high-speed rail operations is the glazing on passenger car windows being damaged or dislodged due to the aerodynamic forces generated as two trains pass each other on adjacent tracks. Aerodynamic forces increase with the square of the vehicle's velocity and**,** therefore**,** can develop to significant levels with increased speed. This fact can be seen in terms of the percentage change of speed and force from the current maximum allowable operating speed for a passenger train of 110 mph. An increase in speed from 110 mph to 150 mph represents a 36 percent increase in speed, but the corresponding aerodynamic force increases by 86 percent.

A passing train generates a pressure wave onto the other (observing) train that peaks to a positive pressure, followed by a rapid drop to a second peak to a negative pressure. For a clearance of 2.5 ft between passing trains, based on Amfleet car dimensions on Northeast Corridor tracks (see Appendix for train and track data), the peak differential pressure coefficients range from - 0.4 to - 0.8 during train passage (Figure 2). Figure 8 presents the aerodynamic pressures acting on the observing train during passing events for a range of pressure coefficients and approaching train speeds.

There are two curves for each pressure coefficient – a positive pressure curve, corresponding to the first peak, pushing the car wall in (pressing the glazing inwards), and a negative pressure curve, corresponding to the second peak, pulling the car wall out (a suction of the glazing outwards). The pressures were plotted with the assumed positive pressure peaking at one-third the pressure differential, while the negative pressures peaked at two-thirds the difference. It is also assumed that the interior or cabin remains at atmospheric pressure.

For a given pressure, the force acting on the glazing depends on the size of the window. Force calculations were made for two window sizes - windows on Amfleet-1 cars, and large size windows on rail cars such as the MBTA's MBB single level commuter coaches and Kawasaki bi-level commuter cars, as shown in Figures 9 and 10, respectively. (Refer to the Appendix for window dimensions.)

The figures present the peak positive load (force pushing glazing into the car), and peak negative load (force pulling glazing out of the car), corresponding to the first and second peaks of the pressure pulse. These are peak loads acting on the glazing, whose dynamic response will be affected by the magnitude, duration, and shape of the aerodynamic pressure pulse, as well as the structural characteristics of the glazing. The figures also present the equivalent static loading on the glazing for some dynamic factors.

As these results show, the resultant force on the window glazing is proportional to the glazing area, so that a larger window size requires a higher force to restrain the glazing on its mount. Since the glazing is fastened only around the edges, it is useful to express the load along the edges as a force per unit perimeter length (lb/in). By relating the force in terms of the size and shape of the window, the effects that these geometric factors have on the loading at the attachment point can be determined. (The relationship between the force per unit length and the geometry of a rectangular plate is shown in the Appendix.)

For windows of the same geometric proportions, the window perimeter, and the force per unit perimeter length, varies as the square root of the window area. As an example, for windows on Amfleet-1 cars, a pressure of 0.16 psi applied to the surface of a glazing, results in a force of 0.892 lb/in along the edge of the glazing. For the MBTA's MBB and Kawasaki commuter cars, where the window areas are over twice that of Amfleet-1 cars, that same pressure applied to the surface of the glazing would produce a force of 1.37 lb/in along the edge of the glazing. For a given pressure applied to the window glazing, the higher applied load, resulting from a larger size window, also exerts a higher loading per unit length on the glazing attachment.

PEAK TRANSIENT AERODYNAMIC PRESSURES ON SIDE WINDOW OF A RAILROAD CAR FROM PASSAGE OF A TRAIN ON ADJACENT TRACK

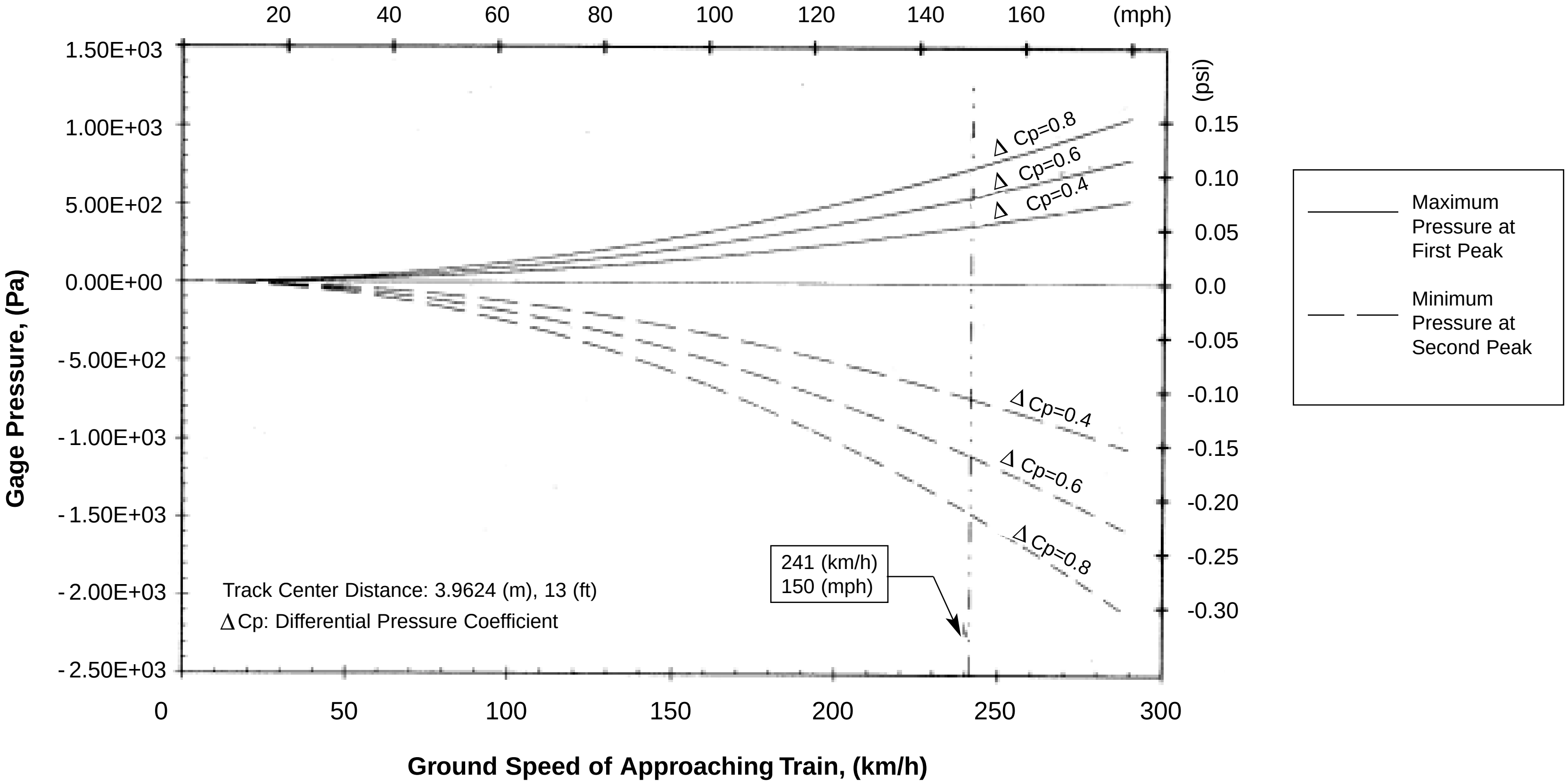


Figure 8. Peak aerodynamic pressures exerted on side windows of a railroad car for specified maximum positive and maximum differential pressure coefficients.

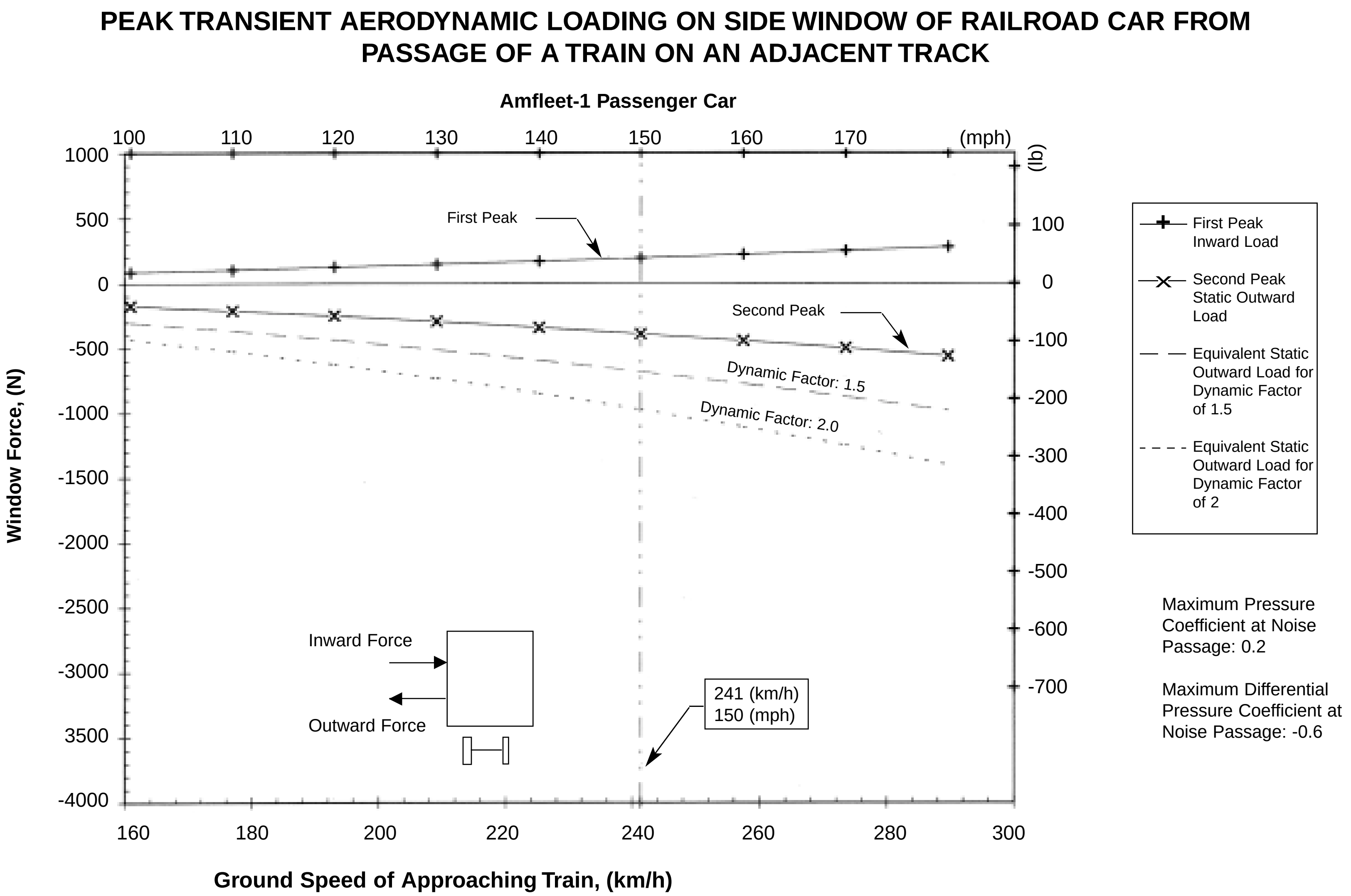
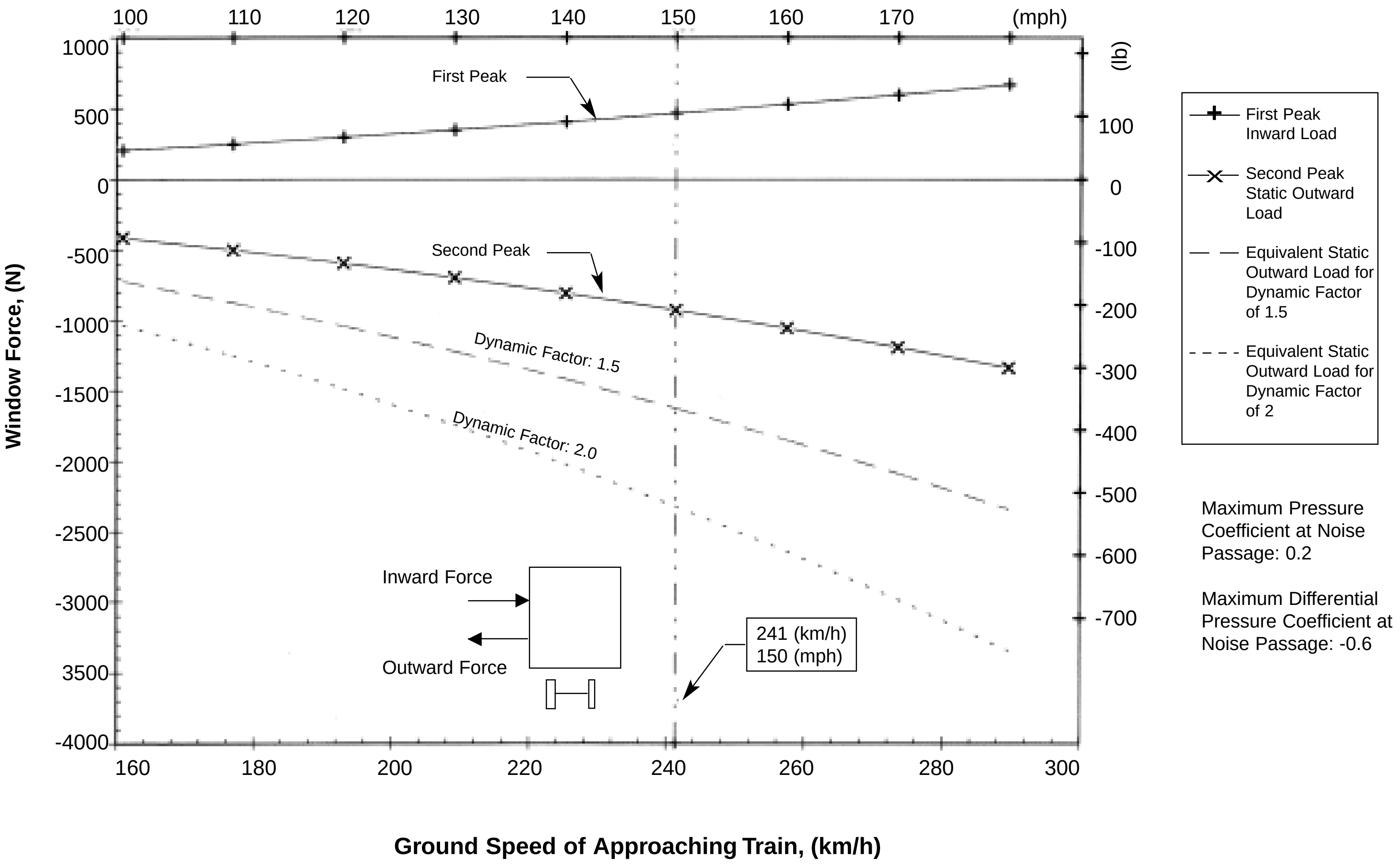


Figure 9. Peak aerodynamic load on side window of an Amfleet 1 car.

PEAK TRANSIENT AERODYNAMIC LOADING ON SIDE WINDOW OF RAILROAD CAR FROM PASSAGE OF A TRAIN ON AN ADJACENT TRACK

MBTA's MBB Single Level & Kawasaki Bi-Level Commuter Cars



Maximum Pressure Coefficient at Noise Passage: 0.2

Maximum Differential Pressure Coefficient at Noise Passage: -0.6

Figure 10. Peak aerodynamic load on side window of MBTA's MBB Single Level & Kawasaki Bi-Level commuter cars.

For windows that are rectangular, the aspect ratio (ratio of dimensions between window width and height) is also a factor affecting the force per unit perimeter length along the glazing edge. For a given surface area, a square window has the smallest perimeter, while the perimeter increases as the window becomes more elongated. Therefore, the edge loading on a per unit length basis is highest for square windows, and lowest for elongated windows.

To maintain the structural integrity of window glazing, the Federal Railroad Administration (FRA) specifies requirements that must be fulfilled in the glazing design. FRA requires that railroad passenger car side window glazing must withstand an impact from the corner of a 24-pound cinder block at an impact speed of 12 ft/s, which translates to an impact energy of 72.81 J. Window glazing meeting this requirement should successfully resist the impact of this large object; however, the form in which this requirement is specified does not readily relate to the ability of the glazing to resist uniformly applied aerodynamic loads**,** given as a force or stress. Determining the force of impact from the cinder block striking the glazing requires a consideration of properties that include material elasticities and dimensions of the glazing and the glazing attachment.

There are two failure modes to consider when assessing the structural integrity of the window glazing. The aerodynamic pressures can cause the glazing to be dislodged from the window mount, or the glazing can crack. The stress developed in the glazing and in the support mount around the glazing will depend on the magnitude, shape, and time duration of the applied load. The failure can occur from excessive stress, or from the cyclic loading leading to fatigue failure.

A determination on the ability of the glazing to remain in the mount under the applied aerodynamic loading requires specifications about the window**,** such as the method on which the glazing is mounted**,** and the types of materials attaching the glazing. Since detailed design information on the windows was not readily available for this study, no assessment was made on whether the glazing will be dislodged, but an estimate can be made on the likelihood that the window glazing will crack.

From the information obtained in this study, an assessment can be made on whether cracking failure of the window glazing is likely to occur for the given loading conditions. Based on the breaking pressures of the three different sizes of 1/4-in.-thick safety plate glass specimens as shown in Table 3, the breaking pressure can be extrapolated to other surface area sizes (see Appendix for extrapolation equation).

It is assumed that the window glazing on the passenger cars is fastened on the edges of the glazing**,** similar to the test specimens. Since some of the extrapolated values apply to glazing sizes that are much larger than those given by the three data points, and since the square test specimens could be of different thickness and construction from the particular railroad car window glazing of interest, these results are used to provide an estimate of any potential outcomes**.**

To assess the likelihood of the window glazing cracking, a comparison has been made between the breaking pressure and the aerodynamic pressure loading on the glazing. For Amfleet-1 car windows with a surface area of 546.9 in.^{2} , the breaking pressure is estimated to be 3.8 psi. The window glazing surface area on the MBTA's MBB single level commuter coaches and Kawasaki bi-level commuter cars is 1,307 in.^{2}, which is over twice the size of an Amfleet-1 window. For these larger size windows, an estimate of the window glazing's breaking pressure is about 1.9 psi.

Table 6 presents the magnitude of the peak positive and negative pressures exerted on the window glazing of the observing train by a train passing on an adjacent track at 150 mph. Since the highest aerodynamic pressure exerted on the window glazing is 0.213 psi, these estimated values suggest that the pressures are below the breaking pressures by a factor of about ten during train passages at a speed of 150 mph. Although these are static loading comparisons, the breaking pressure is sufficiently high, so the stress developed from the dynamic response is not expected to be a problem.

Table 6. Aerodynamic pressures exerted on side window of railroad car from passage of a train on an adjacent track at 241 km/h (150 mph).

Maximum and Minimum Aerodynamic Pressures on Side Window for Various Peak Differential Pressure Coefficients					
ΔCp=-0.4		ΔCp=-0.6		ΔCp=-0.8	
Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
367 Pa (0.0532 psi)	-734 Pa (-0.107 psi)	551 Pa (0.0799 psi)	-1101 Pa (-0.160 psi)	734 Pa (0.106 psi)	-1468 Pa (-0.213 psi)

3.2 Trains Passing Station Platforms

A second area of discussion in high-speed rail operation is the aerodynamic effects on people on station platforms. Whenever people are situated in proximity to a train passing a station at high speeds, they will feel the effects of pressure and airflow created by the passing train. The effects of these two factors will be assessed, and the implications of these results will be applied to some of the stations along the Northeast Corridor.

3.2.1 Pressure Effects on Passengers on Station Platforms

Trains passing through a station at high speed generate a pressure wave that can have an unpleasant effect on the eardrums of people on the platform. The magnitude of the pressure change depends on the geometry of the train nose, and the person's distance away from the passing train. Because pressure coefficients for a train passing a person are not available, the values measured for unrestricted flow (no bodies present) will be used. At 3.3 ft away from the side of a passing train, differential pressure coefficients can range from -0.1 for a slender-nose train, to -0.3 for a train head with a bluff nose (Figure 1).

Figure 11 shows a plot of the pressures at various train-passing speeds for pressure coefficients representing different aspect ratios of the train nose. Also shown in the figure is the pressure change duration for different nose lengths. A short nose is associated with both a stronger pressure wave (in terms of the magnitude of the pressure differential) and a shorter duration at which the pressure changes occur. These effects are unfavorable in terms of human comfort. For

AERODYNAMIC PRESSURE DIFFERENTIALS FROM PASSAGE OF A TRAIN IN OPEN AIR

Pressure Felt by a Person at 1 Meter (3.3Feet) Away from the Side of a Passing Train

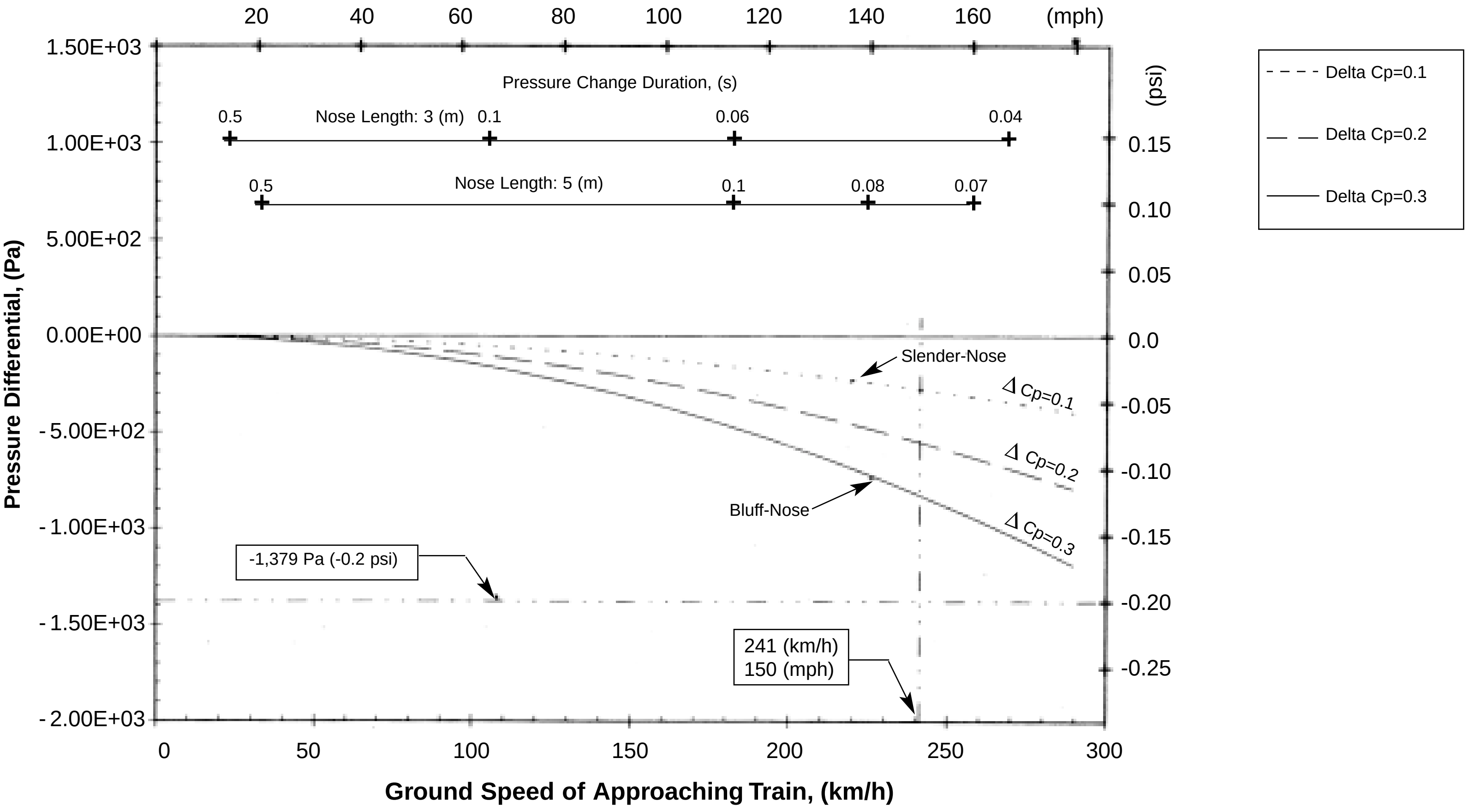


Figure 11. Peak aerodynamic differential pressures that would result for various pressure coefficients and some time intervals of pressure pulse.

a pressure pulse generated at speeds up to 150 mph, the effect on the human ear is an infrasonic pressure variation. Therefore, as an estimate, based on the pressure limits of Table 4, and the suggested infrasound pressure limit for human exposure of 150 dB (see Appendix for sound pressure level), a 0.2 psi peak-to-peak pressure limit is used.

The pressures that are produced from the head perturbation at 3.3 ft. away from the side of the passing train can be compared with the estimated pressure limit of –0.2 psi for human exposure (Figure 11). Based on this maximum pressure limit, trains passing at a speed up to 150 mph for the various train nose geometries generate a pressure differential that is within this limiting value. Therefore, for a person situated at a distance of 3.3 ft. or greater from a passing train, whatever sensation is felt in the eardrums is not likely to be significant.

People standing near a passing train will also experience forces from the pressure wave generated by the head of the train that could affect a person's balance. As described earlier, a body at a distance of 2.36 ft. from the side of a train can experience forces of about 16.9 lb from the pressure wave generated by the head of a TGV-001 train**,** passing at a speed of 143 mph. This force acts for a very short duration of about 0.03 s. For a person weighting 165 lb, this force would produce an acceleration of 0.1 g, about the level of acceleration that would be experienced by a person on a rapid transit train during acceleration. Because the force acts for a very short duration however, a momentary imbalance to a person might occur, which may be a safety issue**,** depending on a person's reaction to the sudden blast of air.

3.2.2 Train-Induced Airflow on Station Platforms

A train passing a station platform induces an airflow in its surroundings that diminishes with distance away from the train. Measured airflow data can vary widely as compared with the three theoretical curves labeled high- medium- and low-induced airflow**,** with each curve passing through some of the measured data (Figure 5). Figure 12 shows computed airflow speeds for two different train-passing speeds**,** based on the high-and low-induced airflow curves shown in Figure 5. The speed of the induced airflow can be very high near the passing train, but drops off sharply a short distance away. It is seen that data for low induced airflow at a train speed of 150 mph is no more severe than data from high-induced airflow at a train speed of 100 mph.

A qualitative description**,** relating wind speed and the effects it produces on the environment**,** was shown on a Beaufort scale in Table 5. For a person standing on a station platform in the midst of an air stream created by a passing train, a force is exerted on that person which can be computed for a given airflow speed to provide a quantitative measurement. Table 7 shows the force that a person can experience when standing with frontal wind exposure at various Beaufort number values. Since a person would be inconvenienced in walking against the wind at a speed corresponding to Beaufort number 7 (Table 5), a wind force exceeding 33 lb could create an un-

INDUCED AIRFLOW FROM A PASSING TRAIN AT TWO TRAIN SPEEDS AND FOR TRAINS WITH HIGH AND WITH LOW INDUCED AIRFLOW STRENGTHS

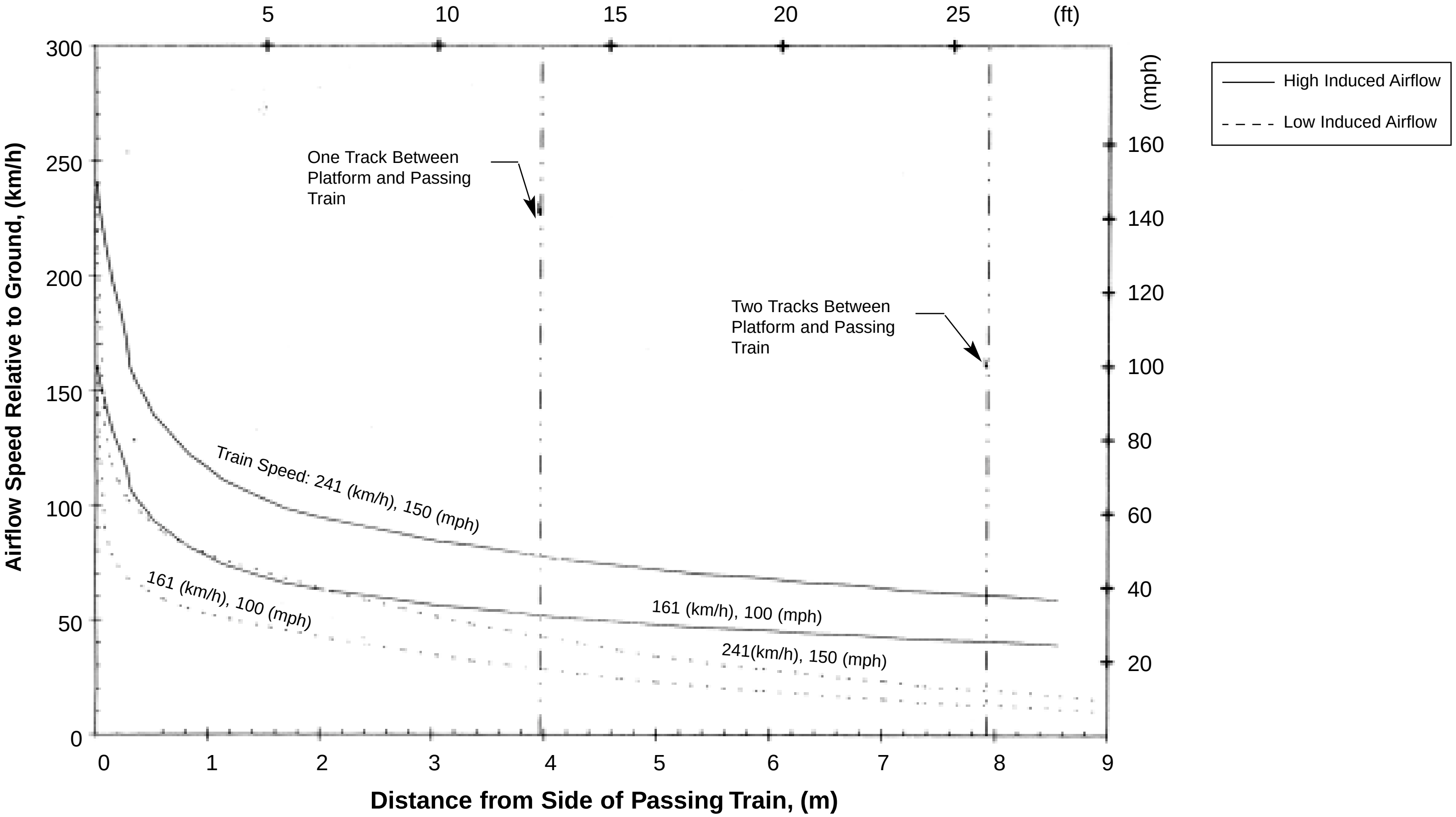


Figure 12. Train induced wind for trains with high and with low induced winds.

comfortable imbalance on a standing person. Forces from the induced airflow of a passing train exceeding this magnitude were measured as shown in Table 2.

Table 7. Forces on a person standing with frontal wind exposure at various Beaufort numbers.

	Force at Corresponding Beaufort Number (BN)			
	BN=4	BN=5	BN=6	BN=7
Standing Person with Frontal Wind Exposure	33 N (7 lb)	60 N (13 lb)	99 N (22 lb)	148 N (33 lb)

(Based on a projected area of 0.73 m^2 and drag coefficient of 1.15)

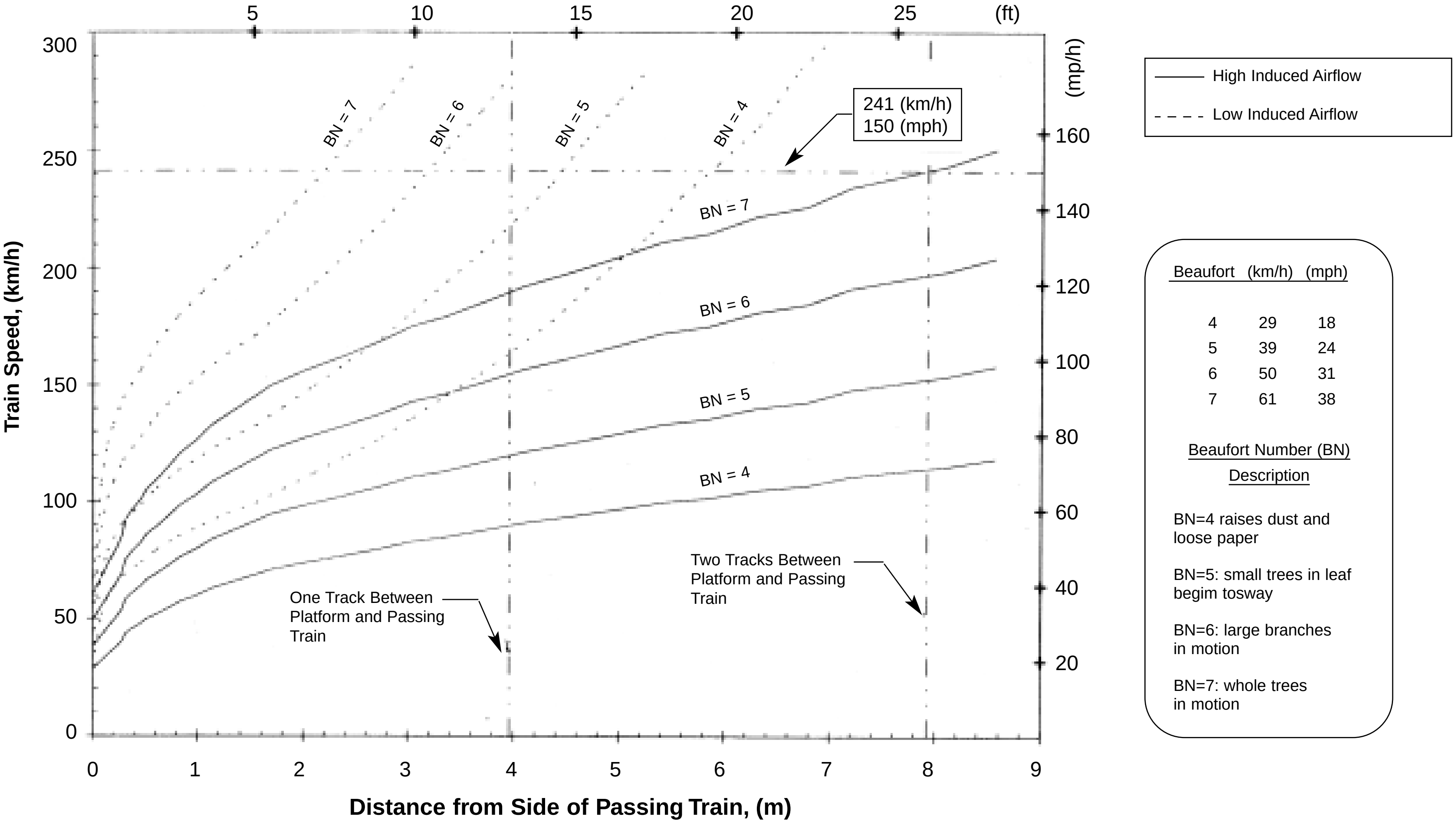
From the general description of wind speed and its effects on a person, it can be understood that the maximum speed that a train should be permitted to pass a station platform depends on the airflow speed that can be tolerated for a given distance away from a passing train. A boundary can be established relating the maximum permissible train speed with the distance away from a passing train for various wind speed limits expressed in terms of Beaufort numbers as shown in Figure 13. The figure shows results for a train with both high- and low-induced airflow. If there is one track separating the platform and a passing train, a wind speed limit corresponding to a Beaufort Number 7 would limit the train to a passing speed of 119 mph, if the train has a high-induced airflow, while a maximum train speed of 217 mph is permitted for a train with low-induced airflow.

When a train is passing a station on a track immediately adjacent to the station platform, passengers waiting on the platform are currently not limited in their proximity to a passing train**,** except by markings along the edge of the platform warning people from being too close to the edge. By using a wind speed limit suggested by British Rail of 24 mph for members of the public**,** and 38 mph for British Rail personnel**,** corresponding to Beaufort Numbers 5 and 7 respectively, a speed limit at which a train can pass a station may be determined. Table 8 shows the maximum speed a passing train can travel for people situated at 3.3 and 6.6 ft away from the side of the train. There is a range of speed because of variations or uncertainties in airflow strength. For example, if a passenger on a platform were situated 3.3 ft away from a passing train, the train would be limited to a speed 50 to 73 mph as it passes the station**,** based on the specified wind strength criterion.

3.2.3 Stations on New Haven to Boston Route

High-speed trains operating along the Northeast Corridor between New Haven, Connecticut, and Boston, Massachusetts, will be passing stations with a variety of track and platform configurations. As shown in Table 9, many of these stations are two-track lines with low-level platforms where high-speed trains are not expected to stop. Since there are only two tracks, a train passing one of these stations will be passing directly next to a platform that has no limit

MAXIMUM PERMISSIBLE TRAIN SPEED TO LIMIT INDUCED AIRFLOW TO VARIOUS BEAUFORT NUMBER VALUES FOR TRAINS WITH HIGH AND WITH LOW INDUCED AIRFLOW STRENGTHS



Beaufort	(km/h)	(mph)
4	29	18
5	39	24
6	50	31
7	61	38

Beaufort Number (BN)
Description

BN=4 raises dust and loose paper

BN=5: small trees in leaf begim tosway

BN=6: large branches in motion

BN=7: whole trees in motion

Figure 13. Train induced wind at various values of Beaufort numbers.

with regard to the proximity that a person can be in to the passing train**,** other than markings to keep people away from the edge of the platform.

Table 8. Maximum permissible train speed to limit induced airflow exposure to members of the public and railroad personnel situated at 1 and 2 meters away from the side of a passing train.

Wind Strength Criterion	Maximum Train Speed at 1 m (3.3 ft) Away from Train	Maximum Train Speed at 2 m (6.6 ft) Away from Train
Beaufort Number 5 (Public)	80 to 118 km/h (50 to 73 mph)	98 to 146 km/h (61 to 91 mph)
Beaufort Number 7 (Railroad Personnel)	127 to 188 km/h (79 to 117 mph)	156 to 232 km/h (97 to 144 mph)

In many of these stations, the current train speeds that are permitted during station passages could potentially expose people to excessively high airflow. Table 10 shows the speeds of the induced airflow at 3.3 ft and 6.6 ft away from the side of a train passing at speeds of 100 mph and 150 mph. At 3.3 ft away from a train passing at 100 mph, the induced airflow could reach speeds of 33 to 48 mph, depending on the train's aerodynamic characteristics. An airflow speed above 39 mph would be equivalent to a fresh gale**,** which is a very strong wind exposure for people (see Table 5). Yet by moving back to 6.6 ft away from a passing train, the airflow speed drops to 26 to 39 mph, corresponding to Beaufort numbers from 6 to 7, which is the limit suggested by British Rail for their own personnel. Given these results for current permissible train speeds during station passages, any speeds above 100 mph would begin to create serious issues for the potential effects on anyone that is in proximity to a passing train.

Although the current permissible train speed for station passages could be producing excessively high airflows on people close to a passing train, an increase in station-passing speed to 150 mph would produce airflows, and whatever dust and debris that is being propelled, to a speed that could be a safety issue**.** At 3.3 ft away from the side of a train traveling at 150 mph, the induced airflow can reach a speed of 49 mph (see Table 10)**,** even for a train with low-induced airflow. A train with a high-induced airflow could generate airflows at a speed of 72 mph. Moving back to 6.6 ft away, the induced airflow remains strong at 40 to 59 mph. These numbers indicate that potential hazard exists for people situated in proximity to a train passing at a speed of 150 mph.

Table 9. Description of railroad stations along New Haven to Boston route.[26]

Station	Number of Tracks	Platform	Current Amtrak Speed
New Haven	8	High level	24 (km/h) 15 (mph)
Branford, Guilford, Madison, Clinton, Westbrook, Old Saybrook	2	Short. low level, adjacent to one track only	80-145 (km/h) 50-90 (mph)
New London	2	Full length, low level, outside both tracks	40 (km/h) 25 (mph)
Mystic	2	Full length, low level, outside both tracks	88 (km/h) 55 (mph)
Westerly	2	Full length, low level, outside both tracks	121 (km/h) 75 (mph)
Kingston	2	Low level, outside eastbound track; narrow low level between tracks on westbound side	161 (km/h) 100 (mph)
Providence	4	Full length, high level.	(all trains stop)
South Attleboro	2	Full length, low level, outside both tracks	161 (km/h) 100 (mph)
Attleboro	3	Full length, low level, outside both tracks	153 -161 (km/h) 95-100 (mph)
Mansfield	2	Full length, low level, outside both tracks	161 (km/h) 100 (mph)
Sharon	2	Full length, low level, outside both tracks	153 (km/h) 95 (mph)
Canton Junction	2	Full length, low level, outside both tracks	129 (km/h) 80 (mph)
Route 128	2	Full length, low level, outside both tracks	97 (km/h) 60 (mph)
Hyde Park	3	Full length, low level, outside outer tracks	161 (km/h) 100 (mph)
Ruggles	3	Full length, high level between western tracks	161 (km/h) 100 (mph)
Back Bay	3	Full length, high level	(all trains stop)
South Station	11	Full length, high level	(all trains stop)

Table 10. Speed of induced airflow at 1 and 2 meters (3.3 and 6.6 ft) away from side of a passing train for train-passing speeds of 161 km/h (100 mph) and 241 km/h (150 mph).

Train Speed	Induced Airflow Speed at 1 Meter (3.3 Ft) Away from Train	Induced Airflow Speed at 2 Meter (6.6 Ft) Away from Train
161 km/h (100 mph)	53 to 78 km/h (33 to 48 mph)	43 to 63 km/h (26 to 39 mph)
241 km/h (150 mph)	79 to 116 km/h (49 to 72 mph)	64 to 95 km/h (40 to 59 mph)

4. CONCLUSIONS

This study was conducted based on a literature survey to assess the possible hazards to people and equipment from the aerodynamic forces generated by the passage of a train at speeds up to 150 mph. There are two primary aerodynamic-related issues associated with operating trains at high speeds:

- the effects that occur on trains due to the aerodynamic forces generated by another train passing on an adjacent track at high speeds, and

- the effects that occur on station platforms due to airflow and pressure effects created by a passing train.

The results indicate that the leading perturbation from trains operating at high speeds can create a strong pressure pulse of short duration when trains pass each other and that high airflow can be created on station platforms in proximity to passing trains. These results are for trains operating in open air without any natural wind components.

Based mainly on the information obtained from the literature survey, it was possible to establish the level of aerodynamic forces and airflow that can be expected in proximity to a passing train. From this study, the assessment is as follows:

- The aerodynamic forces exerted on the window glazing during train passage were determined. For trains passing each other at speeds of 150 mph, it is unlikely that these forces will cause the glazing to crack. An assessment of the strength of the glazing attachment will depend on specific, detailed design of the windows.

- The aerodynamic forces experienced by a person from pressures and induced airflow of a passing train were determined. For persons situated within 6.6 ft from the side of a train passing a station platform at a speed of 150 mph, the effects of pressure and induced airflow are high enough to be a safety issue. The distance of 6.6 ft does not represent a safety limit, but it does indicate that when people are situated within that distance to a passing train, this can be a safety issue.

- When a train is passing a station platform at high speeds, the wake effect of the train with its turbulent fluctuations and buffeting in the air, along with any dust and debris that is blown or propelled, is a serious issue regarding the comfort and safety of people on the platform.

The data on aerodynamic forces, such as pressure coefficients and airflow speed, display a range of values at a given train speed. Train geometry, particularly the shape of the train nose, has a significant influence on the strength of the aerodynamic forces. There are sufficient variations in the strength of the aerodynamic forces to indicate that a train with a slender nose, traveling at 150 mph, creates aerodynamic forces that are no more severe than a train with a bluff nose traveling at a speed of 110 mph. If a train proposed for high-speed operation has a streamlined body design with a slender nose at the head and tail ends, it is possible that its favorable aerodynamic characteristics can offset the higher aerodynamic forces that would otherwise be created by its increase in speed.

5. RECOMMENDATIONS

Aerodynamic forces created by the passage of a train were studied to determine its effects on the window glazing and people on station platforms. With these two specific areas of inquiry in mind, the recommendations from this study are as follows:

- Identify the equipment and fixtures on trains, and on structures along the wayside that are a safety issue when exposed to the aerodynamic effects of pressure and airflow generated from a passing train.

- Identify rail cars that are not designed for high-speed operation, particularly cars with large windows, or loosely fitted windows such as those that are designed to be opened. Obtain design information and data on the windows and glazing for these cars to perform a structural integrity assessment on the window glazing to determine if cracking or dislodgment will occur from the aerodynamic pressures acting on the glazing, also factoring in the effects of material fatigue. The assessment should consider the different types of glazing and glazing systems (frames and gaskets) used throughout the industry.

- Identify conditions that will impact the magnitude of the data in this study, such as natural wind components, and structures along the track, such as the presence of steep embankments, overpasses, tunnels, and assess their effects on the results.

- Confirm the boundaries on passing train speed and distance from the train in terms of human comfort tolerance levels as they impact the safety of people on station platforms. A realistic limiting boundary should include the effects on people when they are exposed to the combined actions of pressure, wind, noise, and blown debris, particularly from the turbulent actions of the wake produced by the passing train.

APPENDIX

Track and Train Data

Track Dimension

Tracks on the Northeast Corridor between New Haven, Connecticut, and Boston, Massachusetts, have the following specifications.[27]

Gage	4 ft 8-1/2 in.	1.4351 m
Distance Between Track Centers		
Main Lines and Sidings	13 ft 0 in.	3.9624 m
Main Lines and Sidings (Minimum for New Construction)	13 ft 0 in.	3.9624 m
Minimum in “Best Fit” Areas	12 ft 0 in.	3.6576 m

Passenger Car Dimension

Passenger car width and height dimensions are as follows:

AAR Standard Contour for New Passenger Cars[28]		
Width over Side Posts	120 in	3.048 m
Height from Top of Rail to Roof	162 in	4.1148 m
Metroliner Car[29]		
Maximum Overall Width	126 in	3.204 m
Maximum Height from Top of Rail	152 in	3.8608 m
ABB X2000 Car[30]		
Maximum Width	121.2 in	3.08 m
Vehicle Height	149.6 in	3.8 m
TGV Atlantique[31]		
Power Car , Maximum Width of Body	110.8 in	2.814 m
Power Car , Maximum Height over Rail	161.4 in	4.100 m
Trailer, Maximum Width	114.3 in	2.904 m
Trailer, Maximum Height over Rail	137.0 in	3.480 m

Clearance Between Two Trains

Clearance between two trains on adjacent tracks is 0.762 m (2.5 ft) based on Metroliner car dimensions.

Side Window Dimension

Measurements were made to obtain window dimensions on Amfleet-1 cars and on different types of commuter cars used by the MBTA (Massachusetts). These window sizes are listed in the following table.

RAILROAD PASSENGER CAR SIDE WINDOW DIMENSION

Car Type	Length	Height	Surface Area
Amfleet-1	0.7938 (m) [31.25 (in.)]	0.4445 (m) [17.50 (in.)]	0.3528 (m^2) [546.9 ($in.^2$)]
MBTA Coach (Massachusetts)	1.403 (m) [55.25 (in.)]	0.4445 (m) [17.50 (in.)]	0.6236 (m^2) [966.9 ($in.^2$)]
MBTA MBB Single Level Coach MBTA Kawasaki Bi-level (Massachusetts)	1.289 (m) [50.75 (in.)]	0.6541 (m) [25.75 (in.)]	0.8431 (m^2) [1,307 ($in.^2$)]

Standard Atmosphere

The standard sea level values of the atmospheric constants are:[32]

Pressure	760 (mm Hg) = 101,325 (Pa)
Density	= 0.0023769 (slug/ft^3) = 1.225 (kg/m^3)
Speed of sound	1116.4 (ft/sec) = 340.29 (m/s)
Kinematic viscosity	0.00015723 (ft^2/sec) = 0.000014607 (m^2/s)
Ratio of specific heats for air 1.4	

Aerodynamic Force Coefficient

Coefficient Definition

The drag and pressure coefficients (C_d and C_p respectively) are defined as follows:

$$C_d = \frac{p - p_\infty}{q_\infty} \qquad C_p = \frac{p - p_\infty}{q_\infty}$$

where $q_\infty = \frac{1}{2}\rho_\infty v_\infty^2$ is the dynamic pressure,

p: pressure,
p_∞: free stream static pressure,
ρ_∞: free stream density,
v_∞: free stream velocity.

For low Mach numbers, the flow can be assumed incompressible so that the pressure coefficient remains relatively constant and the pressure will vary only with the square of the velocity. However, at higher speeds, the pressure coefficient will vary because of compressibility effects. The pressure coefficient obtained at low speed, where the flow can be assumed incompressible, can be corrected for compressibility at a higher Mach number by the Prandtl-Glauert rule, provided that the flow is subsonic and the perturbations are small.[33] The pressure coefficient corrected for compressibility (C_{pc}) is:

$$C_{pc} = \frac{C_{po}}{\sqrt{1 - M_{\infty}^{2}}}$$

where, M_∞: Mach number
C_{po}: pressure coefficient for incompressible flow

Drag on Human Body

An average man weighing 734 N (165 lb) and at a height of 1.80 m (5.9 ft) has a frontal projected area when standing of about 0.836 m^2 (9 ft^2) and a side projected area of about 0.465 m^2 (5 ft^2) with a drag coefficient between 1.0 to 1.3 with clothing.[34]

Size and Shape of Rectangular Plate

For a given load applied to a rectangular plate, the reaction force on a per unit perimeter length basis along the edge of the plate depends on the surface area and the plate geometry.

Given a rectangular plate with sides x and y, the aspect ratio is defined as: $\alpha=(x/y)$.
The plate area A is: $A=xy$
The plate perimeter L is: $L=2(x+y)$

Therefore, $y = \sqrt{\dfrac{A}{\alpha}}$

The perimeter L in terms of area and aspect ratio is: $L = 2(\alpha + 1)\sqrt{\dfrac{A}{\alpha}}$

For a given uniform pressure p over the surface of the plate, the force per unit length around the perimeter F/L is: $\dfrac{F}{L} = \dfrac{p\sqrt{\alpha A}}{2(\alpha + 1)}$

Given a uniform pressure applied to the surface of a rectangular plate, the effects of area and geometry of the plate on the force per unit perimeter length are as follows:

(1) For a given aspect ratio, the force per unit length increases as the square root of the surface area.

(2) For a given surface area, differentiating the perimeter with respect to aspect ratio $(dL/d\alpha)$ and setting the derivative to zero, the minimum perimeter occurs for a square plate, or when $\alpha=1$. Increasing or decreasing the aspect ratio away from a square will reduce the force per unit length.

Glazing Breaking Pressure

The breaking pressures for three different size surface areas of a square 1/4-in. thick safety plate glazing are as follows:

1/4-IN. THICK SQUARE SAFETY PLATE GLAZING (7/64-IN. GLASS, 0.015-IN. PLASTIC, 7/64 IN. GLASS)

Glass Size	Surface Area	Breaking Pressure
0.3048x0.3048 m (12x12 in)	0.092903 m^2 (144 in^2)	75,842 Pa (11 psi)
0.4572x0.4572 m (18x18 in)	0.20903 m^2 (324 in^2)	41,369 Pa (6 psi)
0.6096x0.6096 m (24x24 in)	0.37161 m^2 (576 in^2)	24,132 Pa (3.5 psi)

An equation of the form, $P = CA^q$, where P is the breaking pressure and A is the surface area is used to fit through the data points. Using the method of least squares for the curve fit, the coefficient C and the exponent q are computed as follows:

$q = -0.793$ and $C = 11{,}570$ for A in units of m^2
($C = 567.761$ for A in units of in^2)

From this equation, the extrapolated breaking pressures for square glazings corresponding to the surface areas of the passenger car windows are as follows:

ESTIMATED GLAZING BREAKING PRESSURES FROM EXTRAPOLATION

Car Type	Surface Area	Estimated Breaking Pressure
Amfleet-1	0.3528 (m^2) [546.9 (in^2)]	26,400 Pa (3.83 psi)
MBTA Coach (Massachusetts)	0.6236 (m^2) [966.9 (in^2)]	16,800 Pa (2.44 psi)
MBTA MBB Single Level Coach MBTA Kawasaki Bi-Level (Massachusetts)	0.8431 (m^2) [1,307 (in^2)]	13,300 Pa (1.92 psi)

Pressure Limit for Infrasonic Frequency

The sound pressure level (L_p) is defined as:

$$Lp = 20 \log\left(\frac{p}{p_{ref}}\right) \text{dB}$$

Where P_{ref} is the reference sound pressure of 20 μ N/m^2.

A suggested maximum sound pressure level for human exposure to infrasound is 150 dB, regardless of how short the exposure time. For Lp = 150 dB, the root-mean-square (rms) sound pressure is p = 632.5 Pa (0.0917 psi). The zero-to-peak pressure for a sine wave is 894.4 Pa (0.130 psi).

Code of Federal Regulations 49 CFR 223

Federal Railroad Administration, Department of Transportation
Appendix A to Part 223: Certification of Glazing Materials

As provided in this part, certified glazing materials that are installed in locomotives, passenger cars, or cabooses must be certified by the glazing manufacturer in accordance with the following procedures:

b. Testing Requirements

(11) The Test Specimen for glazing material that is intended for use only in side-facing glazing locations shall be subjected to a Type II test regimen consisting of the following tests:

(i) Ballistic Impact in which a standard 22 caliber long rifle lead bullet of 40 grains in weight impacts at a minimum velocity of 960 ft per second.

(ii) Large Object Impact in which a cinder block of 24 lb minimum weight with dimensions of 8 in. by 8 in. by 16 in. nominally impacts at the corner of the block at a minimum velocity of 12 ft per second. The cinder block must be of the composition referenced in ASTM C33L or TM C90.

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