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High Speed Rail: Cost of Compliance for Noise Mitigation Procedures

DOT/FRA/ORD-22/02

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14. ABSTRACT

This report includes the results of follow-on research related to high speed rail noise. The earlier study, entitled High Speed Rail Noise Standards and Regulations, surveyed noise standards and regulations currently in place within the US, EU, Japan, and China as well as methods employed to mitigate noise impacts. It was found that the identified noise standards and regulations are based on different measurement procedures and metrics, which makes direct comparisons difficult. In addition, detailed costs associated with implementing the mitigation methods were not included. The current study involved two key tasks: 1) develop an analytical tool to allow the global standards and regulations to be compared on a common basis, and 2) assess the cost of compliance for the three categories of noise emission reduction procedures: rolling stock modifications, interruption of noise path to receiver, and building modifications at the receiver. The costs were assessed as $/dB(A) reduction and $/dB(A) reduction per impacted resident. This allowed the various procedures to be cost ranked individually and in combination to achieve an overall noise emission reduction target. The cost analysis was applied to two representative rail lines: the Northeast Corridor (NEC) and California High Speed Rail (CHSR) system.

15. SUBJECT TERMS

High speed rail, noise, noise mitigation, noise regulation comparisons, cost of noise regulation compliance, noise reduction methods, cost, study, rolling stock, Northeast Corridor

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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 tony (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (flu 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 tone (t) = 1,000 kilograms (kg)
= 1.1 short tons

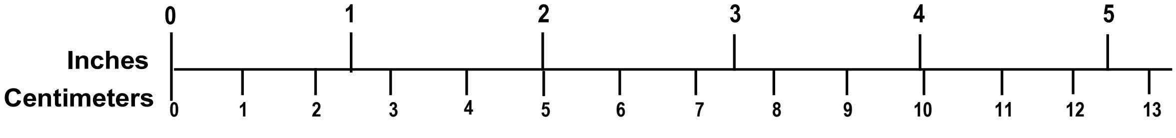
VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fly 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)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°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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Contents

Illustrations

Tables

Equations

Executive Summary

Ricardo, Inc., performed research related to high speed rail noise regulations and compliance from September 13, 2018, to February 20, 2020. The Federal Railroad Administration (FRA) funded the research and included the following goals: 1) develop a spreadsheet-based analysis tool capable of converting values from global rail noise standards and regulations, as well as measured train passby noise data, to a common reference basis, and 2) determine the cost of compliance for various noise reduction techniques to meet the global standards and regulations for high speed rail with speeds in excess of 160 mph.

In a 2016 research study funded by FRA, researchers assessed the global noise regulations and standards for high speed rail, found significant variations in the sound level measurement metrics and procedures (Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S., 2021). This complicates any direct comparisons. However, it was noted that noise theory could be applied to convert the various global standards to a common reference. The research determined it would be valuable to the rail industry if an analysis tool were developed and employed to compare the identified global noise standards and regulations.

As well as researching the respective standards and regulations, the earlier study also identified over 70 high speed train noise mitigation methods. Subsequent interviews with rail industry representatives indicated an interest in defining the comparative cost of the various mitigation technologies that are applied globally and are available for US implementation. The analysis tool developed under this effort allows evaluation of train set passby sound pressure level (SPL) data relative to train noise regulations currently applied within the US, EU, China, and Japan. Known as Comparison Of Noise for TRAin STandards (CONTRAST), the program can be used to: 1) determine whether a train set is in compliance with noise regulations, and 2) using a common reference passby noise data set, to compare the various regulations relative to train speed and, in the case of receiver (immission) regulations, determine the number of passby events allowed during the time periods defined in the regulations. The common reference approach is required because current regulations vary in the reporting metrics, measurement locations, train operating conditions (e.g., speed) and measurement procedures, thus making direct comparisons difficult.

Six data sets are currently included in the CONTRAST library. In addition, a representative passby noise data set was scaled so the equivalent SPL for the passby period was equal to the maximum allowed normalized European Union (EU) Technical Specifications for Interoperability (TSI) Noise regulations. This "Common Reference" data set was then employed to determine the noise metrics corresponding to those of the other countries. The passby data sets and calculation procedures were validated against published data. The impact of microphone position and train speed on SPLs was determined and included in the program. For each passby data set, 15 noise metrics are calculated, corresponding to the respective noise regulations.

The study also indicated with 95 percent confidence that the calculated noise levels are within ±3 dB of the true integrated passby noise levels when at least 20 train passby events of each type under the same operating conditions are measured. For the maximum noise level metrics, the uncertainty increases to approximately ±5 dB for the same number of train passby events.

Since CONTRAST calculates the SPL metrics for the noise regulations of the US, EU, China, and Japan as a function of train speed, microphone position, and number of passby events, the results for the common reference data set can be used to compare these regulations and answer

questions such as “if a train set is compliant with the TSI regulation, how is it expected to perform relative to US, China, and Japan regulations?”

During the cost of compliance portion of the study, it was determined that the optimum noise mitigation techniques to be deployed depending on a variety of factors such as level of noise attenuation required, length of rail line, number of residents impacted, expected cost of the technique, its technology readiness level, the practicality to implement, and expected acceptance by industry. The study involved detailed assessments of each technique to understand trade-offs regarding noise reduction effectiveness and cost in order to inform application decisions.

Key parameters were defined to assess the effectiveness of the over 70 noise reduction methods. These parameters included noise reduction potential, technology readiness level, practicality to implement, industry acceptance and level of cost or investment and were ranked using a 3-point scale (low = 1, medium = 2, high= 3) and parameter weighting system. The resulting score was used to generate an effectiveness ranking from which 30 methods were selected for detailed analysis. Discussions were held with industry stakeholders, including rail operators, technical service providers, and vehicle manufacturers to review interim results, ensure project research was addressing industry needs, assess practicality of identified reduction methods, and gather input for the analysis. Those methods determined to be most cost effective for application to US operations were determined based on application to two representative track systems: the Northeast Corridor and the California High Speed Rail system.

The noise reduction methods were divided into three categories: 1) source reduction (related to noise generated by the train), 2) interruption of noise path (e.g., barriers, deflectors, and sound absorbing materials), and 3) reduction at receiver (e.g., barriers and building modifications). Lifecycle costs were estimated for each of the top 30 noise reduction methods. The life span of each noise reduction method was also identified or estimated as input to the lifecycle cost analysis. Costs were calculated in units of dollars per train set, maintenance costs per year, dollars per track feature (e.g., tunnel or bridge), and dollars per mile of track.

Source noise reduction costs ranged from a high of $50,000,000 per track mile for increasing track curve radii to a low of $18,000 per train set for adding pantograph fairings. Costs for reduction methods applied along the noise path range from a high of $50,000,000 per track mile for increasing the distance to the edge of the railroad property to a low of $133,000 per track mile for adding resilient padding to slab track. Costs for reducing noise levels at the receiver range from a high of $1,800,000 per track mile for sound barriers at property boundaries to a low of $500 per dwelling for caulking and sealing gaps.

The top five most cost-effective noise reduction methods in each category, as identified during the study were: A) at the source: pantograph fairings and shields, skirts, undercar noise absorption, wheel spin slide control, and tuned rail dampers; B) along the noise path: lower track into trenches, apply sound absorption material on barriers, creation of additional buffer zones, installation of barriers at edge of right-of-way, and addition of damping materials on slab track; and C) at receiver: caulking and sealing gaps, installing windows with 3 inch air gap, layered noise attenuation walls, foundation insulation, and façade insulation.

Application of the calculated costs and ranked noise reduction methods to the two representative US high speed train routes allowed determination of the cost of compliance for meeting target reduction levels consistent with US regulations.

1. Introduction

From September 13, 2019, to February 20, 2020, the Federal Railroad Administration (FRA) funded Ricardo, Inc. to conduct research on the cost of mitigation for high speed rail (HSR) noise and development of an analysis tool for comparison of noise standards to a common reference data set.

1.1 Background

During 2017, FRA funded a study to assess the global regulations and standards for HSR (Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S., 2021). The study found that, as well as the standards and regulations varying around the world, the reference basis also changed. This complicates the comparison of standards. However, it was noted that noise theory could be applied to convert the various global standards to a common reference. It was suggested that the analysis tool and a common reference comparison of the global standards and regulations would be a very beneficial addition to the report for the rail industry.

As well as researching the respective standards and regulations, the 2017 study also identified over 70 high speed train (HST) noise mitigation methods. Subsequent interviews with rail industry representatives indicated an interest in defining the comparative cost of the various mitigation options as might be encountered in the US market.

1.1.1 Development Framework

Although HSR operations in Europe and Asia have attained high levels of technology readiness (TRL) 9 (Assistant Secretary of Defense for Research and Engineering, April 2011) (U.S. Department of Defense, 2010), it is not currently deployed in the US at speeds over 149 mph.. Therefore, the best practices for design and noise mitigation strategies for US operations have yet to be fully understood. This would suggest the technology for speeds over 160 mph is at perhaps TRL 7 for the US since the technology is deployed in other global regions and the first sections of the California High Speed Rail (CAHSR) system now under construction.

A review of the literature indicates neither a conversion spreadsheet for noise regulations, nor a cost of compliance calculation procedure, especially for the US market, has yet been developed.

HSR system technologies continue to evolve, especially in Europe and Asia. The existing HSR systems are well established and operate through urban and rural areas. Examples of these global developments include:

- In France, the *trains a grand vitesse* (i.e., a HST, known as TGV) were developed during the mid/late 1970s. The original trains operated with peak speeds of 170 mph. TGV trains continue to be developed and augmented with the TGV 2N2 commissioned in 2011 with a top speed of 200 mph (O'Sullivan, F., 2019).
- In Germany, Intercity Express (ICE) started having high speed trains in revenue service from 1991. The ICE 1 initially had a peak speed of 155 mph, which was subsequently raised to 174 mph. The third generation, ICE 3, trains first came into service in 2000 and can operate up to 199 mph (Deutsche Bahn, 2019).
- In Japan, Shinkansen HST network started in 1964. Today there are 1,623 miles of HS network with speeds between 150 mph and 200 mph (Japan Station, 2019).

- China has the world’s longest HSR network at over 9,900 miles. It also has the world’s longest rail line from Beijing to Guangzhou at 1,428 miles with a maximum operating speed of 220 mph (Berti, A., 2019).
- In April 2015, Central Japan Railway Company set a new train world speed record of 375 mph during test runs for the magnetic-levitation train line planned to operate between Tokyo and Nagoya (McCurry, J., 2015).

Other recent HST technology advancements include increased efficiency propulsion systems (i.e., traction motor design), reduced aerodynamic drag, optimized pantograph/catenary systems improved wheel and brake systems (e.g., regenerative braking), interoperability and safety, and incorporation of noise mitigation methods into the design of new train sets (Mraz, S., 2011).

Although a few passenger trains operate at speeds above 125 mph, such as the Northeast Corridor (NEC) and along Florida’s east coast, the remaining US rail system operates at lower speeds. Recently, there has been interest in consolidating US regional HSR development plans into an extensive cross-country network of rail lines with speeds as high as 250 mph in certain sections. A wider adoption of HSR is expected over the next few years (Banko, F. P., & Xue, J. H., 2012) (Wolf, S., 2010).

The definition of HSR varies by country. In the case of US, there are three categories of HSR that are currently identified by FRA (Progressive Railroading, 2018):

1. *Tier 1*: train speeds of up to 125 mph
2. *Tier 2*: train speeds of 125 mph to 160 mph
3. *Tier 3*: train speeds greater than 160 mph up to 220 mph

To minimize costs, most US passenger trains operate on shared rights of way. However, to operate at higher speeds, Tier 3 trains must have exclusive rights of way and must operate on tracks without grade crossings (Progressive Railroading, 2018).

As of 2019, there are six high speed passenger rail projects underway within the US, each at different levels of development (US High Speed Rail Association, 2018):

1. *California High Speed Rail (owned by the State of California)*: This project is already under construction and the first segment between Merced and Bakersfield is planned to start operating in 2021. This project is expected to allow train speeds up to 220 mph which will be the highest in the world. Due to project delays, Federal funding for the California project was withdrawn (Shepardson, D., 2019).

   XpressWest High-Speed Rail: An extension to the California HS corridor is being planned that would connect Las Vegas, NV, to the CAHSR. With its Southern California station initially in Victorville, CA, fully electric HST would make the trip along the I-15 corridor to Las Vegas at speeds in excess of 150 mph with trains leaving every 20 minutes during peak travel times. The train technology and systems will be fully interoperable with the CAHSR system allowing for future high-speed service into Burbank and Los Angeles. (Brightline's Official Magazine, 2016).

2. *NEC High Speed Rail (jointly owned by Amtrak, New York State, Connecticut Department of Transportation, and the Massachusetts Bay Transportation Authority)*: In 2016, a contract was signed with Alstom to purchase new Avelia Liberty trainsets,

capable of speeds up to 186 miles/h (300 km/h). These are expected to begin operating in 2021 (Rail News: Amtrak, 2016) (Sneider, J., 2016). Due to existing NEC rail infrastructure limitations, the projected maximum train speed is projected to be 160 mph on a limited number of straight sections of track (Brajkovic, V., 2019).

3. *Texas Central High-Speed Rail (privately owned)*: Japanese-funded project to link the cities of Dallas and Houston with travel times under 90 minutes. The trains will reach top speeds of 205 mph and the project is expected to be operational by 2021.
4. *Midwest (Chicago) High Speed Rail (developing business framework)*: The plan centers on Chicago's existing rail infrastructure and plans to upgrade it gradually to higher speeds capability. The initial phase will connect Chicago to nearby large cities with interconnected networks for last mile connectivity. Eventually, the plan is to connect the Midwest network to the NEC to allow for high speed travel from Chicago to New York.
5. *Florida High Speed Rail, Virgin Trains USA (privately owned and operated)*: The Brightline network is the nation's first privately-owned HSR corridor. It is presently operating between Miami and West Palm Beach in Florida's east coast, with plans to connect Orlando and Tampa. Most of the section is restricted to 75 mph, but certain sections can reach 125 mph (Hanson, B., 2018) (Spear, K., 2018).
6. *Cascadia (Northwest) High Speed Rail*: Like the Southwest corridor to Las Vegas, the Cascadia corridor is still under business review and the development stage. Under public-private partnership, Microsoft, the government of British Columbia, and the State of Washington have allocated funds to review plans for a HSR capable of speeds up to 250 mph connecting Seattle and Vancouver, Canada (Nickelsburg, M., 2018).

1.1.2 Description of Need

Increased levels of noise and vibration are the most important concerns to residents living near any HSR line. Recent studies have linked health impacts to high noise levels (Muller, U., Schreckenberg, D., Mohler, U., Liepert, M., 2018). For this reason, it is important to have appropriate regulations in place to control noise emissions from rail operations and ensure a healthy environment for anyone living near HSR lines. In 2017, Ricardo, in conjunction with FRA, studied key global noise standards and regulations to provide insights related to HSR (Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S., 2021). The objectives of that study were to understand: (1) how different jurisdictions have established acceptable noise regulations for HSR; (2) how the noise and associated vibrations are being measured; and (3) the current industry practices to provide effective source noise reduction methods, noise barriers, and receiver noise mitigation strategies.

1.2 Objectives

In conjunction with representatives of FRA's Office of Research, Development & Technology, US Class I railroads, and the US Department of Transportation's Volpe National Transportation Systems Center, the following primary goals were established for the current study:

A. Develop a spreadsheet-based analysis tool to allow direct comparison of the global standards and regulations. This tool is to be capable of converting values from global rail noise standards and regulations as well as measured train passby noise data to a common reference basis.

B. Develop comparative costs for the various noise mitigation options as might be encountered in the US market. Determine the cost of compliance for various noise reduction techniques to meet the global standards and regulations for HSR with speeds in excess of 160 mph.

1.3 Overall Approach

The approaches taken to address the two key project objectives included:

Task 1: Complete research on computational procedures defined in the various noise measurement protocols associated with US, EU, China, and Japan rail noise regulations. Develop equations for converting train passby SPLs to the metrics associated with the identified train noise regulations. Create an Excel® spreadsheet that incorporates the noise metric calculation procedures and include an initial library of six passby noise data sets. Develop a common reference passby SPL data set and employ it to compare the railroad noise regulations currently in place for the US, EU, China, and Japan.

Task 2: Complete research on current and proposed methods for mitigating railroad noise impacts. Rank these in terms of effectiveness. Develop and apply a procedure for evaluating the cost effectiveness of the top 30 noise reduction methods. Apply these methods to two representative US HSR routes (NEC and CAHSR) to assess the cost of meeting a target noise reduction of 20 dB(A) relative to the unmitigated case. It is noted that the Task 2 portion of the current study focused on the "Compliance" section of the rulemaking process and extended Ricardo's earlier analysis on identification of industry practices to provide effective noise mitigation strategies.

1.4 Scope

Based on FRA's review of US standards and regulations for noise emission from HSR (Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S., 2021), it was noted that the US currently has not established noise legislation specific to high speed operations. Currently, US rolling stock, including HST, have the general classification as either locomotives or rail cars relative to noise regulations. Assuming no new noise regulation specific to HSR is introduced, the noise from most currently available trainsets, if operating at speeds above 320 km/hr (200 mph), will exceed current US noise regulations. Thus, noise mitigation techniques and strategies will play a very important role in the successful introduction and growth of HSR transport in the US.

The scope of the two portions of the project are reviewed below.

1.4.1 Conversion Tool

The development of the common reference comparison tool included research into noise reporting metrics (i.e., parameters calculated from measured data) for the US, EU, China, and Japan. It does not include metrics for other countries or for non-railroad modes of surface transportation. At the current time, the library of available train SPL passby data is limited to six data sets.

1.4.2 Cost of Compliance for Rail Noise Mitigation Procedures

The mitigation procedures evaluated during the current study were based on the results of the earlier railroad noise standards and regulations research (Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S., 2021). These were assessed to determine the top 30 most effective methods for reducing SPLs and these 30 were then subjected to a cost of implementation analysis. No additional methods were considered during the current study and only the top 30 were applied to the two representative US HSR routes for the determination of the cost to achieve noise reduction targets. The earlier FRA study was quite comprehensive, so the 30 selected mitigation methods are considered to represent those found to be cost effective by other countries.

The example cost of implementation analyses for the two representative US rail lines was performed at a high level. The mitigation methods applied to each route were identical, so the assessment provides good relative comparisons of the respective implementation costs. Much more detailed analyses would be required to obtain accurate cost estimates for specific routes and would include finer divisions of the track sections and surrounding land use designations.

1.5 Organization of the Report

This report is divided into two key sections. Part 1 describes the development of the spreadsheet-based HSR noise regulations analysis tool. Results of employing the tool to evaluate five passby noise pressure level data sets are included, along with comparative assessments of EU, US, China, and Japan regulations based on a common reference passby data set. Part 2 presents a review of HSR noise mitigation procedures and associated costs. A discussion of the methodology employed in selecting and applying noise mitigation methods on rail lines is included along with assessments of costs associated with application to two represented US HSR lines.

2. Part 1: CONTRAST, Spreadsheet-Based Noise Analysis Tool

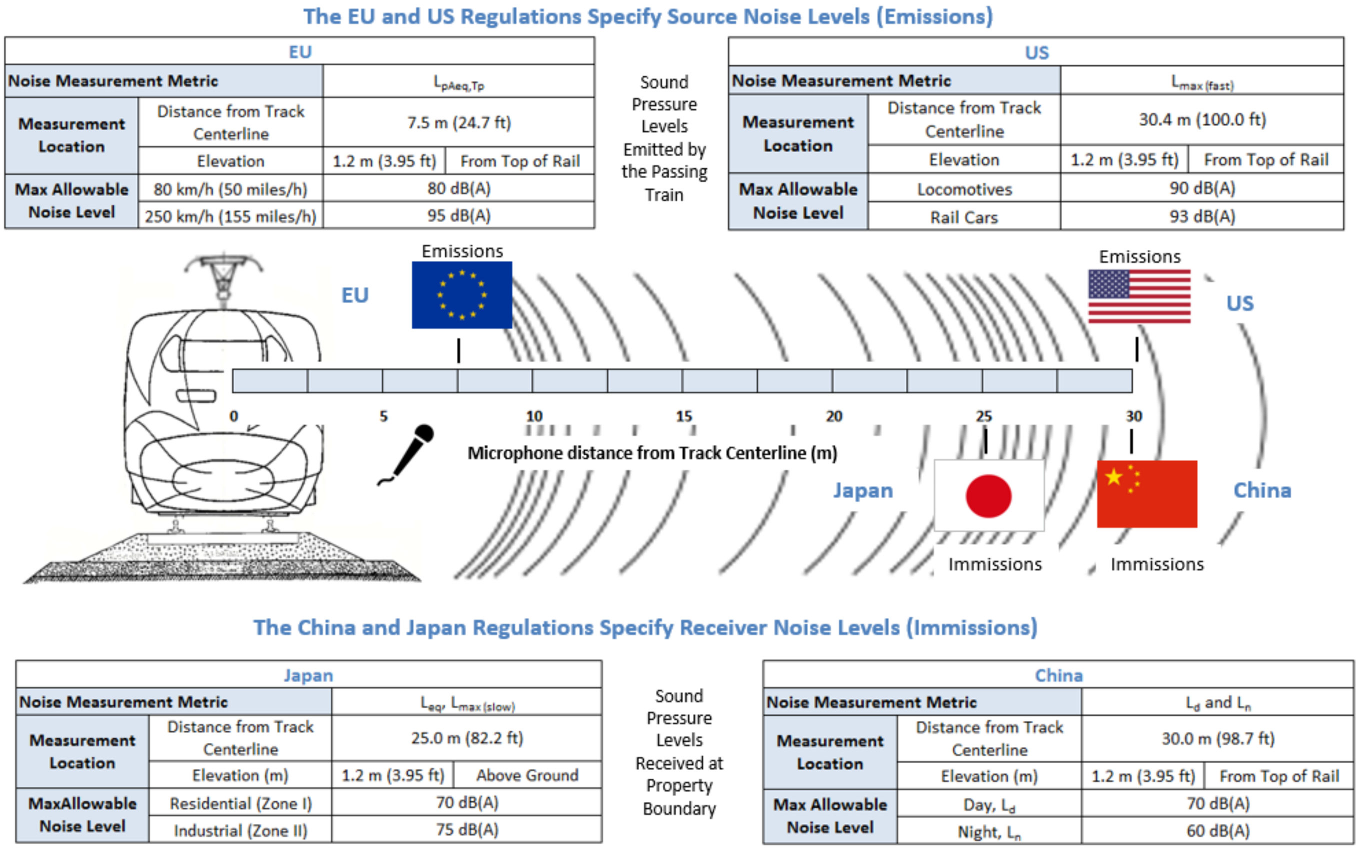
Noise emissions (i.e., SPLs emitted by a source) and immissions (i.e., SPLs measured by a receiver) are typically overseen by different branches of government, with emissions being under the jurisdiction of national transportation agencies and immissions by national environmental agencies, and in some cases, and by State and local governments (Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S., 2021). For example, the US Environmental Protection Agency (EPA) establishes railroad noise emissions limits and FRA enforces regulations that meet the EPA standards. Rolling stock noise emissions limits are specified in EU and US regulations while China and Japan specify immissions limits. Currently, the US does not have specific noise legislation relating to HSR operations. Instead, HST, by default, are classified as locomotives in the US and the maximum noise limit is 90 dB(A), based on $L_{max\ (fast)}$ metric. The limit for US rail car noise is 93 dB(A), based on $L_{max\ (fast)}$ metric, with measurements conducted 30 meters (98.4 feet) from the track centerline. The noise limit for electric HST in the European Union (EU), at a reference speed of 250 km/h (155 mph), is 95 dB(A), based on $L_{pAeq,Tp}$ metric, measured at a distance of 7.5 meters (24.6 feet) from the track centerline.

Currently, EU countries do not have the option to adopt regulations that are stricter than those contained in the Technical Specifications for Interoperability (TSI), thus facilitating inter-country operations. In China, the maximum allowable immissions limit for all rolling stock, including HSR, is 70 dB(A) during the day and 60 dB(A) during the night, based on the L_d and L_n metrics, measured 30 m (98.4 feet) from the track centerline. In Japan, HST must have noise levels of 75 dB(A) or less for commercial and industrial areas and 70 dB(A) or less for residential areas, based on the L_{eq} and $L_{max(slow)}$ metrics, measured 25 m (82 feet) from the track centerline. These regulations are summarized in Figure 1 (Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S., 2021).

Because of significant variations in SPL measurement procedures and data analysis methods associated with US, EU, and Asian—specifically China and Japan—HSR noise codes, standards, and regulations. These variations pose challenges to making direct comparisons of the regulation limits.

The analysis tool, entitled Comparison Of Noise for TRAin STandards (CONTRAST), includes four major components, and was developed for the conversion of noise regulation values to a common reference:

1. A library of passby noise data for HST sets was assembled. The initial version of CONTRAST includes six HST data sets. The spreadsheet program allows other train sets to be added. It is noted that SPL data for the train sets are to be obtained according to regulations and standards requirements for instrumentation and measurement procedures.



The EU and US Regulations Specify Source Noise Levels (Emissions)

EU			
Noise Measurement Metric		$L_{pAeq,Tp}$	
Measurement Location	Distance from Track Centerline	7.5 m (24.7 ft)	
	Elevation	1.2 m (3.95 ft)	From Top of Rail
Max Allowable Noise Level	80 km/h (50 miles/h)	80 dB(A)	
	250 km/h (155 miles/h)	95 dB(A)	

Sound Pressure Levels Emitted by the Passing Train

US			
Noise Measurement Metric		$L_{max\ (fast)}$	
Measurement Location	Distance from Track Centerline	30.4 m (100.0 ft)	
	Elevation	1.2 m (3.95 ft)	From Top of Rail
Max Allowable Noise Level	Locomotives	90 dB(A)	
	Rail Cars	93 dB(A)	

The China and Japan Regulations Specify Receiver Noise Levels (Immissions)

Japan			
Noise Measurement Metric		L_{eq}, $L_{max\ (slow)}$	
Measurement Location	Distance from Track Centerline	25.0 m (82.2 ft)	
	Elevation (m)	1.2 m (3.95 ft)	Above Ground
MaxAllowable Noise Level	Residential (Zone I)	70 dB(A)	
	Industrial (Zone II)	75 dB(A)	

Sound Pressure Levels Received at Property Boundary

China			
Noise Measurement Metric		L_d and L_n	
Measurement Location	Distance from Track Centerline	30.0 m (98.7 ft)	
	Elevation (m)	1.2 m (3.95 ft)	From Top of Rail
Max Allowable Noise Level	Day, L_d	70 dB(A)	
	Night, L_n	60 dB(A)	

Figure 1: Noise Regulations and Measurement Procedures, EU, US, Japan, and China

2. From the passby noise data sets, noise metrics associated with each identified regulation are calculated. This allows comparisons of the train set passby data to each identified regulation. Table 1 includes these noise metrics.

Table 1: Noise Metrics Calculated by CONTRAST

Regulation	Calculated Noise Metrics*
United States	$L_{max\ (fast)}$, L_{pAEmax}
European Union	$L_{pAeq,Tp}$, $L_{pAeq,Tp}$ normalized to 80 km/hr, $L_{pAeq,Tp}$ normalized to 250 km/hr.
China	L_d, L_n
Japan	L_{eq}, L_{Amax}
Other Noise Metrics	L_{pASmax}, L_{pAFmax}, $L_{pAeq\ (passby)}$, TEL, SEL, L_{10}, L_{50}, L_{90}, L_p (maximum)

*Noise metrics are defined the CONTRAST spreadsheet.

Where: $L_{max\ (fast)}$ = Maximum SPL with sound meter on fast setting
L_{pAFmax} = Maximum SPL with sound meter on fast setting = $L_{max\ (fast)}$
$L_{pAeq,Tp}$ = A-weighted SPL for train passby event
L_d = A-weighted SPL during the day period
L_n = A-weighted SPL during the night period
L_{eq} = Receiver cumulative noise exposure over selected time period

L_{Amax} = Energy average of slow maximum SPL over 20 passby events
L_{pASmax} = Maximum SPL with sound meter on slow setting
$L_{pAeq(passby)}$ = A-weighted SPL during passby event
TEL = Transit Exposure Limit
SEL = Sound Exposure Limit
L_{10} = SPL for which 90% of the recorded values are greater
L_{50} = SPL for which 50% of the recorded values are greater
L_{90} = SPL for which 10% of the recorded values are greater
$L_{p(maximum)}$ = Maximum recorded SPL

3. To compare the various regulations, a common reference passby data set was developed. This was accomplished by scaling a selected passby data set to exactly meet EU TSI NOI (2014) normalized noise metrics: $L_{pAeq,Tp}$ normalized to 80 km/hr and $L_{pAeq,Tp}$ normalized to 250 km/hr (per TSI specifications). The scaled data set, as the Common Reference, is then used to calculate noise metrics for each regulation: US, EU, China, Japan. The metrics are adjusted to account for microphone position and train speed.
4. Using noise metrics for the common reference data set, generate Comparison Charts for the US, EU, China and Japan high speed rail noise regulations.

The analysis tool was applied to the regulations and standards identified in the earlier FRA study (Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S., 2021). A copy of the CONTRAST analysis tool, in Excel® spreadsheet format, has also been provided to FRA.

Researchers obtained the SPL data contained in the CONTRAST library using test procedures prescribed by agencies having jurisdiction, such as the European Railway Agency (i.e., in the EU), EPA, Japan Ministry of the Environment, and the China Ministry of Transport. The sound pressure library includes microphone measurements recorded during the train passby events. The reduced data are employed to perform the following comparisons:

A. Compare selected train sets to US regulations
    1. Determine passby noise level at distance of 30 m (100 ft.) from track centerline [microphone elevation is 1.2 m (4 ft.) above track elevation]
    2. Determine $L_{max(fast)}$ for selected train set at 30 m from track centerline and 1.2 m elevation
    3. Compare results to US FRA noise regulations (locomotives and rail cars) at speeds greater than 45 mph (72.4 km/hr)

B. Compare train set passby data to EU regulations
    1. Determine passby noise level at distance of 7.5 m (25 ft.) from track centerline [microphone elevation is 1.2 m (4 ft.) above track elevation]
    2. Normalize $L_{pAeq,Tp}$ data to 80 km/hr (50 mph) and 250 km/hr (155 mph) per TSI 1304 (2014)
    3. Compare results to TSI Noise regulations (electric locomotives) at reference speeds of 80 km/hr (50 mph) and 250 km/hr (155 mph)

C. Compare train set passby data to Japanese regulations

1. Determine passby noise level at boundary of railroad property, defined as 25 m (82 ft.) from outer track centerline and 1.2 m (4 ft.) above top of rail
2. Calculate the noise metrics L_{eq} and L_{Amax} using the energy mean of the peak noise levels
3. Provide an indication whether noise barriers are required

D. Compare train set passby data to Chinese regulations

1. Determine passby noise level at boundary of railroad property, defined as 30 m (100 ft.) from outer track centerline and 1.2 m (4 ft.) above top of rail
2. Determine number of train set passbys allowed during daytime period
3. Determine number of train set passbys allowed during nighttime period

The second key feature of CONTRAST is to employ a common reference high speed train passby sound pressure level data set to compare regulations from the US, EU, China, and Japan. A representative passby noise data set was scaled so the equivalent sound pressure level ($L_{pAeq,Tp}$) for the passby period was equal to the normalized TSI Noise (2014) regulations: $L_{pAeq,Tp}$ for 80 km/hr, which is 80 dB(A), and $L_{pAeq,Tp}$ for 250 km/hr, which is 95 dB(A). This common reference data set was then employed to determine the noise metrics corresponding to the other countries (i.e., US, China, and Japan) to allow a direct comparison of the noise regulations. For countries that impose immission regulations, the program calculates the maximum number of train passby events that will not exceed regulation limits.

2.1 CONTRAST Application and Benefit

Railroad operators would benefit from a procedure that allows an assessment of train noise characteristics relative to existing and proposed regulations. However, direct comparisons of regulated noise limits are difficult to perform due to the variations in metrics, measurement locations, and train operating conditions (e.g., speed) and measurement procedures. A standardized method was developed to allow for a direct comparison of noise limits and test data. Based on an evaluation of noise measurement methods and calculation procedures, it was determined that a global-scale comparison process could be developed as a spreadsheet-based program. The program allows a selection of train type, train speed, microphone position, and metrics. A library of available test data serves as the basis for calculating the various sound measurement parameters, such as $L_{max(fast)}$, $L_{max(slow)}$, $L_{pAeq,Tp}$, L_d, L_n, and L_{pASmax}, as a function of microphone location, train speed, length of measurement time period, and number of train passing (passby) events. From these results, statistical calculations can be completed, including L_{90} (i.e., sound level exceeded 90 percent of the time), and L_{10} (i.e., sound level exceeded 10 percent of the time).

2.2 Regulation Metrics (US, EU, China, and Japan)

Table 2 summarizes the regulations for high speed rail noise for the US, EU, China, and Japan.

Table 2: US, EU, China, Japan HST Noise Regulations Summary

For Moving Trains		Applicable Rolling Stock	Sound Pressure Measurement Method	Train Speed (km/h)	Maximum Allowable Sound Pressure, dB(A)	Measurement Location	
Location	Reference					Elevation (m)	Distance from Track Centerline (m)
US	40 CFR Part 201.12	Locomotives	L_{max}(fast)	all	90	1.2 (above top of rail)	30
	40 CFR Part 201.13	Rail Cars	L_{max}(fast)	>45	93		
EU	TSI Noise 2014	Locomotives	$L_{pAeq,Tp}$	80	84	1.2 (above top or rail)	7.5
				250	99		
		EMUs		80	80		
				250	95		
		DMUs		80	81		
				250	96		
China	GB 12525-90	All Rolling Stock	L_d	all	70	1.2 (above top of rail)	30
			L_n	all	60		
Japan	Environmental Law 91 of 1993	High Speed Rail: Shinkansen	L_{eq}, Zone I	all	70	1.2 above ground	25
			L_{eq}, Zone II	all	75		
Notes:	For China, the L_d and L_n metrics are based on the number of passby events that occur during the day time and night time periods. For Japan, the sound pressure level at receiver, L_{eq}, allows use of barriers and other noise path attenuation methods. For Japan, Zone I is classified as residential and Zone II is classified as commercial/industrial.						

It is noted that the corresponding metrics are different for each regulation. Sections 2.2.1 through 2.2.4 describes the metrics.

2.2.1 US Metrics

L_{pASmax} is the maximum SPL, slow and A-weighted, and L_{pAFmax} is the maximum SPL, fast and A-weighted. Slow and fast refer to the sound meter integration periods. The time period for the "slow" reading is 1 second. The time period for the "fast" reading is 0.125 seconds. L_{pAFmax} is equal to $L_{max(fast)}$. $L_{max\ (fast)}$ can be calculated as the logarithmic average of the recorded SPLs for the 0.125-second time interval containing the highest values.

2.2.2 EU Metrics

$L_{pAeq,Tp}$ is the A-weighted equivalent continuous SPL produced by the train as measured during the passby event and described by the equation (Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S., 2021):

$$L_{pAeq,T_p} = 10 \lg \left(\frac{1}{T_2 - T_1} \int_{T_1}^{T_2} \frac{p_A^2(t)}{p_0^2} dt \right) \quad \text{dB}$$

where T_p is the passby time interval = time when trail tail passes microphone minus time when train nose passes microphone = T_2 - T_1

T_1 is the time when the train nose passes the microphone

T_2 is the time when the train tail passes the microphone

$P_A(t)$ is the A-weighted instantaneous sound pressure in Pa at time t

p_0 is the reference sound pressure: $p_0 = 20\mu Pa = 0.00002$ Pa

Δt_i is the time increment between measured data points (0.05 seconds for the data sets included in this program)

$P_A(i)$ is the A-weighted instantaneous sound pressure in Pa at passby time increment, i

2.2.3 China Metrics

L_d is the A-weighted equivalent sound level measured during the daytime, dB(A). The SPL averaged on an energy basis as shown below (Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S., 2021):

$$L_d = 10\log_{10}\left[\sum_{j=1}^{N} t(j)10^{\frac{L(j)}{10}}\right]$$

where *t(j)* is the fraction of time during which SPL, *L(j)*, occurs during the time period over which L_d applies.

L_n is the A-weighted equivalent sound level measured during the nighttime, dB(A). The equation for L_n would be the same as that for L_d with the sound levels corresponding to the time period defined as night.

Measuring conditions should meet the GB 3222 standards (Measurement Methods for Community Noise) (Zheng, W., 2017) which states measurements should be taken in the absence of rain or snow. Measurement time to be day or night; 16 hours is the duration for day measurements and 8 hours is the duration for night measurements.

2.2.4 Japan Metrics

The key metric for Japan's high speed (Shinkansen) trains is L_{eq} (hour), as defined by this equation (Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S., 2021):

$$L_{eq}\text{(hour)} = 10\log_{10}\left[\sum_{j=1}^{N} t(j)10^{\frac{L(j)}{10}}\right]$$

where L_{eq} is the receiver's cumulative noise exposure from all events over a specified time period (1 hour)

$L_A(t)$ is the A-weighted equivalent continuous SPL produced by the train as measured during the passby event where the 1-hour time interval extends from t_1 to t_2 and $T = t_2 - t_1 = 1$ hour the time increment for calculating t(j) is 1 hour (3,600 seconds) and $L_{A(j)} = L(j)$

For areas adjacent to Japan's high-speed train lines, the Shinkansen Superexpress Railway Noise regulations apply and supersede the stricter environmental quality standards.

Shinkansen noise limits vary by adjacent land use categories. The designation for Zone I are as residential areas and has an L_{eq} (hour) limit of 70 dB(A); Zone 2 is designated as commercial and industrial and has an L_{eq} (hour) limit of 75 dB(A).

Another noise metric employed in Japan is L_{Amax} and is defined as the power- or energy-average of the "slow" maximum SPL ($L_{max,\,s}$) of 20 consecutive train passby events in this equation (Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S., 2021):

$$L_{Amax} = 10\log_{10}\left[\frac{1}{20}\sum_{i=1}^{20} 10^{(L_{max,s})_i/10}\right]$$

2.3 Passby Data Set Library

Table 3 and Table 4 summarizes the current data set library.

Table 3: Current Data Set Library: Train Set Descriptions

Data Set Number	Data Set Name	Train Set	
		Manufacturer	Operator
1	Korean HEMU-430X	Hyundai Rotem	Korail
2	Thalys PBKA	GEC-Alstom	Thalys
3	CRH3 Series	Changchun Railway Vehicles, Siemens	China Railway Corporation
4	CRH3 Series	Changchun Railway Vehicles, Siemens	China Railway Corporation
5	CRH3 Series	Changchun Railway Vehicles, Siemens	China Railway Corporation

Table 4: Current Data Set Library: Operating Parameters and Microphone Positions

Data Set Number	Data Set Name	Passby Information			Microphone Position		
		Train Length (m)	Test Train Speed (km/hr)	Passby Time, T_p (sec)	Position Designa-tion	Distance from Track Centerline (m)	Elevation above Top of Rail (m)
1	Korean HEMU-430X	147.40	400	1.33	2	7.5	3.5
2	Thalys PBKA	200.19	296	2.43	1	7.5	1.2
3	CRH3 Series	200.00	271	2.66	2	7.5	3.5
4	CRH3 Series	200.00	271	2.66	1	7.5	1.5
5	CRH3 Series	200.00	271	2.66	3	25	3.5

The passby data sets are shown in Figure 3 through Figure 7 along with the associated references.

The Korean HEMU-430X consists of six cars: two powered end cars and four intermediate cars. The two end cars are 23.5 m (77.10 ft.) in length and the intermediate cars are 25.1 m (82.35 ft.) in length. The data set is available on the SoundView Instruments website (SoundView Instruments, 2016).

Figure 2: Korean HEMU-430X (SoundView Instruments, 2016)

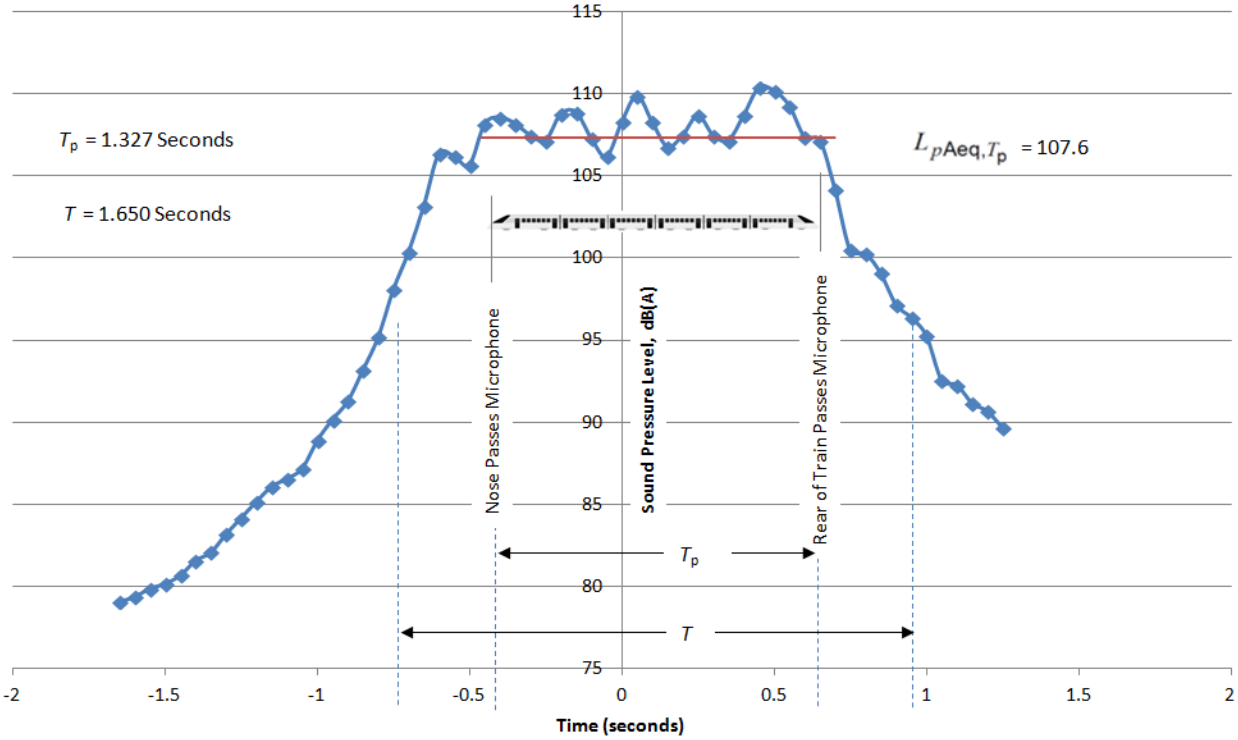


Figure 3: Passby SPLs, Korean HEMU-430X

Figure 4: Thalys PBKA (Free Software Foundation, 2018)

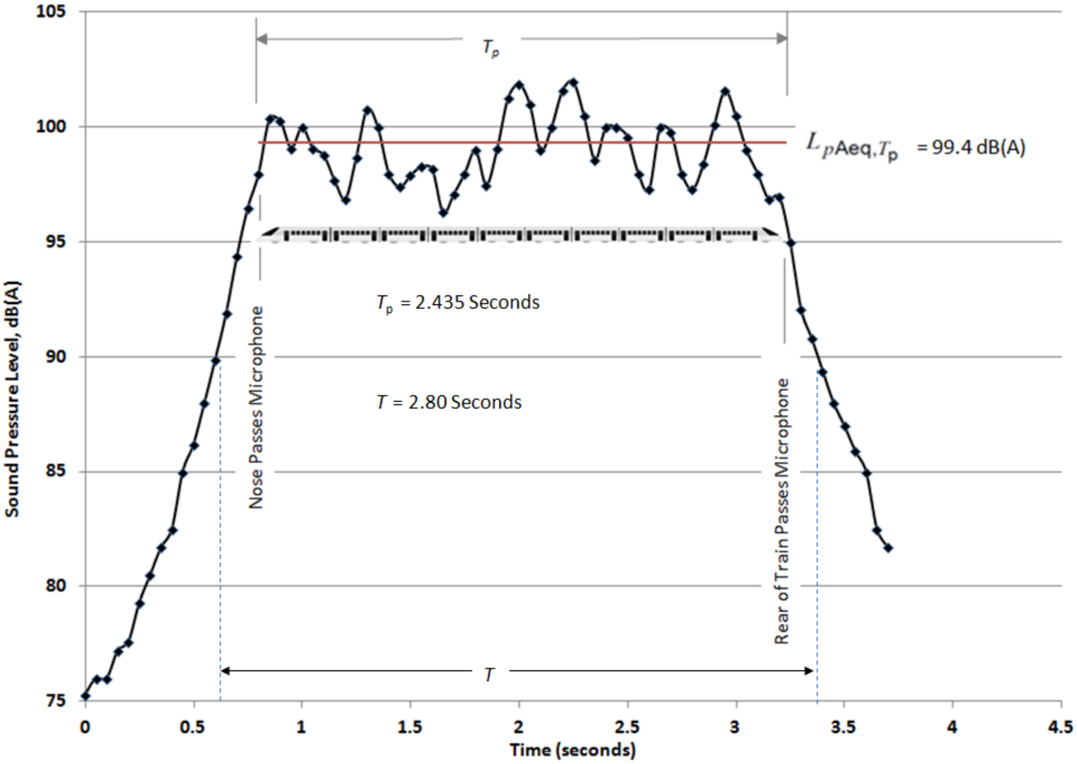


Figure 5: Passby SPLs, Thalys PBKA

The Thalys PBKA consists of 10 cars: 2 powered end cars and 8 intermediate cars. The two end cars are 21.845 m (71.67 ft.) in length and the intermediate cars are 18.7 m (61.35 ft.) in length. The data set is available in the Netherlands TNO Report (Dittrich, M. G., 2010) (Free Software Foundation, 2018).

Figure 6: China CRH3 Series Train Set (China CRH3 Series High Speed Train, 2019)

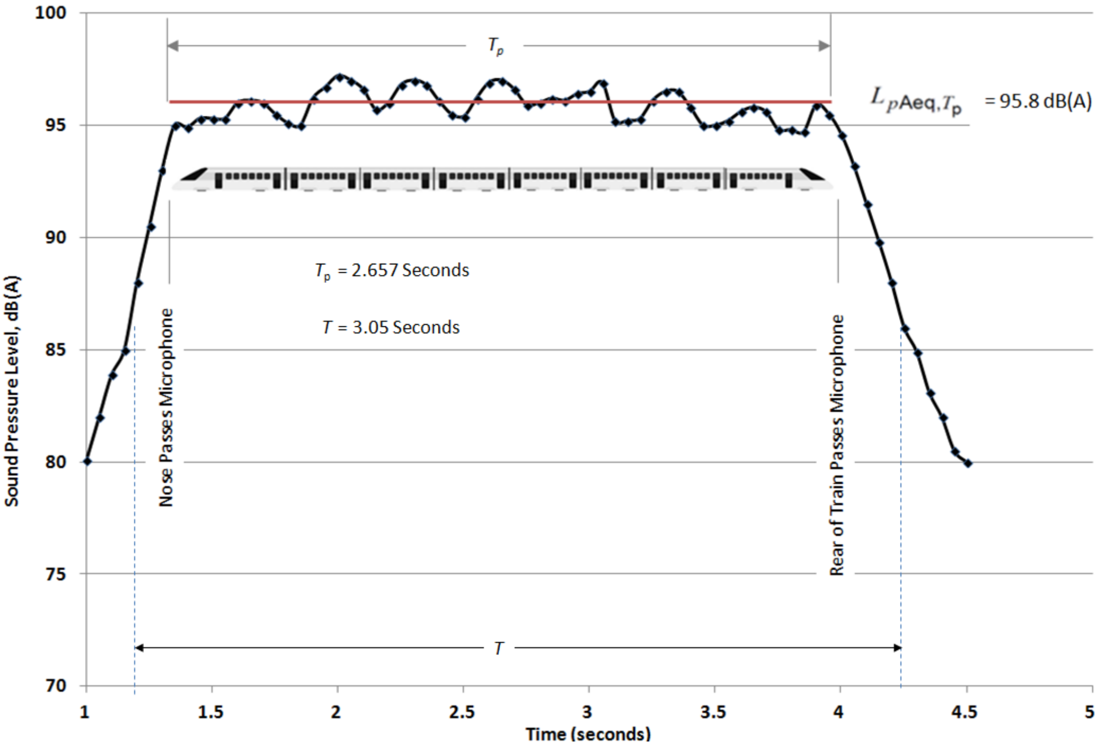


Figure 7: Passby Noise Pressure Levels, China CRH3 Series Train

The microphone for the above data plot is 7.5 m (24.61 ft.) from the track centerline and 3.5 m (11.48 ft.) above the top of rail. Two additional data sets for the China CRH3 series train are also included in the CONTRAST library and are associated with two additional microphone positions: 7.5 m (24.61 ft.) from track centerline and 1.5 m above top of rail, and 25 m (82.02 ft.) from track centerline and 3.5 m above top of rail.

The China CRH3 series trains consist of eight cars: two powered end cars and six intermediate cars. The two end cars are 25.641 m (84.12 ft.) in length and the intermediate cars are 24.786 m (81.32 ft.) in length. The data set is available in the technical paper by He et al. (2014).

2.4 Requirements for Passby Data Sets

The CONTRAST spreadsheet program assumes train passby sound pressure data has been obtained using measurement procedures as defined by the respective regulations. This assumption is necessary to make valid comparisons relative to regulation maximum limits.

Sections 2.4.1 through 2.4.4 reviews the instrumentation and measurement procedures for each of the four identified regulations in.

2.4.1 United States

Instrumentation: Per U.S. Interstate Rail Carriers Noise Regulations under 40 CFR §§ 201.21, 201.22, the EPA measurement criteria are to be made using a sound level meter or alternate sound level measurement system that meets, as a minimum, all the requirements of American National Standard S1.419711 for a Type 1 (or S1A) instrument, to be used with the "fast" or "slow" meter response characteristic. If a Type 1 instrument is not available, the measurements may be made with a Type 2 instrument; but measured SPLs are to be adjusted to account for possible instrument errors. The SPLs (A-weighted) for the instrument "fast" or "slow" meter response characteristics are to be as defined in American National Standard S1.419711.

Measurement Procedures: Per U.S. Interstate Rail Carriers Noise Regulations under 40 CFR § 201.24, EPA measurement criteria for rail car passby tests, the microphone is to be positioned on a line perpendicular to the track 30 m (100 ft.) from the track centerline. The microphone is to be located at an elevation of 1.2 m (4 ft.) above the track. Brake squeal should not be present, and tracks are to be well maintained (see Section 2.4.5).

Per U.S. Interstate Rail Carriers Noise Regulations under 40 CFR § 201.25, EPA measurement criteria, measurement locations must be selected such that no substantially vertical plane surface, other than a residential or commercial unit wall or facility boundary noise barrier, that exceeds 1.2 m (4 ft.) in height is located within 10 m (33.3 ft.) of the microphone and that no exterior wall of a residential or commercial structure is located within 2.0 m (6.6 ft.) of the microphone. Average wind velocity should be 12 mph (19.3 km/hr) or less and maximum wind gust must be 20 mph (32.2 km/hr) or less.

2.4.2 European Union

Instrumentation: Per EN ISO 3095: 2013, Acoustics - Railway Applications - Measurement of Noise Emitted by Railbound Vehicles, the instrumentation system, including the microphones, cables and recording devices shall meet the requirements for a type 1 instrument specified in EN 61672-1. The microphones shall have an essentially flat frequency response in a free sound field. The one-third octave band filters shall meet the requirements of Class 1 according to EN 61260. A suitable windscreen shall always be used. Before and after each series of measurements a sound calibrator meeting the requirements of Class 1 according to EN 60942 shall be applied to the microphone(s) for verifying the calibration of the entire measuring system at one or more frequencies over the frequency range of interest. If the difference between the two calibrations is more than 0.5 dB, then all the measurement results shall be rejected. The compliance of the calibrator with the requirements of EN 60942 shall be verified at least once a year. The compliance of the instrumentation system with the requirements of EN 61672-1 and EN 61672-2 shall be verified at least every 2 years. The date of the last verification of the compliance with the relevant European Standards shall be recorded.

Measurement Procedures: Per EN ISO 3095: 2013, Acoustics - Railway Applications - Measurement of Noise Emitted by Railbound Vehicles Test Environment: test conditions must meet acoustical environment (ground flatness, free of large reflecting objects), meteorological conditions (no rain or falling snow), and background SPLs (10 dB below value during passby event). Table 5 summarizes the permitted microphone positions.

Table 5: EU Noise Regulations, Permitted Microphone Locations

Perpendicular Position from Track Centerline (m)	Elevation above Top of Rail (m)
7.5	1.2
7.5	3.5
25	3.5

Vehicle conditions must also meet requirements: Vehicle shall have run in normal conditions at least 3,000 km (1,864.11 miles) on track with normal traffic. The train is to be unloaded and unoccupied except for the train crew. Doors and windows are to be kept closed and normally operating auxiliary equipment shall be in action.

Track Conditions: The track is to meet guidelines specified in ISO 3095 including levelness, curvature, and roughness.

Test Procedure: Measurements to be made for passby events include: LpAeq,Tp and, if frequency analysis is included, at lease in one-third octave bands according to EN ISO 266.

2.4.3 China

Instrumentation: Chinese Standard GB/T 3785.2-2010, sound level meters applies to multi-channel sound level meters, testing and test methods for Class l and 2 sound level meters. Its purpose is to ensure that all testing laboratories can perform consistent evaluation tests. Instruments must meet the following standards (i.e., compatible with global standards IEC 651 and ANSI S1.4):

- GB 9254-2008 radio disturbance limits and measurement methods for information technology equipment (CISPR22.1997, IDT)
- GB/T 17312 sound level meter random incidence and diffusion field calibration (GB/T 17312-1998, eqvIEC 61183.1994)
- GB/T 17799.2-2003 electromagnetic compatibility - General standards - Immunity test in industrial environments (IEC 61000-6-2.1999, IDT)
- GB/T 3785.1-2010 electroacoustics sound level meter - Part 1. Specifications (IEC 61672-1.2002, IDT): sound meter performance
- GB/T 15173 (IEC 60942) electroacoustic sound calibrator
- IEC 61000-4-2.2001 electromagnetic compatibility (EMC) - Part 4-2. Test and measurement techniques Electrostatic discharge immunity test 1)

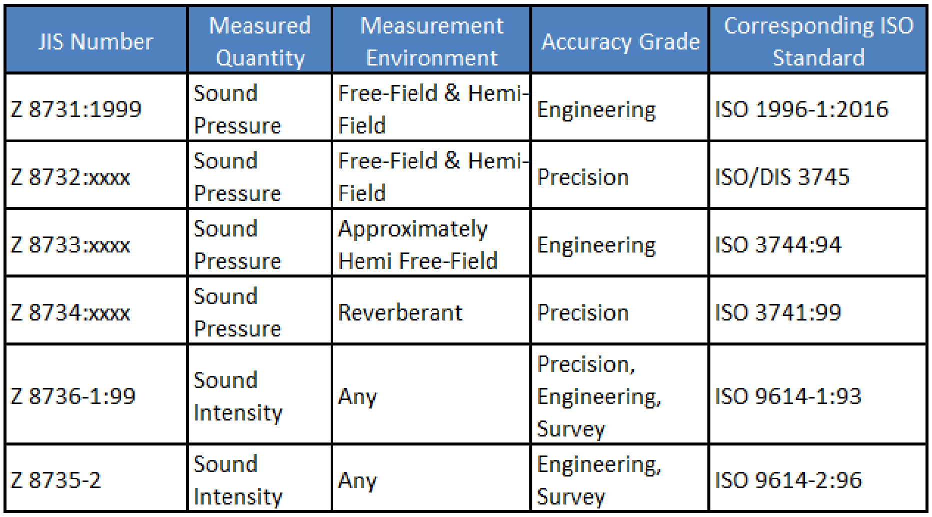
- IEC 61000-4-3.2002 electromagnetic compatibility (EMC) - Part 4-3. Test and measurement techniques radio frequency electromagnetic radiation immunity Test 2)
- IEC 61000-4-6.2001 electromagnetic compatibility (EMC) - Part 4-6. Test and measurement techniques, conducted disturbance of radio frequency field induction Immunity 3
- Measurement of microphones - Part 1. Specification for laboratory standard microphones (IEC 61094-1.2000); ISO Presentation Guide, Guidance on Measurement Uncertainty
- ISO /IEC, international basic and general metrology terminology
- CISPR16-1.1999 specification for radio frequency interference and immunity test instruments and methods
- Part 1. Radio frequency interference and immunity test

Measurement Procedures: Per Chinese Regulation GB 12525-90. The regulation requires five measurement points to be taken at the border of the railway property with the microphone located 1.2 m (3.94 ft.) above the ground and not less than 1 m (3.28 ft.) from a reflective surface. Measurements are taken 30 m (98.4 ft.) from the centerline of the outer track. Measuring conditions should meet the GB 3222 standards (Measurement Methods for Community Noise) which states measurements should be taken in the absence of rain or snow. Measurement time to be day or night; 16 hours is the duration for day measurements and 8 hours is the duration for night measurements.

2.4.4 Japan

Instrumentation: Instrumentation must comply with the Japanese Industrial Standard (JIS) C1502 which requires the precision noise meter prescribed by International Electric Standards Conference (IESC) Publication 179. Table 6 summarizes the Japanese Noise Instrument Standards and Corresponding ISO Standards (Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S., 2021).

Table 6: Japanese Noise Instrument Standards



JIS Number	Measured Quantity	Measurement Environment	Accuracy Grade	Corresponding ISO Standard
Z 8731:1999	Sound Pressure	Free-Field & Hemi-Field	Engineering	ISO 1996-1:2016
Z 8732:xxxx	Sound Pressure	Free-Field & Hemi-Field	Precision	ISO/DIS 3745
Z 8733:xxxx	Sound Pressure	Approximately Hemi Free-Field	Engineering	ISO 3744:94
Z 8734:xxxx	Sound Pressure	Reverberant	Precision	ISO 3741:99
Z 8736-1:99	Sound Intensity	Any	Precision, Engineering, Survey	ISO 9614-1:93
Z 8735-2	Sound Intensity	Any	Engineering, Survey	ISO 9614-2:96

***Measurement Procedures*:** Compliance is required with ISO 11201:95 Acoustics - Noise Emitted by Machinery and Equipment (Free Field over a Reflecting Plane). Compliance is also required with ISO 112012:95 Acoustics - Noise Emitted by Machinery and Equipment (Environmental Corrections). The Shinkansen Superexpress Railway Noise regulation requires a power mean of the peak noise level shall be measured at 1.2 m (3.94 ft.) above the ground in the open air along the railway line with the measuring point located at 25 m (82 ft.) from the centerline of the near side of the track. This is not applicable in sparsely inhabited forests, agricultural lands, etc. According to the environmental quality standards for the Shinkansen Superexpress, noise measurements are to be performed as described below:

- Measurement are to be carried out by recording the peak noise level of each of the Shinkansen trains passing in both the directions, in principle for 20 successive trains.
- Measurement shall be carried out outdoors and in principle at the height of 1.2 m above the ground. Measurement points shall be selected to represent Shinkansen railway noise levels in the area concerned as well as the points where the noise is posing a problem.
- Any period when there are special weather conditions or when the speed of the trains is lower than normal shall not be considered.
- The Shinkansen railway noise shall be evaluated by the energy mean value of the higher half of the measured peak noise levels.
- The measuring instrument used shall be a noise meter that meets the requirements of Article 88 of the measuring Law (Law No 207 of 1951), with A weighted calibration and slow dynamic response.
- The environmental quality standards shall apply between 6am to 12 midnight.

2.4.5 Track Roughness

Track roughness can impact passby SPLs by up to 9 dB(A), depending upon train speed, microphone distance, and degree of roughness. It is thus important to conduct passby noise measurements under acceptable roughness conditions. The CONTRAST program assumes the passby noise data sets were obtained at sites with acceptable track roughness levels. The EU TSI NOI provided guidelines for determining acceptable levels of track surface roughness.

The EU Technical Specifications for Interoperability define track surface roughness and dynamics characteristics for passby noise measurements (Biasin, D., & Leermakers, B., 2010). The “rail acoustic roughness” of the test track is considered suitable for comparable measurements if the one-third octave band roughness spectra assessed according to EN15610 (European Standard for Rail Roughness Measurement Related to Rolling Noise Generation) (European Committee for Standardization (CEN), 2009) throughout the test, fulfill the following upper limit: the wavelength bandwidth is to be at least 0.003 m to 0.10 m (0.3 cm to 10.0 cm) [0.12 ft. to 3.94 inches) corresponding to Figure 8.

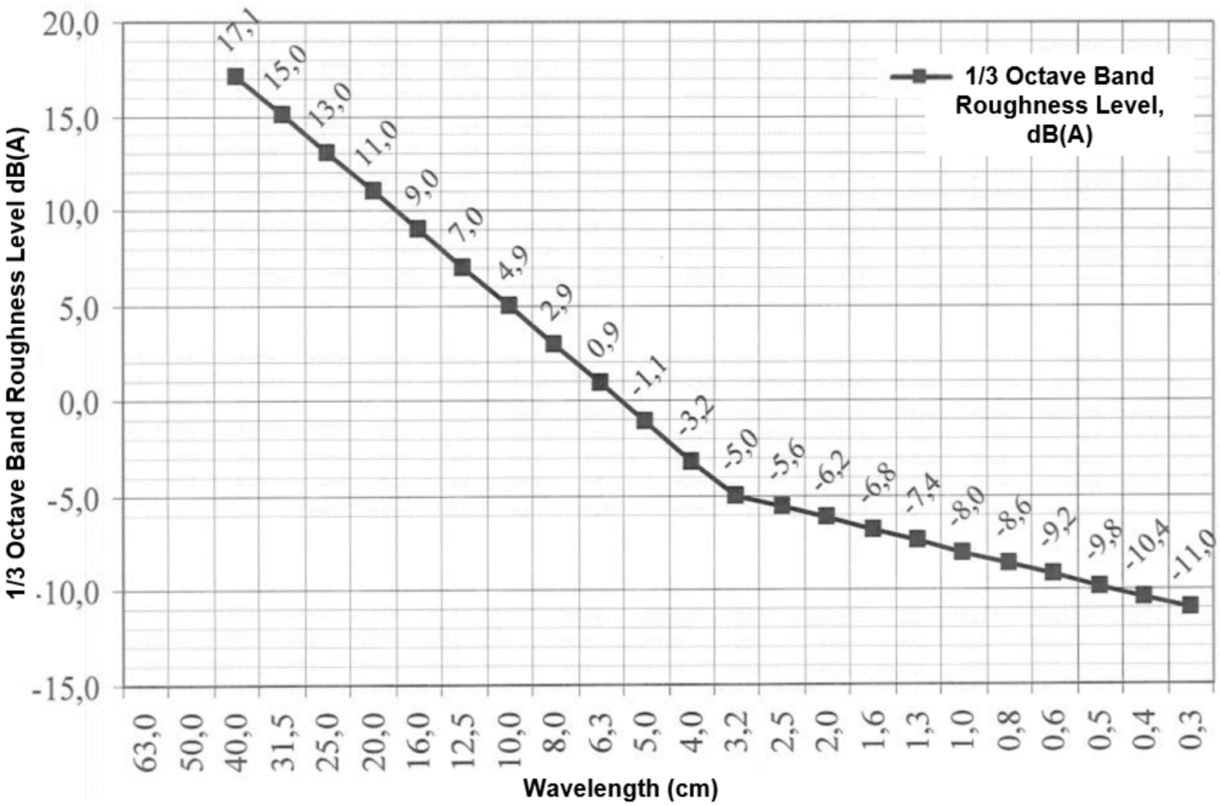


Figure 8: Upper Limit Curve for TSI-Compliant Acoustic Rail Roughness[1]

The dynamic properties of the test track are considered suitable for acceptable noise measurements if the one-third octave band track decay rates spectra measured according to EN15461 (European Standard for Characterization of the Dynamic Properties of Track Selections for Pass By Noise Measurements) (European Union for Standardization (CEN), 2008) throughout the test section fulfill the limits shown in Figure 9.

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[1] Reference: TSI Noise Regulations (2014)

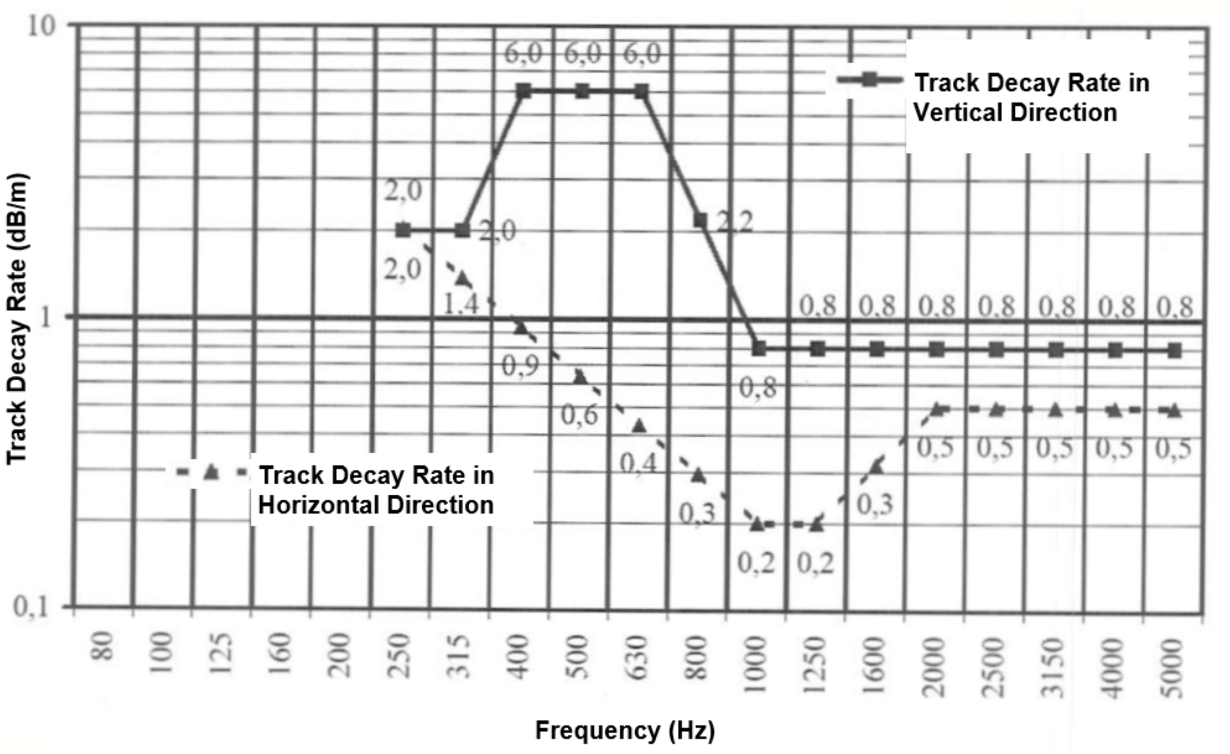


Figure 9: Lower Limit Curves for TSI-Compliant Decay Rates (see footnote #1)

2.5 Digitization and Verification of Passby Data

A procedure has been developed for converting available train passby SPL measurements to defined metrics. The analog signal from the sound pressure meter is digitized using a superimposed grid as shown in Figure 10.

Once the passby SPL data has been digitized, calculations can be made using the defined metrics discussed in Section 2.2 above. These can be compared to published measurements to verify the calculation process.

One key parameter is the time of the passby event, T_P, which is the train length divided by the train speed. For each of the data sets, the lengths of the end and intermediate cars of each train in the library were determined. An example train geometry, in this case the Korean HEMU-430X is shown in Figure 11.

As an example of how the noise metrics were calculated, the value of the A-weighted equivalent continuous SPL, $L_{pAeq,Tp,}$ produced by the HEMU-430X is shown in Figure 10 and Figure 11. The integral is estimated using a midpoint Reimann sum scheme (Osgood, B. G., McCallum, W. G., Hughes-Hallett, D., Gleason, A. M., & Flath, D. E., 2005) and then checked for accuracy against the reported measured value from the calibrated sound meter.

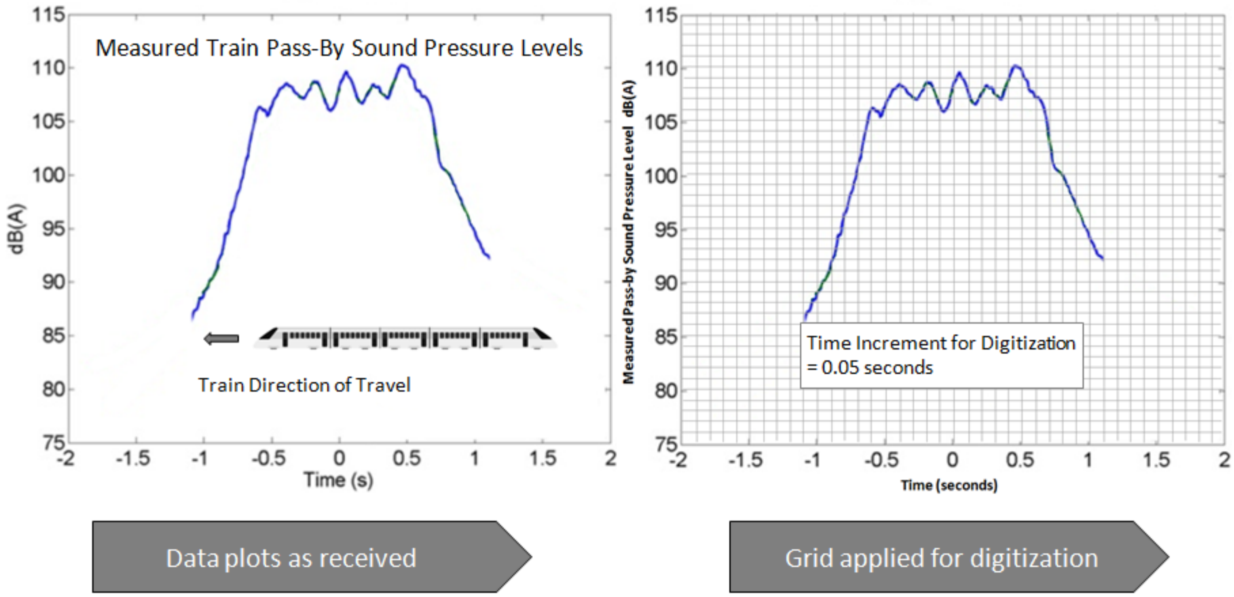


Figure 10: Digitization of Analog SPL Data

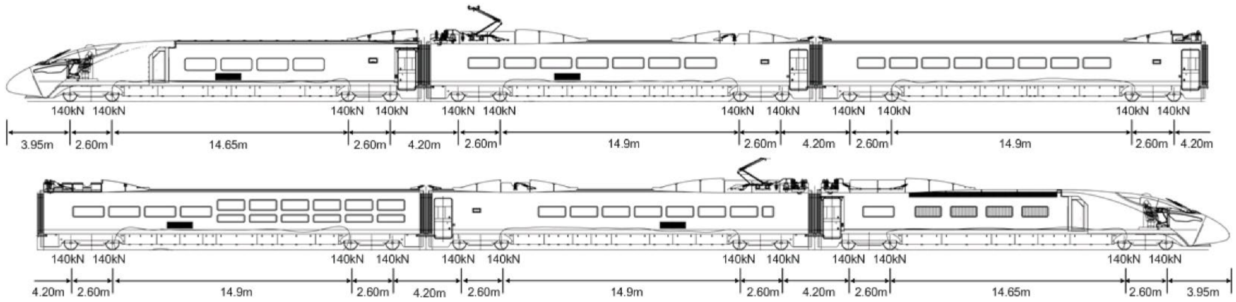


Figure 11: Side View and Dimensions of HEMU-430X High Speed Train (Kaloop, M. R., Hu, M. R., & Elbeitagl, E., 2016)

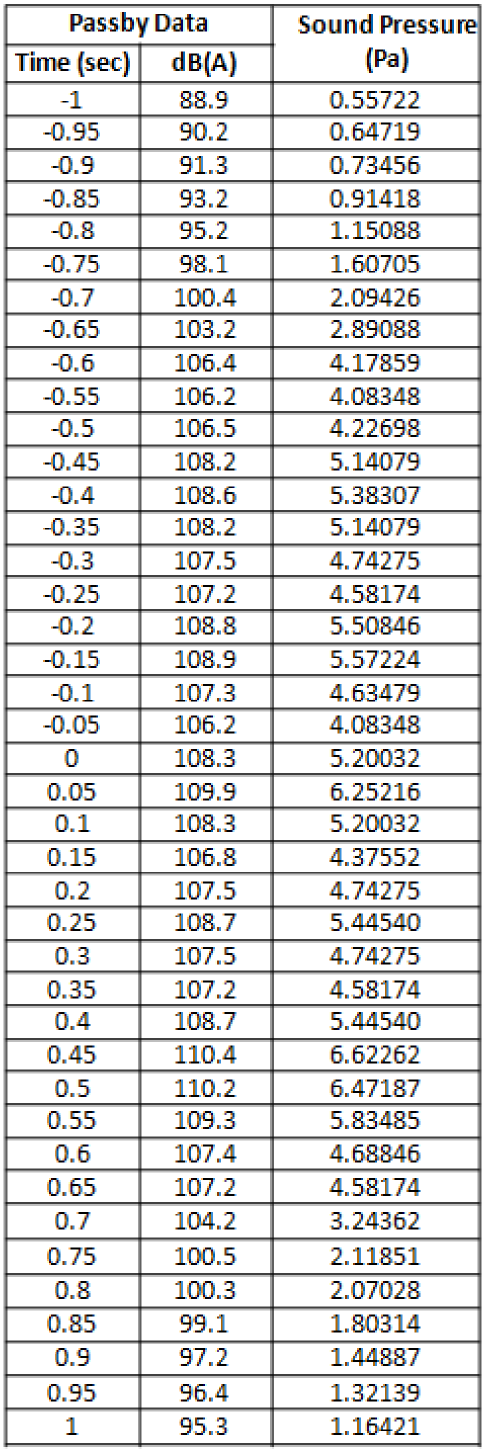
Thus, the integral for the $L_{pAeq,Tp}$ can be determined from the digitized passby data using the following Reimann relationship in Equation 1:

$$\int_{T_1}^{T_2} \frac{p_A^2(t)}{p_0^2} dt \approx \sum_{i=1}^{i=n} \left(\frac{\mathrm{Pa}(i)^2}{p_0^2} \right) \Delta t_i$$

Equation 1. $L_{pAeq,Tp}$ Determined from Digitized Passby Data Using Reimann Relationship

The measured pressures, in dB(A) must be converted to Pascals (Pa) to complete the calculations. Table 7 shows an example of the digitized data for the HEMU-430X. In this case, the passby speed is 400 km/hr and the time of the entire passby event, defined as the duration between when the nose of the train passes the microphone and the tail of the train passes the microphone is 1.33 seconds. The equation for converting the SPL values in dB(A) to units of Pa, is: Pa = $0.00002 \times 10^{(dB/20)}$ where 0.00002 is the reference pressure (threshold of hearing).

Table 7: Example Digitized SPL Data for HEMU-430X



Passby Data		Sound Pressure (Pa)
Time (sec)	dB(A)	
-1	88.9	0.55722
-0.95	90.2	0.64719
-0.9	91.3	0.73456
-0.85	93.2	0.91418
-0.8	95.2	1.15088
-0.75	98.1	1.60705
-0.7	100.4	2.09426
-0.65	103.2	2.89088
-0.6	106.4	4.17859
-0.55	106.2	4.08348
-0.5	106.5	4.22698
-0.45	108.2	5.14079
-0.4	108.6	5.38307
-0.35	108.2	5.14079
-0.3	107.5	4.74275
-0.25	107.2	4.58174
-0.2	108.8	5.50846
-0.15	108.9	5.57224
-0.1	107.3	4.63479
-0.05	106.2	4.08348
0	108.3	5.20032
0.05	109.9	6.25216
0.1	108.3	5.20032
0.15	106.8	4.37552
0.2	107.5	4.74275
0.25	108.7	5.44540
0.3	107.5	4.74275
0.35	107.2	4.58174
0.4	108.7	5.44540
0.45	110.4	6.62262
0.5	110.2	6.47187
0.55	109.3	5.83485
0.6	107.4	4.68846
0.65	107.2	4.58174
0.7	104.2	3.24362
0.75	100.5	2.11851
0.8	100.3	2.07028
0.85	99.1	1.80314
0.9	97.2	1.44887
0.95	96.4	1.32139
1	95.3	1.16421

For this example, using a time step, $\Delta t_i = 0.05$ seconds, the midpoint Reimann sum for the integral is in Equation 2.

$$\sum_{i=1}^{i=n}\left(\frac{Pa(i)^2}{p_0^2}\right)\Delta t_i \quad = \quad 7.67250E+10$$

Equation 2: Midpoint Reimann Sum for the Integral

$$L_{pAeq,Tp} = 10\ \lg\left(\frac{1}{T_2-T_1}\int_{T_1}^{T_2}\frac{p_A^2(t)}{p_0^2}\,dt\right) \qquad L_{pAeq,Tp} = \quad 107.62 \quad dB(A)$$

Equation 3: Calculated Value for $L_{pAeq,Tp}$

The reported measured value for $L_{pAeq,Tp}$ is: 107, shown in Equation 3. Thus, the calculated value is well within the uncertainty level of the passby measurement instruments and procedure (see Section 2.9).

Impact of Time Increment for the Reimann Sum Approach

The impact of the selected time increment on the results of the calculated equivalent continuous SPL (i.e., produced by the train based upon measured data recorded during the passby event) was evaluated to determine the acceptable time step resolution for the CONTRAST program. A test passby noise analog data set was digitized using two grid resolutions: 0.050 seconds and 0.025 seconds. Figure 12 shows the two grids.

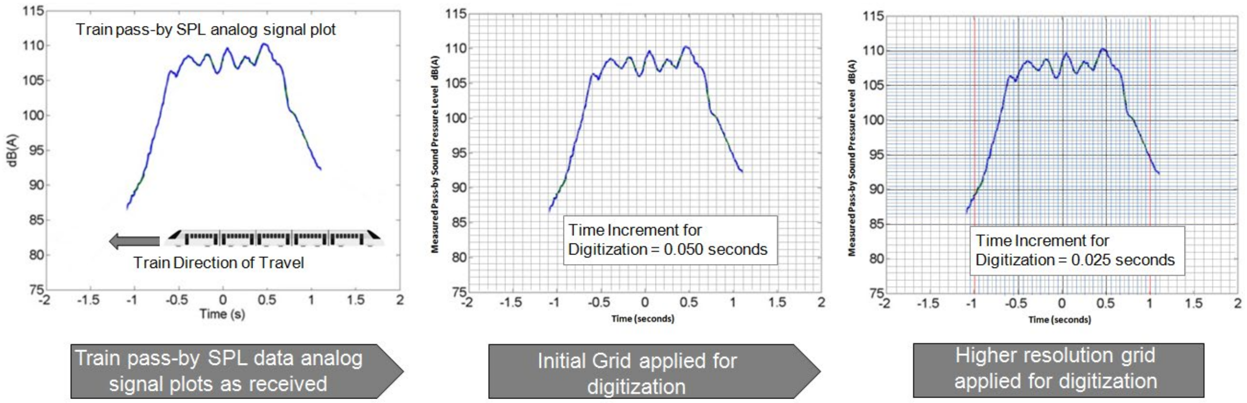


Figure 12: Grids Used in the Digitization Time Step Analysis

It is noted that the Reimann sum digitization methods do not rely on any data curve fitting or interpolation/extrapolation techniques. Rather, the digitization technique is based on recording data points (SPL values) from the analog signal at locations corresponding to the selected time increments. As shown in Figure 13, smaller time increments capture more details of the analog signal. By varying the time increment, the impact on the integrated continuous sound pressure values can be calculated to determine whether finer grids provide higher agreement with the sound meter results.

The data are shown in Table 8 and include the SPL values in dB(A) for the 0.025 second time step. Figure 14 shows the two-digitized passby SPL curves next to each other.

Table 9 shows the results of the time step analysis. It is noted that the difference in calculated values for $L_{pAeq,Tp}$ is 0.15 dB(A), well within the measurement accuracy of the meter. Thus, it is concluded that a time step of 0.050 seconds is adequate to calculate the noise metrics for the selected train passby data sets.

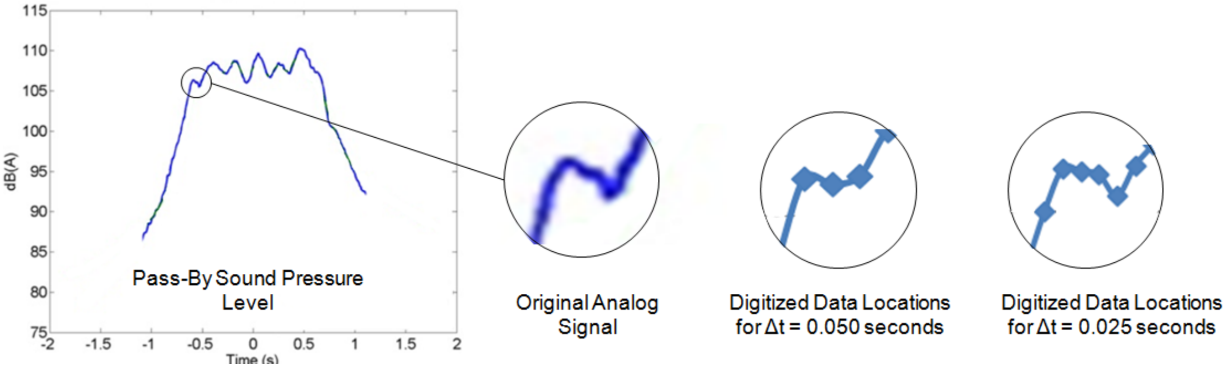


Figure 13: Comparison of Time Step Impact: Digitized & Analog Curves

Table 8: Digitized Passby Data with 0.025 Second Time Step

Passby Data					
Time (sec)	dB(A)	Time (sec)	dB(A)	Time (sec)	dB(A)
0.000	88.9	0.700	107.2	1.400	108.7
0.025	89.5	0.725	107.1	1.425	109.5
0.050	90.2	0.750	107.2	1.450	110.4
0.075	90.5	0.775	108.0	1.475	110.3
0.100	91.3	0.800	108.8	1.500	110.2
0.125	92.5	0.825	108.8	1.525	109.2
0.150	93.2	0.850	108.7	1.550	109.1
0.175	94.5	0.875	107.5	1.575	107.8
0.200	95.2	0.900	107.0	1.600	107.4
0.225	96.7	0.925	106.0	1.625	107.4
0.250	98.1	0.950	106.2	1.650	107.0
0.275	99.0	0.975	107.4	1.675	105.7
0.300	100.4	1.000	108.3	1.700	104.2
0.325	101.5	1.025	109.2	1.725	101.8
0.350	103.2	1.050	109.9	1.750	100.5
0.375	105.0	1.075	108.8	1.775	100.4
0.400	106.4	1.100	108.0	1.800	100.3
0.425	106.3	1.125	107.0	1.825	99.6
0.450	106.2	1.150	106.8	1.850	99.1
0.475	105.5	1.175	107.0	1.875	98.0
0.500	106.5	1.200	107.5	1.900	97.2
0.525	107.2	1.225	108.0	1.925	96.7
0.550	108.2	1.250	108.5	1.950	96.0
0.575	108.3	1.275	108.3	1.975	95.2
0.600	108.6	1.300	107.5	2.000	94.7
0.625	108.3	1.325	107.4	Data Digitized with Δt = 0.025 seconds	
0.650	108.2	1.350	107.2		
0.675	107.5	1.375	107.6		

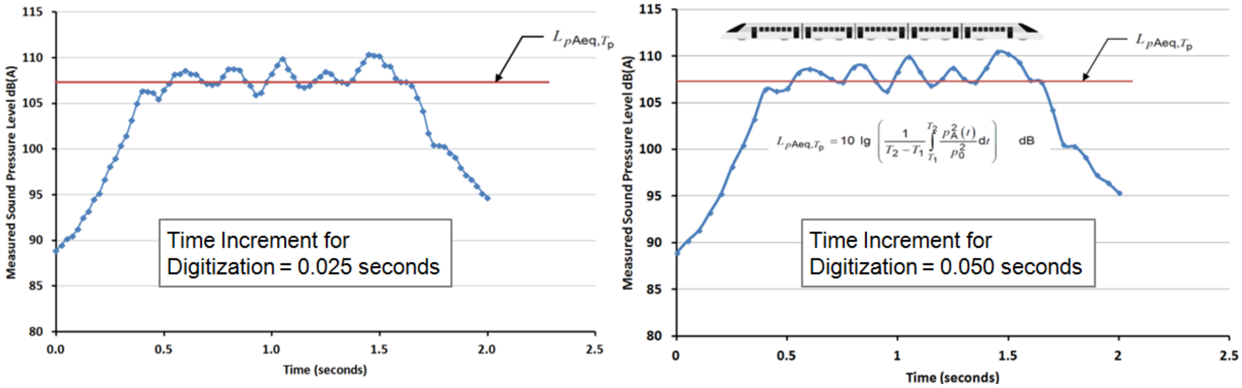


Figure 14: Comparison of Digitized Passby Curves

Figure 14 shows the curve on left has resolution of 0.025 seconds, curve on right has resolution of 0.050 seconds.

Table 9: Results of Reimann Sum Time Step Analysis

Time Step Size (seconds)	Calculated Pass-By SPL, $L_{pAeq,Tp}$ dB(A)	Difference between Calculated and Published Value of $L_{pAeq,Tp}$ dB(A)
0.050	107.622	0.622
0.025	107.472	0.472
Published Value	107	

2.6 Impact of Microphone Position

The traditional approach to calculating the impact of distance on sound energy levels is the inverse square law because the area of a surface around the point increases with the square of the distance from the source (Collman, R., 2015). In the real world, the inverse square law is always an idealization because it assumes exactly equal sound propagation in all directions. If there are reflective surfaces in the sound field, then reflected sounds will add to the directed sound to produce more sound energy at a field location than the inverse square law predicts (Nave, C. R., n.d.).

Noise regulations set limits based on SPLs rather than sound energy levels. While sound energy levels vary with the square of distance from the source, SPLs vary linearly with the distance from the source: (Sengpiel, 2010)

Sound Pressure: $P_d = P_0 (d_0/d)$,
where P_d is the SPL at distance d and P_0 is the SPL at distance d_0

Sound Energy: $I_d = I_0 (d_0/d)^2$
where I is the sound energy (intensity) at distance d and I_0 is the sound energy at distance d_0

Acoustical studies of train passby noise suggests the impact of distance on SPLs can be calculated using the logarithmic version of the sound pressure relationship: $L_d = L_{d0} - 10*LOG(d/d_0)$, where L_{d0} is the equivalent A-weighted constant SPL for the microphone at distance d_0, and d is the distance for L_d. (Gautier, P. E., Poisson, F., & Letourneaux, F., 2008).

This relationship was found to under-predict SPLs for train passby events, based on an evaluation of extensive microphone placement testing related to the Chinese CRH3 high speed train (Lu, L., Hu, X., Zhang, Y., & Zhou, X., 2014). The reason the sound pressure relationship produces high error values is because in the near field (i.e., microphone placed near the passing train), the train noise behaves as a distributed source (i.e., variation of SPL and frequency in both the vertical and horizontal directions) rather than action as a point source. The CONTRAST program employs the inverse square law with correction factors (ratios) based on the CRH3 test data. To determine these correction factors, the following data from the CRH3 measurements were analyzed (Lu, L., Hu, X., Zhang, Y., & Zhou, X., 2014).

Table 10: Measured Variations in SPL with Microphone Position and Speed

Sound Pressure Variations for Microphone Positions and Train Speed			
Speed (km/hr)	$L_{pAeq,Tp}$ dB(A)		
	M1	M2	M3
271	93.2	95.8	82.0
341	96.5	98.0	85.5
386	98.5	100.1	88.1

Microphone Locations		
Microphone Position	Distance from Train Centerline (m)	Distance above Top of Rail (m)
M1	7.5	1.2
M2	7.5	3.5
M3	25	3.5

To begin the correlation factor analysis, the measured SPLs is converted to Pascals as shown in Table 11.

Table 11: Measured SPL Variations in Units of Pascals

Speed (km/hr)	$L_{pAeq,Tp}$ (Pa)		
	M1	M2	M3
271	0.9142	1.2332	0.2518
341	1.3367	1.5887	0.3767
386	1.6828	2.0232	0.5082

The SPLs vary with microphone position and train speed. A parametric analysis indicates the variation can be represented by the following relationship:

$$P_d = P_{d0} *(d/d_0)*V*K$$

where P_d is the SPL (Pascals) at microphone location d

P_{d0} is the SPL (Pascals) at microphone location d_0

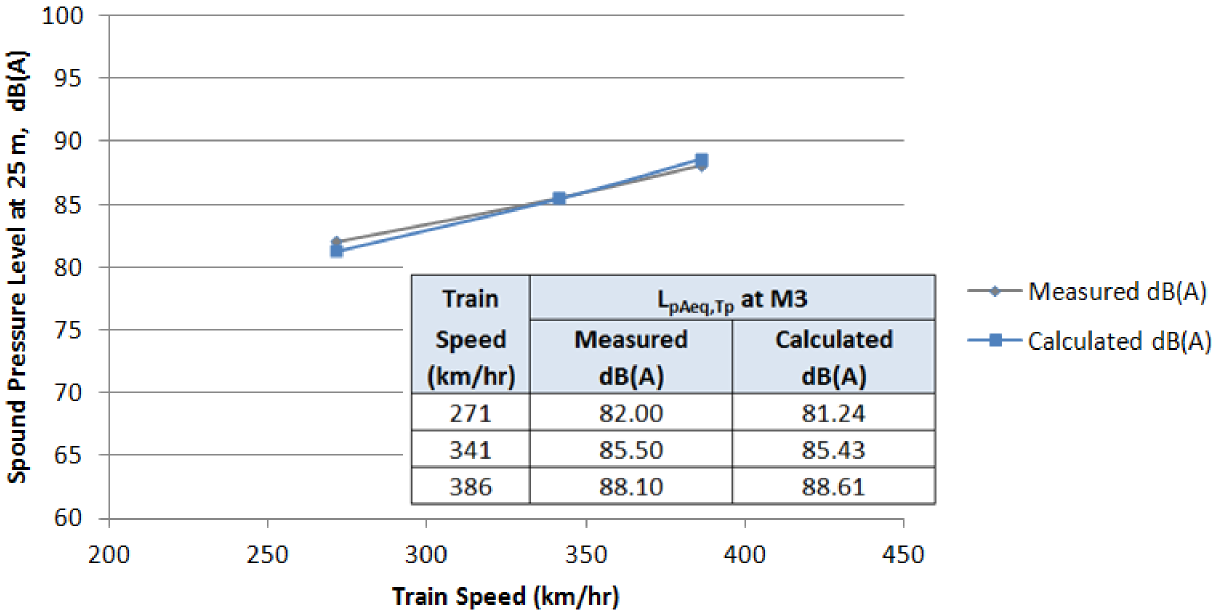
V is the train speed in km/hr

K is an empirical factor that accounts for acoustic characteristics of the train and Track environment. This factor varies with train speed.

This equation is applied to the CRH3 data and the results are shown in Table 12. Note that the analysis was based on calculating SPLs at microphone position M3, using measurements at microphone position M2, for the range of test speeds. Both microphone positions are at the same elevation (3.5 m [11.48 ft.]) above top of rail) but vary in distance from the track centerline (7.5 m vs. 25 m [24.61 ft. vs. 82.02 ft.]). The results shown in Table 12 are plotted in Figure 15.

Table 12: Calculated SPL Based on P_d Equation

Train Speed (km/hr)	Measured Sound Pressure Levels (Pa)		Calculated Sound Pressure Levels at Microphone Position M3 (Pa)	
	M2	M3	(Pa)	dB(A)
271	1.2332	0.2518	0.231	81.236
341	1.5887	0.3767	0.374	85.432
386	2.0232	0.5082	0.539	88.609



Train Speed (km/hr)	$L_{pAeq,Tp}$ at M3	
	Measured dB(A)	Calculated dB(A)
271	82.00	81.24
341	85.50	85.43
386	88.10	88.61

Figure 15: Comparison of Measured and Calculated SPLs, CRH3 Train Set

The adjustment factors, based on SPLs in units of dB(A), are summarized in Table 13. These are the factors incorporated into the CONTRAST program:

Table 13: Microphone Position and Train Speed SPL Adjustment Factors

Microphone Position Adjustment Factors: SPL in Units of dB(A) Variation with Microphone Location and Train Speed			
Speed (km/hr)	M1	M2	M3
271	1.000	1.028	0.880
341	1.035	1.052	0.917
386	1.057	1.074	0.945

2.7 Impact of Train Speed

The variation of passby SPL variations with train speed is the subject of many research papers, including those associated with earlier FRA-funded studies (Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S., 2021) (Hanson, C. E., Ross, J. C., & Towers, D. A., 2012) (Kim, T., & Kim, S., 2011) (Gautier, P. E., Poisson, F., & Letourneaux, F., 2008) (Poisson, F., Gautier, P. E., & Letourneaux, F., 2008). During the current study, these predictive methods were compared to available test data in an effort to develop a calculation procedure for the CONTRAST program with an acceptable level of uncertainty. The method developed by Gautier et al. (2008) provided the highest level of correlation with measured data and was employed as the basis for a modified procedure that was incorporated into CONTRAST. The Gautier et al. (2008) method is based on sound pressure measurements for a TGV POS, composed of Duplex power cars and eight single-floor coaches, for speeds ranging from 100 km/hr (62.14 mph) to 380 km/hr (236.12 mph), and the microphone positioned 25 m from the track centerline. A linear regression was performed to determine the relationship between the measured $L_{pAeq,Tp}$ and the logarithm of the train speed. The resulting equation is:

$$L_{pAeq,Tp}(V) - L_{pAeq,Tp}(V_0) = K \text{ LOG}(V/V_0)$$

where V is the train speed (km/hr)

V_0 is the reference train speed (km/hr)

K is an empirical factor = the regression coefficient

Gautier et al. (2008) indicated that $K = 30.4$ provides an acceptable correlation with test data over the indicated speed range. However, when applied to the passby data sets in the CONTRAST library, it was found that K varied as a function of train speed.

Another method for calculating the variation of SPL with train speed was also investigated. This method was developed by Ivanov et al. (2017) and is shown below:

$$L_{Aeq,Tp25j} = 62 \text{ LOG}(V) - 10\text{LOG}[\text{arctangent}(L_j/50)] - 60.6$$

where 25 is the microphone distance in meters from the track centerline

L_j is the train length in meters

This method did not provide acceptable levels of correlation as the one developed by (Gautier, P. E., Poisson, F., & Letourneaux, F., 2008). It was decided to look at the variation of the empirical factor, K, variation with train speed. The reason for the speed variation in K is that the contribution of noise sources (e.g., wheel/rail interaction, propulsion components, aerodynamics) varies with train speed. The K factor values were calculated for 12 passby noise data sets and subjected to a linear regression analysis. The relationship between the K factor and train speed is provided by the following equation:

$$K = aV + b \text{ where } a = 0.0625 \text{ and } b = 25.00$$

Figure 16 plots this relationship. It is noted that the empirical factor varies from $K = 30$ at lower speeds where rolling noise (i.e., wheel/rail interaction) is the largest contributor to $K = 50$ at higher speeds where aerodynamic noise is dominant. This correlates to sound pressure variation analyses that indicate rolling noise is proportional to the third power train speed and aerodynamic noise is proportions to the sixth power of train speed (Hemsworth, B., 2008) (Kim, T., & Kim, S., 2011). The version of the SPL/train speed equation incorporated into CONTRAST is:

$$L_{pAeq,Tp}(V) = (0.0625V+25)*LOG(V/V_0) + L_{pAeq,Tp}(V_0)$$

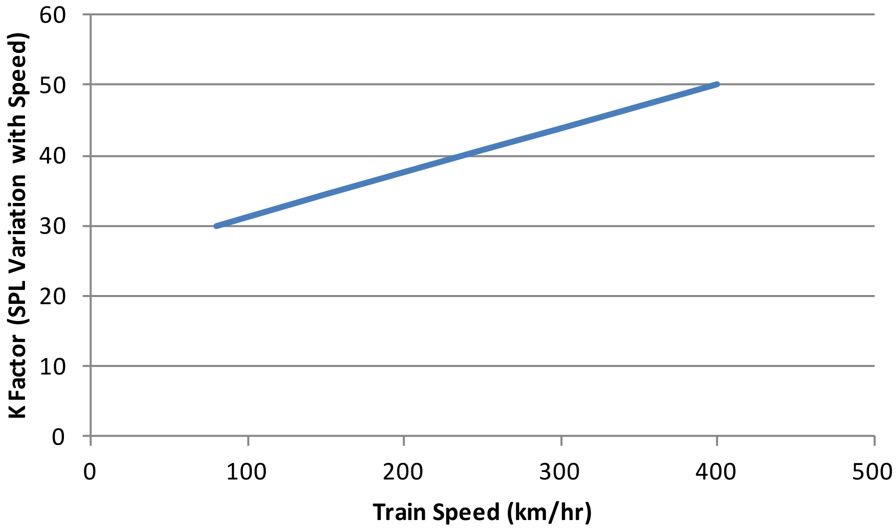


Figure 16: K Factor vs. Train Speed, SPL Variation with Speed

2.8 Calculation of Passby Noise Metrics

The calculation procedures for other noise metrics, as incorporated into CONTRAST are reviewed below.

$L_{p(maximum)}$	is the maximum recorded passby SPL

Calculation procedure: Employ Excel® MAX function for each passby data set

L_{pASmax}	is the maximum SPL, slow and A-weighted
L_{pAFmax}	is maximum SPL, fast and A-weighted
	The time period for the "slow" reading is 1 second.
	The time period for the "fast" reading is 0.125 seconds.

Calculation procedure: L_{pASmax} and L_{pAFmax} can both be calculated as the logarithmic average of the recorded SPLs for the respective time increments: 1 second time interval and 0.125 second time interval containing the highest values for the entire data set. The logarithmic average for an Excel® array is: {=10*LOG(AVERAGE(10^(ARRAY/10)))} array-entered, i.e., using CTRL-Shift-Enter keys where array is of the form A10:A15.

$L_{pAeq,passby}$	is the A-weighted equivalent continuous SPL produced during the entire passby event, including approach, T_p (time of passby), and departure (used for L_d, L_n, etc. calculations). The calculation includes all the passby data points. Equation 4 shows the formula

$$L_{pAeq,passby} = 10 \lg \left(\frac{1}{T_2 - T_1} \int_{T_1}^{T_2} \frac{p_A^2(t)}{p_0^2} dt \right)$$

Equation 4: The Formula for $L_{pAeq,passby}$

TEL (Hanson, C. E., Ross, J. C., & Towers, D. A., 2012), is measured over the time interval starting when the SPL is 10 dB(A) lower than $L_{pAeq,Tp}$ and ending when the SPL again reaches a value that is 10 dB(A) lower than $L_{pAeq,Tp}$. TEL is calculated using the following formula:

$$TEL = L_{pAeq,Tp} + 10*LOG(T_{TEL}/T_p)$$

SEL (Hanson, C. E., Ross, J. C., & Towers, D. A., 2012), like $L_{pAeq,Tp}$ integrates the total sound energy over a measurement period, but for SEL, the measurement period is normalized to a duration of 1 second. SEL is the cumulative noise exposure (i.e., "dose") for a single noise event normalized over 1 second. The fact that SEL is a cumulative measure means that (1) louder events have higher SELs than quieter ones, and (2) events that last longer in time have higher SELs than shorter ones. At a microphone distance of 30 m (100 ft.).

$$SEL = L_{pAeq,Tp} + 10*LOG(T_p) + 1$$

The following parameters are determined by specifying the indicated percentile of the data values using Excel® Function PERCENTILE(range,P), where" range" is the array of values (e.g., K10:K68) and P = the percentile (between 0 and 1, for example, P for the 90th percentile would be entered as 0.9).

L10	is the SPL for which 90 percent of the recorded values are greater. It includes lead-in (prior to nose passing microphone) and trail-off (after tail of train passes) data.
L50	is the SPL for which 50 percent of the recorded values are greater. It includes lead-in (prior to nose passing microphone) and trail-off (after tail of train passes) data.
L90	is the SPL for which 10 percent of the recorded values are greater. It includes lead-in (prior to nose passing microphone) and trail-off (after tail of train passes) data.

The European Technical Standards for Interoperability (TSI) include two normalized values for $L_{pAEq,Tp}$ (European Union, 2014). The values are normalized to 80 km/hr and 250 km/hr. The measurements are made at a lateral distance of 7.5 m (24.61 ft.) from the rail centerline and 1.2 m (3.94 ft.) above the top of the rail. Procedures defined within the TSI to allow noise levels to be calculated at various train speeds based on measurements made at 80 km/hr (50 mph) and 250 km/hr (155 mph).

For those data sets containing no noise measurements for trains traveling at either 80 km/hr or 250 km/hr, the modified Gautier method was used to calculate $L_{pAeq,Tp\ (80\ km/hr)}$ and $L_{pAeq,Tp\ (250\ km/hr)}$.

2.9 Accuracy and Uncertainty

The data sets contained in the library for the CONTRAST spreadsheet-based analysis tool were obtained by several researchers using standardized test procedures and instruments. There are many factors that affect the accuracy and uncertainty of these data sets, such as: speed variations, differences in rolling stock (e.g., due to manufacturing tolerances, age of vehicle and associated changes to suspensions, wheel surface roughness, bearings, etc.), track surface roughness, track alignment/curvature, track structure decay rates, and intermittent effects such as level of wheel hunting and flanging. Tests performed by Weber & Zoontjens (2016) in Australia for both passenger and freight trains included extensive measurements of passby noise levels (L_{AE}). Statistical analyses were performed for each set of data to obtain the standard deviation for each passby event and for multiple data sets collected over periods ranging from 1 week to over 6 months. The maximum range in log-averaged measured noise levels was analyzed for single data sets as well as 5, 10, 15, 20, and 60 data sets for each site.

Tests conducted on passenger trains using ISO standard-compliant instruments and procedures, showed standard deviations in L_{AE} of approximately 5 dB which led to the statement: "For the measurements in this study, there is a 95 percent confidence that the calculated noise levels are within ±3 dB of the true $L_{Aeq(period)}$ noise levels when at least 20 train passbys of each type under the same operating conditions are measured. For the L_{Amax} assessment parameter, the uncertainty increases to approximately ±5 dB for the same number of train passbys." It is noted that these tests were conducted on trains with speeds lower than those associated with high-speed classifications. Thus, the accuracy analysis may not be representative of high-speed operations, but the study does provide an indication of the repeatability and range for these noise measurements.

The 2008 version of the EU TSI Noise Regulation included an uncertainty level of ±1 dB(A) relative to maximum passby sound pressure measurement limits. This allowance factor was not included in the 2014 version of the TSI Noise Regulation.

Sound measurement instruments: The microphone of a noise measurement system includes a transducer that converts sound pressure to an electrical signal. The electrical signal is amplified, filtered (i.e., typically including a weighted filter over a selected range of frequencies), and rectified. The rectifier provides the root mean squared (RMS) value of the signal. The RMS value is then exponentially (log) averaged using a selected time constant. Typically, the “FAST” meter setting employs a time constant of 0.1 seconds; i.e., the values are log averaged over each 0.1 second time period. For the “SLOW” meter setting, signals are log averaged over a 1.0 second time period. Results are displayed digitally on the instrument meter and stored for export via transportable storage media such as a thumb drive or directly to another computer (International Electrotechnical Commission, 2005) (International Electrochemical Commission, 2003).

Sound level meters are addressed in International Standard IEC 61672-1: Electroacoustics, Sound Level Meters, Part 1: Specifications (Roberts, C., 2012). ISO Standard 3095 (Railway Applications – Acoustics – Measurement of Noise Emitted by Railbound Vehicles) (International Organization for Standardization, 2013) requires the instrumentation system, including microphones, cables, and recording devices to meet Type 1 requirements as specified in EN 61672-1 (Roberts, C., 2012).

Sound level meters are divided into two classes. The accuracy of Class 1 meters is ±0.3 dB and the accuracy of Class 2 meters is ±0.5 dB (Noise Meters, Inc., n.d.). It is recommended that accuracy levels be considered regarding high speed train noise regulations. Meters should meet the standard IEC 60942 and should be calibrated to the recommended schedule (International Electrotechnical Commission, 2003).

2.10 CONTRAST Output: Train Passby Noise Data Comparisons

The five passby noise data sets contained in the current version of CONTRAST were evaluated and compared using the noise metrics described in Section 2.9. In addition, the analyses included comparisons to US, EU, China, and Japan train noise regulations.

2.10.1 Comparison of Noise Metrics at Train Speed = 250 km/hr

Passby noise metrics for the three train types currently included in CONTRAST were calculated at two selected train speeds, 250 km/hr and 80 km/hr (155.34 and 49.71 mph). These two speeds were chosen because they correspond to the EU TSI regulation normalized values, and they represent both low and high speed conditions. The results for microphone position 1 (7.5 m [24.61 ft.] from track centerline, 1.2 m [3.94 ft.]) above top of rail) and the train speed equal to 250 km/hr are summarized in Table 14 and Figure 17.

Table 14: Noise Metric Comparison: Train Speed = 250 km/hr

Train Set	Pass-By Noise Metric: Measurement Uncertainty is ±3 dB									
	$L_{pAeq,Tp}$	$L_{p(maximum)}$	L_{pASmax}	L_{pAFmax}	$L_{pAeq,passby}$	TEL	SEL	L_{10}	L_{50}	L_{90}
Korean HEMU-430X	97.61	100.34	98.38	99.43	94.98	98.54	105.73	72.40	90.50	98.69
Thalys PBKA	96.35	99.02	96.68	98.12	94.21	96.96	107.24	73.38	94.32	97.48
CRH3 Series (based on Siemens)	91.71	93.28	92.23	92.96	91.32	92.51	102.97	81.78	91.98	92.68

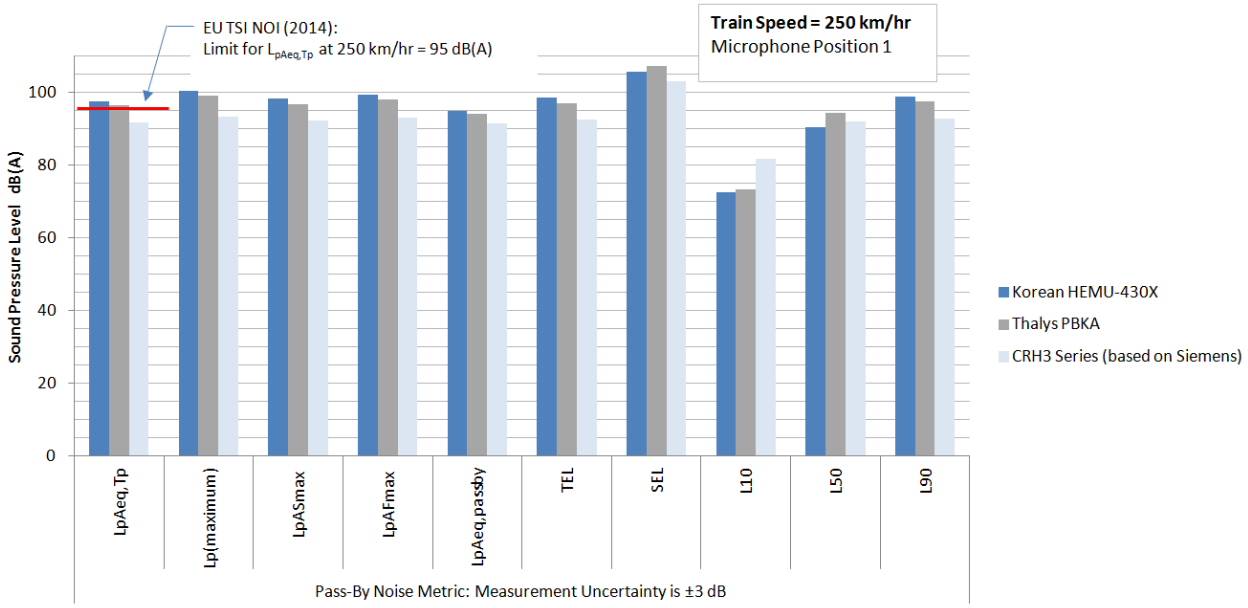


Figure 17: Noise Metric Comparison: Train Speed = 250 km/hr

It is interesting to note that two of the three passby data sets indicate noncompliance with the EU TSI NOI (2014) regulation for $L_{pAeq,Tp\ (250\ km/hr)}$, which is 95 dB(A). However, all the train sets meet the TSI regulation if measurement uncertainty levels are included in the assessment. Another observation is that the values of the key passby noise metrics, $L_{pAeq,Tp}$, $L_{p(maximum)}$, L_{pASmax}, and L_{pAFmax}, exhibit values that are within ±3 dB(A) of each other. The other metrics, $L_{pAeq,passby}$, TEL, SEL, L_{10}, L_{50}, and L_{90} show greater variations due to the wide range of corresponding passby time values.

2.10.2 Comparison of Noise Metrics at Train Speed = 80 km/hr

The results for microphone position 1 (7.5 m from track centerline, 1.2 m above top of rail) and the train speed equal to 80 km/hr are summarized in Table 15 and Figure 18.

Table 15: Noise Metric Comparison: Train Speed = 80 km/hr

Train Set	Pass-By Noise Metric: Measurement Uncertainty is ±3 dB									
	$L_{pAeq,Tp}$	$L_{p(maximum)}$	L_{pASmax}	L_{pAFmax}	$L_{pAeq,passby}$	TEL	SEL	L_{10}	L_{50}	L_{90}
Korean HEMU-430X	84.93	87.67	85.71	86.76	82.30	85.86	93.05	59.72	77.83	86.01
Thalys PBKA	82.29	84.95	82.62	84.05	80.14	82.89	93.17	59.31	80.25	83.41
CRH3 Series (based on Siemens)	77.23	78.80	77.76	78.49	76.85	78.04	88.50	67.30	77.50	78.20

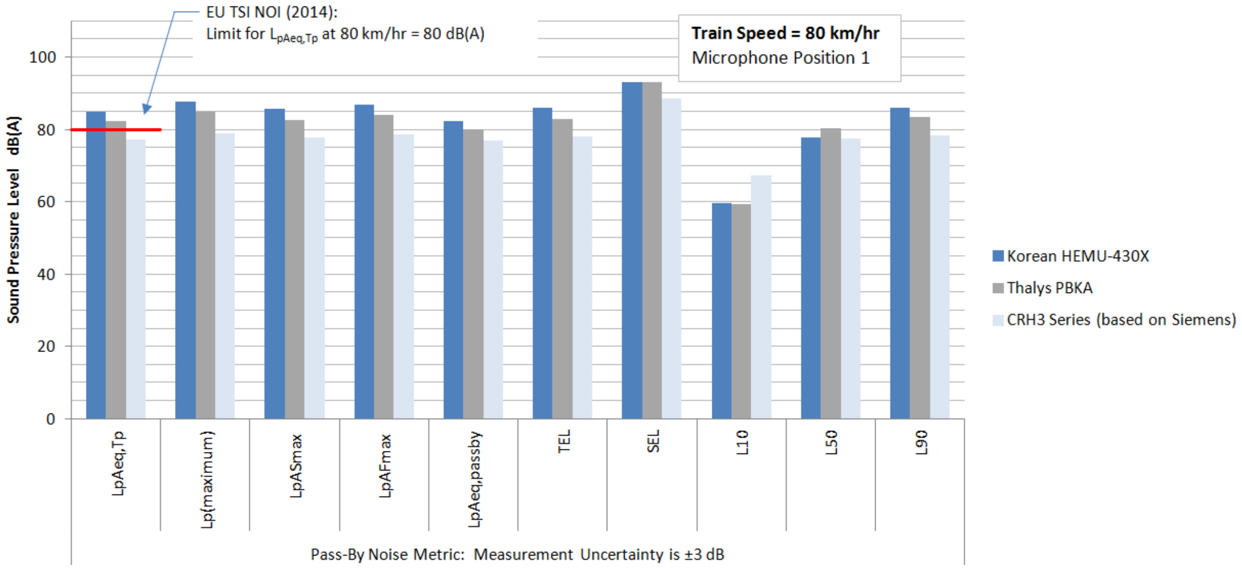


Figure 18: Noise Metric Comparison: Train Speed = 80 km/hr

As with the 250 km/hr train speed, CONTRAST predicts that two of the three passby data sets are not in compliance with the EU TSI NOI (2014) regulation for $L_{pAeq,Tp}$ (80 km/hr), which is 80 dB(A). One of the train sets, the Korean HEMU-430X exceeds the 80 dB(A) limit by more than the measurement uncertainty level (±3 dB). Also, as with the 250 km/hr simulations, the values of the key passby noise metrics, $L_{pAeq,Tp}$, $L_{p(maximum)}$, L_{pASmax}, and L_{pAFmax}, exhibit values that are within ±3 dB(A) of each other, and the other metrics, $L_{pAeq,passby}$, TEL, SEL, L_{10}, L_{50}, and L_{90} show greater variations due to the wide range of correspond passby time values.

2.10.3 Comparison of Calculation Methods for Normalized EU Metrics

As noted in Section 2.9, the European TSI include two normalized values for the A-weighted equivalent continuous SPL produced by the train during a passby event, $L_{pAeq,Tp}$ (European

Union, 2014). The values are normalized to 80 km/hr and 250 km/hr. The formulas for calculating $L_{pAeq,Tp\ (80\ km/hr)}$ and $L_{pAeq,Tp\ (250\ km/hr)}$, as defined in TSI NOI (2014) are:

$$L_{pAeq,Tp(80\ km/h)} = L_{pAeq,Tp(vtest)} - 30 * \log\ (vtest/80\ km/h)$$

$$L_{pAeq,Tp(250\ km/h)} = L_{pAeq,Tp(vtest)} - 50 * \log\ (vtest/250\ km/h)$$

where vtest is the train velocity during the passby test in km/hr.

As noted in Section 2.8, the CONTRAST program employs a modified version of the train speed calculation method developed by Gautier et al. (2008). The TSI and CONTRAST speed normalization procedure calculations for the five passby data sets are compared in Table 16 and the graph of Figure 19.

Table 16: Comparison of TSI and CONTRAST Speed Normalization Calculations

Train Set	Train Test Speed (km/hr)	$L_{pAeq,Tp\ (80\ kph)}$ dB(A)		$L_{pAeq,Tp\ (250\ kph)}$ dB(A)	
		Calculation Method		Calculation Method	
		CONTRAST	TSI*	CONTRAST	TSI*
Korean HEMU-430X	400	84.9	84.9	97.6	95.7
Thalys PBKA	296	82.3	82.3	96.4	95.7
China CRH3 Series, Microphone Position 1	271	77.2	77.2	91.7	91.4
China CRH3 Series, Microphone Position 2	271	77.0	77.0	91.5	91.1
China CRH3 Series, Microphone Position 3	271	77.4	77.4	91.9	91.5

*EU Technical Standard for Interoperability, NOI, 2014, Calculation Procedure for Normalization to 80 km/hr & 250 km/hr

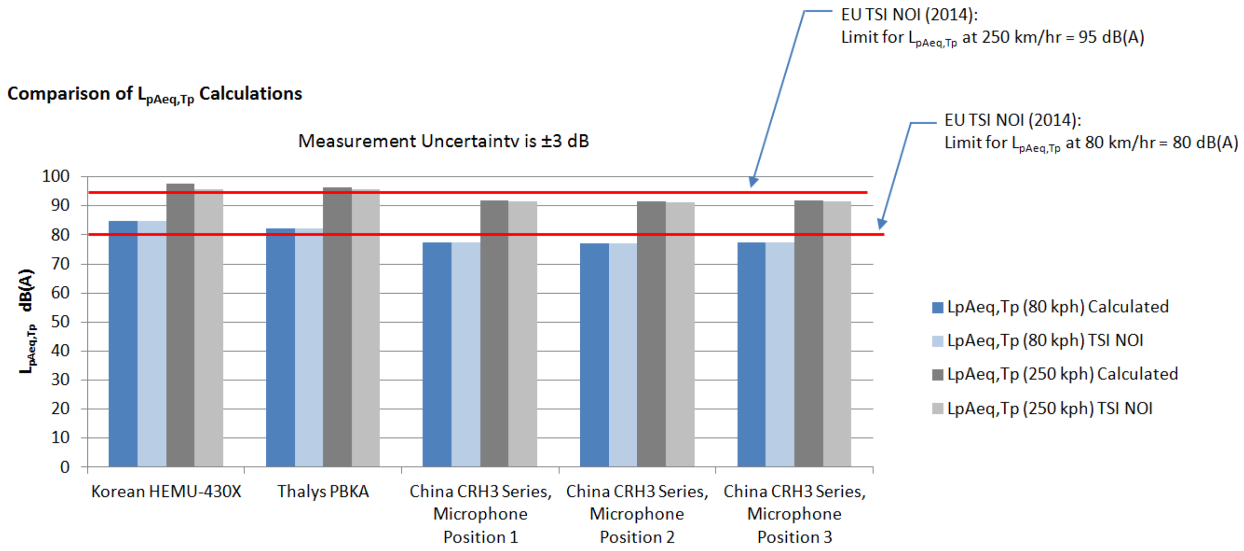


Figure 19: Comparison of TSI and CONTRAST Speed Normalization Calculations

The TSI and CONTRAST calculation procedures provide normalized speed-adjusted values for $L_{pAeq,Tp}$ that are within the uncertainty levels of the measurement procedures.

2.10.4 Comparison of Passby Data to US Noise Regulations

The CONTRAST program was employed to evaluate the passby noise emissions of three train models (i.e., from the passby data sets contained in the CONTRAST library) relative to current

US noise regulations. This required processing the passby data to account for train speed and microphone position using the procedures described in Sections 2.8 and 2.7. The results are shown in Table 17 and Figure 20. The metric for US noise measurements is $L_{max(fast)}$ and the microphone position is 30 m (100 ft.) from the track centerline at an elevation of 1.2 m (4 ft.). Note that the metric $L_{max(fast)}$ is equal to L_{pAFmax}.

Table 17: Calculated SPLs vs. Train Speed

	$L_{max\ (fast)}$ dB(A)					
Train Set	**Train Speed (km/hr)**					
	80	**150**	**200**	**250**	**300**	**350**
Korean HEMU-430X	78.9	85.2	88.6	91.6	94.4	97.2
Thalys PBKA	71.1	78.0	81.8	85.2	88.4	91.6
China CRH3 Series, Microphone 4	66.6	73.6	77.5	81.0	84.4	87.7

*The microphone position for the US regulations is 30 m from track centerline and 1.2 m above top of rail.

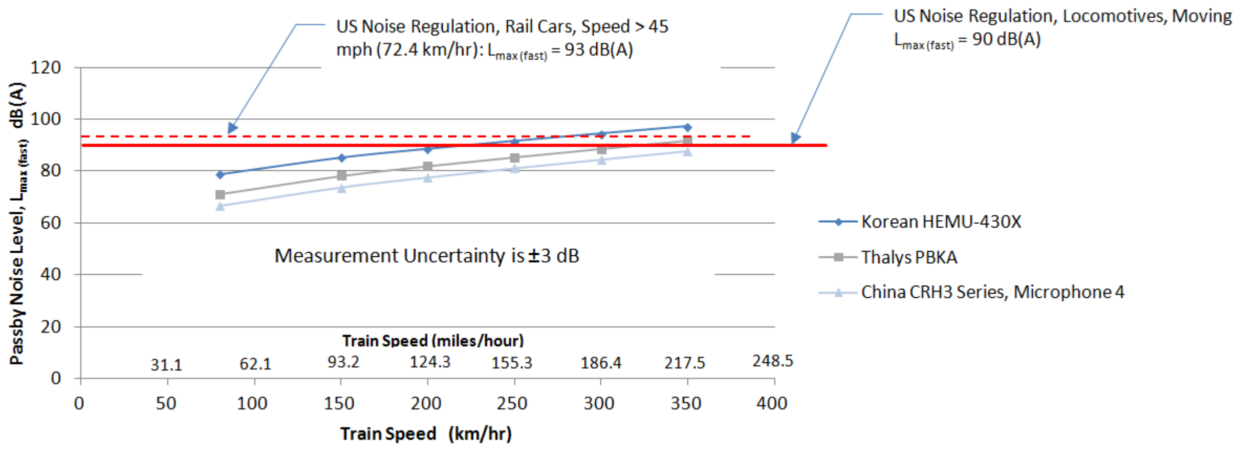


Figure 20: Passby SPLs Relative to US Noise Regulations

The calculations indicate the Chinese CRH3 series train set would exceed US noise limits at speeds above 350 km/hr (217.5 mph). The Thalys PBKA train set is predicted to exceed the US noise limits at speeds above 300 km/hr (185.4 mph) and the Korean HEMU-430X train set is expected to exceed the limit at speeds above 200 km/hr (124.3 mph).

2.10.5 Comparisons to China Noise Regulations

Like the US, China requires passby measurement microphone placement to be 30 m (98.43 ft.) from the track centerline and 1.2 m (3.94 ft.) above the top of the rail. The A-weighted equivalent sound level measured during the daytime, L_d, and the corresponding equivalent sound level measured during the nighttime, L_n, both reported in dB(A), are the specified metrics. The daytime period is defined as having a duration of 16 hours, and the nighttime period is the remaining 8 hours each day. Both L_d and L_n are the accumulated logarithmic exposures over the respective time periods, as defined in Section 2.9. The calculation procedure includes defining the A-weighted equivalent sound level for each passby event, and then summing these for the day and nighttime periods. This approach is used to determine the number of passby events that are allowed by the regulation limits.

Example, the Thalys PBKA traveling at a speed of 296 km/hr (183.93 mph), has a SPL, $L_{pAeq\ (passby)}$ = 84.7 dB(A) for microphone position 4 (30 m (98.43 ft.) from track centerline, 1.2 m (3.94 ft.) above top of rail). The passby time is 4.2 seconds. If the passby event occurs during the 8-hour nighttime period, the fraction of time for each passby event is equal to 4.2 seconds divided by 8 hours (28,800 seconds). Since $t(j)$ is the fraction of time during which the SPL, L_j, occurs, it has a value = 0.00014583. Thus, the information required to calculate the summation term in the L_d formula is known. The summation term is shown in Equation 5:

$$\left[\sum_{j=1}^{N} t(j)10^{\frac{L(j)}{10}}\right]$$

Equation 5: Calculated Summation of L_d Formula

If two passby events occur during the 8-hour nighttime period, L_d would have the following value:

10*LOG10(2*t(j)*10^(84.7/10)) which is equal to: 49.35 dB(A)

Using this approach, the maximum number of passby events that do not exceed the noise regulation limit can be determined for each train set.

L_n Calculations

Table 18 shows the common parameters associated with the calculation of the nighttime equivalent sound level, L_n.

Table 18: Common Parameters for Calculation of L_n

Common Parameters	Value	Units
Duration of Night Time Period	8	hours
	28,800	sec
Korean HEMU-430X Train Length	147.4	m
Thalys PBKA Train Length	200.19	m
China CRH3 Series Train Length	200	m

The results of the CONTRAST calculations are summarized in Table 19 for microphone position 4 (30 m from track centerline and 1.2 m above top of rail). China's maximum allowable value for L_n is 60 dB(A). Mitigation methods (e.g., noise barriers) are required if L_n exceeds this limit.

Table 19: Variation of L_n as a Function of Number of Passby Events

Specific Parameters	Units	Train Speed:	80	km/hr	Train Speed:	250	km/hr	Train Speed:	300	km/hr	Train Speed:	350	km/hr
			22.22	m/sec		69.44	m/sec		83.33	m/sec		97.22	m/sec
		Korean HEMU-430X	Thalys PBKA	China CRH3 Series	Korean HEMU-430X	Thalys PBKA	China CRH3 Series	Korean HEMU-430X	Thalys PBKA	China CRH3 Series	Korean HEMU-430X	Thalys PBKA	China CRH3 Series
Time of Passby Event	sec	6.63	9.01	9.00	2.12	2.88	2.88	1.77	2.40	2.40	1.52	2.06	2.06
t(j): Ratio of Passby Time to 8-Hour Night Period		0.0002303	0.0003128	0.0003125	0.0000737	0.0001001	0.0001000	0.0000614	0.0000834	0.0000833	0.0000526	0.0000715	0.0000714
$L_{pAEQ,passby}$ (microphone position 4)	dB(A)	74.38	67.67	65.04	87.06	81.74	79.51	89.89	84.97	82.86	92.64	88.13	86.14
Number of Trains during 8-Hour Night Period		L_n (the A-weighted equivalent sound level measured during the night time), dB(A)											
8		47.04	41.65	39.02	54.77	50.77	48.54	56.80	53.21	51.10	58.88	55.70	53.71
16		50.05	44.66	42.03	57.78	53.78	51.55	59.81	56.22	54.11	61.89	58.71	56.72
24		51.81	46.42	43.79	59.54	55.54	53.31	61.57	57.98	55.87	63.65	60.47	58.48
32		53.06	47.67	45.04	60.79	56.79	54.56	62.82	59.23	57.12	64.90	61.72	59.73
40		54.03	48.64	46.01	61.76	57.76	55.53	63.79	60.20	58.09	65.87	62.69	60.70
48		54.82	49.43	46.80	62.55	58.55	56.32	64.58	61.00	58.88	66.66	63.48	61.49
56		55.49	50.10	47.47	63.22	59.22	56.99	65.25	61.66	59.55	67.33	64.15	62.16

Plots of L_n as a function of number of passby events, for the three train types at four different speeds are shown in Figure 21 through Figure 24.

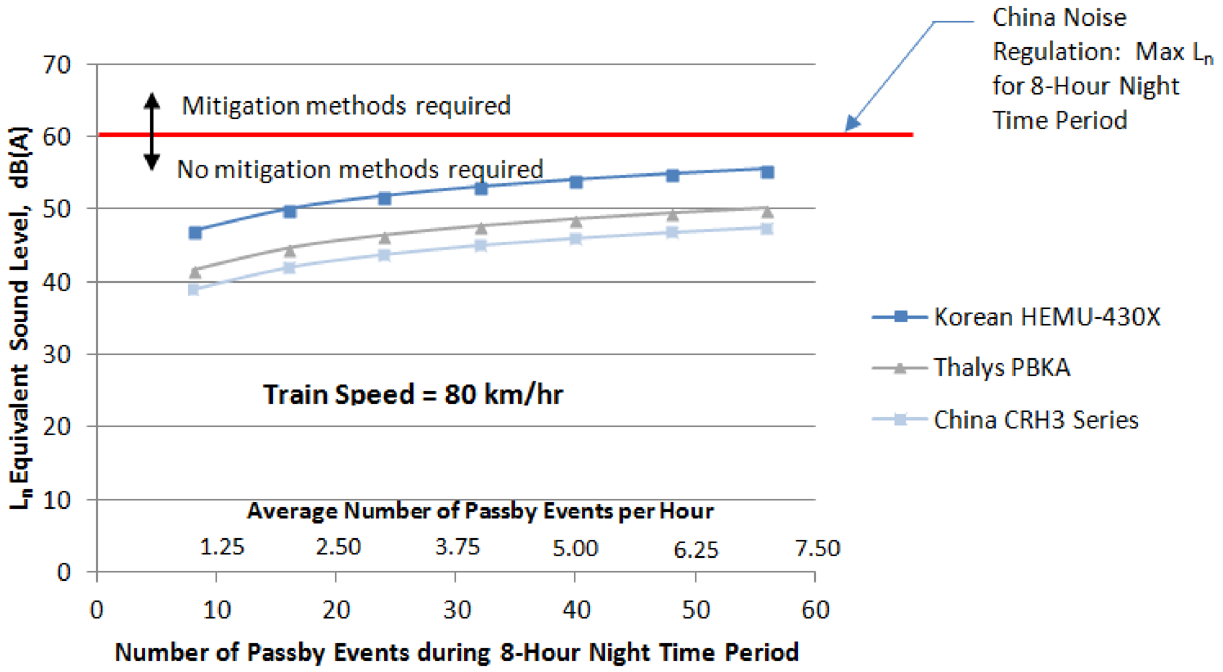


Figure 21: L_n for Train Speed = 80 km/hr

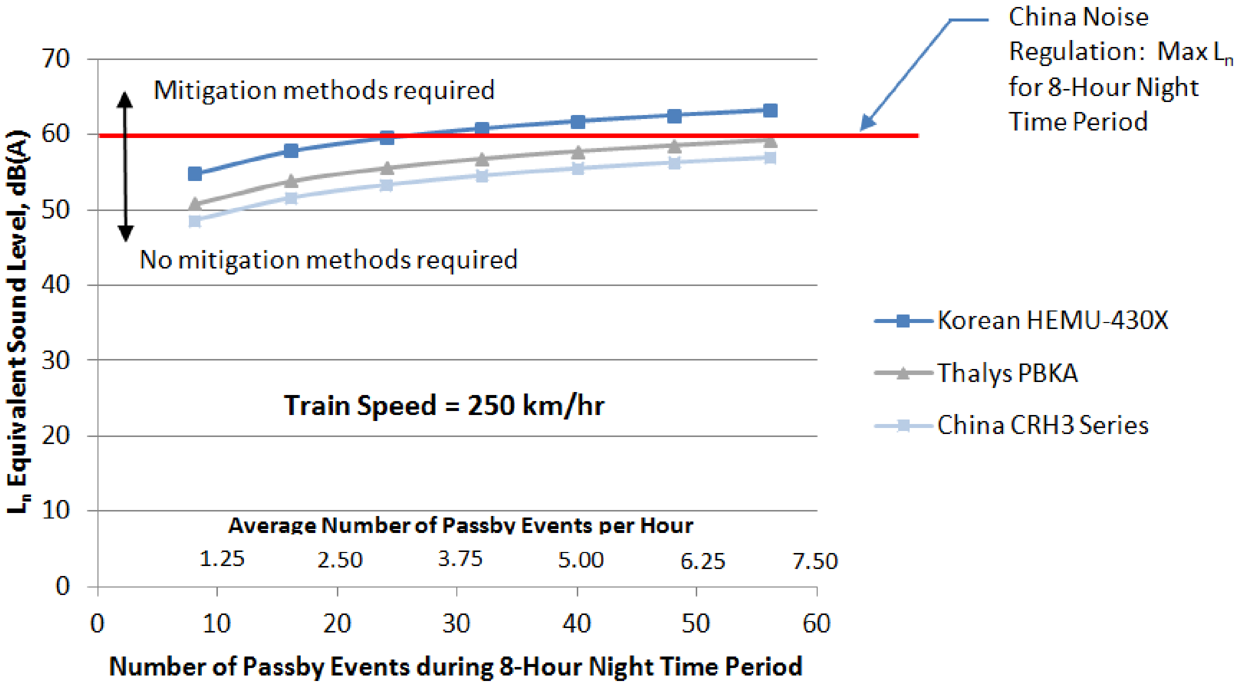


Figure 22: L_n for Train Speed = 250 km/hr

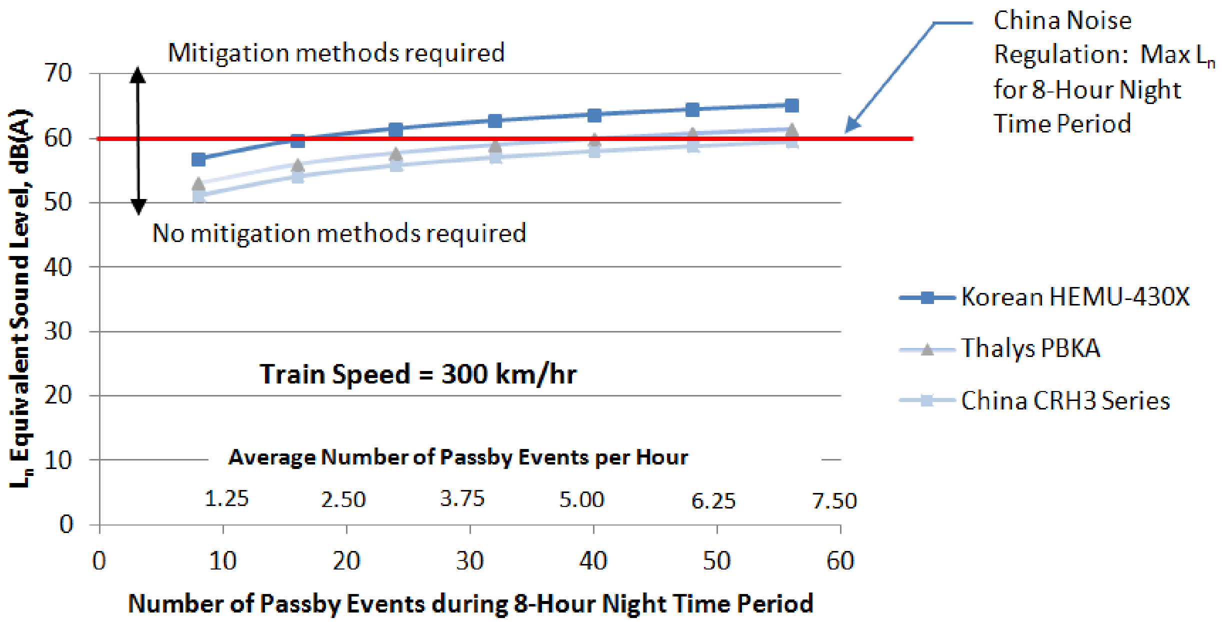


Figure 23: L_n for Train Speed = 300 km/hr

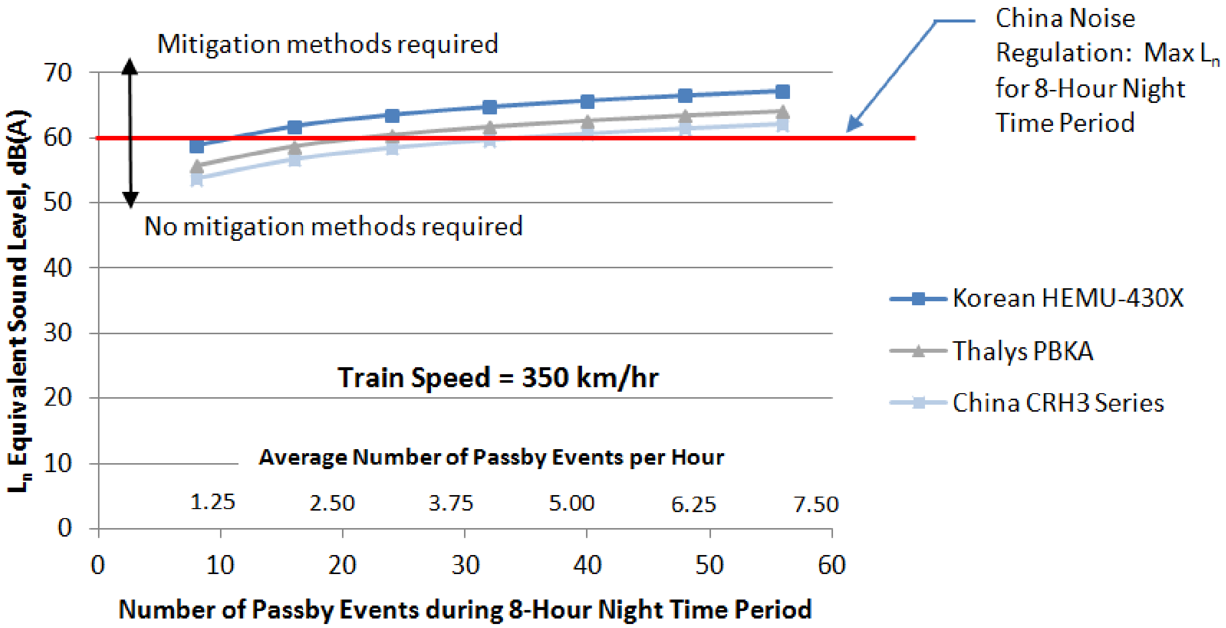


Figure 24: L_n for Train Speed = 360 km/hr

China has over 2,800 high speed train sets in operation, connecting over 550 cities. Train speeds range from 200 km/hr to 350 km/hr (124.27 to 217.48 mph) (Travel China Guide, 2019). At higher speeds, the number of passby events that meet the L_n maximum decreases. At speeds above 300 km/hr (186.41 mph), it appears noise mitigation methods might be required if the number of trains per hour during the nighttime period exceeds 4. This is unlikely based on train operating times and frequencies. The number of trains per day and operating hours for several of China's high-speed trains is shown in Table 20 (China Discovery, 2019).

Table 20: China High Speed Train Frequency

Route	Frequency (trains/day)	Operating Times	Hours per Day	Average Trains per Hour
Beijing - Zhengzhou	50	6:30 – 20:00	13.5	3.7
Beijing-Wuhan	30	6:30 – 19:00	12.5	2.4
Beijing - Changsha	15	7:00 – 15:30	8.5	1.8
Guangzhou - Changsha	100	6:30 – 21:00	14.5	6.9
Guangzhou - Wuhan	60	6:30 – 18:30	12	5.0
Guangzhou - Zhengzhou	20	6:30 – 16:30	10	2.0
Note: no trains operate between 21:00 and 6:30, thus reducing the night time equivalent sound pressure levels				

Since the trains are not operated during most of the nighttime period, 9:00pm to 6:30am, it appears the maximum L_n requirement is not a significant limitation to Chinese train operations.

L_d Calculations

Table 21 showed the common parameters associated with the calculation of the daytime equivalent sound level, L_d.

Table 21: Common Parameters for Calculation of L_d

Common Parameters	Value	Units
Duration of Day Time Period	16	hours
	57,600	sec
Korean HEMU-430X Train Length	147.4	m
Thalys PBKA Train Length	200.19	m
China CRH3 Series Train Length	200	m

The results of the CONTRAST calculations are summarized in Table 22. China's maximum allowable value for L_d is 70 dB(A) for microphone position four (30 m [98.43 ft.] from track centerline and 1.2 m [3.94 ft.] above top of rail). Mitigation methods, for example noise barriers, are required if L_d exceeds this limit.

Table 22: Variation of L_d as a Function of Number of Passby Events

Specific Parameters	Units	Train Speed:	80	km/hr	Train Speed:	250	km/hr	Train Speed:	300	km/hr	Train Speed:	350	km/hr
			22.22	m/sec		69.44	m/sec		83.33	m/sec		97.22	m/sec
		Korean HEMU-430X	Thalys PBKA	China CRH3 Series	Korean HEMU-430X	Thalys PBKA	China CRH3 Series	Korean HEMU-430X	Thalys PBKA	China CRH3 Series	Korean HEMU-430X	Thalys PBKA	China CRH3 Series
Time of Passby Event	sec	6.63	9.01	9.00	2.12	2.88	2.88	1.77	2.40	2.40	1.52	2.06	2.06
t(j): Ratio of Passby Time to 16-Hour Day Period		0.0001152	0.0001564	0.0001563	0.0000369	0.0000500	0.0000500	0.0000307	0.0000417	0.0000417	0.0000263	0.0000357	0.0000357
$L_{pAEQ,passby}$ (microphone position 4)	dB(A)	74.38	67.67	65.04	87.06	81.74	79.51	89.89	84.97	82.86	92.64	88.13	86.14
Number of Trains during 16-Hour Day Period		L_d (the A-weighted equivalent sound level measured during the day time), dB(A)											
30		49.77	44.38	41.75	57.50	53.50	51.27	59.53	55.94	53.83	61.61	58.43	56.44
60		52.78	47.39	44.76	60.51	56.51	54.28	62.54	58.95	56.84	64.62	61.44	59.45
90		54.54	49.15	46.52	62.27	58.27	56.04	64.30	60.71	58.60	66.38	63.20	61.21
120		55.79	50.40	47.77	63.52	59.52	57.29	65.55	61.96	59.85	67.63	64.45	62.46
150		56.76	51.37	48.74	64.49	60.49	58.26	66.52	62.93	60.82	68.60	65.42	63.43
180		57.55	52.16	49.53	65.28	61.28	59.05	67.31	63.73	61.61	69.39	66.21	64.22
210		58.22	52.83	50.20	65.95	61.95	59.72	67.98	64.39	62.28	70.06	66.88	64.89

Plots of Ld as a function of number of passby events, for the three train types at four different speeds are shown in Figure 25 through Figure 28.

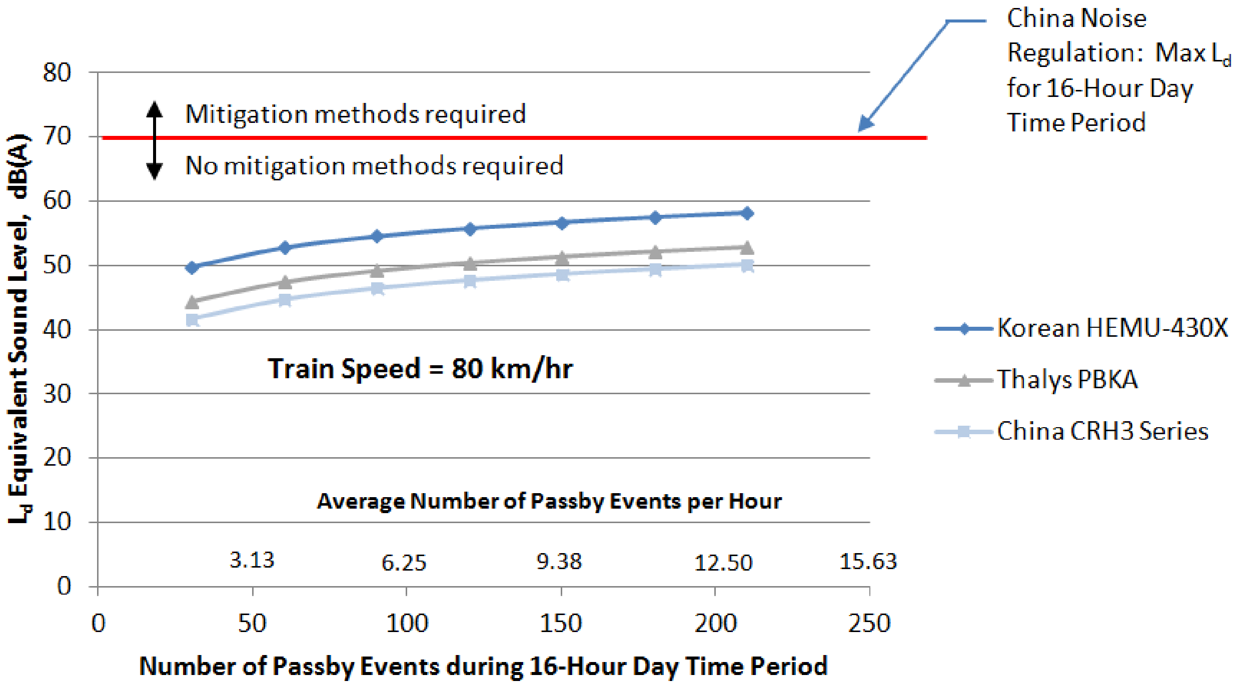


Figure 25: Ld for Train Speed = 80 km/hr

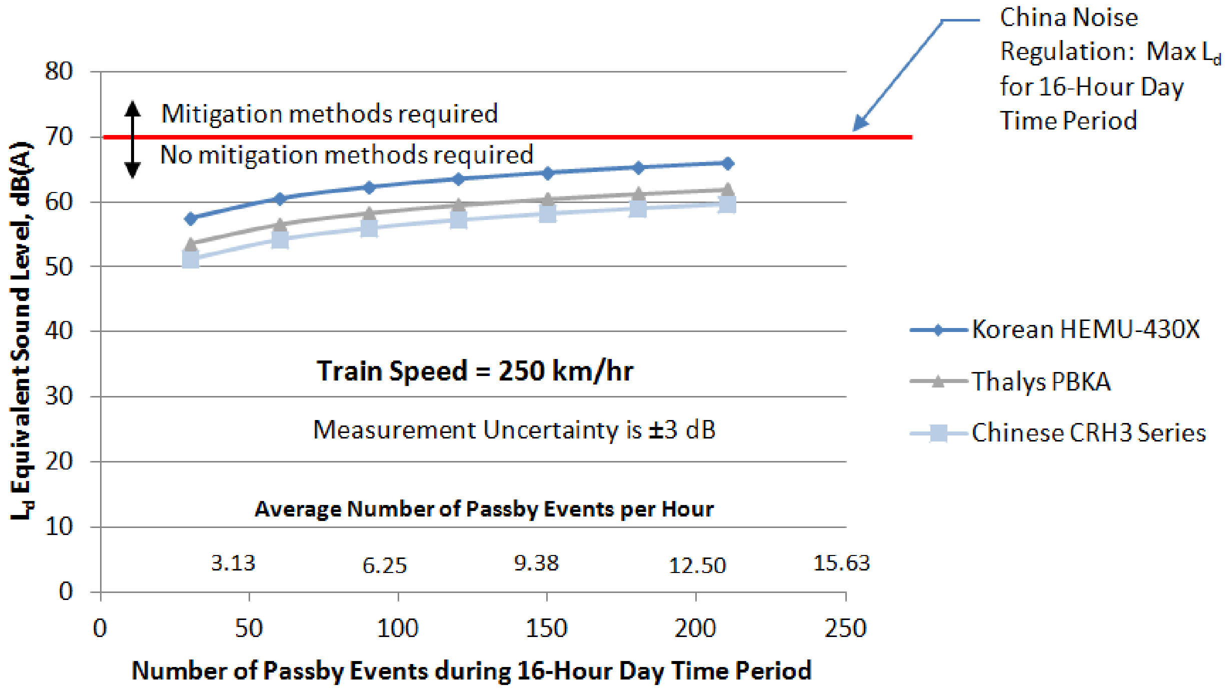


Figure 26: Ld for Train Speed = 250 km/hr

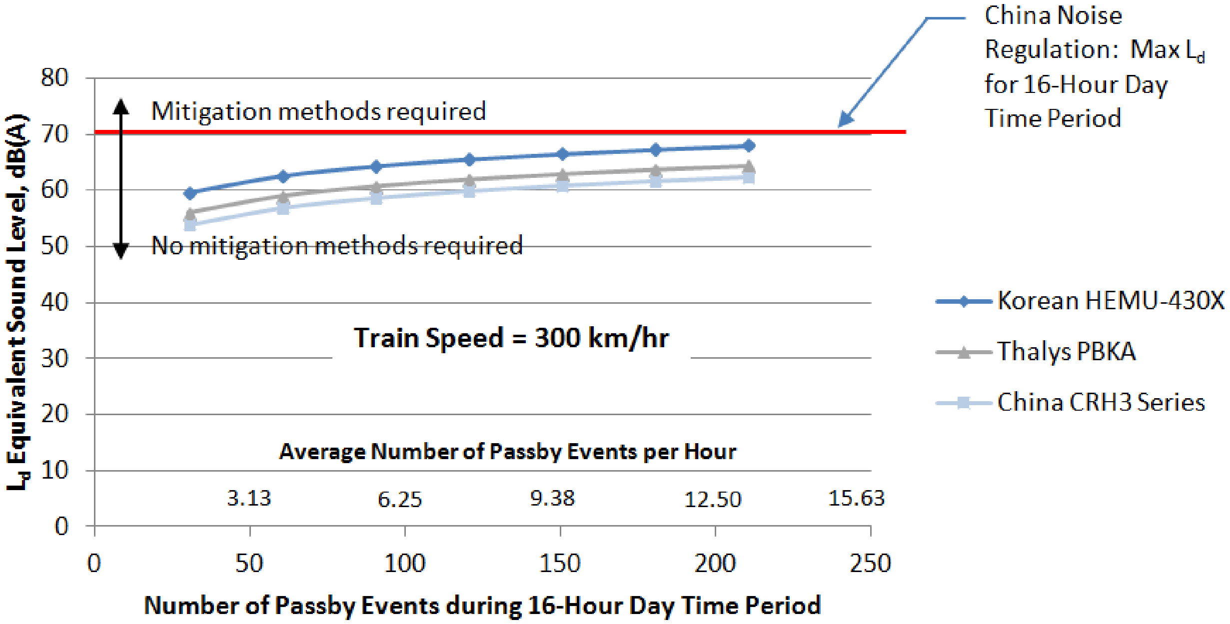


Figure 27: Ld for Train Speed = 300 km/hr

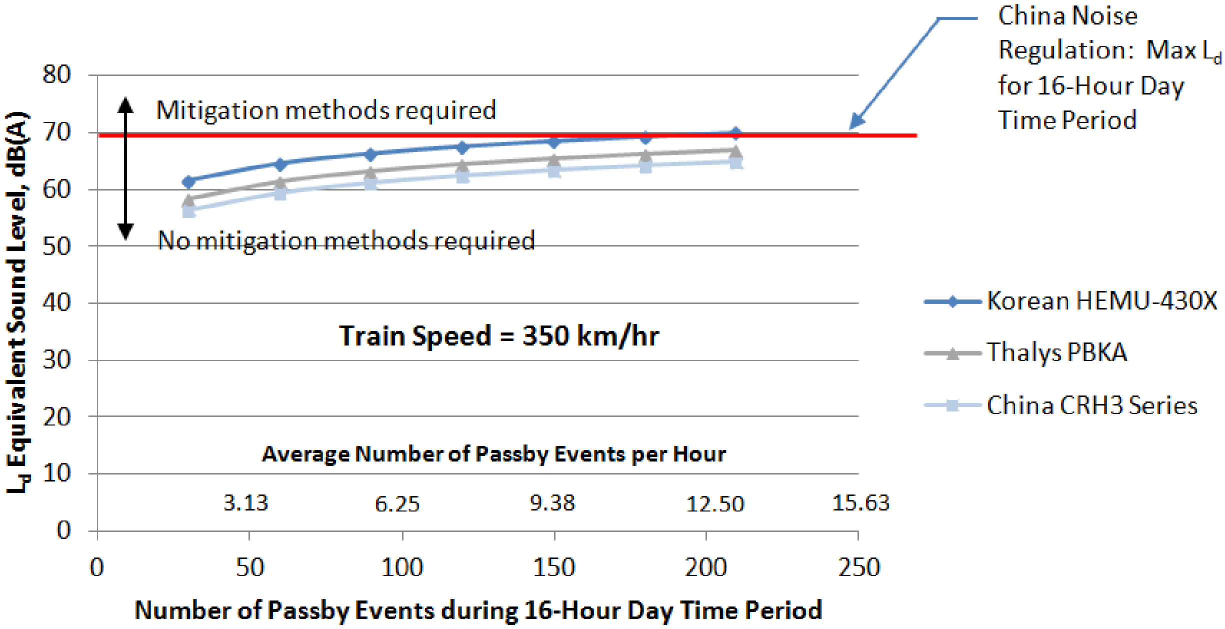


Figure 28: Ld for Train Speed = 350 km/hr

Since the highest average number of trains passing per hour is seven for the Chinese high-speed rail network, it appears noise at the railroad property boundaries (microphone position 30 m [98.43 ft.] from track centerline and 1.2 m [3.94 ft.] above the top of rail) will not exceed the L_d maximum for any of the train sets evaluated.

2.10.6 Comparisons to Japan Noise Regulations

In Japan, noise measurements for high speed rail are required to be taken at the railroad property line (microphone position 3) 25 m (82.02 ft.) from the track centerline and 1.2 m (3.94 ft.) above the top of rail. Regulated maximum SPLs vary by land use category as summarized in Table 23 (Ministry of the Environment, 1993) (Ministry of the Environment, 1998).

Table 23: Noise Limits for Japan Shinkansen High Speed Rail

<table>
<tr><th colspan="6">Noise Limits for Japan Shinkansen High Speed Rail</th></tr>
<tr><th>Code</th><th>Applies to:</th><th>Area Category</th><th>Maximum Sound Pressure Level dB(A)</th><th>Metric for Noise Measurement</th><th>Measurement Location</th></tr>
<tr><td rowspan="2">In accordance with Basic Environmental Law (Law 91 of 1993)</td><td rowspan="2">Shinkansen (HS Rail)</td><td>I</td><td>70 or less</td><td rowspan="2">L_{eq}, L_{Amax}</td><td rowspan="2">25 m from track centerline at elevation of 1.2 m</td></tr>
<tr><td>II</td><td>75 or less</td></tr>
<tr><td colspan="6">Notes:
1. Area Categories: I Residential Zones
II Commercial and Industrial Zones
2. The noise metric L_{eq} is calculated using the energy mean of the peak noise levels
3. Sound pressure limits are not indexed by train speed
4. Measurements are to be carried out by recording the peak noise level of each of the Shinkansen trains passing in both directions, in principle for 20 successive trains
5. Wayside noise mitigation methods, such as barriers, can be implemented to meet noise limits.</td></tr>
</table>

Calculation of L_{eq}

The L_{eq} noise metric is defined by Equation 6:

$$L_{eq}(hour) = 10 \log_{10} \left[\frac{1}{T} \int_{t_1}^{t_2} 10^{L_A(t)/10} \mathrm{d}t \right]$$

Equation 6: L_{eq} noise metric

where L_{eq} is the receiver's cumulative noise exposure from all events over a specified time period

$L_A(t)$ is the A-weighted equivalent continuous SPL produced by the train as measured during the passby event where the 1-hour time interval extends from t_1 to t_2 and $T = t_2 - t_1 = 1$ hour

The maximum speed for Shinkansen trains is 320 km/hr (198.84 mph). Train speeds of 300 km/hr (186.41 mph) and 350 km/hr (217.48 mph) are included in the following analysis, based on the CONTRAST spreadsheet program.

Again, the Reimann sum approach is employed to calculate the integral for the L_{eq} equation in Equation 7 (Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S., 2021):

$$L_{eq}(hour) = 10 \log_{10} \left[\frac{1}{T} \sum_{j=1}^{N} 10^{L_{A_j}(t)/10} \, \Delta t \right]$$

Equation 7: Calculation of Integral L_{eq}

since $\Delta t/T = t(j)$ = the fraction of time during which the SPL $L_{Aj}(t)$ occurs during the time period over which L_{eq} applies, the authors obtained a relationship similar to that for L_d and L_n, except for the time period being equal to 1 hour (3,600 seconds) (see Equation 8) (Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S., 2021). Thus,

$$L_{eq}\ (\text{hour}) = 10 \log_{10} \left[\sum_{j=1}^{N} t(j) 10^{\frac{L(j)}{10}} \right]$$

Equation 8: Relationship to L_d and L_n, Except for Time Period Equal to 1 hour (3,600 seconds)

where the time increment for calculating t(j) is 1 hour (3,600 seconds) and $L_{Aj} = L(j)$

The calculation includes all the passby data points from the time recording of the microphone SPL signals starts until the time recording of microphone SPL signals ends.

The common parameters associated with calculation of the daytime equivalent sound level, L_d, are shown in Table 24.

Table 24: Common Parameters for Calculation of L_{eq}

Common Parameters	Value	Units
Duration of Night Time Period	1	hour
	3,600	sec
Korean HEMU-430X Train Length	147.4	m
Thalys PBKA Train Length	200.19	m
China CRH3 Series Train Length	200	m

The results of the CONTRAST calculations are summarized in Table 25. Japan's maximum allowable value for L_d is 70 dB(A) for residential areas and 75 dB(A) for commercial and industrial areas (microphone position 3, which is 25 m [82.02 ft.] from track centerline and 1.2 m [3.94 ft.] above top of rail). Mitigation methods, for example noise barriers, are required if L_{eq} exceeds this limit.

Table 25: Variation of L_{eq} as a Function of Number of Passby Events

Specific Parameters	Units	Train Speed:	80	km/hr	Train Speed:	250	km/hr	Train Speed:	300	km/hr	Train Speed:	350	km/hr
			22.22	m/sec		69.44	m/sec		83.33	m/sec		97.22	m/sec
		Korean HEMU-430X	Thalys PBKA	China CRH3 Series	Korean HEMU-430X	Thalys PBKA	China CRH3 Series	Korean HEMU-430X	Thalys PBKA	China CRH3 Series	Korean HEMU-430X	Thalys PBKA	China CRH3 Series
Time of Passby Event	sec	6.63	9.01	9.00	2.12	2.88	2.88	1.77	2.40	2.40	1.52	2.06	2.06
t(j): Ratio of Passby Time to 1-Hour L_{eq} Time Period		0.0018425	0.0025024	0.0025000	0.0005896	0.0008008	0.0008000	0.0004913	0.0006673	0.0006667	0.0004211	0.0005720	0.0005714
$L_{eq,passby}$ (microphone position 3)	dB(A)	75.18	68.46	65.83	87.85	82.53	80.30	90.68	85.76	83.66	93.43	88.92	86.93
Number of Trains during 1-Hour L_{eq} Time Period		L_{eq} (the A-weighted equivalent sound level measured during a one-hour time period), dB(A)											
8		56.86	51.48	48.84	64.59	60.59	58.36	66.62	63.04	60.93	68.70	65.52	63.53
16		59.87	54.49	51.85	67.60	63.60	61.37	69.63	66.05	63.94	71.71	68.53	66.54
24		61.63	56.25	53.61	69.36	65.36	63.13	71.40	67.81	65.70	73.47	70.29	68.30
32		62.88	57.50	54.86	70.61	66.61	64.38	72.64	69.06	66.95	74.72	71.54	69.55
40		63.85	58.47	55.83	71.58	67.58	65.35	73.61	70.03	67.92	75.69	72.51	70.52
48		64.64	59.26	56.62	72.37	68.37	66.14	74.41	70.82	68.71	76.48	73.30	71.31
56		65.31	59.93	57.29	73.04	69.04	66.81	75.08	71.49	69.38	77.15	73.97	71.98

The Japanese Shinkansen trains currently operate 24 hours per day on nine primary routes: Tokaido, Sanyo, Tohoku, Hokkaido, Yamagata, Akita, Joetsu, Hokuriku, and Kyushu/Kagoshima. Four additional routes are planned or under construction (i.e., Hokuriku, Hokkaido, Kuushu/Nagasaki, and Linear Chuo) (Nippon Communications Foundation, 2014). There are 360 train sets operating on these routes (Osbourne, R., 2018). The busiest Shinkansen lines have up to 17 trains per hour (Hayashi, 2019).

Plots of L_{eq} as a function of number of passby events, for the three train types at four different speeds are shown in Figure 29 through Figure 32.

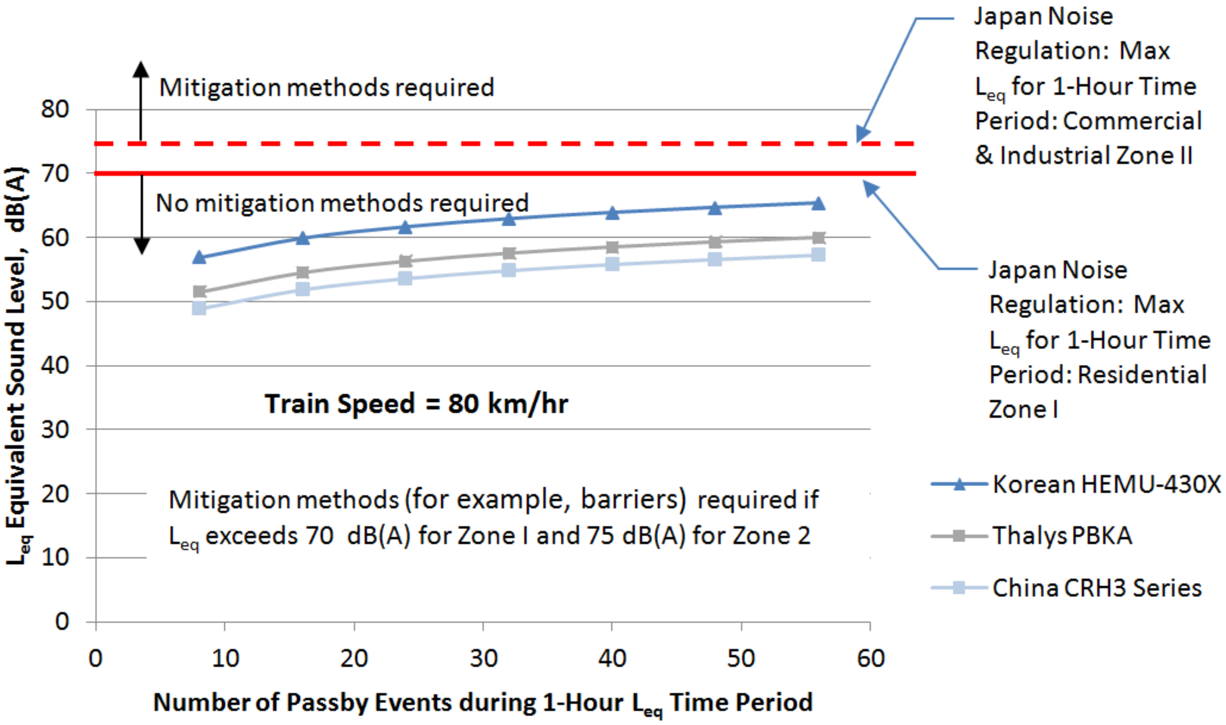


Figure 29: L_{eq} for Train Speed = 80 km/hr

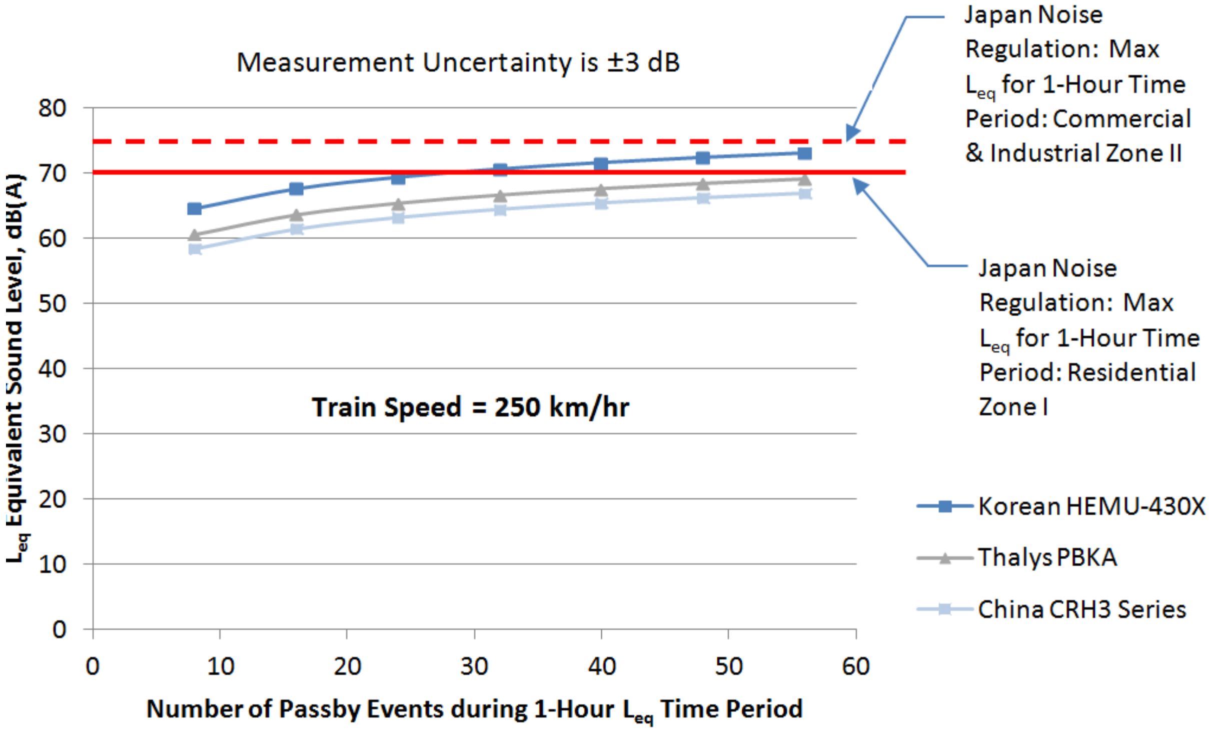


Figure 30: L_{eq} for Train Speed = 250 km/hr

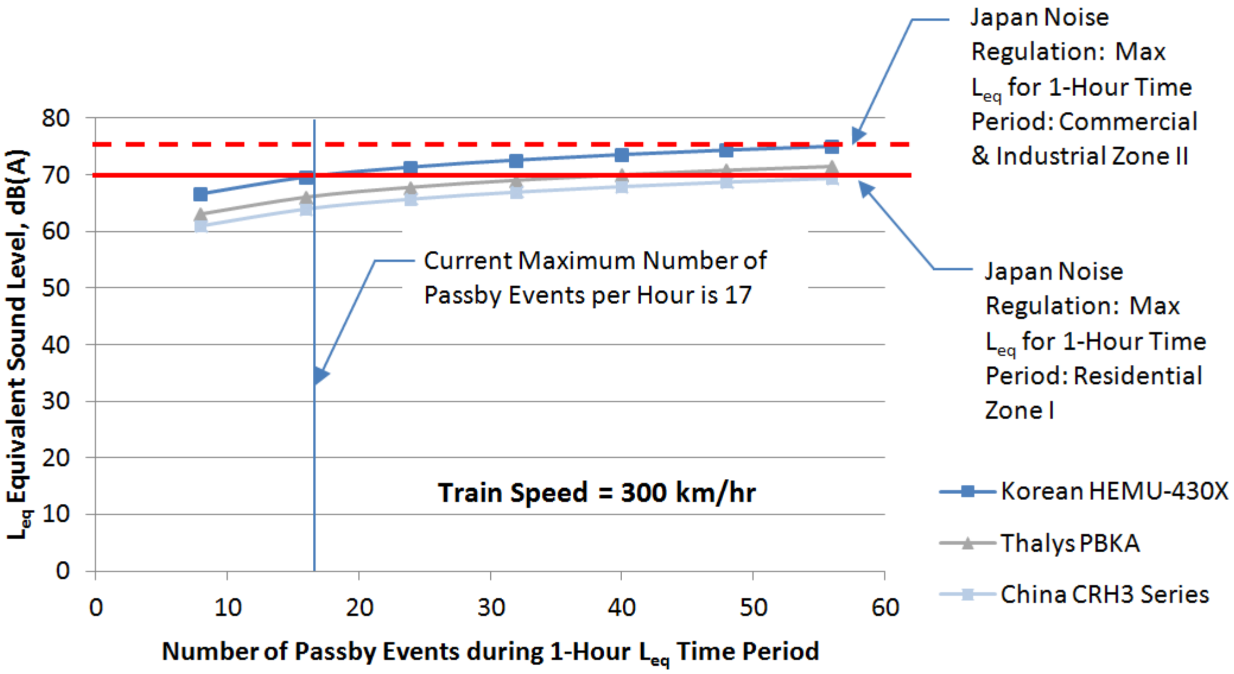


Figure 31: L_{eq} for Train Speed = 300 km/hr

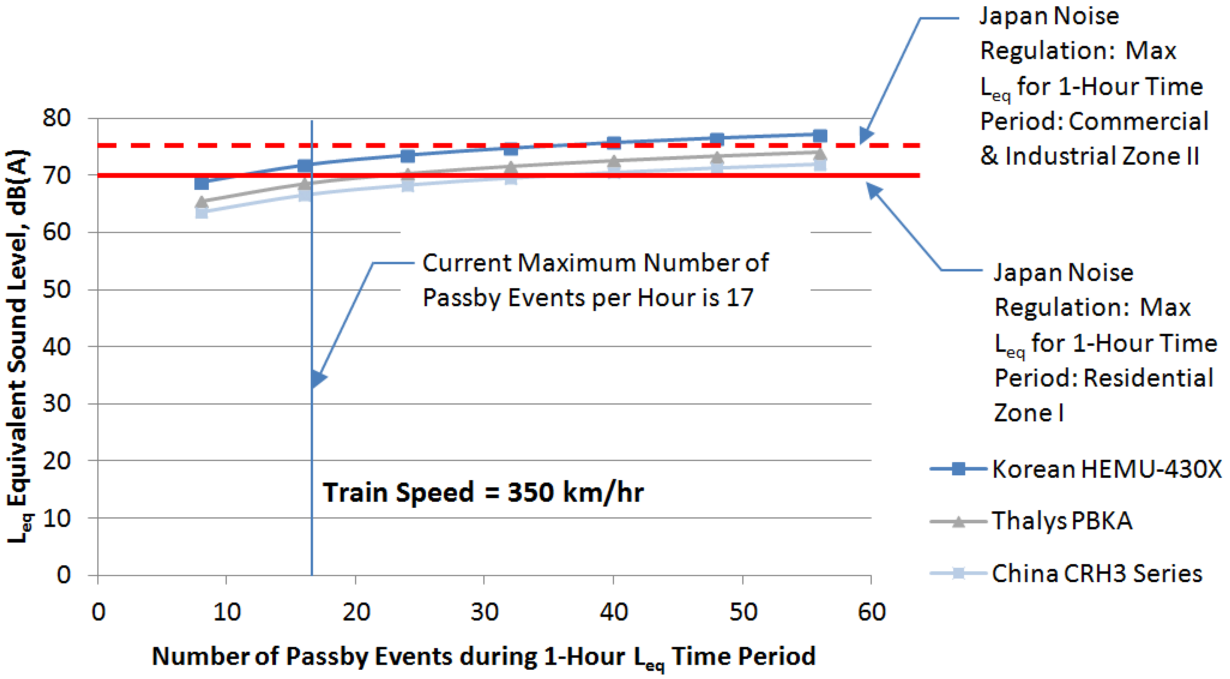


Figure 32: L_{eq} for Train Speed = 350 km/hr

Since the current Shinkansen trains operate at maximum speeds of 320 km/hr (199 mph), (Japan Rail Pass, 2019), and the maximum number of passby events per hour is 17 or less, the train sets in the CONTRAST library meet the Zone II (commercial/industrial) noise limit for L_{eq}, and all but one (the Korean HEMU) meets the L_{eq} limit for Zone I (residential) for microphone position

3 (25 m [82.02 ft.] from track centerline and 1.2 m [3.94 ft.] above top of rail) for current operating speeds.

Calculation of L_{Amax}

Another noise metric employed to evaluate noise emanating from Shinkansen high speed trains is L_{Amax}. For the Shinkansen, noise measurements are to be made for 20 train passing events in each direction, consecutively (Maeda, T., 1999). The regulation requires that measurements are to be taken outdoors with the measurement instruments positioned adjacent to locations known to have high levels of railway-generated noise and when noise from the Shinkansen has been determined to be an issue. The measurements are to be taken with a meter with A-weighted calibration and slow dynamic response during "normal" weather conditions and when trains pass the measurement point at "normal speeds" (Maeda, T., 1999). Equation 9 for L_{Amax} is (Hanson, C. E., Ross, J. C., & Towers, D. A., 2012):

$$L_{Amax} = 10 \log_{10}\left[\frac{1}{20}\sum_{j=1}^{20} 10^{(L_{pASmax})_j/10}\right]$$

Equation 9: Calculation of L_{Amax}

For the current calculations, if we assume all 20 consecutive passby measurements are identical, for purposes of comparing noise metrics, researchers find $L_{Amax} = L_{pASmax}$ as shown in Equation 10:

$$L_{Amax} = 10 \log_{10}\left[\frac{20}{20} 10^{(L_{pASmax})/10}\right] = 10 \log_{10}\left[10^{(L_{pASmax})/10}\right] = \left[\frac{L_{pASmax}}{10}\right] 10 \log_{10}(10) = L_{pASmax}$$

$$\text{Since:} \quad \log_{10}(x^y) = y \log_{10}(x) \quad \text{and} \quad \log_{10}(10) = 1$$

Equation 10: Calculation of $L_{Amax} = L_{pASmax}$

The L_{Amax} requirement for 20 consecutive passby events is more stringent than L_{eq} as shown in Table 26:

Table 26: L_{Amax} for 20 Consecutive Passby Events

$L_{Amax\,(slow)}$ dB(A), Microphone Position 3						
Train Set	**Train Speed (km/hr)**					
	80	**150**	**200**	**250**	**300**	**350**
Korean HEMU-430X	78.6	85.0	88.3	91.3	94.1	96.9
Thalys PBKA	70.6	77.5	81.3	84.7	87.9	91.1
China CRH3 Series	67.1	74.1	78.0	81.5	84.9	88.2

These results are plotted in Figure 33. Because the regulation is based on peak noise levels during the passby event, rather than the equivalent SPL, the maximum value of L_{Amax} is exceeded at all train speeds above 80 km/hr, necessitating the installation of mitigation methods, such as wayside barriers and onboard modifications, such as pantograph shields. These results are consistent with reported levels of SPLs corresponding to changes in train speeds and installations of noise reduction systems (Maeda, T., 1999).

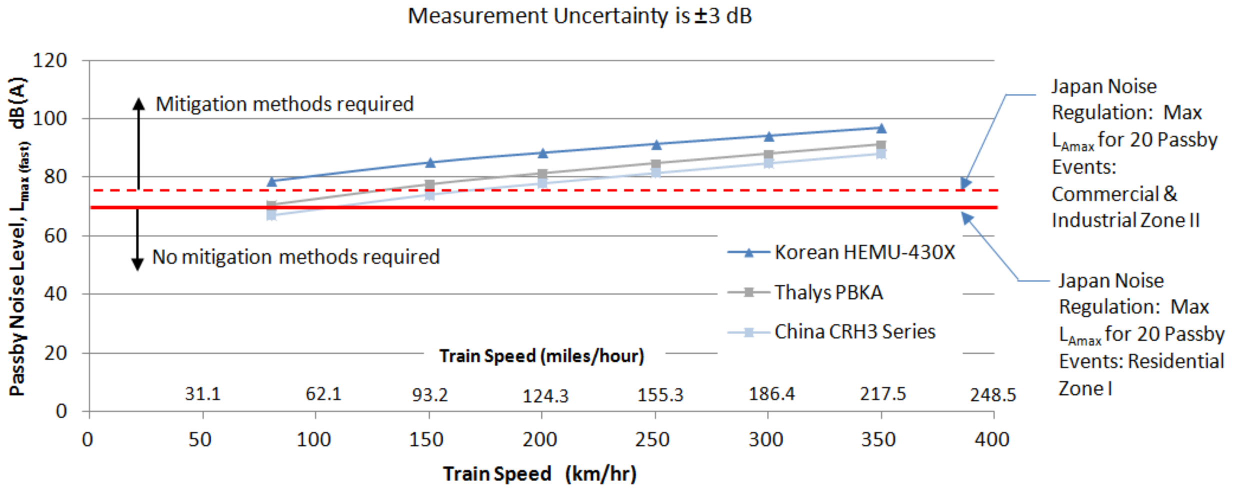


Figure 33: L_{Amax} for 20 Consecutive Passby Events

2.11 Common Reference Data Set

A common reference train passby event was chosen to compare current noise regulations for the US, EU, China, and Japan. The criteria for developing this common reference include:

1. The passby sound pressure signature was based on a scaled version of a currently operational train set.
2. The train speed was chosen as representative of current high-speed operations.
3. The train composition, or "consist" (a consist is in general terms is "a group of rail vehicles which make up a train" (Wiktionary, 2019)) is representative of current high speed train sets.
4. The distance to the microphone corresponds to a current noise regulation (i.e., in this case, the EU TSI).
5. The time step for the passby noise data is 0.05 seconds, which provides the required level of resolution based on the accuracy and uncertainty evaluation described in Section 2.9.
6. It is assumed the track roughness meets TSI requirements as acceptable for taking noise measurements.
7. The data set exactly meets the TSI NOI regulation, i.e., the value for $L_{pAeq,Tp\ (80\ km/hr)} = 80$ dB(A) and $L_{pAeq,Tp\ (250\ km/hr)} = 95$ dB(A).

Program CONTRAST is then used to calculate the noise metrics associated with US, Japan, and China regulations so the regulations can be directly compared.

The characteristics of the common reference data set are included in Table 27. The passby data set (SPL vs. time) is plotted in Figure 34.

Table 27: Common Reference Data Set

Parameter	Value	Units
Number of Cars in Train	10	
Number of End Cars	2	
Number of Intermediate Cars (ends)	2	
Number of Intermediate Cars (middle)	6	
Length of End Cars	22.15	m
Length of Intermediate Cars (ends)	21.845	m
Length of Intermediate Cars (middle)	18.7	m
Train Length	200.19	m
Train Speed	296	km/hr
Track Roughness	TSI Compliant	
Microphone Distance from Track Centerline	7.5	m
Microphone Elevation above Top of Rail	1.2	m
Time Increment for Passby Data	0.05	sec
Number of Data Points for Passby Event	85	
Time of Passby Event (nose to tail passing microphone)	2.435	sec

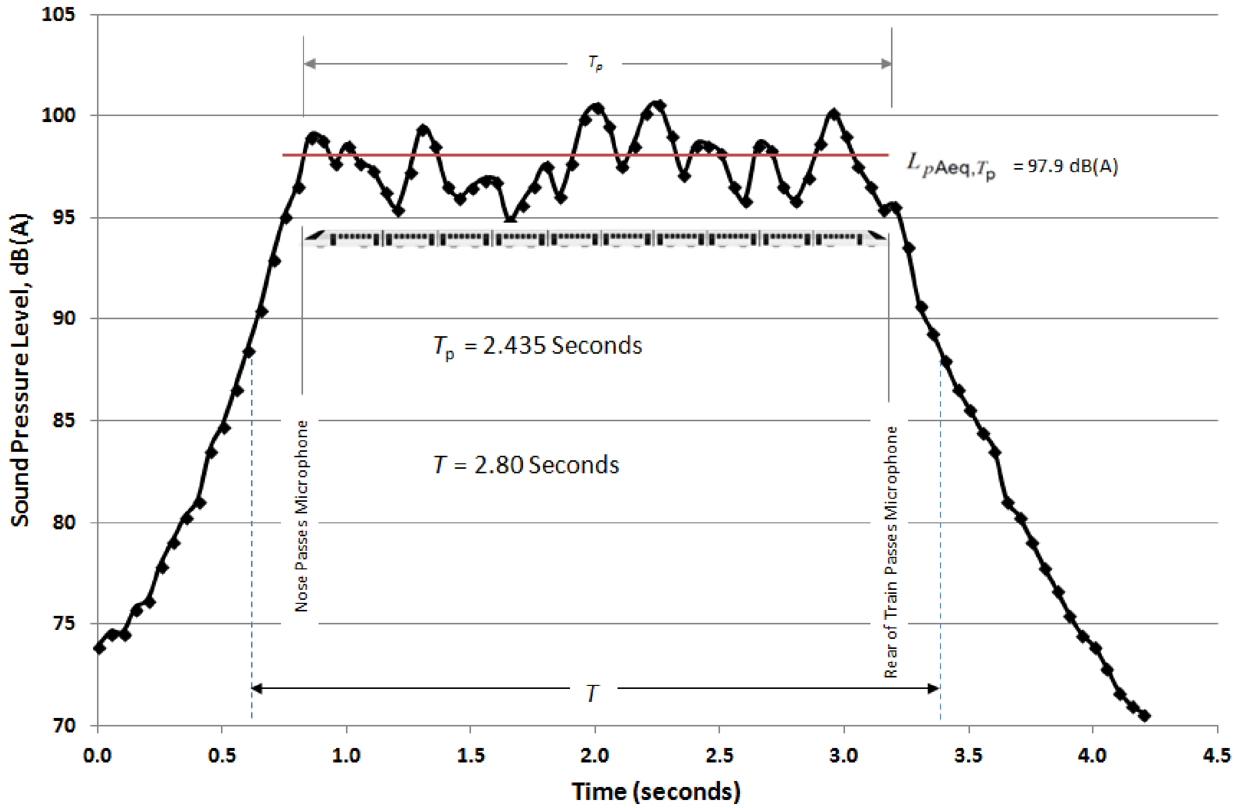


Figure 34: Common Reference Passby Data Set, SPL vs. Speed

The common reference data set provides the following values for the normalized SPLs associated with the TSI NOI (2014) regulation. The TSI normalization formulas for $L_{pAeq,Tp(80\ km/hr)}$ and $L_{pAeq,Tp(250\ km/hr)}$ are discussed in Section 2.8.

Table 28: Common Reference Data Set, TSI NOI Parameters

Parameter	Regulated Limit	As Calculated for Common Reference Data Set	As Calculated Using the TSI Normalization Formulas
$L_{pAeq,Tp\ (80\ km/hr)}$	80 dB(A)	80 dB(A)	80.9 dB(A)
$L_{pAeq,Tp\ (250\ km/hr)}$	95 dB(A)	95 dB(A)	94.3 dB(A)

Since CONTRAST calculates the noise metrics for the US, EU, China, and Japan noise regulations as a function of train speed, microphone position, and number of passby events, the results for the common reference data set can be used to compare the regulations and answer questions such as "if a train set is compliant with the TSI regulation, how is it expected to perform relative to US, China, and Japan regulations?"

2.12 Description of the CONTRAST Program

The CONTRAST program is organized as a series of connected Excel® worksheets, which are summarized in Table 29.

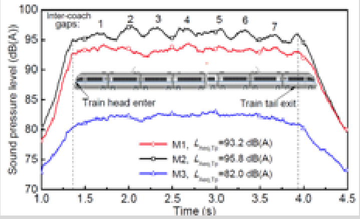
The CONTRAST program is based on a library of high-speed train passby SPL data, including a scaled "common reference" data set. The passby data are assumed to meet measurement requirements defined in the train noise regulations of the EU, US, China, and Japan. From the passby data sets, the noise metrics associated with the various noise regulations are calculated and plotted. The plots show maximum allowed values associated with each regulation. Thus, CONTRAST can be used to assess whether a selected train set is likely to meet noise regulations for each of the four jurisdictions. CONTRAST also employs a common reference data set to compare the EU, US, China, and Japan regulations. Comparisons of the various regulations are presented in tabular and graphic formats. Because the regulations vary by metrics, the comparison plots include both emissions and immissions calculations. Figure 35 shows the CONTRAST program flow chart.

Table 29: CONTRAST Program Worksheets

Worksheet Name	Contents
Program Overview	Program Description, Program Capabilities, Legal Terms & Conditions
Train Set Data Requirements	Descriptions of Instrumentation and Measurement Procedures Regulations and Standards, Note on Measurement Accuracy and Uncertainty.
Passby Data Library Summary	Descriptions of Train Sets Contained in the Current Library
Regulations (US EU China Japan)	Summary of Current High Speed Train Noise Regulations and Metrics
Common Reference Analysis	Comparisons of US, EU, China, and Japan High Speed Noise Regulations to a Common Reference. The common reference train passby noise data set is based on a scaled sound pressure level graph that exactly meets the EU TSI Normalized Equivalent 80 km/hr and 250 km/hr normalized limits. The corresponding US, China, and Japan limits are then calculated using the same data set, thus allowing direct comparisons.
Data Set Comparisons	Comparisons of the data sets in the program library relative to the identified passby noise metrics associated with the regulations of each country.
Passby Data Set 1	Train set information and passby sound pressure measurement data for the Korean HEMU-430X
Passby Data Set 1 Output	Calculated noise metrics for the Korean HEMU-430X based on the passby data set.
Passby Data Set 2	Train set information and passby sound pressure measurement data for the Thalys PBKA
Passby Data Set 2 Output	Calculated noise metrics for the Thalys PBKA based on the passby data set.
Passby Data Set 3	Train set information and passby sound pressure measurement data for the China CRH3 Series Trains, Microphone Position 2
Passby Data Set 3 Output	Calculated noise metrics for the China CRH3 Series Trains, Microphone Position 2, based on the passby data set.
Passby Data Set 4	Train set information and passby sound pressure measurement data for the China CRH3 Series Trains, Microphone Position 1
Passby Data Set 4 Output	Calculated noise metrics for the China CRH3 Series Trains, Microphone Position 1, based on the passby data set.
Passby Data Set 5	Train set information and passby sound pressure measurement data for the China CRH3 Series Trains, Microphone Position 3
Passby Data Set 5 Output	Calculated noise metrics for the China CRH3 Series Trains, Microphone Position 3, based on the passby data set.
Common Reference Data Set	The scaled passby data set that exactly meets the TSI NOI (2014) normalized limits
Common Reference Data Set Output	Analysis of the noise metrics for the common reference data set.

Assemble library of passby noise data for high speed train sets. The initial version of CONTRAST includes five HS train data sets. The spreadsheet program allows other train sets to be added.

Data are to be obtained according to regulations and standards requirements for instrumentation and measurement procedures.



From the passby noise data sets, calculate the noise metrics associated with each regulation:

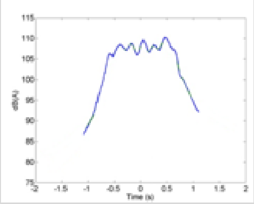
US: $L_{max\ (fast)}$, L_{pAEmax}

EU: $L_{pAeq,Tp}$, $L_{pAeq,Tp}$ normalized to 80 km/hr, $L_{pAeq,Tp}$ normalized to 250 km/hr.

China: L_d, L_n **Japan:** L_{eq}, L_{amax}

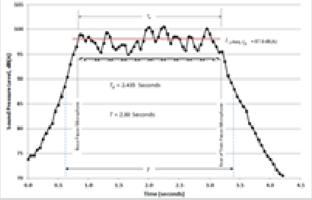
Other: L_{pASmax}, L_{pAFmax}, $L_{pAeq\ (passby)}$, TEL, SEL, L_{10}, L_{50}, L_{90}, L_p (maximum)

$$L_{pAeq,T_p} = 10\ \lg \left(\frac{1}{T_2 - T_1} \int_{T_1}^{T_2} \frac{p_A^2(t)}{p_0^2} dt \right) \quad \text{dB}$$

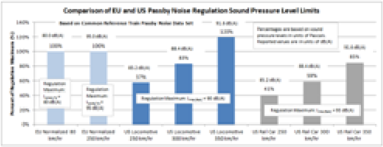


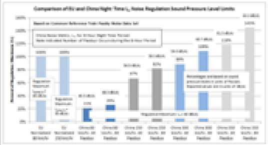
Scale selected passby data set to exactly meet EU TSI NOI (2014) normalized noise metrics: $L_{pAeq,Tp}$ normalized to 80 km/hr, $L_{pAeq,Tp}$ normalized to 250 km/hr.

Use this scaled data set as the Common Reference to calculate noise metrics for each regulation: US, EU, China, Japan. Adjust metrics to account for microphone position and train speed.



Using noise metrics for the Common Reference Data Set, generate Comparison Charts for the US, EU, China and Japan high speed rail noise regulations.





Comparison charts are shown as percentages of maximum allowable sound pressure level values for each regulation.

Figure 35: CONTRAST Program Flow Chart

2.13 Common Reference Data Set Analysis

The CONTRAST program and the common reference data set were utilized to evaluate the four train noise regulations: US, EU, China, and Japan. Comparisons are made based on sound pressure measurements in units of Pascals (Pa) and decibels (dB). To clarify actual differences and to avoid confusion regarding SPLs, percentages are based on Pascals, and comparison tables are plotted in the more common units of decibels.

2.13.1 U.S. Regulations Comparison

EU regulations are based on car type and speed. U.S. regulations are based on car type only. Comparisons are thus made for the common reference data set at the two normalized TSI speeds (80 km/hr [49.71 mph] and 250 km/hr [155.34 mph]) relative to the two car types specified in the US regulations (e.g., locomotives and rail cars). The results are shown in Table 30 and plotted in Figure 36.

Table 30: Comparison of US and EU Regulations

Regulation	Maximum Value, dB(A)	Common Reference Value, dB(A)	Maximum Value, Pa	Common Reference Value, Pa	Percent of Maximum Allowed Value %
EU Normalized 80 km/hr	80	80	0.2000000	0.200000	100%
EU Normalized 250 km/hr	95	95	1.1246827	1.124683	100%
US Locomotive 250 km/hr	90	85.2	0.6324555	0.363038	57%
US Locomotive 300 km/hr	90	88.4	0.6324555	0.526865	83%
US Locomotive 350 km/hr	90	91.6	0.6324555	0.757735	120%
US Rail Car 250 km/hr	93	85.2	0.8933672	0.363038	41%
US Rail Car 300 km/hr	93	88.4	0.8933672	0.526865	59%
US Rail Car 350 km/hr	93	91.6	0.8933672	0.757735	85%

The common reference data set was scaled so that the passby SPLs at train speeds of 80 km/hr and 250 km/hr are such that the $L_{pAeq,Tp}$ metric is exactly equal to the European TSI limit. If the common reference data set (i.e., SPL vs. time) is then used to calculate the U.S. noise metric $L_{max(fast)}$, the results can be directly compared to the EU result. Thus, from Table 30 and Figure 36, it can be stated that a train set that exhibits passby noise characteristics that are equal to the maximum allowed values under the EU TSI would produce passby SPLs that range from 41 to 120 percent of the maximum levels allowed by US railroad noise regulations, depending upon train classification, microphone position, and train speed.

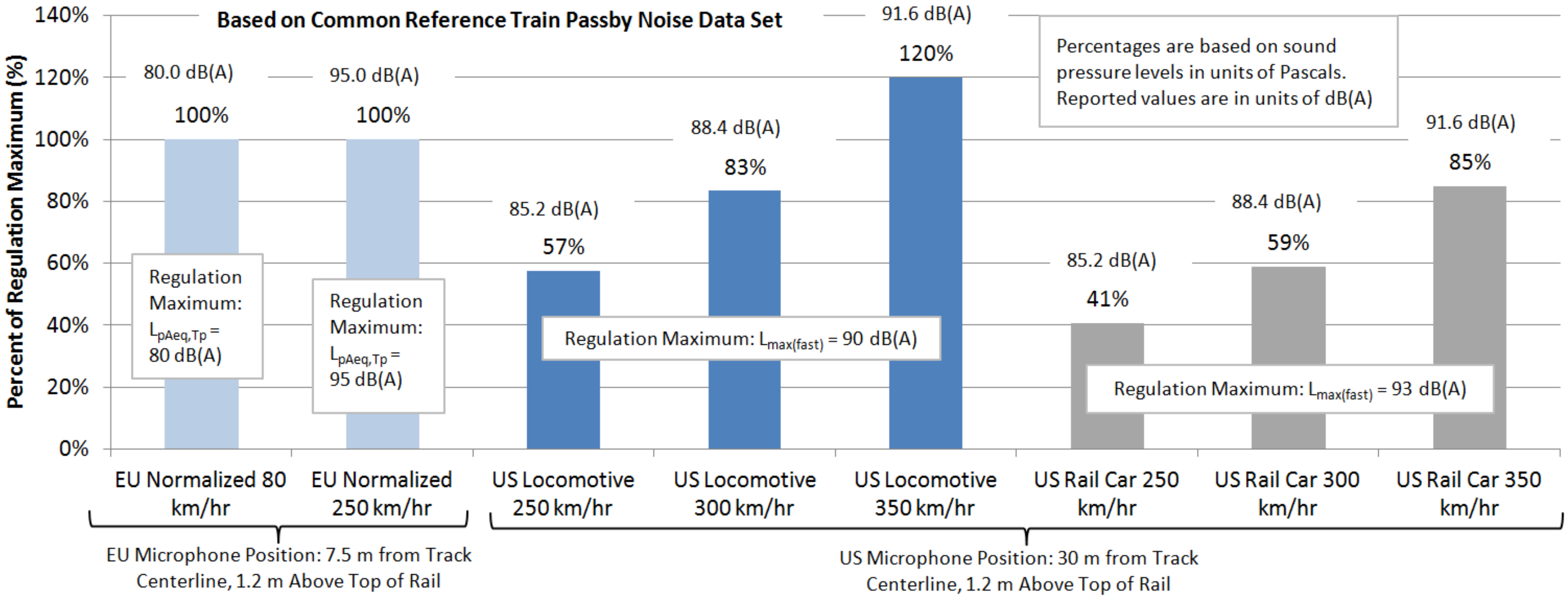


Figure 36: Comparison of EU and US Passby Noise Regulations

Other observations that can be made regarding the comparison between EU and US passby noise regulations include:

- A train set that exhibits SPLs that correspond to the maximum allowed TSI levels, would produce an SPL that is 4.8 dB lower than the US maximum for locomotive classification trains operating at 250 km/hr (155.34 mph).
- Similarly, the same train set operating at 350 km/hr (217.48 mph) and classified in the locomotive category would exceed the US noise limit by 1.6 dB. Because of the logarithmic relationship for dB units, this is 120 percent of the maximum US noise limit based on SPL in units of Pa.
- If the common reference train set is classified as a rail car under US regulations, it would meet the maximum allowed SPL specified by those regulations for all speeds up to 350 km/hr (217 mph). It is noted from Section 2.10.4 that not all the train sets in the CONTRAST library are capable of meeting US regulations at speeds above 300 km/hr (185 mph).

2.13.2 China Regulations Comparisons

China regulations are based on immissions levels measured at the rail property boundary (30 m from track centerline and 1.2 m above top of rail). Two metrics are used, L_n and L_d. Using the common reference data set, the common parameters for the L_n comparisons are shown in Table 31.

Table 31: Common Parameters for Common Reference China L_n Analysis

Common Parameters	Value	Units
Duration of Night Time Period	8	hours
	28,800	sec
Reference Train Length	200.19	m

Based on the number of passby events, the common reference train set was evaluated using CONTRAST to determine the SPLs for train speeds ranging from 80 km/hr to 350 km/hr. The results are shown in Table 32. Comparison of these values to the EU and China L_n noise regulations are shown in Table 33.

The EU and China regulations are plotted in Figure 37 for a range of train speeds and number of passby events.

Table 32: Calculated Values of L_n based on Common Reference Data Set

Calculation of Chinese L_n based on Common Reference Train Data Set					
Time of Passby Event	sec	9.01	2.88	2.40	2.06
t(j): Ratio of Passby Time to 8-Hour Night Period		0.0003128	0.0001001	0.0000834	0.0000715
Train Speed	km/hr	80.00	250.00	300.00	350.00
	m/sec	22.22	69.44	83.33	97.22
$L_{pAEQ,passby}$ (microphone position 4)	dB(A)	65.55	80.50	83.74	86.89
Number of Trains during 8-Hour Night Period		L_n (the A-weighted equivalent sound level measured during the night time), dB(A)			
8		39.53	49.54	51.98	54.47
16		42.55	52.55	54.99	57.48
24		44.31	54.31	56.75	59.24
32		45.56	55.56	58.00	60.49
40		46.52	56.53	58.97	61.46
48		47.32	57.32	59.76	62.25
56		47.99	57.99	60.43	62.92
60		**48.29**	**58.29**	60.73	63.22

Table 33: Comparison: EU and China L_n Noise Regulations: Common Reference Data Set

Regulation	Maximum Value, dB(A)	Common Reference Value, dB(A)	Maximum Value, Pa	Common Reference Value, Pa	Percent of Maximum Allowed Value %
EU Normalized 80 km/hr	80	80.0	0.2000000	0.2000000	100%
EU Normalized 250 km/hr	95	95.0	1.1246827	1.1246827	100%
China 80 km/hr, 40 Passbys	60	46.5	0.0200000	0.0042389	21%
China 80 km/hr, 60 Passbys	60	48.3	0.0200000	0.0051916	26%
China 250 km/hr, 40 Passbys	60	56.5	0.0200000	0.0134105	67%
China 250 km/hr, 60 Passbys	60	58.3	0.0200000	0.0164245	82%
China 300 km/hr, 40 Passbys	60	59.0	0.0200000	0.0177665	89%
China 300 km/hr, 60 Passbys	60	60.7	0.0200000	0.0217595	109%
China 350 km/hr, 40 Passbys	60	61.5	0.0200000	0.0236563	118%
China 350 km/hr, 60 Passbys	60	63.2	0.0200000	0.0289729	145%

As shown in Table 32, the number of passby events was increased until the L_n metric exceeded the regulation limit. The L_n values for 40 passby events and 60 passby events over the 8-hour nighttime period are included in Figure 37.

Observations regarding the comparison of EU regulations to the China L_n noise regulations include:

- A train set that produces SPLs that correspond to the maximum allowed EU TSI limits would produce an A-weighted equivalent sound level, L_n, measured during the night time, that ranges from 21 percent of the China noise limit (train speed = 80 km/hr, number of passby events during 8 hour time period = 40) to 145 percent of the China noise limit (train speed = 350 km/hr [217.48 mph], 60 passby events during 8 hour time period).
- As noted earlier, it is unlikely that the Chinese noise limits would be exceeded due to the limited nighttime train activity and the limited number of passby events. In addition, the SPLs based on the common reference data set ranged from 13.5 dB lower than the 60 dB(A) L_n limit to 3.2 dB(A) greater than the 60 dB(A) limit. With the measurement uncertainty of ±3 dB(A), it appears the L_n limit does not pose a serious threat to current and future nighttime operations of the Chinese high-speed rail system.

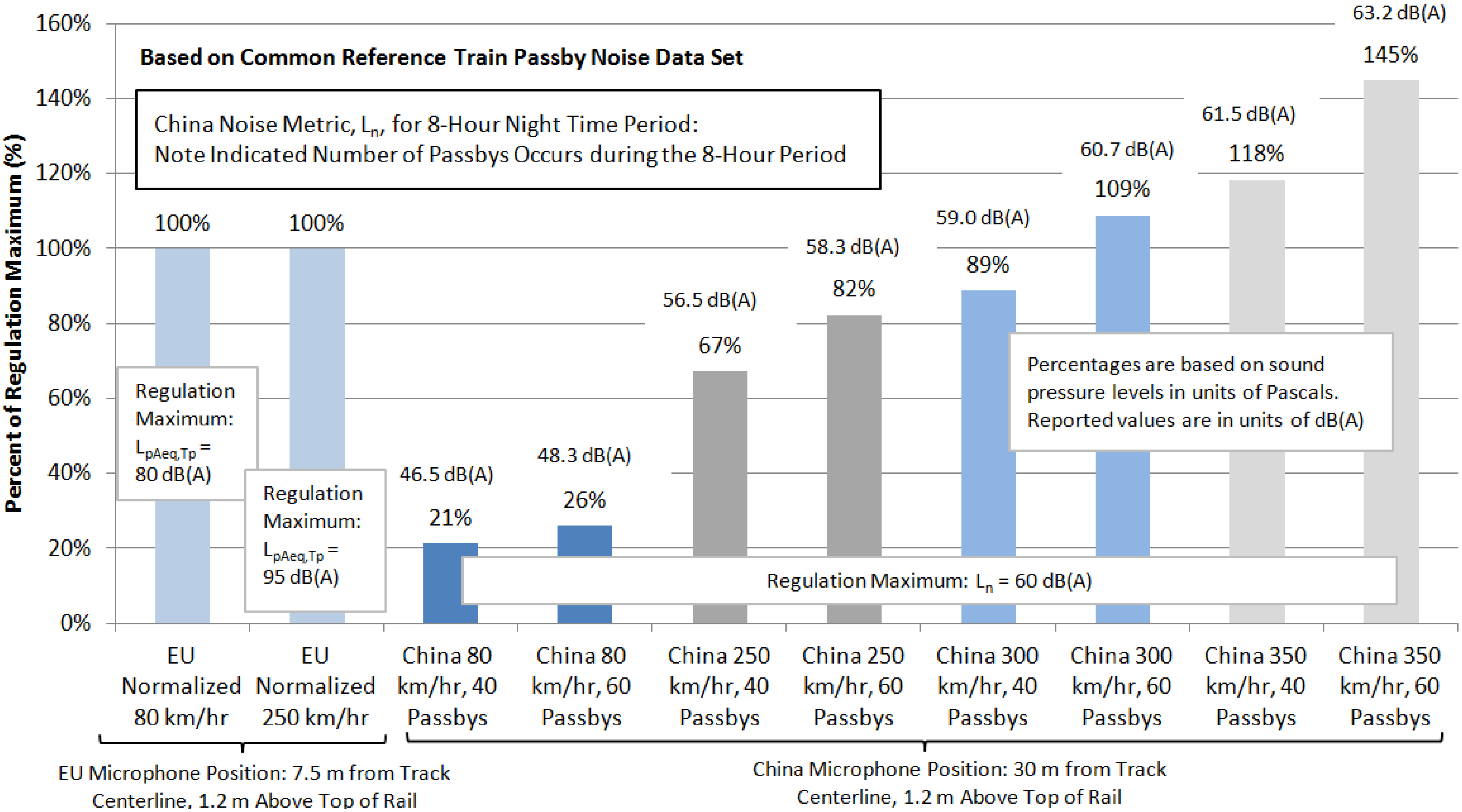


Figure 37: Comparison of EU and China Ln Passby Noise Regulations

A similar analysis was conducted based on the common reference data set to compare the EU regulation to the China L_d regulation. The common parameters for the L_d analysis are shown in Table 34.

Table 34: Common Parameters for Common Reference China L_d Analysis

Common Parameters	Value	Units
Duration of Day Time Period	16	hours
	57,600	sec
Reference Train Length	200.19	m

CONTRAST and the common reference data set were again utilized to determine the SPLs, L_d, for train speeds ranging from 80 km/hr (49.71 mph) to 350 km/hr (217.48 mph). The results are shown in Table 35. Comparison of these values to the EU and China L_d noise regulations are shown in Table 36. As with the L_n analysis, the number of train passby events during the 16-hour day period was varied to determine the impact on the A-weighted equivalent sound level, L_d.

Table 35: Calculated Values of L_d Based on Common Reference Data Set

Calculation of Chinese L_d based on Common Reference Train Data Set					
Time of Passby Event	sec	9.01	2.88	2.40	2.06
t(j): Ratio of Passby Time to 16-Hour Day		0.0001564	0.0000500	0.0000417	0.0000357
Train Speed	km/hr	80.00	250.00	300.00	350.00
	m/sec	22.22	69.44	83.33	97.22
$L_{pAEQ,passby}$ (microphone position 4)	dB(A)	65.55	80.50	83.74	86.89
Number of Trains during 16-Day Time Period		L_d (the A-weighted equivalent sound level measured during the day time), dB(A)			
50		44.48	54.49	56.93	59.42
100		47.49	57.50	59.94	62.43
150		49.25	59.26	61.70	64.19
200		50.50	60.51	62.95	65.44
250		51.47	61.48	63.92	66.41
300		52.26	62.27	64.71	67.20
350		52.93	62.94	65.38	67.87
400		53.51	63.52	65.96	68.45

Note that due to the longer time period for L_d, the number of train passby events were increased compared to those corresponding to the L_n analysis. The average passby events per hour for the 16-hour time period range from 3.2 (50 total passby events during the time period) to 25 (400 passby events during the 16-hour time period).

The EU and China regulations are plotted in Figure 38 for a range of train speeds and number of passby events.

Table 36: Comparison: EU and China L_d Noise Regulations: Common Reference Data Set

Regulation	Maximum Value, dB(A)	Common Reference Value, dB(A)	Maximum Value, Pa	Common Reference Value, Pa	Percent of Maximum Allowed Value %
EU Normalized 80 km/hr	80	80.0	0.2000000	0.2000000	100%
EU Normalized 250 km/hr	95	95.0	1.1246827	1.1246827	100%
China 80 km/hr, 250 Passbys	70	51.5	0.0632456	0.0074935	12%
China 80 km/hr, 400 Passbys	70	53.5	0.0632456	0.0094786	15%
China 250 km/hr, 250 Passbys	70	61.5	0.0632456	0.0237067	37%
China 250 km/hr, 400 Passbys	70	63.5	0.0632456	0.0299868	47%
China 300 km/hr, 250 Passbys	70	63.9	0.0632456	0.0314071	50%
China 300 km/hr, 400 Passbys	70	66.0	0.0632456	0.0397272	63%
China 350 km/hr, 250 Passbys	70	66.4	0.0632456	0.0418188	66%
China 350 km/hr, 400 Passbys	70	68.4	0.0632456	0.0528971	84%

Observations regarding the comparison of EU regulations to the China L_d noise regulations include:

- A train set that produces SPLs that correspond to the maximum allowed EU TSI limits would produce an A-weighted equivalent sound level, L_d, measured during the 16-hour day time period, that ranges from 12 percent of the China noise limit (train speed = 80 km/hr, number of passby events during the 16 hour time period = 250) to 84 percent of the China day time noise limit (train speed = 350 km/hr, 400 passby events during the 16 hour time period).
- The Chinese day time high speed train noise limits are relatively easy to achieve, even without the use of wayside sound mitigation installations, such as noise barriers. With the current maximum average number of daytime train passby events at seven, there is significant room for expansion of train frequency. Even at 25 trains per hour, at a speed of 350 km/hr (the upper part of the current China train speeds), the value for L_d is projected to be 16 percent lower (1.6 dB) than the 70 dB(A) limit.

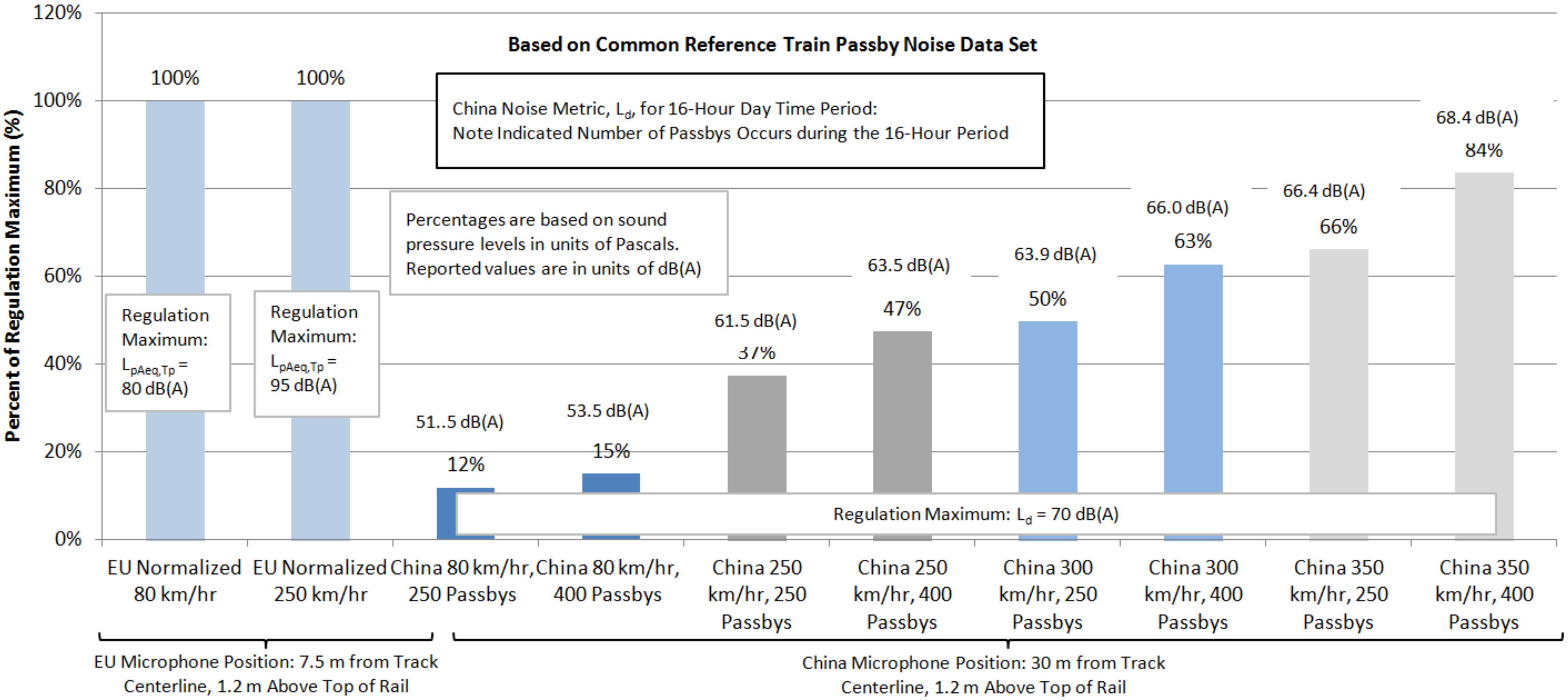


Figure 38: Comparison of EU and China Ld Passby Noise Regulations

2.13.3 Japan Regulations Comparisons

Three of Japan's immission noise regulation metrics were evaluated using the common reference train passby data set for microphone position 3 (25 m = 82.0 ft. from track centerline and 1.2 m = 3.94 ft. above top of rail). These include $L_{eq(hour)}$ for Zone I (residential), $L_{eq(hour)}$ for Zone II (commercial and industrial), and L_{Amax} for both Zones I and II.

L_{eq} for Zone I

The common parameters for the L_{eq} analysis are shown in Table 37.

Table 37: Common Parameters for Common Reference Japan L_{eq} Analysis

Common Parameters	Value	Units
Duration of Day Time Period	1	hour
	3,600	sec
Reference Train Length	200.19	m

As with the US and Chinese regulation comparisons, CONTRAST and the common reference data set were employed to determine the SPLs, $L_{eq(hour)}$, for train speeds ranging from 80 km/hr to 350 km/hr (49.71 to 217.48 mph) and for a range of passby events for Zone I, microphone position 3, and the 1 hour reference time period. Table 38 shows the results. Table 39 shows comparisons of these values to the EU and Japan L_{eq} noise regulations for Zone I (residential).

The EU and Japan $L_{eq(hour)}$ regulations for Zone 1 are plotted in Figure 39 for a range of train speeds and number of passby events.

Observations regarding the comparison of EU regulations to the Japan L_{eq} noise regulations relative to Zone 1 include:

- A train set that produces SPLs that correspond to the maximum allowed EU TSI limits would produce an A-weighted equivalent sound level over a reference 1-hour time period, $L_{eq\ (hour)}$, relative to Zone 1 (residential), that ranges from 21 percent of the Japan noise limit (train speed = 80 km/hr, number of passby events during the reference time period = 40) to 142 percent of the Japan $L_{eq\ (hour)}$ noise limit (train speed = 350 km/hr, 60 passby events during reference 1-hour time period).
- Since the current Shinkansen trains operate at maximum speeds of 320 km/hr (199 mph), and the maximum number of passby events per hour is 17 or less, it is expected the Zone 1 noise limits, based on L_{eq}, will not pose a challenge to Japan's high-speed train operations. At 350 km/hr and 40 passby events per hour, $L_{eq(hour)}$ is predicted to have a value of 71.3 dB(A) vs. the Zone I limit of 70 dB(A). Note that this is not the case for the L_{Amax} noise metric (based on 20 passby events) as described in Table 38 to Table 39.

Table 38: Calculated Values of L_{eq} Based on Common Reference Data Set

Calculation of Japanese L_{eq} based on Common Reference Train Data Set					
Time of Passby Event	sec	9.01	2.88	2.40	2.06
t(j): Ratio of Passby Time to 16-Hour Day		0.0025024	0.0008008	0.0006673	0.0005720
Train Speed	km/hr	80.00	250.00	300.00	350.00
	m/sec	22.22	69.44	83.33	97.22
$L_{pAEQ,passby}$ (microphone position 3)	dB(A)	66.34	81.30	84.53	87.69
Number of Trains during 1-Hour Time Period		L_{eq} (the A-weighted equivalent sound level measured during the 1-Hour time period), dB(A)			
8		49.36	59.36	61.80	64.29
16		52.37	62.37	64.81	67.30
24		54.13	64.13	66.58	69.06
32		55.38	65.38	67.83	70.31
40		56.35	66.35	68.79	71.28
48		57.14	67.14	69.59	72.07
56		57.81	67.81	70.26	72.74
60		58.11	68.11	70.56	73.04

Table 39: Comparison: EU and Japan L_{eq} Zone I Common Reference Data Set

Regulation	Maximum Value, dB(A)	Common Reference Value, dB(A)	Maximum Value, Pa	Common Reference Value, Pa	Percent of Maximum Allowed Value %
EU Normalized 80 km/hr	80	80.0	0.2000000	0.2000000	100%
EU Normalized 250 km/hr	95	95.0	1.1246827	1.1246827	100%
Japan 80 km/hr, 40 Passbys	70	56.3	0.0632456	0.0131339	21%
Japan 80 km/hr, 60 Passbys	70	58.1	0.0632456	0.0160856	25%
Japan 250 km/hr, 40 Passbys	70	66.4	0.0632456	0.0415510	66%
Japan 250 km/hr, 60 Passbys	70	68.1	0.0632456	0.0508893	80%
Japan 300 km/hr, 40 Passbys	70	68.8	0.0632456	0.0550476	87%
Japan 300 km/hr, 60 Passbys	70	70.6	0.0632456	0.0674193	107%
Japan 350 km/hr, 40 Passbys	70	71.3	0.0632456	0.0732964	116%
Japan 350 km/hr, 60 Passbys	70	73.0	0.0632456	0.0897693	142%

Like the China regulations analysis, Table 38 includes the impact of the number of passby events during the regulated time period on the L_{eq} (1 hour) noise metric.

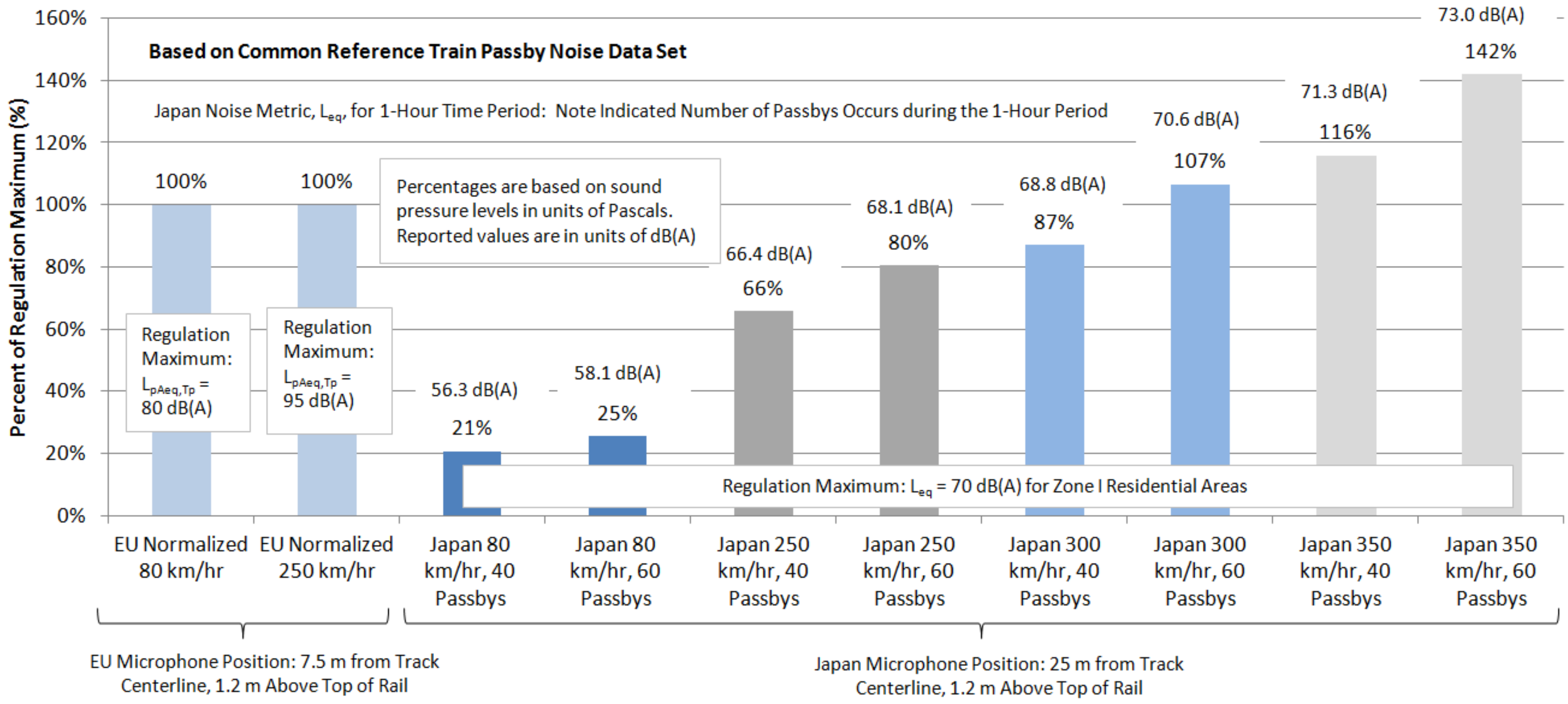


Figure 39: Comparison of EU and Japan Zone 1 L_{eq} Passby Noise Regulations

L_{eq} for Zone II

Similar to the Zone I $L_{eq(hour)}$ analysis, CONTRAST and the common reference data set were employed to determine the SPLs, $L_{eq(hour)}$, for train speeds ranging from 80 km/hr to 350 km/hr (217.48 mph) and for a range of passby events (number per hour) for Zone II, microphone position 3 (25 m (82.02 ft.) from track centerline and 1.2 m (3.94 ft.) above top of rail) and the 1 hour reference time period. Comparisons of these values to the EU and Japan $L_{eq(hour)}$ noise regulations for Zone II (i.e., commercial and industrial) are shown in Table 40.

Table 40: Comparison: EU and Japan L_{eq} Zone II Common Reference Data Set

Regulation	Maximum Value, dB(A)	Common Reference Value, dB(A)	Maximum Value, Pa	Common Reference Value, Pa	Percent of Maximum Allowed Value %
EU Normalized 80 km/hr	80	80.0	0.2000000	0.2000000	100%
EU Normalized 250 km/hr	95	95.0	1.1246827	1.1246827	100%
Japan 80 km/hr, 40 Passbys	75	56.3	0.1124683	0.0131339	12%
Japan 80 km/hr, 60 Passbys	75	58.1	0.1124683	0.0160856	14%
Japan 250 km/hr, 40 Passbys	75	66.4	0.1124683	0.0415510	37%
Japan 250 km/hr, 60 Passbys	75	68.1	0.1124683	0.0508893	45%
Japan 300 km/hr, 40 Passbys	75	68.8	0.1124683	0.0550476	49%
Japan 300 km/hr, 60 Passbys	75	70.6	0.1124683	0.0674193	60%
Japan 350 km/hr, 40 Passbys	75	71.3	0.1124683	0.0732964	65%
Japan 350 km/hr, 60 Passbys	75	73.0	0.1124683	0.0897693	80%

The EU and Japan $L_{eq(hour)}$ regulations for Zone II are plotted in Figure 40 for a range of train speeds and number of passby events.

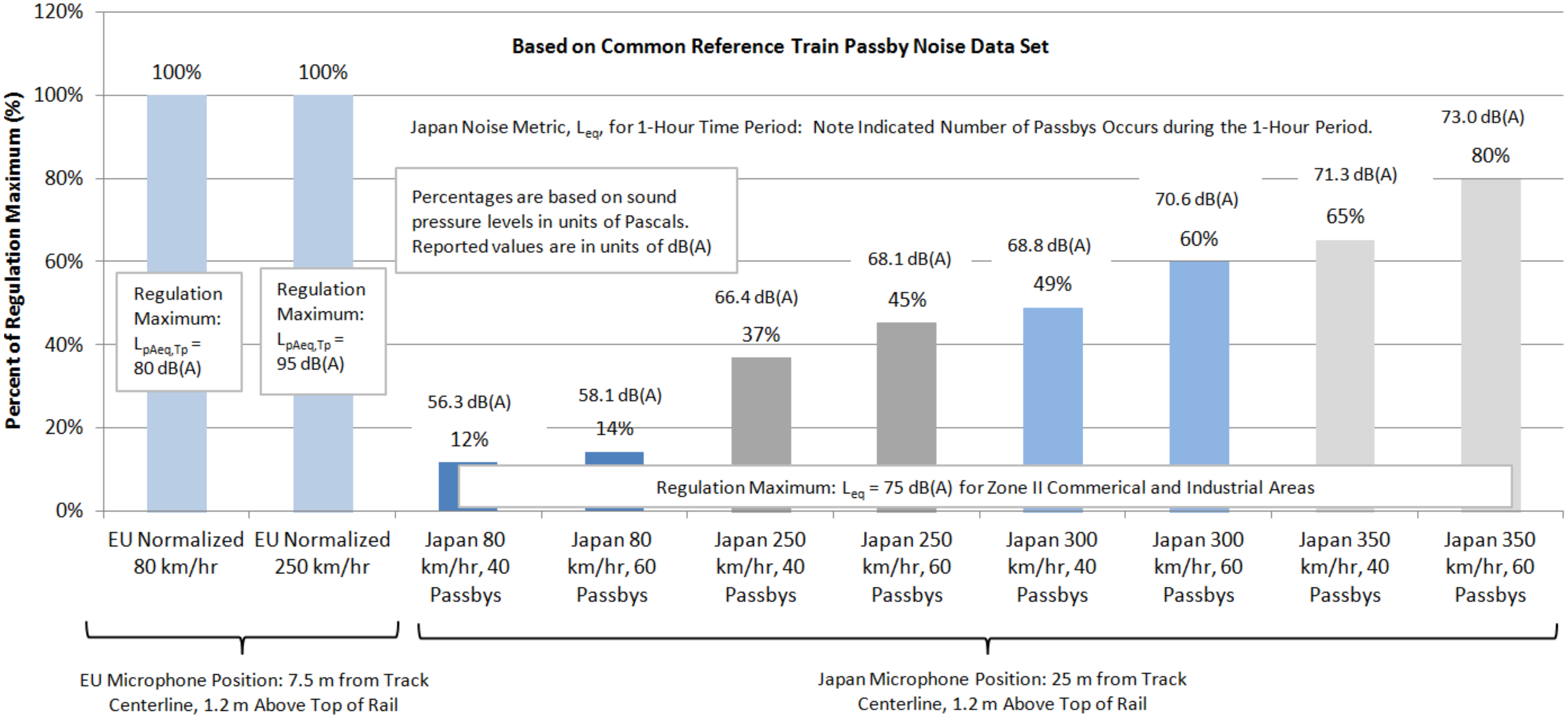


Figure 40: Comparison of EU and Japan Zone II L_{eq} Passby Noise Regulations

Observations regarding the comparison of EU regulations to the Japan L_{eq} noise regulations relative to Zone II include:

- A train set that produces SPLs that correspond to the maximum allowed EU TSI limits would produce an A-weighted equivalent sound level over a reference 1-hour time period, $L_{eq\ (hour)}$, relative to Zone II (i.e., commercial and industrial), that ranges from 12 percent of the Japan noise limit (train speed = 80 km/hr, number of passby events during the reference time period = 40) to 80 percent of the Japan $L_{eq\ (hour)}$ noise limit (train speed = 350 km/hr, 60 passby events during reference 1-hour time period). Note that SPL comparisons are based on $L_{eq(hour)}$ in units of Pascals.
- At train speeds of 350 km/hr, the value for $L_{eq(hour)}$ would be 71.3 dB(A) for 40 passby events. This can be compared to the regulation limit for Zone II of 75 dB(A).
- Due to the short time periods associated with the train passing, the equivalent SPL allows for a high number of passby events before the regulated exposure limit is reached. At current speeds (320 km/hr), the $L_{eq(hour)}$ metric would not be exceeded even if the number of passby events was three times greater than current maximums (17 per hour).

L_{Amax} for Zones I & II

As discussed in Section 2.10.6, Like the Zone I $L_{eq(hour)}$ analysis, another noise metric employed to evaluate noise emanating from Japanese high-speed trains is L_{Amax}. The regulation requires noise measurements to be made for 20 consecutive train passing events in each direction (Maeda, T., 1999). The analysis below indicates this regulation is much more stringent than the corresponding $L_{eq(hour)}$ metric.

CONTRAST and the common reference data set were employed to determine the values for L_{Amax} for train speeds ranging from 80 km/hr to 350 km/hour relative to Zones I (i.e., residential) and II (i.e., commercial and industrial) for microphone position 3 (25 m from track centerline and 1.2 m above top of rail) and 20 consecutive passby events. As noted in Section 2.10.6, the calculations are facilitated by the observation that $L_{Amax} = L_{pASmax}$ (when the 20 passby events are identical as is the case when using the common reference data set). Comparisons of these values to the EU and Japan L_{Amax} noise regulations for Zones I & II are shown in Table 41.

Observations regarding the comparison of EU regulations to the Japan L_{Amax} noise regulations relative to Zones I & II include:

- Because the Japan L_{Amax} regulation is based upon maximum SPLs measured during a series of passby events, it is more difficult to achieve than the other noise regulations evaluated during the current study and requires application of both onboard and wayside mitigation methods to meet noise regulations in both residential (Zone I) and commercial/industrial (Zone II) land use areas.
- For Zone I, the maximum allowed value of L_{Amax} is 70 dB(A). The common reference data set (based on scaled SPLs for a European train set) exhibits SPLs that vary from 69.8 dB(A) at 80 km/hr to 91.1 dB(A) at 350 km/hr for microphone position 3 (microphone 25 m from track centerline). The Shinkansen trains have undergone significant modifications to reduce onboard noise emissions and 3 m high straight and L-type wayside barriers have been installed to reduce noise levels to meet the L_{max} regulation (Maeda, T., 1999).

- For Zone II, the maximum allowed value of L_{Amax} is 75 dB(A). The L_{Amax} Zone II maximum noise pressure level is exceeded at speeds above 80 km/hr for the common reference data set. Thus, the train associated with the common reference data set would require significant application of mitigation methods, both onboard and wayside, to meet the L_{Amax} 20-passby event noise regulation in Japan. At the current Japan train speeds of 270 to 320 km/hr on the main lines and 130 km/hr to 160 km/hr on local lines, the L_{Amax} noise limit would be exceeded by all train types included in the CONTRAST library if no wayside barriers were installed.

Table 41: Comparison: EU and Japan L_{Amax} Passby Noise Regulations

Regulation	Maximum Value, dB(A)	Common Reference Value, dB(A)	Maximum Value, Pa	Common Reference Value, Pa	Percent of Maximum Allowed Value %
EU Normalized 80 km/hr	80	80.0	0.2000000	0.2000000	100%
EU Normalized 250 km/hr	95	95.0	1.1246827	1.1246827	100%
Japan Zone I, 80 km/hr	70	69.8	0.0632456	0.0614819	97%
Japan Zone I, 250 km/hr	70	84.7	0.0632456	0.3438436	544%
Japan Zone I, 300 km/hr	70	87.9	0.0632456	0.4990093	789%
Japan Zone I, 350 km/hr	70	91.1	0.0632456	0.7176721	1135%
Japan Zone II, 80 km/hr	75	69.8	0.1124683	0.0614819	55%
Japan Zone II, 250 km/hr	75	84.7	0.1124683	0.3438436	306%
Japan Zone II, 300 km/hr	75	87.9	0.1124683	0.4990093	444%
Japan Zone II, 350 km/hr	75	91.1	0.1124683	0.7176721	638%

The EU and Japan L_{Amax} regulations for Zones I & II are plotted in Figure 41 for the 20 consecutive passby events and a range of train speeds.

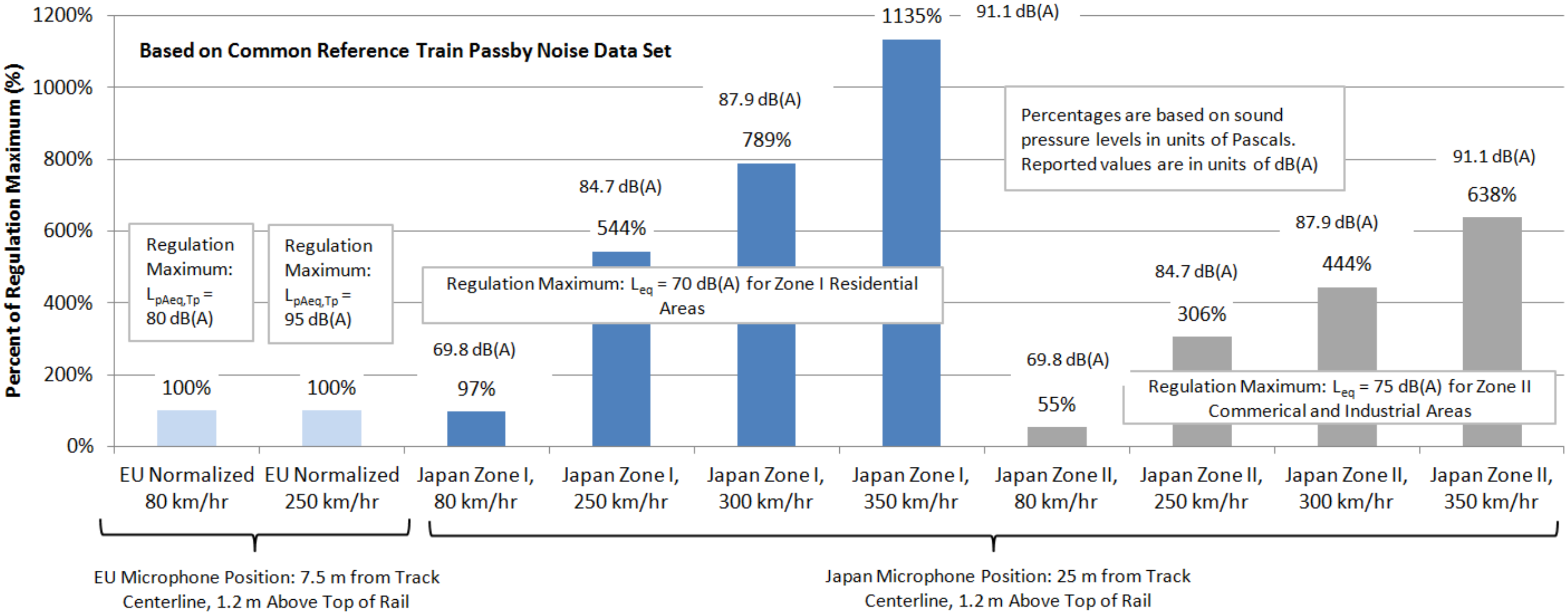


Figure 41: Comparison of EU and Japan L_{Amax} Passby Noise Regulations

2.14 Common Reference: Summary of Results

This section of the report contains a summary of the outcomes and conclusions for the noise regulations comparison to a common reference tasks. CONTRAST, can be used to 1) determine whether a train set is in compliance with noise regulations, and 2) using a common reference passby noise data set, to compare the various regulations relative to train speed and, in the case of receiver (immission) regulations, determine the number of passby events allowed during the time periods defined in the regulations. The common reference approach is required because current regulations vary in the metrics, measurement locations, train operating conditions (e.g., speed) and measurement procedures, thus making direct comparisons difficult.

Six data sets are currently included in the CONTRAST library: Korean HEMU-430X, Thalys PBKA, China CRH3 series at three microphone locations, and the common reference data set. Requirements for obtaining the passby data measurements were defined to ensure validity of the calculation procedures. A representative passby noise data set was scaled so the equivalent SPL ($L_{pAeq,Tp}$) for the passby period was equal to the normalized TSI Noise (2014) regulations: $L_{pAeq,Tp}$ for 80 km/hr, which is 80 dB(A), and $L_{pAeq,Tp}$ for 250 km/hr, which is 95 dB(A). This "Common Reference" data set was then employed to determine the noise metrics corresponding to those of the other countries. The passby data sets were digitized to allow a Reimann sum approach to be employed for calculating the equivalent passby SPL integrals associated with the various noise metrics.

Validation of the passby data sets and calculation procedures was conducted by comparing the CONTRAST program results to published data. Studies were conducted to determine the impact of microphone position and train speed on SPLs. These were verified based on results reported in the literature.

Based on several journal articles identified during the study, the level of uncertainty related to measurements of train passby noise pressure levels was determined. There is a 95 percent confidence that the calculated noise levels are within ±3 dB of the true $L_{Aeq(period)}$ noise levels when at least 20 train passbys of each type under the same operating conditions are measured. For the L_{Amax} assessment parameter, the uncertainty increases to approximately ±5 dB for the same number of train passbys.

For each passby data set, 11 noise metrics are calculated: $L_{pAea,Tp}$ (including normalized values to speeds of 80 km/hr and 250 km/hr), $L_{pAeq,Tp}$, $L_{p(maximum)}$, L_{pASmax}, L_{pAFmax}, $L_{pAeq,passby}$, TEL, SEL, L_{10}, L_{50}, and L_{90}. In addition, for the China and Japan regulations, equivalent, A-weighted noise metrics (i.e., exposure over defined time periods) at the railroad property boundaries are calculated, including L_d, L_n, $L_{eq(hour)}$, and L_{Amax}).

For the three train types included in the CONTRAST library, the Chinese CRH3 series train set is predicted to have passby SPLs that would exceed US noise limits at speed above 350 km/hr (217.5 mph). The Thalys PBKA train set is predicted to exceed the US noise limits at speeds above 300 km/hr (185.4 mph) and the Korean HEMU-430X train set is expected to exceed the limit at speeds above 200 km/hr (124.3 mph).

Based on non-operation during the time period 9:00pm to 6:30am and the number of trains in operation, it is unlikely the Chinese night time noise limit, $L_n = 60$ dB(A), will be exceeded. Also, since the highest average number of trains passing per hour is seven for the Chinese high-speed rail network, it appears noise at the railroad property boundaries (microphone position 30 m from track centerline and 1.2 m above the top of rail) will not exceed the day time maximum, L_d = 70 dB(A), for any of the train sets evaluated.

The Japan noise regulations include two noise metrics and two land use zones. The noise metrics are both equivalent sound pressures integrated over a reference 1-hour time increment (L_{eq}) or the logarithmic average maximum SPL measured during 20 consecutive passby events using the slow setting on the sound meter (L_{Amax}). The limits for these two metrics are 70 dB(A) for Zone 1 (residential) and 75 dB(A) for commercial/industrial. The highest frequency Japan high speed train lines have up to 17 trains per hour. These trains operate at maximum speeds of 320 km/hr (199 mph). The train sets in the CONTRAST library meet the Zone II noise limit for L_{eq}, and all but one (the Korean HEMU) meets the L_{eq} limit for Zone I (residential) for microphone position 3 (25 m from track centerline and 1.2 m above top of rail) for current operating speeds.

However, because the L_{Amax} regulation is based on peak noise levels during the 20-consecutive passby events, rather than the equivalent SPL, the maximum allowed value of L_{Amax} is exceeded at all train speeds above 80 km/hr, necessitating the installation of mitigation methods, such as wayside barriers and onboard modifications, for example pantograph shields. These results are consistent with reported levels of Japanese train SPLs corresponding to variations in train speeds and installations of noise reduction systems

Since CONTRAST calculates the SPL metrics for the US, EU, China, and Japan noise regulations as a function of train speed, microphone position, and number of passby events, the results for the common reference data set can be used to compare the regulations and answer questions such as “if a train set is compliant with the TSI regulation, how is it expected to perform relative to US, China, and Japan regulations?”

The following observations were made regarding the US, EU, China, and Japan noise regulations.

US: A train set that exhibits SPLs that correspond to the maximum allowed EU TSI levels, would produce an SPL that is 4.8 dB lower than the US maximum for locomotive classification trains operating at 250 km/hr. Similarly, the same train set operating at 350 km/hr and classified in the locomotive category would exceed the US noise limit by 1.6 dB. Because of the logarithmic relationship for dB units, this is 120 percent of the maximum US noise limit based on SPL in units of Pa. If the common reference train set is classified as a rail car under US regulations, it would meet the maximum allowed SPL specified by those regulations for all speeds up to 350 km/hr (218 mph). Not all train sets in the CONTRAST library are capable of meeting US regulations at speeds above 300 km/hr (185 mph).

EU: Since the common reference data set was scaled so that the passby SPLs at train speeds of 80 km/hr and 250 km/hr are such that the $L_{pAeq,Tp}$ metric is exactly equal to the European TSI limit, if the common reference data set is then used to calculate the U.S. noise metric $L_{max(fast)}$, the results can be directly compared to the EU result. Thus, it can be stated that a train set that exhibits passby noise characteristics that are equal to the maximum allowed values under the EU TSI would produce passby SPLs that range from 41 to 120 percent of the maximum levels allowed by US railroad noise regulations, depending upon train classification, microphone position, and train speed. Similarly, a train set that produces SPLs that correspond to the maximum allowed EU TSI limits would produce an A-weighted equivalent sound level, L_n, measured during the night time, that ranges from 21 percent of the China noise limit (train speed

= 80 km/hr, number of passby events during 8 hour time period = 40) to 145 percent of the China noise limit (train speed = 350 km/hr, 60 passby events during 8 hour time period). The same train set would produce an A-weighted equivalent sound level, L_d, measured during the 16-hour day time period, that ranges from 12 percent of the China noise limit (train speed = 80 km/hr, number of passby events during 16-hour time period = 250) to 84 percent of the China day time noise limit (train speed = 350 km/hr, 400 passby events during 16-hour time period). In Japan, for Zone I (residential) land use, the maximum value of L_{Amax} is 70 dB(A) and the Zone II (commercial/industrial) maximum L_{Amax} value is 75 dB(A). The common reference data set (based on scaled SPLs for a European train set) exhibits SPLs that vary from 69.8 dB(A) at 80 km/hr to 91.1 dB(A) at 350 km/hr for microphone position 3 (microphone 25 m from track centerline) and thus exceed the limit at higher speeds, requiring the application of noise mitigation methods.

China: It is unlikely that the Chinese noise limits would be exceeded due to the limited night time train activity and the limited number of passby events. In addition, the SPLs based on the common reference data set ranged from 13.5 dB lower than the 60 dB(A) L_n limit to 3.2 dB(A) greater than the 60 dB(A) limit. With the measurement uncertainty of ±3 dB(A), it appears the L_n limit does not pose a serious threat to current and future night time operations of the Chinese high-speed rail system. The Chinese day time high speed train noise limits are relatively easy to achieve, even without the use of wayside sound mitigation installations, such as noise barriers. With the current maximum average number of day time train passby events at seven, there is significant room for expansion of train frequency. Even at 25 trains per hour, at a speed of 350 km/hr (the upper part of the current China train speeds), the value for L_d is projected to be 16 percent lower (1.6 dB) than the 70 dB(A) limit.

Japan: Two noise metrics are associated with Japan rail noise regulations, $L_{eq(hour)}$ and L_{Amax}. The $L_{eq(hour)}$ regulation is readily met with existing train set designs and no wayside mitigation methods. Because the L_{Amax} measurements are based on the maximum SPLs obtained for 20 consecutive passby events, they are much more stringent. For the Zone I land use designation, the maximum allowed value of L_{Amax} is 70 dB(A). The common reference data set train set exhibits SPLs that vary from 69.8 dB(A) at 80 km/hr to 91.1 dB(A) at 350 km/hr and thus exceed the limit. For Zone II, the maximum value of L_{Amax} is 75 dB(A) and is exceeded at speeds above 80 km/hr for the common reference data set. Thus, the train associated with the common reference data set would require significant application of mitigation methods, both onboard and wayside, to meet the L_{Amax} 20-passby event noise regulation in Japan. At the current Japan train speeds of 270 to 320 km/hr on the main lines and 130 km/hr to 160 km/hr on local lines, the L_{Amax} noise limit would be exceeded by all the train types included in the CONTRAST library if no wayside barriers were installed. The Shinkansen trains have undergone significant modifications to reduce onboard noise emissions and 3 m high straight and L-type wayside barriers have been installed to reduce noise levels to meet the L_{max} regulation.

3. Part 2: Cost of Compliance for Noise Procedures

The main focus of the cost study was the rating and ranking of identified noise mitigation methods to select the top 30 most effective procedures for further analysis, including the definition of costs.

3.1 Objectives

The cost study included a review of high-speed rail noise mitigation procedures. These were ranked in order of noise reduction levels based on reported test results, typically in units of dB(A). Up to 30 of the most impactful approaches were then studied in more detail to determine the cost effectiveness when applied within the US market. The selected procedures were representative of all three noise mitigation categories—at source, along the path and at receiver. The potential noise emission reduction and the cost of implementation were reported in terms of:

1. Lifecycle costs, $ per dB(A) at the receiver, and
2. Cost per impacted resident, $ per dB(A) per resident

This cost analysis was completed for two representative high speed US rail lines. These simplified lines mimic, on a macro level, the NEC and the CHSRail system. The macro level approach allows ready comparisons of mitigation methods for those lines. A discussion of the methodology employed in selecting and applying noise mitigation methods on rail lines follows.

Note: *The analysis does NOT attempt to estimate or define the true cost of applying noise mitigation methods onto existing or planned actual high-speed rail lines, as that will require a much deeper analysis of the full length of the track including specific topographical and other external factors that are outside the scope of this study*.

3.2 Approach

Defining the cost of noise regulation compliance included identification of top noise mitigation methods, estimation of lifecycle costs for the top 30 methods, and application of the selected methods to two representative rail lines. These are summarized below:

1. *Identification and selection of the 30 top noise mitigation procedures to be studied in more detail for lifecycle cost and $ per dB(A)* – Beginning with the over 70 methods that were highlighted in the FRA study "High Speed Rail Noise Standard and Regulations" (Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S., 2021), key parameters were defined to assess the effectiveness of each method. These parameters were noise reduction potential (in dB[A]), technology readiness level, practicality to implement, industry acceptance, and level of cost or investment. Each method was assessed based on these parameters and calculating the weighted score to enable ranking them in order of effectiveness. Section 1.4.2 describes the division of methods into three categories to facilitate comparisons. For each category, the methods were ranked in order of effectiveness and the top 30 methods were selected for further cost analysis.
2. *Estimation of lifecycle costs and $ per dB(A) for top 30 methods* – For each of the top 30 methods, the lifecycle costs of implementation were estimated. This consists of all estimated costs for noise mitigation methods that are expected to be incurred through the life of the railway line. The cost categories reviewed for lifecycle cost were—research

and development/initial investment, capital and construction, labor and materials, permits and operating expenses, and other maintenance costs. The earlier literature review was expanded, to include references on each topic. In some instances, assumptions were made using representative data to provide a bottom-up cost estimation where information and data were not directly available, e.g., in the case of acoustical gap sealing. In such cases, there was typically a good source of representative public information available from adjoining industries such as construction, in terms of both labor and materials, for given activities such as window fitting and isolation matting installation. This allowed for a good approximation of cost for several noise mitigation methods. These assumptions were also discussed and reviewed with various industry stakeholders to confirm the validity of this representative data set from adjoining industries. The final objective was to sum up the cost categories and estimate the total lifecycle cost as a unit cost that can be scaled based on track features like track length, number of tunnels, etc., to be used for the next step.

3. *Application of noise mitigation methods on two-representative simplified high-speed rail tracks* – The objective of this portion of the study was to estimate the cost of compliance for applying the top 30 noise mitigation methods to two-representative simplified high-speed rail tracks. These tracks were based on macro level data from the CAHSR track from San Jose to Burbank; and the Northeast Corridor High Speed Rail (NEC HSR) track connecting Boston, MA, to Washington, DC. The analysis was used to introduce the methodology for selecting and applying noise mitigation methods on high speed rail tracks, but not to attempt to calculate the true cost of applying these methods to actual rail operations, which could be vastly different based on specific topographical and engineering factors. The cost of compliance for these representative simplified tracks was estimated as a total cost across the track (in US dollars), $ per dB(A) (for the average noise reduction expected across the track) and $ per dB(A) per residents impacted (based on estimated population density data). To apply the reduction method lifecycle costs to these representative tracks, track feature assumptions were made so that unit costs could be scaled appropriately. Key track features included track route, track length, number and length of tunnels, number and length of bridges, population density and residents impacted around the track. Effective combinations of methods were selected to minimize noise and cost.

3.3 Discussions with Industry Stakeholders

Although there has been strong growth for high speed rail operations around the world, application in the US remains limited. Most of the research associated with estimating costs of compliance and noise reduction potential of various methods relates to high speed rail systems in Europe and Asia. To ensure that all factors affecting the implementation of these methods in the US market have been addressed, Ricardo arranged periodic reviews and discussions with various industry stakeholders, including representatives of project partners Amtrak and the California High Speed Rail Authority (CaHSRA) (and CaHSRA contractor WSP USA). Frequent reviews of project assumptions and intermediate research results with key industry stakeholders and project partners were conducted to ensure that this project remained relevant to the US market. Researchers prepared summary reports and discussion documents prior to these meetings and included the project background, understanding of industry requirements, research progress, and interim study results. Study direction, content and analysis was then re-aligned based on feedback from the project partners and industry stakeholders.

To ensure that input was received from a representative cross section the industry, discussions and reviews were arranged with representatives of four key stakeholder categories:

1. Rail operators
2. Technical service providers
3. Vehicle manufacturers

Table 42 highlights the stakeholders that were available to meet and review project results. Insights from these discussions have been included throughout this report, including review and validation of methodology, analysis, and results.

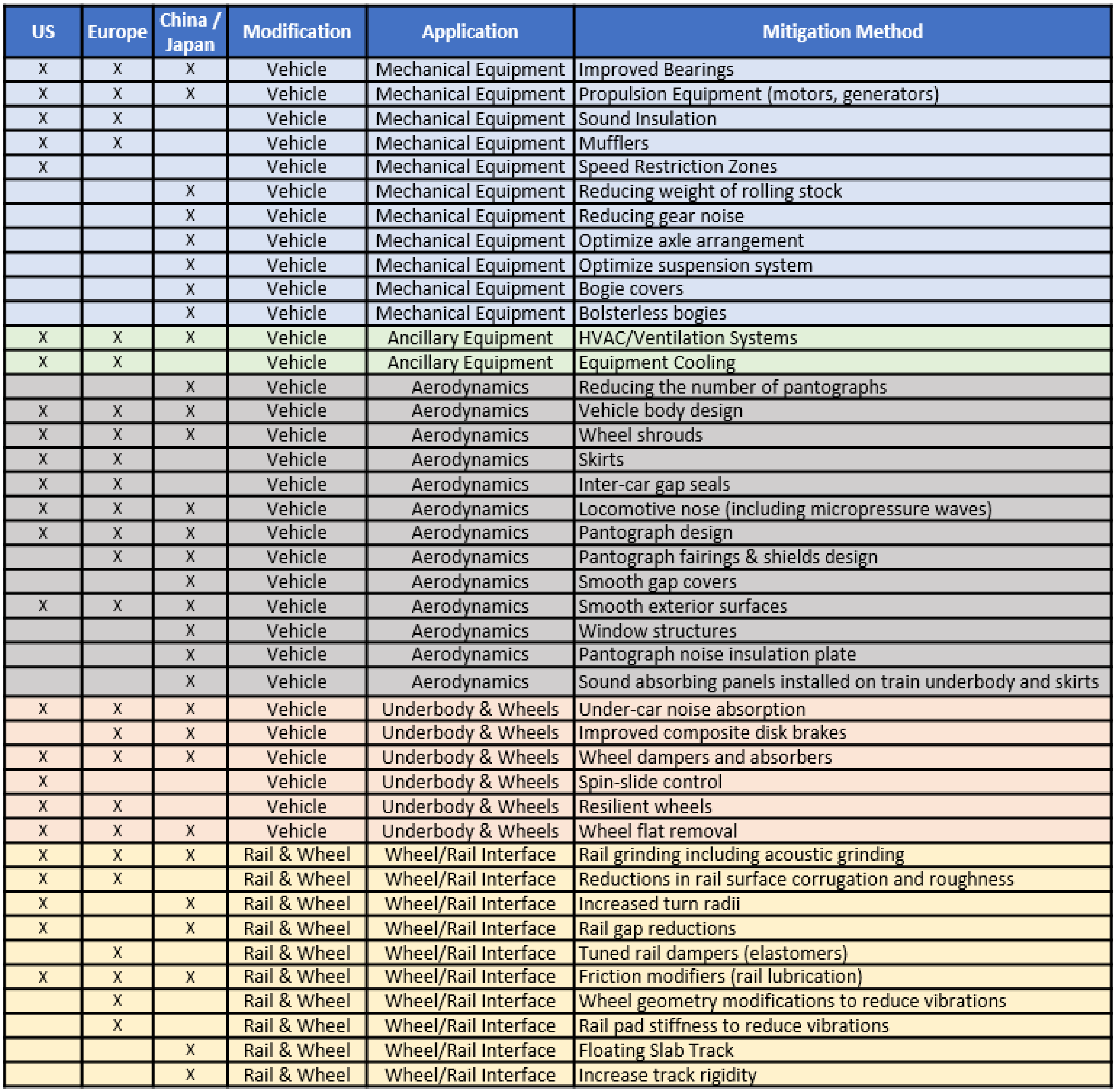
Table 42: List of Stakeholders for Discussions and Reviews

Stakeholder Number	Location and Category	Organization & Discussion Date	Team Association with High Speed Rail Noise
1	US Passenger Rail Operator	Amtrak In-person – Jan-2019	Multiple discussions with engineering teams for train sets and tracks
2	US Passenger Rail Operator	California High Speed Rail Authority, Phone – Jan-2019	Operations and Maintenance team
3	Technical Service Provider	WSP In-person – Jan-2019	Various discussions with fleet and facilities team, rail vehicle engineering teams
4	Technical Service Provider	Ricardo Rail Phone – Dec-2018	Multiple discussions with consultant and mangers leading global high-speed rail related strategy / technical consulting and engineering projects
5	Vehicle manufacturers	Progress Rail Phone – Jan-2019	Engine and locomotive development teams
6	Vehicle manufacturers	Alstom Phone – Jan-2019	Marketing and strategy teams

4. Noise Mitigation Techniques Deployed Across the World

During the earlier FRA-funded high-speed rail noise regulations and compliance study (Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S., 2021), over 70 noise mitigation methods were identified. Table 43 through Table 45 summarizes the strategies and techniques identified for achieving noise compliance for the US, EU, China, and Japan.

Table 43: Noise Mitigation Approaches at the Source
(Kaloop, M. R., Hu, M. R., & Elbeitagl, E., 2016)

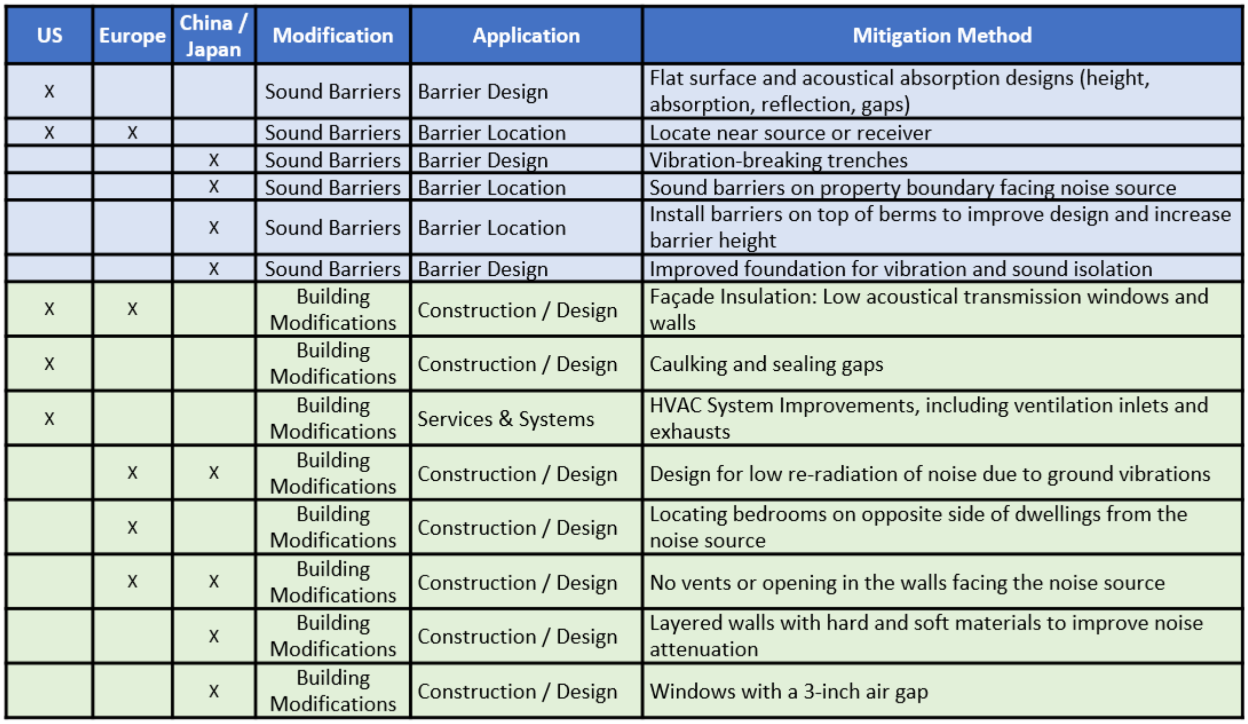


US	Europe	China / Japan	Modification	Application	Mitigation Method
X	X	X	Vehicle	Mechanical Equipment	Improved Bearings
X	X	X	Vehicle	Mechanical Equipment	Propulsion Equipment (motors, generators)
X	X		Vehicle	Mechanical Equipment	Sound Insulation
X	X		Vehicle	Mechanical Equipment	Mufflers
X			Vehicle	Mechanical Equipment	Speed Restriction Zones
		X	Vehicle	Mechanical Equipment	Reducing weight of rolling stock
		X	Vehicle	Mechanical Equipment	Reducing gear noise
		X	Vehicle	Mechanical Equipment	Optimize axle arrangement
		X	Vehicle	Mechanical Equipment	Optimize suspension system
		X	Vehicle	Mechanical Equipment	Bogie covers
		X	Vehicle	Mechanical Equipment	Bolsterless bogies
X	X	X	Vehicle	Ancillary Equipment	HVAC/Ventilation Systems
X	X		Vehicle	Ancillary Equipment	Equipment Cooling
		X	Vehicle	Aerodynamics	Reducing the number of pantographs
X	X	X	Vehicle	Aerodynamics	Vehicle body design
X	X	X	Vehicle	Aerodynamics	Wheel shrouds
X	X		Vehicle	Aerodynamics	Skirts
X	X		Vehicle	Aerodynamics	Inter-car gap seals
X	X	X	Vehicle	Aerodynamics	Locomotive nose (including micropressure waves)
X	X	X	Vehicle	Aerodynamics	Pantograph design
	X	X	Vehicle	Aerodynamics	Pantograph fairings & shields design
		X	Vehicle	Aerodynamics	Smooth gap covers
X	X	X	Vehicle	Aerodynamics	Smooth exterior surfaces
		X	Vehicle	Aerodynamics	Window structures
		X	Vehicle	Aerodynamics	Pantograph noise insulation plate
		X	Vehicle	Aerodynamics	Sound absorbing panels installed on train underbody and skirts
X	X	X	Vehicle	Underbody & Wheels	Under-car noise absorption
	X	X	Vehicle	Underbody & Wheels	Improved composite disk brakes
X	X	X	Vehicle	Underbody & Wheels	Wheel dampers and absorbers
X			Vehicle	Underbody & Wheels	Spin-slide control
X	X		Vehicle	Underbody & Wheels	Resilient wheels
X	X	X	Vehicle	Underbody & Wheels	Wheel flat removal
X	X	X	Rail & Wheel	Wheel/Rail Interface	Rail grinding including acoustic grinding
X	X		Rail & Wheel	Wheel/Rail Interface	Reductions in rail surface corrugation and roughness
X		X	Rail & Wheel	Wheel/Rail Interface	Increased turn radii
X		X	Rail & Wheel	Wheel/Rail Interface	Rail gap reductions
	X		Rail & Wheel	Wheel/Rail Interface	Tuned rail dampers (elastomers)
X	X	X	Rail & Wheel	Wheel/Rail Interface	Friction modifiers (rail lubrication)
	X		Rail & Wheel	Wheel/Rail Interface	Wheel geometry modifications to reduce vibrations
	X		Rail & Wheel	Wheel/Rail Interface	Rail pad stiffness to reduce vibrations
		X	Rail & Wheel	Wheel/Rail Interface	Floating Slab Track
		X	Rail & Wheel	Wheel/Rail Interface	Increase track rigidity

Table 44: Noise Mitigation Approaches Along the Path of Propagation (Kaloop, M. R., Hu, M. R., & Elbeitagl, E., 2016)

US	Europe	China / Japan	Modification	Application	Mitigation Method
X		X	Sound Barriers	Barrier Location & Design	Near Passing Vehicles (height, absorption, reflection, gaps)
X			Sound Barriers	Barrier Location & Design	Barriers at the Edge of the Right-of-Way
	X		Sound Barriers	Barrier Location & Design	Barriers Placed within the Shadow Zone
	X		Sound Barriers	Barrier Location & Design	Sound Absorption Material on the Barrier, Facing the Noise Source
	X		Sound Barriers	Barrier Location & Design	Barriers angled to reflect sound skyward
		X	Sound Barriers	Barrier Location & Design	Tunnel Hoods
		X	Sound Barriers	Barrier Location & Design	Sound absorbing pads below the rails
		X	Sound Barriers	Barrier Location & Design	Bridge beam supports to reduce structure-induced noise
X			Sound Barriers	Sound Path	Alternation of horizontal and vertical alignments - trenches
X			Sound Barriers	Sound Path	Creation / acquisition of Buffer Zones between source & receiver
	X		Sound Barriers	Sound Path	Lower elevation of the tracks into trenches
	X		Sound Barriers	Sound Path	Increasing distance from source to receiver
X	X		Reflective Surfaces	Ballast & Track Support	At-grade ballast
X			Reflective Surfaces	Ballast & Track Support	Elevated track ballast, increase absorption
X	X		Reflective Surfaces	Ballast & Track Support	Resilient track supports and baseplates that absorbs noise and vibrations
	X		Reflective Surfaces	Ballast & Track Support	Resilient padding for slab track
	X		Reflective Surfaces	Ballast & Track Support	Damping materials distributed between ballast-less tracks
		X	Reflective Surfaces	Ballast & Track Support	Placing spacers and grooved mats below slab tracks
		X	Reflective Surfaces	Ballast & Track Support	Damping materials at the upper surface of the slab tracks
		X	Reflective Surfaces	Ballast & Track Support	Using track pads with a lower elastic coefficient

Table 45: Noise Mitigation Approaches at the Receiver[2]



US	Europe	China / Japan	Modification	Application	Mitigation Method
X			Sound Barriers	Barrier Design	Flat surface and acoustical absorption designs (height, absorption, reflection, gaps)
X	X		Sound Barriers	Barrier Location	Locate near source or receiver
		X	Sound Barriers	Barrier Design	Vibration-breaking trenches
		X	Sound Barriers	Barrier Location	Sound barriers on property boundary facing noise source
		X	Sound Barriers	Barrier Location	Install barriers on top of berms to improve design and increase barrier height
		X	Sound Barriers	Barrier Design	Improved foundation for vibration and sound isolation
X	X		Building Modifications	Construction / Design	Façade Insulation: Low acoustical transmission windows and walls
X			Building Modifications	Construction / Design	Caulking and sealing gaps
X			Building Modifications	Services & Systems	HVAC System Improvements, including ventilation inlets and exhausts
	X	X	Building Modifications	Construction / Design	Design for low re-radiation of noise due to ground vibrations
	X		Building Modifications	Construction / Design	Locating bedrooms on opposite side of dwellings from the noise source
	X	X	Building Modifications	Construction / Design	No vents or opening in the walls facing the noise source
		X	Building Modifications	Construction / Design	Layered walls with hard and soft materials to improve noise attenuation
		X	Building Modifications	Construction / Design	Windows with a 3-inch air gap

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[2] Table 45 References: (Hanson, C. E., Ross, J. C., & Towers, D. A., 2012) (Boeker, E. R., Fleming, G., Rapoza, A. S., & Barberio, G., 2009)(Wolf, S., 2010)(Clausen, U., Doll, C., Franklin, F., Franklin, G., Heinrichmeyer, H., Kochsiek, J., Rothengatter, W., & Sieber, N., 2012)(de Vos, P., 2016)(European Commission, 2015)(Oertli, J., & Hubner, P., 2008)(Schulte-Werning, B., Beier, M., Grutz, H. P., Jager, K., Kock, G., Onnich, J., & Strube, R., 2001)(Delow, P., 2011)(Maeda, T., 1999)(Nishiyama, T., 2011)(Zhang, Y., Xhang, J., Li, T., Zhang, L., & Zhang, W.)(Lu, L., Hu, X., Zhang, Y., & Zhou, X., 2014)(Federal Highway Administration, 2016)(Federal Highway Administration, 2016)

5. Methodology to Select Mitigation Procedures for Cost Analysis

To enable a comparison and ranking of the various noise mitigation methods, a set of assessment parameters was defined. The selection of these parameters incorporated relevant aspects of each mitigation method and enabled a comparative rating for applicability in the US region. The parameters were normalized and quantified to allow consistent comparison for the various mitigation methods.

5.1 Parameters to Rate Each Noise Mitigation Technique

The following defines the parameters:

1. *Noise Reduction Potential*: For each method, an average expected noise reduction potential for high-speed rail application was determined. This was based on a review of available literature describing methods that were either deployed in a specific high-speed rail application, or in some cases, were based on theoretical models predicting the mitigation potential of design concepts. In other cases, the noise reduction potential was assessed based upon stakeholder interviews conducted during earlier studies (Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S., 2021).

   It is noted that the measured level of noise reduction for the mitigation methods can vary significantly based on several factors, including distance of the microphone from the train, methodology of measurement, instrumentation, regulation requirements, as well as type and condition of the rail. Thus, to make valid comparisons of the various methods, the level of noise reduction that can be achieved must be normalized. For the current study, the identified noise reduction methods were divided ("banded") into three effectiveness levels: high, medium, and low. A score was assigned to each level to provide a quantitative factor that can be later used to compare and rank the noise reduction potential for the identified methods.

   The banding methodology was as follows: methods with an average expected noise mitigation potential of more than 10 dB(A) were considered at "High" level and were assigned a score of 3 points. Methods having an expected noise mitigation potential between 5 dB(A) and 10 dB(A) were considered at "Medium" level and were assigned a score of 2 points. Finally, methods with average expected noise mitigation potential of less than 5 dB(A) were considered at "Low" level and were assigned a score of 1 point.

2. *Technology Readiness Level*: The Department of Defense (DOD) has defined standardized Technology Readiness Levels (TRLs) to estimate the maturity of Critical Technology Elements (CTE) for a program (U.S. Department of Defense, 2010). These levels are used extensively during a Technology Readiness Assessment (TRA) to examine program concepts, technology requirements, and demonstrated capabilities. TRLs are based on a scale from 1 to 9 with 9 being the most mature. The use of TRLs enables consistent, uniform, and comparisons of technical maturity. Decision makers extensively review recommended TRLs when assessing any program risk.

   As was done for noise reduction effectiveness, the methodology for TRL normalization included banding the various DOD standardized categories into three levels: high, medium, and low. A "Low" level of maturity (and associated score of 1 point) was assigned to those technologies that are still in a "Concept" phase and are based on theoretical or experimental models. Prototypes are typically laboratory scale and their effectiveness has not yet been proven in various real-world conditions. These technologies generally require further research to advance to the next level. The level of confidence for noise mitigation and cost are quite low for these technologies. Based on the DOD scale, these "low level of maturity" technologies include TRL levels between 1 and 5.

Technologies that are more mature and are in the prototype stage of testing and validation, were designated as "Medium" and given a score of 2 points. For this category, theory and experimental analysis has been completed and prototype parts are being deployed to validate assumptions. Prototype testing is typically performed under real-world conditions. In terms of a standardized DOD TRL, these technologies would typically be categorized as level 6 or 7. Due to the presence of more real-world data, the level of confidence for noise mitigation and cost effectiveness is higher for these technologies.

The third group includes successfully "Commercialized" technologies and are being used in various regions of the world for rail and high-speed applications. Such technologies have been marked as "High" and have been given a score of 3 points. These technologies are typically commercially available. Their effectiveness and level of noise mitigation has been proved under real-world conditions and there is a high level of confidence in the reported effectiveness. From the standardized DOD TRL scale, these technologies would typically be categorized as level 8 or 9.

3. *Practicality to Implement*: Another important factor to consider when comparing noise mitigation methods is their ease of implementation within the US rail system. Many of the methods employed in other countries may not be practical for US deployment due to variations in geography (e.g., short track distances vs. long distances), level of urbanization (e.g., dense cities vs. suburbs), political (i.e., based on political support, incentives, etc.), legislative (e.g., existing noise regulations), etc.

   To maintain consistency with other rating parameters, a 3-point scale was selected to assess practicality for implementation within the US. Methods marked as "High" offered fewer obstacles to adoption and were typically related to onboard, noise source modifications that remain effective through all aspects of train operation. These methods were given a score of 3 points.

   Methods that require more effort to implement, due to low maturity of the technology or limited scalability (e.g., to require deployment along the entire length of track) were rated as "Medium" and were given a score of 2 points. This assessment was based on review of experiences faced by stakeholders when deploying them on other high-speed rail projects, either in commercial, or in prototype stage.

   Lastly, methods that are expected to face considerable resistance from stakeholders during deployment have been rated as "Low" and have been given a score of 1 point. Some of these "Low" ranked methods would need support from external stakeholders like city planning groups, builder groups, etc. and may require extensive effort to implement due to poor scalability based on the length of rail.

4. *Industry Acceptance*: The level of acceptance by the U.S. rail industry for the identified noise mitigation methods was included in the ranking process. To capture the "voice of the industry" for this parameter, all ratings were assigned, either through discussions with industry experts (see Section 3.3), or through deployment experiences reported in the literature. Ratings were based on an assessment of acceptance specific to US applications.

   Using the same 3-point scale as defined for other parameters and to keep the comparison consistent, a rating of "high" was assigned to those methods that were expected to face the least resistance to implement, and where industry stakeholders are anticipated to support their deployment. Such methods were given a score of 3 points. The methods expected to face low resistance are those that advance the current state of rail technologies and have minimal change or impact on the rail operations, such as serviceability, customer aesthetics, etc.

   Methods were assigned a rating of "Medium" and given a score of 2 points if there was a low level of disruption resulting from deployment. Some of these methods have faced varying levels of resistance from industry stakeholders in other regions either due to concerns with the serviceability of the train, or for reduced levels of customer satisfaction due to adverse impacts on time and aesthetics. Similar resistance might be expected if these methods are adopted by US operators. However, the level of resistance for the methods in the medium category is expected to be low enough that they will be considered for US application.

   In some cases, methods are expected to have stronger resistance from US industry stakeholders. These methods, when deployed in other regions were unsuccessful, due to concerns related to rolling stock maintenance, safety, incompatibility with train operations, and visual impairment. Methods identified as unsuitable for deployment have been marked as "low" for industry acceptance and have been given a score of 1 point.

5. *Level of Cost or Investment*: Methods that produce high scores based on the first four criteria must still be assessed regarding their potential cost impacts. In making the selections for the 30 methods to undergo detailed analyses, each was rated based on a qualitative assessment of lifetime cost. The assessments were performed based on detailed industry cost information supported by industry interviews. To be consistent with the parameter scoring procedure, methods with low cost of implementation are more attractive and thus are rated "High" with a score of 3 points. Similarly, methods with high cost of implementation are rated as "Low" attractiveness with a score of 1 point. "Medium" methods are assigned a score of 2 points.

   The rating parameters for the cost categories were assigned based on the location of each noise mitigation method. For example, all methods that can be applied at the source of the noise were rated relative to each other for cost of implementation. Similarly, costs for all methods that can be applied along the path of noise propagation were rated relative to each other. The rationale for making these distinctions is that the cost of implementation scales differently. For example, methods applied at the source may scale with the number, speed, and size of train, whereas methods applied at the receiver scale with the size or number of buildings impacted by noise and vibration. If all methods in all categories were rated relative to each other, it is possible some potentially cost-effective methods may not be ranked high enough at the end of the initial assessments to be included in the detailed portion of the analysis.

5.2 Rating and Ranking Methodology

With the rating parameters defined, each mitigation method's effectiveness was assessed to determine their relative importance using a weighting factor. The weighting ranges from 0 to 100 percent. The final rating factor for each mitigation method was calculated as follows:

$$
\begin{aligned}
\textit{Rating Factor} = \quad & (\textit{Noise Reduction Potential} * W1) \quad + \\
& (\textit{Technology Readiness Level} * W2) \quad + \\
& (\textit{Practicality to Implement} * W3) \quad + \\
& (\textit{Industry Acceptance} * W4) \quad + \\
& (\textit{Level of Cost or Investment} * W5)
\end{aligned}
$$

where W_1 through W_5 are the relative weights of each parameter.

Based on Ricardo's research, insights provided by internal experts, and discussions with industry stakeholders, "Noise Reduction Potential" and "Practicality to Implement" were assigned a weight of 100 percent each, and the other three parameters were assigned a weight of 50 percent each, thereby assigning double the importance to these two parameters. These rating factors, when sorted in descending order, can be used to identify the most effective methods.

6. Rating and Ranking of Noise Mitigation Techniques

Based on the parameters and calculation methodology defined in Section 5, the ratings and ranking were determined for the identified noise mitigation methods and for each of the three application locations (i.e., at the source, along the path, and at the receiver). The rankings for the methods were calculated and then ranked based on the descending order of the "Rating Factor." A color scheme was incorporated to highlight the "Rank" number, with colors corresponding to the relative effectiveness of a method at the three locations (i.e., green representing the highest, yellow and orange intermediate, and red the lowest). The full list of noise mitigation methods is then divided into three tables based on the application location. For each table, the methods are grouped based on application to enable quick comparison of methods that are applied at similar locations.

The effectiveness of each method is based on its application in isolation for a given high speed train or route. Because of the logarithmic relationships employed in acoustics, the addition of two or more noise sources—or in this case noise reductions—have a net effect that is not an arithmetic sum, but rather a power law addition, as shown in Table 46. It is noted that in the case of two noise sources that individually differ by 10 dB, the source with the lower SPL contributes less than 0.4 dB to the combined SPL, independent of the absolute value of the lower value source SPL. This will be of interest when the effectiveness of multiple noise reduction methods is evaluated in combination. It is possible that the costs associated with the combined methods might increase disproportionately to the realized noise reductions.

Table 46: Adding Two Sound Levels (dB)

Difference between the two SPLs to be Added, dB(A)	Amount to be added to the larger of the two SPLs to obtain the combined SPL, dB(A)
0	3.0
1	2.5
2	2.1
3	1.8
4	1.5
5	1.2
6	1.0
7	0.8
8	0.6
9	0.5
10	0.4

6.1 Rating of Methods Applied at the Source

To prepare Table 47 and Table 48, researchers used the parameters defined in Section 5 and the methodology employed to calculate ratings and rankings. Note that some of the methods appear in more than one category. For these cases, the entries are moved to the most representative category and the ranking values for the minor category are not repeated (i.e., table cells are colored dark gray).

Table 47: Ratings for Methods Applied at the Source: Part 1 of 2:

Modification	Application	Method	Noise Reduction	TRL	Practicality	Industry Acceptance	Cost / Investment	Rating Factor	Rank
Vehicle	Mechanical Equipment	Improved Bearings[1]							
Vehicle	Mechanical Equipment	Propulsion Equipment (motors, generators)	2	2	2	3	1	7	19
Vehicle	Mechanical Equipment	Sound Insulation[1]							
Vehicle	Mechanical Equipment	Mufflers	2	2	1	3	3	7	19
Vehicle	Mechanical Equipment	Speed Restriction Zones	2	3	2	2	3	8	10
Vehicle	Mechanical Equipment	Reducing weight of rolling stock[1]							
Vehicle	Mechanical Equipment	Reducing gear noise[1]							
Vehicle	Mechanical Equipment	Optimize axle arrangement[1]							
Vehicle	Mechanical Equipment	Optimize suspension system[1]							
Vehicle	Mechanical Equipment	Bogie covers[2]							
Vehicle	Mechanical Equipment	Bolsterless bogies	1	3	3	3	2	8	10
Vehicle	Ancillary Equipment	HVAC/Ventilation Systems[3]							
Vehicle	Ancillary Equipment	Equipment Cooling	1	2	1	2	3	5.5	47
Vehicle	Aerodynamics	Reducing the number of pantographs	1	2	2	2	3	6.5	31
Vehicle	Aerodynamics	Vehicle body design	1	2	2	2	2	6	38
Vehicle	Aerodynamics	Wheel shrouds	1	2	2	1	3	6	38
Vehicle	Aerodynamics	Skirts	2	3	3	2	3	9	1
Vehicle	Aerodynamics	Inter-car gap seals	1	3	2	2	3	7	19
Vehicle	Aerodynamics	Locomotive nose (including micropressure waves) [4]							
Vehicle	Aerodynamics	Pantograph design	1	2	2	2	2	6	38
Vehicle	Aerodynamics	Pantograph fairings & shields design	2	2	3	3	3	9	1

The color scheme highlights the “Rank” number, with colors corresponding to the relative effectiveness of a method at the three locations green representing the highest, yellow & orange intermediate, and red the lowest.

🟩 High
🟨 ↓
🟧
🟥 Low

Note that some of the methods appear in more than one category. For these cases, the entries are moved to the most representative category and the ranking values for the minor category are not repeated (table cells are colored gray). ▨

Notes:

1. Included in Propulsion Equipment and together considered as an “Improved Locomotive”
2. Included in Skirts
3. Included in Equipment Cooling
4. Included in Vehicle Body Design
5. Included in Inter-car gap seals
6. Included in Section 6.2
7. Rank: green representing the highest, yellow and orange intermediate, and red the lowest

Table 48: Ratings for Methods Applied at the Source: Part 2 of 2

Modification	Application	Method	Noise Reduction	TRL	Practicality	Industry Acceptance	Cost / Investment	Rating Factor	Rank
Vehicle	Aerodynamics	Smooth gap covers[5]							
Vehicle	Aerodynamics	Smooth exterior surfaces	3	2	2	3	2	8.5	7
Vehicle	Aerodynamics	Window structures	2	2	3	3	2	8.5	7
Vehicle	Aerodynamics	Pantograph noise insulation plate	1	2	2	3	2	6.5	31
Vehicle	Aerodynamics	Sound absorbing panels installed on train underbody and skirts	2	3	3	2	2	8.5	7
Vehicle	Underbody & Wheels	Under-car noise absorption	2	2	2	3	2	7.5	15
Vehicle	Underbody & Wheels	Improved composite disk brakes	3	2	3	2	2	9	1
Vehicle	Underbody & Wheels	Wheel dampers and absorbers	1	2	3	2	2	7	19
Vehicle	Underbody & Wheels	Spin-slide control	2	3	3	3	2	9	1
Vehicle	Underbody & Wheels	Resilient wheels	1	3	3	1	2	7	19
Vehicle	Underbody & Wheels	Wheel flat removal	2	2	1	1	2	5.5	47
Rail & Wheel	Wheel/Rail Interface	Rail grinding including acoustic grinding	1	2	1	1	1	4	53
Rail & Wheel	Wheel/Rail Interface	Reductions in rail surface corrugation and roughness	3	2	1	2	1	6.5	31
Rail & Wheel	Wheel/Rail Interface	Increased turn radii	3	3	1	2	1	7	19
Rail & Wheel	Wheel/Rail Interface	Rail gap reductions	1	2	1	1	2	4.5	51
Rail & Wheel	Wheel/Rail Interface	Tuned rail dampers (elastomers)	2	3	2	3	1	7.5	15
Rail & Wheel	Wheel/Rail Interface	Friction modifiers (rail lubrication)	2	2	1	2	2	6	38
Rail & Wheel	Wheel/Rail Interface	Wheel geometry modifications to reduce vibrations	1	2	2	3	2	6.5	31
Rail & Wheel	Wheel/Rail Interface	Rail pad stiffness to reduce vibrations	1	2	2	2	1	5.5	47
Rail & Wheel	Wheel/Rail Interface	Floating Slab Track[6]							
Rail & Wheel	Wheel/Rail Interface	Increase track rigidity[6]							

The color scheme highlights the "Rank" number, with colors corresponding to the relative effectiveness of a method at the three locations green representing the highest, yellow & orange intermediate, and red the lowest.

🟩 High
🟨 ↓
🟧
🟥 Low

Note that some of the methods appear in more than one category. For these cases, the entries are moved to the most representative category and the ranking values for the minor category are not repeated (table cells are colored gray). ▨

Notes:

1. Included in Propulsion Equipment and together considered as an "Improved Locomotive"
2. Included in Skirts
3. Included in Equipment Cooling
4. Included in Vehicle Body Design
5. Included in Inter-car gap seals
6. Included in Section 6.2
7. Rank: green representing the highest, yellow and orange intermediate, and red the lowest

During the earlier FRA-funded study of high-speed rail noise regulations, 42 mitigation methods were identified for application at the source (Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S., 2021). Of these, 13 are associated with mechanical or ancillary equipment, another 13 were related to aerodynamic improvements, 6 were associated with vehicle underbody or wheels, and 10 were related to the wheel-rail interface.

6.1.1 Mechanical and Ancillary Equipment

Noise mitigation methods involving mechanical or ancillary equipment did not receive favorable rankings relative to high speed rail applications. This is because noise originating from mechanical equipment is typically a small component of the overall noise generated by high speed trains (Clausen, U., Doll, C., Franklin, F., Franklin, G., Heinrichmeyer, H., Kochsiek, J., Rothengatter, W., & Sieber, N., 2012). A paper published by the International Union of Railways (UIC), written by Hemsworth (2008), quantified SPLs for various high-speed train noise sources as a function of train speed (see Figure 42). The study indicates that noise from onboard equipment is a significant contributor for low train speeds (up to 40 km/h, approximately 25 mph) as shown by the green line. At higher speeds, rolling noise sources and aerodynamic noise sources become predominant. For high speed rail operations, it can be concluded that when improvements are made to the onboard mechanical and ancillary equipment, corresponding reductions to passby noise are limited, while the associated costs to upgrade locomotive equipment can be significant.

The effectiveness of combining locomotive mechanical systems noise reduction methods was investigated. In some publications, these combined modifications are categorized as "propulsion system improvements" or an "updated locomotive" and include changes to bearings, gear systems, axles, motors, and generators. An updated locomotive is generally more energy-efficient as well as having lower noise levels. For such a locomotive, the net noise mitigation is expected to be around 8–10 dB(A) ("Medium" rating for noise mitigation parameter). Further, the methods applied to improve locomotives have been the subject of various research programs (Clausen, U., Doll, C., Franklin, F., Franklin, G., Heinrichmeyer, H., Kochsiek, J., Rothengatter, W., & Sieber, N., 2012), and though many of them are incorporated into current production locomotives, there are additional improvements that can be made (these are assigned a "Medium" rating for TRL and Practicality). Low levels of industry resistance are anticipated for these changes since noise improvements typically bring higher efficiencies mentioned during the stakeholder interviews, these are thus assigned a "High Rating." Lastly, it is more difficult and costly to make additional improvements to in-service locomotives (thus, retrofits are assigned a "Low" rating).

Addition of mufflers on locomotives is a mitigation method that has the potential to reduce noise levels by 5–6 dB(A) (Croft, B., Brown, S., Miller, A., & Parker, A., 2014), yielding them a noise rating of "Medium." However, some of these models are still in prototype stage ("Medium" for TRL) and most high-speed rail applications involve electric locomotives ("Low" for Practicality).

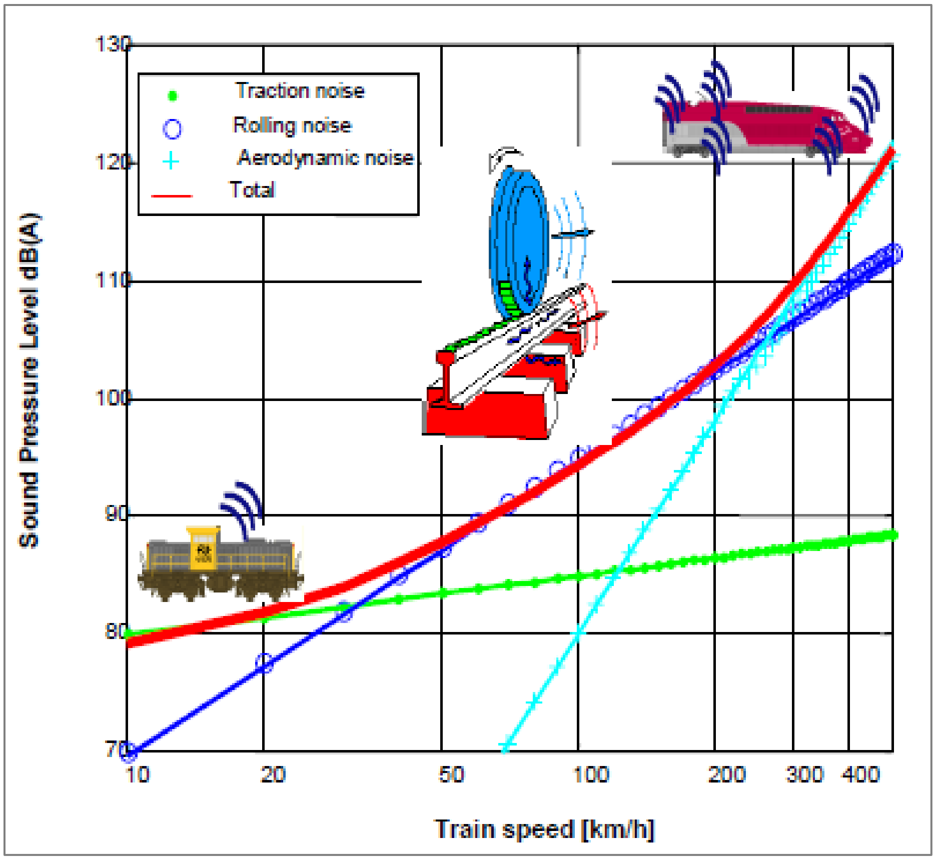


Figure 42: Effect of Noise Sources Based on Train Speed (Hemsworth, B., 2008)

Other methods for onboard mechanical equipment noise reduction include “Bolsterless Bogies” and “Speed Restriction Zones.” For bolsterless bogies, the magnitude of noise reduction is “Low” at about 1–3 dB(A), but the technology is readily available and is being deployed globally on most high-speed rail applications (“High” TRL). Further, the practicality to implement this method is “High” as bolsterless bogies generally tend to lower the unsprung mass of the train and reduce side sway, leading to a better ride for passengers. The industry attractiveness is also “High” as most locomotive and train manufacturers have been deploying this technology in new vehicle applications. Finally, attractiveness of cost for this method is considered “Medium” as it may be difficult to retrofit older trains with this technology, but it can be incorporated in new train purchases.

In the case of “Speed Restriction Zones,” a study by Poisson et al. (2008) on passby noise levels for the French TGV Duplex indicate that a noise reduction of 8 dB(A) is expected when the train slows from 350 km/hr (217 mph) to 250 km/hr (155 mph), thereby falling in the “Medium” ranking category. From the TRL and cost attractiveness perspective, this method is rated as “High” as there is no real technology to be implemented. However, for practicality and industry acceptance, this method gets a “Medium” rating as passengers may complain if many speed restriction zones significantly increase travel times. Further, industry stakeholders may also be concerned about the much higher energy consumption to speed up and slow down the train at regular intervals.

A final method related to noise mitigation for on-board mechanical equipment is related to “Equipment Cooling” and “HVAC / Ventilation Systems.” These two methods have been merged into one category since, for passby noise mitigation on high speed rail, noise reduction approaches are similar. Both methods address noise generated by fans, blowers, motors, and pumps (Frid, A., Aborn, M., Jiang, Y., & Fehse, K. R., 2007). The expected noise reduction is around 3–6 dB(A), giving them a rating of “Low.” Further, such technologies are mostly in the prototype stage (“Medium” for TRL), and not many commercially available solutions exist to mitigate noise from the ventilation systems. The practicality to implement is “Low” and industry acceptance is “Medium” as deployment of this mitigation method has in some cases led to increased noise in the locomotive crew and passenger cabins. Thus, both approaches are best addressed as a coupled system.

6.1.2 Aerodynamic Improvements

Because of the predominance of aerodynamic noise sources for high speed operations, significant mitigation research has been conducted. Two of the most effective noise reduction methods are “Skirts” and “Pantograph fairings and shields” that when applied individually can yield approximately 6–7 dB(A) of noise reduction (Zhang, Y., Xhang, J., Li, T., Zhang, L., & Zhang, W., 2016), thereby getting a rating of “Medium.” Both methods address regions of turbulent flow, periodic pressure changes and vortex shedding that produce significant SPLs. Skirts that cover equipment at the lower regions of the train, such as wheel trucks, are a mature technology (“High” TRL) that is employed throughout the industry. Pantograph fairings are a newer technology that is still evolving (“Medium” TRL). In terms of practicality, both these methods earn a “High” rating due to their relatively easy application onto existing trains, or to be purchased with new train sets. However, from an industry acceptance perspective, skirts tend to face some resistance from train operators and maintenance personnel (“Medium” rating) due to the increased difficulty to service equipment on the underbody, but such concerns are not present for pantograph shields and fairings (“High” rating). Finally, from a cost perspective, both these methods get a “High” rating due to the relatively low cost of adding them to existing trainsets. Sound absorbing materials are sometimes added to the train underbody during application of skirts. This application is less attractive than adding skirts alone because the incremental noise reduction is minimal and adding the absorbing material along the full length of the train adds considerable cost.

Methods involving improvements to the train exterior surfaces like “Smooth Exterior Surfaces” and “Window Structures” have been shown to provide effective noise mitigation. For smooth exterior surfaces, the expected noise reduction is roughly 14 dB(A), earning them a “High” rating for noise (Zhang, Y., Xhang, J., Li, T., Zhang, L., & Zhang, W., 2016). However, the practicality to implement this method may be categorized as “Medium,” due to the challenges of modifying the exterior geometry of existing locomotives and coaches. On the other hand, for window structures, a 7 dB(A) noise reduction may be possible by reducing window recesses and improving seal geometry (“Medium” noise rating). These methods have a “High” practicality rating because they can be applied to existing trains. Both these methods remain in prototype stage (“Medium” TRL) as many studies are ongoing to continually improve vehicle body aerodynamics. Both these methods have “High” ratings since they have minimal impact on train operations, especially for high speed rail, where windows remain permanently closed. Both methods have cost ratings of “Medium” as they introduce changes to the train body and in many cases may lead to the purchase of new train sets.

"Inter-car gap seals" and "Smooth gap covers" are considered less effective noise reduction methods. Both address the disruption of flow in the region between cars but are identified separately because of variations in geometry and operation. By improving the inter-car gap and seals, 4–5 dB(A) of noise reduction is expected, thus falling in the "Low" range (Yamazaki, N., Takaishi, M., Toyooka, M., Nagakura, K., Sagawa, A., & Yano, H., 2007). Though commercial versions are common for high speed train sets ("High" TRL), their practicality is rated as "Medium" due to the typical relative movement of train cars leading to reduced effectiveness within regions of high lateral movement and curves. A "Medium" rating is also assigned for industry acceptance as increasing complexity on inter-car seals impacts serviceability of the train and increases train coupling and decoupling times. From a cost perspective, this method is rated "High" as the relative cost of improving inter-car seals is low.

Methods related to "Reducing number of Pantographs," "Pantograph design" and "Pantograph noise insulation plates," are noted to be relatively low in terms of additional noise reduction opportunities, likely due to the large amount of development that has been conducted on this topic over the last two decades. Due to their exposed location relative to the air stream, pantographs present an opportunity for additional noise reduction, estimated to be on the order of 1–2 dB(A) when these methods are applied in isolation (Nishiyama, T., 2011) (Yamada, H., Wakabayashi, Y., Kurita, T., & Horiuchi, M., 2008). Many of these methods are in prototype stage ("Medium" TRL), with limited commercially availability options, leading to a "Medium" practicality to implement rating. Though the pantograph noise insulating plate is rated as a "High" for industry acceptance, reducing the number of pantographs and changing pantograph design is considered "Medium" due to expected resistance from industry stakeholders. Reducing the number of pantographs increases the burden on electrical equipment due to increased variability in contact with the overhead catenary (Mitsumoji, et al., 2016). In terms of cost, reducing the pantographs is most favorable ("High" rating), compared to changing the design or adding noise insulating plates ("Medium" rating).

Other aerodynamic improvements that have relatively lower reported noise reductions are "Vehicle body design" improvements and addition of "Wheel shrouds," which offer noise reduction opportunities of 1–4 dB(A) (Brüel & Kjær, n.d.). This is because high speed train body shapes have already incorporated significant levels of drag reduction to reduce rolling resistance, with resulting decreases in aerodynamically-induced noise levels. Additionally, most of the continuing vehicle body design and wheel shroud research and development has only recently reached the prototype stage ("Medium" rating), along with a "Medium" practicality to implement due to difficulty in changing the design of existing train sets. The industry acceptance for these methods is also not high, specifically for wheel shrouds, where industry stakeholders typically face access difficulties for maintenance. From a cost perspective, vehicle body design is a "Medium" and wheel shrouds are "High" as they are mostly restricted to particular train sets and do not always require the purchase of new trains.

6.1.3 Vehicle Underbody and Wheels

Vehicle underbody and wheel/brake modifications provide additional opportunities for noise mitigation. Methods like "Improved composite disk brakes" and "Spin-slide control" are ranked amongst the most effective as they tend to reduce damage to the wheels during operation, thus decreasing rolling noise during general train operation. Composite disk brakes can provide noise reduction of more than 10 dB(A) ("High" noise rating) and spin-slide control can reduce noise by around 6 dB(A) (“Medium” rating) (Thompson, D., & Jones, C., 2003) (Hanson, C. E., Ross, J. C., & Towers, D. A., 2012). New high-speed train set designs typically include disk brakes, but the technology is still relatively new and many of the designs are in prototype and in-service trial stages (“Medium” TRL and “Medium” industry acceptance). Spin-slide control technology is very common for high speed rail applications (“High” TRL) and has strong support from the industry (“High” industry acceptance) because it has the added benefit of improved performance and safety. Both these methods have a “High” practicality-to-implement rating as modifications can be performed on existing train sets, though from a cost perspective, the rating is “Medium” as these methods are expensive to deploy on trains.

Some of the lower ranked noise reduction methods associated with the train underbody are “Under-car noise absorption,” “Wheel dampers and absorbers” and “Resilient wheels.” These methods can reduce passby noise from high speed trains by 2–5 dB(A), thereby getting a rating of “Low” or “Medium.” Resilient wheels technology has been available commercially for some time (“High” TRL) and the method is very practical to implement (Hanson, C. E., Ross, J. C., & Towers, D. A., 2012). However, it faces strong resistance from industry due to reduced passenger safety. In June 1998, one of the most devastating high-speed rail crashes occurred in Germany and was later linked to the use of resilient wheels (Wikipedia, 2018). Wheel dampers and absorbers and undercar noise absorption technologies are mostly in the prototype stage (“Medium” TRL) with a “medium” cost attractiveness rating as they can be applied to existing train sets (Holzl, G., 2000). From an industry acceptance perspective, undercar noise absorption is preferred (“High”) as it causes minimal impact to serviceability and rail operations, compared to wheel dampers, which increases maintenance tasks. “Wheel flat removal” is the least effective underbody application method, even though it has a noise mitigation effect of roughly 7 dB(A) (Iwnicki, S., Spiryagin, M., Cole, C., & McSweeney, T., n.d.), leading to a rating of “Medium” for noise. The chief reasons for reduced effectiveness are the “Low” practicality to implement and “Low” industry acceptance as wheels need frequent flat removal and grinding. Further as the material on a wheel is limited, this flat removal cannot be done indefinitely, without having to replace the wheels during maintenance.

6.1.4 Wheel Rail Interface

The last category of source (on vehicle) noise mitigation methods is related to the wheel rail interface. Most of these methods have low comparison rankings due to “Low” cost attractiveness and “Low” practicality to implement as they involve modifications to the rail or rail foundation, which is not readily scalable for the US due to lengths of tracks (Hanson, C. E., Ross, J. C., & Towers, D. A., 2012) (Clausen, U., Doll, C., Franklin, F., Franklin, G., Heinrichmeyer, H., Kochsiek, J., Rothengatter, W., & Sieber, N., 2012). These methods include—rail grinding, reducing rail surface corrugations, rail gap reductions, rail lubrication, and increasing rail pad stiffness. Most of these methods also provide “Low” noise reduction potential, except for reducing rail surface corrugation, which has the potential to reduce noise by roughly 10 dB(A). Many of these methods are also in prototype stage thereby receiving a rating of “Medium” for TRL.

The two methods that have relatively better overall effectiveness for wheel rail interface are “Increasing turn radii” and “Tuned rail dampers (elastomers).” For increasing turn radii, the expected noise reduction potential is roughly 10 dB(A), thus putting it in the “High” rating for noise reduction. This method is primarily applicable to the planning and design stage for new track installations since modifying track curve sections can be costly once rights-of-way are established. Thus, though its TRL level is "High," its practicality to implement is "Low," along with "Low" cost attractiveness. Further, its industry acceptance is also "Medium" mainly because increasing track radii impacts the land use. For tuned rail dampers, though this method has a relatively lesser noise reduction potential of around 6 dB(A) ("Medium"), its TRL level is "High," along with its industry acceptance, as this method has been applied successfully in various global high-speed applications. The practicality to implement tuned rail dampers is better than other rail modifications (rated at "Medium") as the modification is only on the upper part of the rail and this method does not require frequent repair. However, its cost attractiveness is "Low" again, as it needs to be scaled with the length of the track, which can be a concern for US applications.

6.2 Rating of Methods Applied Along the Path

Table 48 shows the rating and rankings for noise mitigation methods that researchers applied along the path of noise propagation. The rank column employs the same color scheme specified in Section 6. The individual modifications highlighted in dark gray have been included under aggregated categories.

For the second category of mitigation methods, along the noise path, 20 methods were identified that can reduce train passby SPLs. Of these, eight are related to the construction of sound barriers and include variations in location and design. Another four methods are based on noise reduction by restricting the sound path and eight methods are based on changes to the track ballast and supporting foundation. In general, noise mitigation methods based on sound barriers have been found to be the most effective for this application category.

6.2.1 Sound Barriers

The literature indicates many variations in location and design of sound barriers to reduce noise from passing trains (Federal Highway Administration, 2016). The noise reduction performance of barriers can depend on the height, length, type of material used, distance from the track, distance from the receivers, and geometry. However, the most effective barriers are those that are placed very close to the track near the passing vehicles and must have the necessary design elements to maximize their effect (e.g., height of 2 m or more, barrier proportional to length of train and noise exposure of the receiver) (Schulte-Werning, B., Beier, M., Grutz, H. P., Jager, K., Kock, G., Onnich, J., Strube, R., 2001). Such barriers are expected to reduce passby noise from high speed trains on the order of 10 dB(A) or more ("High" noise reduction rating). Most designs are based on concrete wall technologies with minor modifications for baffles, diffusers, and sound absorbing materials (Farina, A., & Fausti, P., 1995), and are commercially available ("High" TRL). Unfortunately, due to the high cost of constructing concrete barriers ("Low" rating for cost), their practicality is also impacted and has been assigned a rating of "Medium." The application of sound barriers is generally restricted to densely populated areas where the sound reduction benefit affects many receivers, thus justifying their high cost. Another concern related to barriers is that they obstruct the view of onboard passengers and reduce the aesthetics of rail travel. Industry stakeholders seek to minimize their use ("Medium" rating for industry acceptance). It is possible to move the barriers to locations farther from the track into what is known as the 'shadow zone,' but this reduces their effectiveness to sound reductions around 6 dB(A) (Farina, A., & Fausti, P., 1995) ("Medium" noise reduction rating). For the shadow zone barrier location, practicality is rated “Low” due to increased difficulty of procuring a wider right of way. Thus, this method is ranked lower in terms of noise effectiveness. Lastly, the specific case of “Barriers angled to reflect sound skyward” is not ranked separately as this is a design feature of sound barriers and it is assumed that the most effective design techniques will be used to construct the barrier at various locations.

Table 49: Ratings for Methods Applied Along the Path

Modification	Application	Method	Noise Reduction	TRL	Practicality	Industry Acceptance	Cost / Investment	Rating Factor	Rank
Sound Barriers	Barrier Location & Design	Near Passing Vehicles (height, absorption, reflection, gaps)	3	3	2	2	1	8	10
Sound Barriers	Barrier Location & Design	Barriers at the Edge of the Right-of-Way[1]							
Sound Barriers	Barrier Location & Design	Barriers Placed within the Shadow Zone	2	3	1	2	1	6	38
Sound Barriers	Barrier Location & Design	Sound Absorption Material on the Barrier, Facing the Noise Source	2	2	3	3	3	9	1
Sound Barriers	Barrier Location & Design	Barriers angled to reflect sound skyward[1]							
Sound Barriers	Barrier Location & Design	Tunnel Hoods	2	2	2	3	2	7.5	15
Sound Barriers	Barrier Location & Design	Sound absorbing pads below the rails[2]							
Sound Barriers	Barrier Location & Design	Bridge beam supports to reduce structure-induced noise	2	1	1	3	2	6	38
Sound Barriers	Sound Path	Alternation of horizontal and vertical alignments – trenches[3]							
Sound Barriers	Sound Path	Creation / acquisition of Buffer Zones between source & receiver	2	3	1	2	2	6.5	31
Sound Barriers	Sound Path	Lower elevation of the tracks into trenches	2	3	2	2	1	7	19
Sound Barriers	Sound Path	Increasing distance from source to receiver	1	3	1	3	2	6	38
Reflective Surfaces	Ballast & Track Support	At-grade ballast	1	3	2	2	3	7	19
Reflective Surfaces	Ballast & Track Support	Elevated track ballast, increase absorption	2	3	1	2	3	7	19
Reflective Surfaces	Ballast & Track Support	Resilient track supports and baseplates that absorbs noise and vibrations	1	2	1	2	1	4.5	51
Reflective Surfaces	Ballast & Track Support	Resilient padding for slab track	1	3	1	3	2	6	38
Reflective Surfaces	Ballast & Track Support	Damping materials distributed between ballast-less tracks[4]							
Reflective Surfaces	Ballast & Track Support	Placing spacers and grooved mats below slab tracks[5]							
Reflective Surfaces	Ballast & Track Support	Damping materials at the upper surface of the slab tracks	1	3	2	3	2	7	19
Reflective Surfaces	Ballast & Track Support	Using track pads with a lower elastic coefficient[6]							

The color scheme highlights the “Rank” number, with colors corresponding to the relative effectiveness of a method at the three locations green representing the highest, yellow & orange intermediate, and red the lowest.

🟩 High
🟨 ↓
🟧
🟥 Low

Note that some of the methods appear in more than one category. For these cases, the entries are moved to the most representative category and the ranking values for the minor category are not repeated (table cells are colored gray). ⬜

Notes:

1. Included in Barrier Location and Design methods
2. Included in Ballast Track and Support methods
3. Included in “Vibration Breaking Trenches” in Section 6.3
4. Included in “Damping materials at upper surface of slab tracks”
5. Included in “Resilient padding for slab track”
6. Included in “Resilient track supports and baseplates”
7. Rank Color Scheme: green representing the highest, yellow & orange intermediate, and red the lowest.

The addition of the sound absorbing material to barriers provides a noise reduction of around 8–9 dB(A) (Federal Highway Administration, 2016), leading to a “Medium” rating. Though there are many types of sound absorbing materials currently available, research continues and the overall state of technology for absorbing materials can be rated as a “Medium” TRL. However, as the impact to operations is minimal for putting sound absorbing material on existing barriers, the practicality to implement, industry acceptance and cost attractiveness can all be rated as “High.”

Some other, lesser effective noise mitigation methods include “Tunnel hoods” and “Bridge beam supports.” Although these methods are not directly related to the construction of sound barriers, they similarly reduce passby noise through modifications to wayside structures. Hoods and train nose design modifications are quite effective at reducing the sonic boom that occurs when high speed trains enter tunnels. The sound levels resulting from the reflected pressure waves can annoy residents living nearby (Morgan, P. A., & Peeling, J., 2012). The addition of tunnel entrance hoods reduces SPLs by approximately 8 dB(A). Though the benefit for noise reduction is “Medium” in this case, the overall rating is reduced because the technology is still in prototype stage (“Medium” TRL) and retrofitting hoods to existing tunnels along the rail track may be difficult (“Medium” practicality). Further, the cost of making structural changes to existing tunnels can also be significant (“Medium” cost attractiveness). A similar evaluation can be made for bridge beam supports where the expected noise reduction is around 6 dB(A) (“Medium” rating), but their effectiveness is reduced due to that technology being mostly experimental (“Low” TRL) and the “Low” practicality of retro-fitting existing bridges.

6.2.2 Noise Mitigation on Sound Path

One of the most effective methods for mitigating passby high speed rail noise along the sound path is to “Lower the track into trenches.” This method is based on the noise reduction sound dampening effect of earth and soil. This method reduces passby noise by roughly 6 dB(A), achieving a “Medium” noise reduction rating (Wolf, S., 2010). Though the method is relatively mature and commonly deployed for high-speed rail (“High” TRL), the practicality to implement and cost attractiveness are rated as “Medium” and “Low” respectively, mainly because making any grade changes to existing tracks is quite costly. Even for new track installations, it may not be practical to employ trenches over the full-length due to presence of existing infrastructure (i.e., pipes and cables), land topography, drainage requirements, and access to the lower portion of the train. As with sound barriers, the industry acceptance rating has been assigned a value of “Medium.” Lowering the train into a trench can also reduce the quality of the view for onboard passengers.

The other two identified methods for noise mitigation along the sound path are “Creating buffer zones” and “Increasing distance from source to receiver.” Both these methods are based on the concept of increasing distance between the noise source and the receiver (Hanson, C. E., Ross, J. C., & Towers, D. A., 2012) and involve acquisition of land, controlling land-use, changing the route of trains, etc. Though the expected benefit from these methods is roughly 4–5 dB(A) (“Medium” to “Low” noise reduction rating), the practicality to implement them is “Low” since relatively large areas of land must be procured and controlled, which may not be feasible along the entire length of the track. The industry may be more open to increasing the distance to source by re-routing the rail path (“High” industry acceptance rating), but this also has an adverse impact on cost (“Medium” cost rating).

6.2.3 Ballast and Track Support

Identified noise reduction methods associated with improvements to ballast and track supports have lower rankings than many of the methods described above. The key reason for this is that ballast and track support modifications must be applied over large sections for the track, thereby greatly increasing the cost of application and reducing the practicality. These methods have noise reduction levels of 3–5 dB(A), which places them in the "Low" to "Medium" rating category (Hanson, C. E., Ross, J. C., & Towers, D. A., 2012). Adding "At grade ballast," "Elevated track ballast," or "Damping materials above the slab" are more effective as their cost tends to be relatively lower ("Medium" or "High" cost attractiveness). These methods are also commercially mature and generally accepted for not just high-speed rail, but general rail track design, thus getting a "High" TRL rating.

In the case of "Resilient track supports" and "Resilient padding for slab tracks," the average expected noise reduction is roughly 3–4 dB(A) ("Low" noise reduction rating) (Oertli, J., & Hubner, P., 2008). Both these methods involve the addition of elastomers or padding materials below the track, or below the slab, thereby making them the least practical for large distances ("Low" practicality rating). This also greatly increases the cost of application as existing tracks would need to be retrofitted, thus giving them a "Low" to "Medium" cost attractiveness rating.

6.3 Rating of Methods Applied at the Receiver

The final group of noise mitigation measures includes those that can be applied at the receiver. Table 50 summarizes the ratings and rankings for these methods. Once again, the rank column includes the color scheme specified in Section 6 and some modifications are included in aggregated categories (indicated by dark gray highlighting).

There are 14 methods identified to reduce passby noise for high speed rail that can be applied at the receiver. Of these, six are related to the construction of sound barriers close to receivers, which, in principal work like near-track sound barriers, with some minor considerations. The other eight methods are based on building modifications that can be applied at receiver locations. In general, noise mitigation at the receiver is the least cost-effective approach in urban areas because of the many affected residential and commercial buildings and the relatively small number of receivers at each location. Methods to reduce noise at the source or along the path can impact all receivers, thus making them much more effective.

Table 50: Ratings for Methods Applied at the Receiver

Modification	Application	Method	Noise Reduction	TRL	Practicality	Industry Acceptance	Cost / Investment	Rating Factor	Rank
Sound Barriers	Barrier Design	Flat surface and acoustical absorption designs (height, absorption, reflection, gaps)	1	3	2	2	2	6.5	31
Sound Barriers	Barrier Location	Locate near source or receiver[1]							
Sound Barriers	Barrier Design	Vibration-breaking trenches	1	2	1	2	2	5	50
Sound Barriers	Barrier Location	Sound barriers on property boundary facing noise source	2	3	2	2	2	7.5	15
Sound Barriers	Barrier Location	Install barriers on top of berms to improve design and increase barrier height[1]							
Sound Barriers	Barrier Design	Improved foundation for vibration and sound isolation	3	3	1	3	2	8	10
Building Modifications	Construction / Design	Façade Insulation: Low acoustical transmission windows and walls	3	2	1	2	1	6.5	31
Building Modifications	Construction / Design	Caulking and sealing gaps	2	3	1	3	2	7	19
Building Modifications	Services & Systems	HVAC System Improvements, including ventilation inlets and exhausts[2]							
Building Modifications	Construction / Design	Design for low re-radiation of noise due to ground vibrations[3]							
Building Modifications	Construction / Design	Locating bedrooms on opposite side of dwellings from the noise source[4]							
Building Modifications	Construction / Design	No vents or opening in the walls facing the noise source[2]							
Building Modifications	Construction / Design	Layered walls with hard and soft materials to improve noise attenuation	1	3	1	3	2	6	38
Building Modifications	Construction / Design	Windows with a 3-inch air gap	3	3	2	3	2	9	1

The color scheme highlights the "Rank" number, with colors corresponding to the relative effectiveness of a method at the three locations green representing the highest, yellow & orange intermediate, and red the lowest.

🟩 High
🟨
🟧 ↓
🟥 Low

Note that some of the methods appear in more than one category. For these cases, the entries are moved to the most representative category and the ranking values for the minor category are not repeated (table cells are colored gray). ▨

Notes:

1. Included in general barrier design and location, Section 6.2
2. Included in "Façade insulation" as its related to removing openings
3. Included in "Improved foundation"
4. Minimal impact on noise reduction as that change is internal to the building, so excluded
5. Rank Color Scheme: green representing the highest, yellow and orange intermediate, and red the lowest

6.3.1 Sound Barriers at Receiver

The most effective method of reducing noise and vibration at the receiver is to "Improve building foundations for noise and vibration isolation." This can typically be done by installing an elastomer below the building foundations so that vibrations from the ground are not transferred to the building (Vibration Isolation of Building Foundations, 2018). This method provides a noise reduction than can exceed 15 dB(A), resulting in a "High" rating for noise reduction. These elastomers are commercially available and have been in use for many years; thus, the assigned rating is "High" TRL and "High" acceptance from the industry stakeholders. A key concern for this method is the practicality to implement, as it is extremely difficult and, in some cases, cost prohibitive to retrofit existing structures ("Low" practicality rating).

Another method of reducing noise at receivers is to “Install barriers on the edge of the property facing the train.” This method is analogous to installing sound barriers near the track, however, since the noise source is much farther away, the effectiveness is somewhat lower at 8 dB(A) (Hanson, C. E., Ross, J. C., & Towers, D. A., 2012) (“Medium” noise reduction). Though the technology maturity is “High” as barriers are quite common, their high cost (“Medium” cost rating), “Medium” practicality due to limited scalability, and “Medium” industry acceptance due to reduced aesthetics, lead to a relatively lower overall effectiveness rating.

Another method for reducing noise is “Vibration breaking trenches” near receiver locations. The expected benefit from digging trenches near receivers is around 4 dB(A) (Yang, W., Yuan, R., & Wang, J., 2018) (“Low” rating). Though it is common to dig trenches to isolate noise, vibration, and vibration-transmitted noise, additional research is being performed to improve effectiveness through modification of trench characteristics such as geometry and surface coatings. This method was assigned a “Medium” TRL rating. Due to land requirements for constructing trenches, a “Medium” cost attractiveness rating and “Medium” industry acceptance rate were assigned. The practicality to implement this method for the case where high speed train noise impacted large numbers of receivers is low due to limited scalability.

6.3.2 Building Modifications

Building modifications have been identified for reducing noise levels at receiver locations. In general, these methods are less attractive than source modifications because of the potentially large number of buildings. Additional challenges include the need to work with various building owners, achieving access for performing the retrofits, compatibility with a wide range of building construction methods, meeting local building code requirements, and compliance with historical and local architectural specifications.

One of the most effective noise-reducing building modifications is the installation of insulated double layered “Windows with a 3-inch air gap.” SPLs for this method can be more than 15 dB(A) (U.S. Federal Highway Administration, 2011), thus providing a “High” noise reduction rating. This insulation technology is quite common, especially in cold climate locations—as this can also be effectively used for temperature insulation—thus achieving “High” ratings for TRL and industry acceptance. From the practicality and cost attractiveness rating, these are both at “Medium” level mainly due to a concern with scalability. In dense urban areas, it is challenging to retrofit all buildings with insulated windows.

Additional identified methods for noise reduction at the receiver include “Caulking and sealing gaps,” “Façade insulation,” and “Layered walls.” Façade insulation, has a “High” expected noise reduction potential of more than 15 dB(A) (U.S. Federal Highway Administration, 2011), but it also has a relatively high cost, “Low” cost attractiveness (and “Low” practicality to implement) because of the potentially large number of structures that would have to be modified. This reduces its overall rating compared to other methods that can be applied at the receiver. Similar issues are also present when using layered walls to improve noise attenuation, albeit, with a “Low” noise reduction potential. Caulking and sealing gaps is a slightly better method as it has a relatively lower cost requirement to implement on existing buildings (“Medium” cost attractiveness). However, its “Medium” noise reduction potential at 6–7 dB(A) and low practicality due to concerns about scalability restrict its overall effectiveness.

6.4 Selected Top 30 Methods for Further Cost Analysis

Based on the ratings and rankings assigned to the various noise mitigation methods, researchers selected 30 for detailed analysis regarding cost of implementation as shown in Table 51 and Table 52. To select these, all the methods were grouped in order of ranking (i.e., most preferred to least preferred). Then, methods that were similar in application were culled to reduce duplication and to ensure a wider representation of approaches. Though an effort was made to select a reasonable number of methods from the 3 groups of applications (i.e., 10 methods each), it was found that for the case of mitigation at the receiver, the total number of effective methods was lower than the target (i.e., 7 methods selected). This was compensated by selecting more methods to be applied at the source (i.e., 13 selected), as these tend to be more effective.

Table 51: Top 30 Selected Methods for Cost Analysis: Part 1 of 2

Location of Mitigation	Rank	Specific Application	Selected
At Source	1	Improved composite disk brakes	Yes
	1	Pantograph fairings & shields design	Yes
	1	Skirts	Yes
	1	Spin-slide control	Yes
	7	Smooth exterior surfaces	Yes
	7	Sound absorbing panels installed on train underbody and skirts	No
	7	Window structures	Yes
	10	Bolsterless bogies	Yes
	10	Speed Restriction Zones	Yes
	15	Tuned rail dampers (elastomers)	Yes
	15	Under-car noise absorption	Yes
	19	Increased turn radii	Yes
	19	Inter-car gap seals	Yes
	19	Wheel dampers and absorbers	Yes
	19	Mufflers	No
	19	Propulsion Equipment (motors, generators)	No
	19	Resilient wheels	No
	19	Smooth gap covers	No
	31	Pantograph noise insulation plate	No
	31	Reducing the number of pantographs	No
	31	Reductions in rail surface corrugation and roughness	No
	31	Wheel geometry modifications to reduce vibrations	No
	31	Wheel shrouds	No
	39	Friction modifiers (rail lubrication)	No
	39	Pantograph design	No
	39	Vehicle body design	No
	47	Equipment Cooling	No
	47	Rail pad stiffness to reduce vibrations	No
	47	Wheel flat removal	No
	51	Rail gap reductions	No
	53	Rail grinding including acoustic grinding	No

Table 52: Top 30 Selected Methods for Cost Analysis: Part 2 of 2

Location of Mitigation	Rank	Specific Application	Selected
Along Path	1	Sound Absorption Material on the Barrier, Facing the Noise Source	Yes
	10	Barriers at the Edge of the Right-of-Way	Yes
	10	Near Passing Vehicles (height, absorption, reflection, gaps)	No
	17	Tunnel Hoods	Yes
	21	At-grade ballast	Yes
	21	Damping materials at the upper surface of the slab tracks	Yes
	21	Elevated track ballast, increase absorption	No
	21	Lower elevation of the tracks into trenches	Yes
	31	Creation / acquisition of Buffer Zones between source & receiver	Yes
	39	Barriers Placed within the Shadow Zone	No
	39	Bridge beam supports to reduce structure-induced noise	Yes
	39	Increasing distance from source to receiver	Yes
	39	Resilient padding for slab track	Yes
	51	Resilient track supports and baseplates that absorbs noise and vibrations	No
At Receiver	1	Windows with a 3-inch air gap	Yes
	10	Improved foundation for vibration and sound isolation	Yes
	17	Sound barriers on property boundary facing noise source	Yes
	21	Caulking and sealing gaps	Yes
	31	Façade Insulation: Low acoustical transmission windows and walls	Yes
	31	Flat surface and acoustical absorption designs (height, absorption, reflection, gaps)	No
	39	Layered walls with hard and soft materials to improve noise attenuation	Yes
	50	Vibration-breaking trenches	Yes

The color scheme highlights the "Rank" number, with colors corresponding to the relative effectiveness of a method at the three locations green representing the highest, yellow & orange intermediate, and red the lowest.

🟩 High
🟨 ↓
🟧
🟥 Low

Note that some of the methods appear in more than one category. For these cases, the entries are moved to the most representative category and the ranking values for the minor category are not repeated (table cells are colored gray). ▨

7. Review of Implementation Costs for Noise Mitigation Techniques

Using the previously discussed ranking procedure investigations were performed to develop an understanding for the cost of implementation for the top 30 mitigation strategies, including those implemented at the source, along the noise path, and at the receiver. The research team conducted a broad literature review and included research that took place in North America, Europe, China, Japan and several other countries. Many of these studies included full-scale deployment and testing. In some instances, assumptions were made using representative data to provide a bottom-up cost estimation where primary research was not directly available, for example, in the case of acoustical gap sealing. In such cases, there was typically a good source of representative public information available from adjoining industries such as construction, in terms of both labor and materials, for given activities such as window fitting and isolation matting installation. This allowed for a good approximation of cost for several noise mitigation methods. Various industry stakeholders discussed and reviewed these assumptions to confirm the validity of representative data sets from adjoining industries.

The objective of the cost analysis exercise was to compile costs associated with noise mitigation methods expected to be incurred over the lifecycle time periods associated with each application. The cost categories for life cycle cost are as follows: 1) research and development/Investment, 2) Capital/Construction, 3) Labor/Materials, 4) Permits/Operating and 5) Maintenance/Lifecycle. The research and development cost category were removed from the analysis as most of the selected methods are mature and are being implemented in various high-speed train systems. Further, for methods that may be still under development, or with a potential to improve mitigation potential, data on research and development costs are limited and typically pursued independently for non-aligned applications.

Researchers scaled the total lifecycle cost of non-rolling stock applications on track-related parameters, such as track length and number of tunnels. As most mitigation methods have an expected life span that may not be the same as the life of the track, a replacement frequency concept was incorporated into the model, and was estimated based on the typical lifespan of high-speed rail infrastructure which is defined as 35 years (Campos, Rus, & Barron, 2007). If the life of the method was lower than that of the track, the maintenance/lifecycle costs were adjusted accordingly to address this factor. Using the concept of unit cost, by applying these costs on features of various tracks, the total cost for a given noise reduction level can be estimated, as is described in Section 7.1.

7.1 Cost Analysis for Methods Applied at the Source

In other cases, when an operator plans to implement upgrades to reduce noise and improve performance, newer and more efficient train sets are purchased having advanced noise reduction features. These new trainsets typically possess advancements like bolsterless bogies, disk brakes, and aerodynamic window structures.

7.1.1 Mechanical and Ancillary Equipment

For bolsterless bogies (see Figure 43), the noise reduction benefit for high speed applications is approximately 2 dB(A). This is the difference in noise emissions between a trainset equipped with conventional, bolstered bogies and one equipped with bolsterless bogies (see Figure 43).

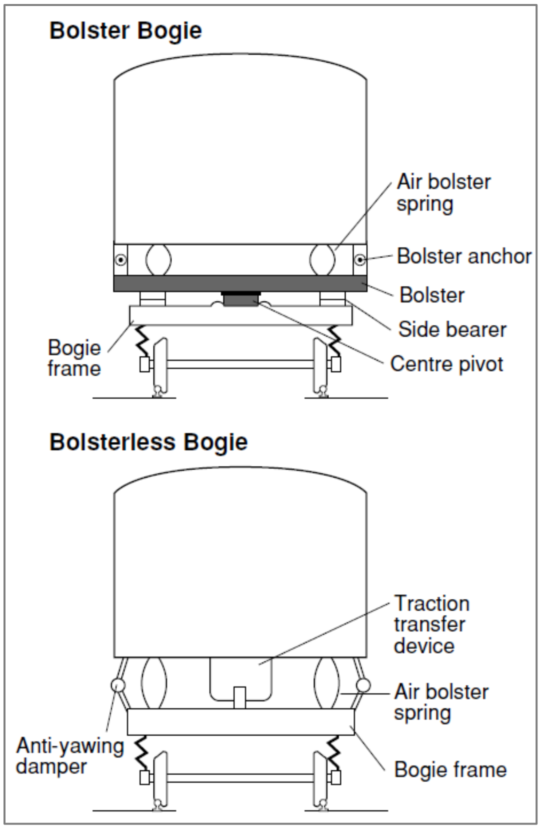
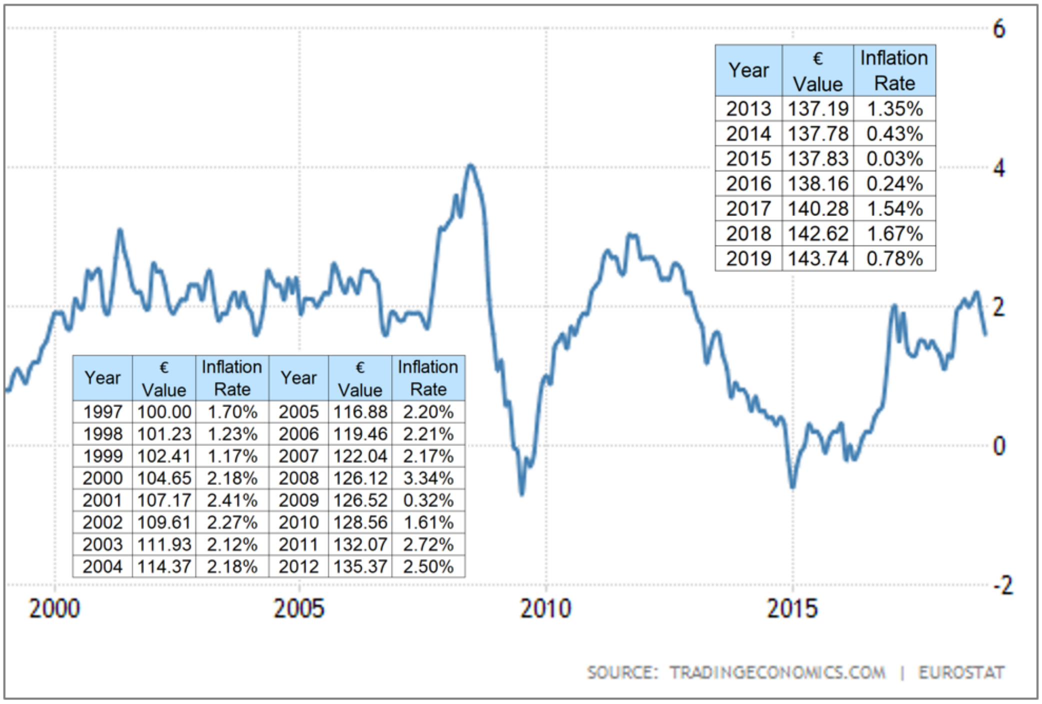


Figure 43: Comparison of Bolster and Bolsterless Bogies (Okamoto, I., 1998)

Industry publications provided summaries of recent high-speed train orders (see for example, Siemens Velaro High Speed Trains [2019])]. These indicate eight-car high speed train sets have prices in the range of $US 44 million to $US 60 million. Ricardo received train set component pricing from an international rail engineering firm (Anonymous, 2019) indicating the bogies (i.e., complete wheel truck assembly) represent between 10 and 12 percent of the total train set cost. Thus, the cost of the bogies on an 8-car trainset (16 bogies) would range from $US 4.4 million to $US 6.0 million.



Year	€ Value	Inflation Rate
2013	137.19	1.35%
2014	137.78	0.43%
2015	137.83	0.03%
2016	138.16	0.24%
2017	140.28	1.54%
2018	142.62	1.67%
2019	143.74	0.78%

Year	€ Value	Inflation Rate	Year	€ Value	Inflation Rate
1997	100.00	1.70%	2005	116.88	2.20%
1998	101.23	1.23%	2006	119.46	2.21%
1999	102.41	1.17%	2007	122.04	2.17%
2000	104.65	2.18%	2008	126.12	3.34%
2001	107.17	2.41%	2009	126.52	0.32%
2002	109.61	2.27%	2010	128.56	1.61%
2003	111.93	2.12%	2011	132.07	2.72%
2004	114.37	2.18%	2012	135.37	2.50%

SOURCE: TRADINGECONOMICS.COM | EUROSTAT

Figure 44: Average Percent Inflation in Europe from 1997

Similarly, this methodology can be extended to estimate the annual maintenance and upkeep expenses of the redesigned bogeys. Train set maintenance costs were calculated to be 25 percent related to the carbody, 50 percent to mechanical systems, and 25 percent miscellaneous. This ratio is based on industry expert interviews which indicated the relatively higher cost of maintenance of mechanical systems, as they require stringent and frequent preventive tasks to meet safety requirements. Baumgartner's analysis estimates the economic life of bogies to be 25 years and their periodic maintenance to be on the order of EUR €0.3 per vehicle per km (Baumgartner, J. P., 2001). This relatively high cost is because many of the maintenance tasks require the carbody to be lifted to provide access to the bogies (Connor, P., 2019). A typical high-speed train may travel roughly 1,000 miles per day (i.e., average return trip distance for two popular high-speed rail tracks—California High Speed rail and Northeast Corridor track) and may run with 85 percent uptime (Baumgartner, J. P., 2001). Using these assumptions, the annual upkeep and maintenance cost of bogies can be estimated as $660,000 per train. The increase in maintenance costs for bolsterless bogies, compares to conventional, bolstered bogies, is estimated to be 10 percent (Orlova, A., Savushkn, R., Boronenko, I., Kyakk, K., Rudakova, E., Gusev, A., Fedorova, V., & Tanicheva, N., 2020) and is related to the traction transfer device and anti-yawing damper (see Figure 43). Thus, the increase in maintenance costs per year for applying bolsterless bogies to high speed train sets is estimated to be $66,000.

7.1.2 Aerodynamic Improvements

The impact of aerodynamic noise specific to high speed rail applications encourages the adoption of body and pantograph modifications. Each of these improvements provides opportunity for as much as a 7 to 8 dB(A) reduction in SPLs. In the case of skirts, the costs to retrofit existing trainsets (e.g., those installed on the Denver and Portland light rail systems) have been estimated at roughly US $10,000 per vehicle (Transportation Research Board, 1997). By considering the size of these vehicles, with the assumption of a 1 m (3.28 ft.) skirt height on both sides, allows the approximation of installation costs of $170 per square meter. Extrapolating this cost to implement on a Siemens Velaro (Siemens AG, 2005) trainset that has eight-railcars of 25 m (82.0 ft.) length each, gives a cost per trainset of $68,000. Further, it is expected that similar applications would be required for pantograph fairings and from supplier data sources, a conservative projection of pantograph area would be 17.5 square meter (188.4 square feet) (STEMMANN-TECHNIK GmbH, n.d.) (Toyo DenkiI Seizo K.K., n.d.) yielding a cost of $3,000 per pantograph. This can then be extended to the full trainset as $18,000, once again using the Siemens Velaro as a representative trainset.

Figure 45: Siemens ICE4 Train with Aerodynamic Improvements

Additional aerodynamic noise mitigation can be accomplished by providing uninterrupted, smooth exterior surfaces on the train bodies, and by using window structures that are flush with the side panels, especially those with fixed (non-opening) windows. When applied individually, smooth exterior surfaces have the potential to reduce high speed train noise by as much as 14 dB(A) in certain applications, while window structures can provide noise reduction benefit of approximately 7 dB(A). These improvements have high associated costs and are typically considered for purchase only when new train sets are specified.

Another key aerodynamic improvement that can help reduce noise from a high-speed train is the inter-car gap seals. By reducing vortex shedding from these seals and improving airflow from one coach to the other, smoothly enclosing the inter-car cavities, a roughly 4.5 dB(A) noise reduction can be expected. The cost of this specific improvement can be estimated relative to a surrogate application at Hong Kong Mass Transit Railway (MTR). For this surrogate application, a material was used that would meet requirements of the inter-car gap seal. On the Hong Kong trains, the material was used as an inflatable door seal, where inflatable seals were installed on the doors to reduce noise in the compartments (Lee, A., 2013). Although this application is not identical to high speed train inter-car gap seals, it is assumed that a similar type of polymer will be implemented. Further, it is assumed that the surface area of inflatable seal required to seal six doors on each light rail vehicle passenger coach is approximately equal to the surface area required to seal the gap between two coaches.[3] Thus, for this project, HK $200,000,000.00 was estimated for 90 trains in 2013. Adjusting for an average inflation of 3 percent for Hong Kong (Trading Economics, 2019) and using an average exchange rate of US $0.1277 per HK$ (OFX, 2017), the investment cost for putting improved inter-car gap seals on one train is roughly $330,000.00. The annual maintenance cost for these seals is taken as negligible, but the life of the seals is roughly 15 years, and so they will need to be replaced during the life of the train.

7.1.3 Vehicle Underbody and Wheels

Improvements to the vehicle underbody and wheels can also help reduce noise at the source. A key method identified for this category is disk brakes (see Figure 46), with the potential to reduce noise by as much as 10 dB(A). Due to the large noise benefit, this feature has become quite popular with high speed applications and most modern train sets are now equipped with disk brakes.

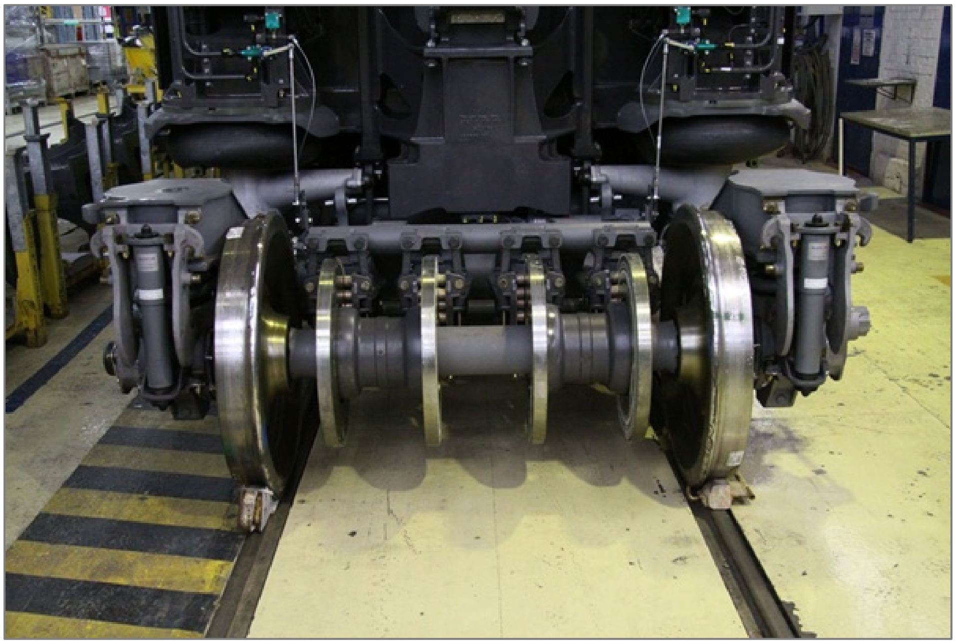


Figure 46: TGV Disc Brakes

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[3] For the light rail vehicles, the dimensions of the doors are 8.54 ft. high x 6.12 ft. wide and there are six doors per vehicle (three each side). The seal material is attached to the car frame and has a circumference of 34.5 inches (2.88 ft.). Thus, the surface area of the material required for the light rail door seals is [(8.54 x 2) + 6.12] x 2.88 x 6 doors = 401 square feet. For the high-speed train, the body height is 11.09 ft. and the body width is 16 ft. The inter-car gap is 2.5 ft. amount of material required for five inter-car gap seals is [(11.09 x 2) + 16] x 2.5) x 5 gaps = 477 square feet (based on six-unit train).

Figure 47: Wheel Dampers and Absorbers

Implementation of spin-slide controls can provide a host of benefits to high speed rail applications. These systems reduce wear to train wheels by improving braking efficiency, thus leading to a noise reduction of about 6 dB(A), but also thereby decreasing the associated maintenance costs for fixing flat spots and surface roughness. Since spin-slide control is currently incorporated into most new high-speed train sets and not broken out as a separate cost item, another approach determined the cost of retrofitting this system to existing trains. A conservative estimate can be taken as $10,000/car from Eastern Rail Transit System data. This is for a typical railcar with eight wheels, and the reference suggests a potentially higher cost for articulated trains (adjacent cars sharing a bogie). Thus, extrapolating to an eight-railcar train suggests a total system investment of roughly $80,000. Additionally, an annual maintenance cost of $3,200 can be expected due to material wear and associated labor, with a useful life of 30 years or more (Transportation Research Board, 1997).

Various forms of train-based noise absorbers have been shown to yield a decrease of 3–5 dB(A) in passby sound tests. Simple under-car noise absorbing assemblies have associated costs between $10–15 per square feet for glass fiberboard, which in operation, could last for upwards of 30 years (Transportation Research Board, 1997). In the case of an application for the Velaro trainset, taking a simplistic plan view of area at 6,500-square feet, the investment would be approximately $81,000 for under-car noise absorbing materials, though this estimate can be much larger for highly complex underbody geometries. Note that some literature sources recommend under-car noise absorption to be paired with aerodynamic skirts to provide the maximum benefit (Transportation Research Board, 1997). Wheel noise absorbers offer additional benefits (see Figure 47). The cost of application for these in-wheel noise absorption systems has been reported by multiple sources to be in the range of $3,900–$9,200 per wheel. For the current study, an estimate of $4,600 for noise absorbing wheel systems was selected which then extrapolated to eight wheels per car and eight cars per train, can yield an estimate of $294,000.00 per train. In terms of maintenance, the life of such systems can be assumed to be 20 years with literature sources suggesting an annual investment of $460 per wheel for a trainset completing 80,000 miles/year (Royal HaskoningDHV, 2013) (Hemsworth, B., 2008), or $3,200 per train.

7.1.4 Wheel Rail Interface

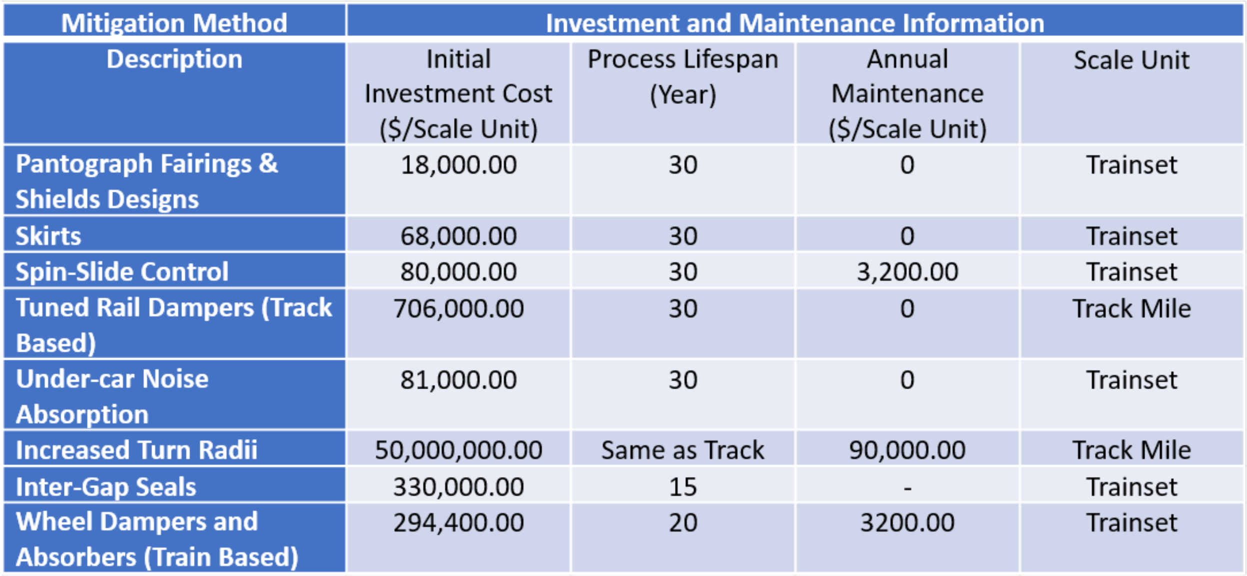
Figure 48: Tuned Rail Dampers

A significant portion of train noise can be attributed to the wheel-rail interface. Often, a small misalignment between a wheel and rail—something not uncommon with short radius turns or directional changes in track routing—results in high noise emissions. A substantial decrease of about 10 dB(A) can be achieved with an increased turn radius, specifically to reduce wheel squeal. However, in most cases, it may not be feasible to alter the track radius due to nearby topography, features, land use, etc. To provide an estimate of the costs associated with this approach, details for the track topography are required, as a difficult construction terrain can lead to a six-times increase to the overall cost of implementation. For example, a double-track arrangement typically costs approximately $20,000,000–$130,000,000 per mile, but in extreme circumstances this can even reach $160,000,000 (such as for the UK HS2 line) without even considering the requirements for tunnels or bridges. For the purposes of this study a rough estimate of $50,000,000 per mile was used (Gattuso, D., & Restuccia, A., 2013) (Attina, M., Basilico, A., Botta, M., Brancatello, I., Gargani, F., Gori, V., Willhelm, F., Menting, M., Odoardi, R., Piperno, A., & Ranieri, M., 2018) (Trabo, I., Landex, A., Nielen, O. A., & Schneider-Tili, J. E., May 2013). It is also worth noting that any increase to track length will lead to additional maintenance costs. An approximation for maintenance of standard double track is about $90,000 per mile across the lifetime (Zarembski, A. M., & Cikota, J. F., 2008).

Tuned dampers and absorbers (see Figure 48), as fitted directly to the rail, provide another method to reduce passby noise emissions by as much as 6 dB(A). From a cost perspective, there is some inconsistency between European and North American sources. One source suggests costs as high as $863,000 per mile for a double track[4] (Hemsworth, B., 2008), while another suggests around $422,000/mile (Transportation Research Board, 1997). Yet another source, from the UIC, uses actual data from a German train line which had a cost of $832,000 per mile (Scossa-Romano, E., & Oertli, J., October 2012). From these points of reference, an average value can be calculated as $706,000 per mile, which is used for the current study. Maintenance would be mostly negligible, as any required mechanical tightening could be readily amortized into normal track way upkeep (Transportation Research Board, 1997).

Table 51 summarizes the cost analysis of costs for sound reduction methods applied at the source.

Table 53. Summary of Cost Analysis for Methods Applied at the Source



Mitigation Method	Investment and Maintenance Information			
Description	Initial Investment Cost ($/Scale Unit)	Process Lifespan (Year)	Annual Maintenance ($/Scale Unit)	Scale Unit
Pantograph Fairings & Shields Designs	18,000.00	30	0	Trainset
Skirts	68,000.00	30	0	Trainset
Spin-Slide Control	80,000.00	30	3,200.00	Trainset
Tuned Rail Dampers (Track Based)	706,000.00	30	0	Track Mile
Under-car Noise Absorption	81,000.00	30	0	Trainset
Increased Turn Radii	50,000,000.00	Same as Track	90,000.00	Track Mile
Inter-Gap Seals	330,000.00	15	-	Trainset
Wheel Dampers and Absorbers (Train Based)	294,400.00	20	3200.00	Trainset

7.2 Cost Analysis for Methods Applied Along the Path

The second category of noise reduction methods includes sound barriers, interruption of the sound path, and modifications to the ballast and track supports.

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[4] €400,000/km highest estimate for year 2008 x 1.14 (inflation rate 2008 to 2019) x 1.18 (€/$) x 1.6093 km/mile = $863,000

7.2.1 Sound Barriers

Figure 49: Sound Barriers at Edge of Right-of-way

As mentioned in Section 6.2.1, there are significant variations to the way sound barriers are implemented to reduce noise transmission from passing trains. Height is a key factor influencing cost. Concrete structures with only minor modifications for increased sound attenuation (e.g., sound absorbing panels or surface geometry) are the most prevalent and effective type of barriers used in the rail industry. A review of multiple sources indicates that construction costs, likely with some minor influences due to local labor and material considerations, would cost approximately $1,840,000 per mile (Hemsworth, B., 2008). These costs are for a 2 m (6.56 ft.) high barrier capable of achieving upwards of 10 dB(A) noise reduction if placed close to the track. In addition to a concrete barrier impeding, reflecting and, to a lesser extent, absorbing train noise emissions, it is common to apply additional sound absorption material on the track-facing side of the structure. This application can yield an additional decrease in noise transmission of approximately 8 dB(A). The literature search indicates that this is achievable at a cost of $10 per sq.ft. or, in keeping consistent with the 2 m barrier size, $340,000 per mile (Transportation Research Board, 1997). For lifecycle considerations, both the concrete barrier and the sound absorption material are reported to have lifespans upwards of 30 years (Transportation Research Board, 1997) (Betonwerk Rieder GmbH, 2016). Note that the values above increase to $3,680,000 per mile and $680,000 per mile for implementation on both sides of a track. For this study, the assumption that sound barriers would typically be used in sections of the track with high population densities and thus will typically be implemented on both sides of the track.

Figure 50: Type of Tunnel Hood

Slightly less effective mitigation approaches include entrance hoods (see Figure 50) to minimize sonic boom effects when a train passes into a tunnel, and beam supports to reduce structure-induced vibration noise for steel bridges. Though these methods have the potential to reduce noise from passing trains by about 8 dB(A) and 6 dB(A) respectively, the effect is mostly realized only in the immediate vicinity of these specific structures and thus the cost incurred may be focused to specific residents impacted. The United States Government Accountability Office (GAO) conducted interviews with railroad officials to develop an understanding of the replacement and/or renewal costs for bridges and tunnels (United States Government Accountability Office, 2007). Although not specific to noise mitigation modifications, the GAO study evaluated tunnel ventilation and tunnel opening (or "daylighting") modifications having work scopes similar to those required to install tunnel hoods. The estimation of these tunnel opening modifications requires an investment of roughly \$3,000,000.00 each. This value has been corroborated with academic research and assumptions of similar cost to construct a double-track tunnel (Ishikawa, S., Nakade, K., Yaginuma, K., Watanabe, Y., & Masuda, T., 2010) (Gattuso, D., & Restuccia, A., 2013). Annual maintenance costs for this type of structure are typically minimal with a conservative estimated being roughly \$2,000 (Loubinoux, J. -P., Barron de Angoiti, I., & Cau, G., 2013). The same GAO study indicated that to upgrade a steel bridge to support heavier railcars, in this case up to 286,000 lbs., would require an investment of \$100,000.00. This may not be the same as the implementation of vibration-reduction beam supports but can be considered as a close approximation for the costs to retrofit existing bridge structures with strength and rigidity related modifications. It should be noted that the lifespan of both tunnel hoods and bridges would likely far exceed that of a railway track when considering renewal costs.

7.2.2 Noise Mitigation on Sound Path

Utilization of the shielding and natural dampening effects of earth and soil due to lowering the train track into a trench, can deliver up to a 6 dB(A) noise reduction. For a double track with standard center-to-center spacing and sleepers, the width of the trackway cut should be a minimum of 23 ft., and have a depth of approximately 12 ft. to provide adequate noise absorption (Conners, T., 2008) (Burlington North Santa Fe Railway Company, 2018) (Siemens AG, 2005). From these dimensions, the amount of material that would have to be removed to excavate the trench would be 53,000 cubic yards (41,300 cubic meters) and the estimated cost for implementing this mitigation strategy can be in the region of $210,000 per mile (with excavation at $0.14 per cubic-ft. from construction industry estimates) (URS Corporation, 2003). A further point of note on this method, based on interviews with various stakeholders, is that excavating trenches can interfere with existing infrastructure such as drainage, sewage, electrical, water, and gas lines. Thus, additional cost may be incurred to relocate the impacted infrastructure facilities, which are not included in the current analysis, as this is very project/region dependent and should be appropriately allocated into the full project cost as a contingency factor.

Buffer zones are another method of providing attenuation for railway noise. Determination of cost effectiveness for this approach is heavily dependent on the population density and land use in adjoining areas. This mitigation strategy is typically not applicable in highly built-up, urban environments such as cities. In the 2017 issue of the United States Department of Agriculture (USDA) report on farmland values, the estimated cost of the pacific coast (i.e., California, Oregon, and Washington) cropland was roughly $6,570 per acre and pasture land at $1,650 per acre. The value of cropland for the Northeast (i.e., Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont) was at $5,350 per acre and pasture at $3,420 per acre (National Agriculture Statistical Service, 2017). According to the Federal Transit Administration, the noise reduction from a 100-ft. buffer zone (i.e., on both sides of the track) is on the order of 5 dB(A) (Federal Transit Administration, 2018). Using the higher Northeast regional cost for the pasture land, it is possible to implement buffer zones for approximately $83,000 per mile of track length. Further, landscape maintenance of the buffer zone would cost $15,000 per mile (National Association of Realtors, 2017).

In some situations, it may not be possible to achieve target noise reduction levels through installation of accepted mitigation measures. In these cases, it may be necessary to relocate the track. An estimated reduction of 3–6 dB(A) can be expected when doubling the distance of a noise source to the receiver. An estimate of $50,000,000 per mile can be used as an investment cost for track construction and implementation for this approach (Gattuso, D., & Restuccia, A., 2013) (Attina, M., Basilico, A., Botta, M., Brancatello, I., Gargani, F., Gori, V., Willhelm, F., Menting, M., Odoardi, R., Piperno, A., & Ranieri, M., 2018) (Trabo, I., Landex, A., Nielen, O. A., & Schneider-Tili, J. E., May 2013). Section 7.1.4 contains more details, which discusses increasing turn radii as a noise mitigation approach, which similarly leads to increasing the length of the track. Additional maintenance, from increased track length, would add $90,000 per mile over the lifetime of a double track (Zarembski, A. M., & Cikota, J. F., 2008), as previously estimated.

7.2.3 Ballast and Track Support

The application of at-grade ballast for noise reduction is a common practice and considered a mature technology, having been utilized for this purpose long before implementation of high-speed trains. A study by the UIC benchmarked track longevity to understand maintenance and renewal costs: the reported median figure for reapplication of ballast was $920,000 per mile (Stalder, O., 2001). Norfolk Southern recommends a minimum ballast layer of 12 inches. Assuming a complete reapplication is not required and that a 1-inch top layer is added for acoustic sealing purposes, this figure can be reduced to approximately $150,000 per mile of double track. The lifespan of the ballast depends on track usage, i.e., both train passby frequency and train weight, but typically 2,500 passby events would occur before the required reapplication of top ballast (McGonigal, R. S., 2006). This would likely translate into a renewal interval of about 1 year for high-speed rail applications, even for a lightly used segment of railway.

Figure 51: Damping Material Above Slab Tracks

In addition to at-grade ballast, applying damping materials can absorb sound pressure pulses from passing trains. Placing the material above the slab track (see Figure 51) and under the track bed can also address the impact of ground-borne vibration. One approach to above track installations is a glass fiberboard encased in Tedlar®, protected by a powdered-coated metal sheet. Such a material would cost approximately $10 per sq. ft. (Transportation Research Board, 1997). For application to a double track, this would require an investment of $528,000 per mile and a projected lifespan of 20 years. For the sub-ballast matting, which is installed under the track and encompasses the sleepers (typically 2.6 m in width), has a projected cost of $133,000 per mile, again, for a double-track (Greilinger, 2018) (U.S. Department of Labor: Bureau of Labor Statistics, 2018). The high durability of the material results in a useful lifetime projection of more than 40 years (Wolfendale, 2018).

Table 52 summarizes the costs for the noise reduction method applied along the propagation path.

Table 54: Summary of Cost Analysis for Methods Applied Along the Path

Mitigation Method	Investment and Maintenance Information			
Description	Initial Investment Cost ($ / Scale Unit)	Process Lifespan (Year)	Annual Maintenance ($ / Scale Unit)	Scale Unit
Barriers at the Edge of the Right-of-Way	3,680,000	30	0	Track Mile
Sound Absorption Material on the Barrier, Facing the Noise Source	680,000	30	0	Track Mile
Tunnel Hoods	3,000,000	> Track	2,000	Tunnel
At-grade Ballast	150,000	1	0	Track Mile
Damping Materials at the Upper Surface of the Slab Tracks	528,000	20	0	Track Mile
Lower Elevation of the Tracks into Trenches	210,000	> Track	0	Track Mile
Creation / Acquisition of Buffer Zones between Source and Receiver	83,000	> Track	15,000	Track Mile
Bridge Beam Supports to Reduce Structure-induced Noise	100,000	> Track	0	Bridge
Increasing Distance from Source to Receiver	50,000,000	> Track	90,000	Track Mile
Resilient Padding for Slab Track	133,120	40	0	Track Mile

7.3 Cost Analysis for Methods Applied at the Receiver

The third category of noise reduction methods includes sound barriers and building modifications.

7.3.1 Sound Barriers at Receiver

New construction near railroad property offers the opportunity to implement foundation modifications for vibration and sound isolation. Installation of sub-foundation matting, such as Regupol® (see Figure 52), has been shown to provide a reduction of up to 15 dB(A) when properly installed. Assuming a flat-raft style foundation with 6 ft.-depth in conjunction with an average US house (Perry, M. J., 2014), a foundation vibration and implementing a sound isolation system for $14,000 based on a direct quotation from a supplier and fully-burdened labor rates (U.S. Department of Labor: Bureau of Labor Statistics, 2018) (Good, 2019).

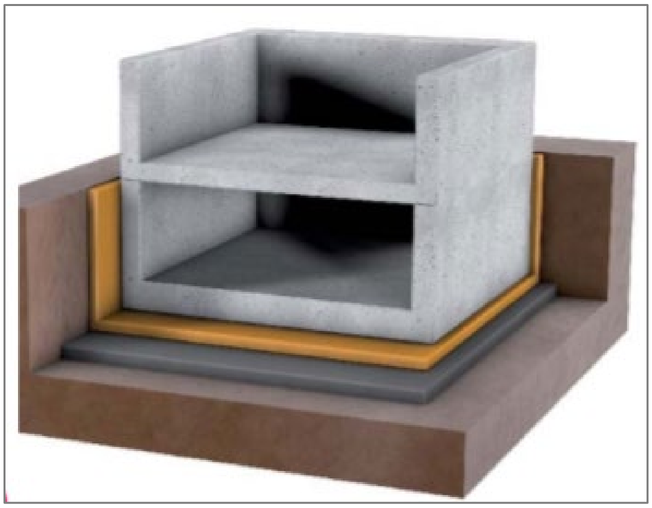


Figure 52: Example of Application of Sub-Foundation Matting

Trenches are used for the reduction of ground-borne vibrations and vibration-induced noise at receivers with the advantage of reduced negative visual impact compared to fencing or façade modifications. Unfortunately, the noise reduction benefit of this approach is relatively low, with an improvement of approximately 4 dB(A). In addition, the estimated cost incurred is to be \$57,000 per trench for a single building at a depth of 1.5 m. This depth has been demonstrated to provide a moderate reduction of vibration (de Vos, P., 2016). Further noise and vibration reduction may be possible with 4.5 m depths, albeit at much higher costs.

Another more simplistic method to reduce noise transmission at receivers is the installation of sound barriers on the property boundary facing the train line. This is much the same, from a cost perspective, as those installations discussed in Section 7.2.1 for sound barriers near the track. For a 2 m (6.56 ft.) high structure, it is likely that construction would fall in the region of \$1,840,000 per mile (Hemsworth, B., 2008) with minimal maintenance for a 30-year period (Transportation Research Board, 1997) (Betonwerk Rieder GmbH, 2016). However, note that in terms of effectiveness, sound barriers offer a far better return when used near the noise source (12 dB(A) at source vs. 8 dB(A) at receiver).

7.3.2 Building Modifications

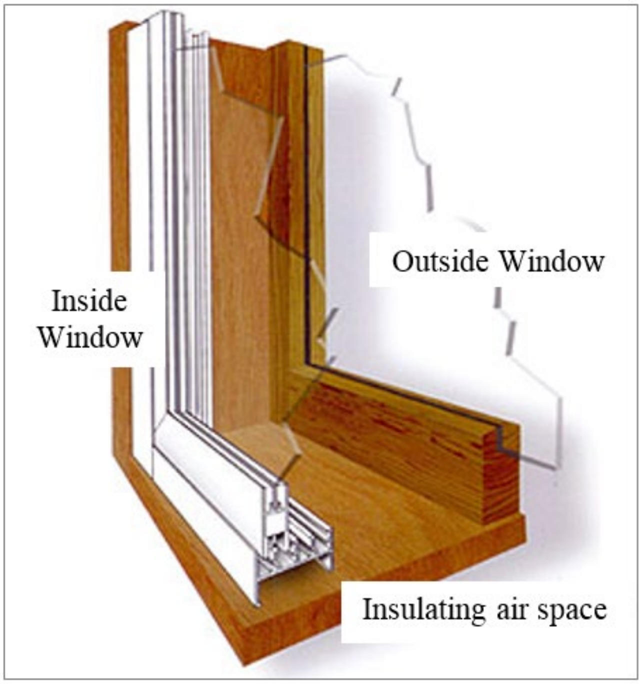


Figure 53: Example of Windows with 3-Inch Air Gap

As mentioned earlier, one of the most effective building modifications to reduce noise transmission at the receiver is the installation of double-glazed windows with a large 3–4” air gap between panes (see Figure 53). Installation of units with an outside-inside transmission class (OITC) rating of 25 provides a reduction of up to 20 dB(A) across a full spectrum of emission frequencies (Viracon, 2019). Such a unit, double hung and with adequate dimensions (48” x 48”), can be purchased for $500 from most large home improvement stores (Home Depot Product Authority, LLC., 2019) (Lowe's Companies, Inc., 2019). The cost of removal of the original frame and installation of the improved window can be $300/window (Craftsman Book Company, 2016). This corroborates with the cost estimated by the UIC, which suggests four insulated windows could be fitted for $2,500–$9,000 per building (Hemsworth, B., 2008). Researchers assume an average of eight windows per household resulting in a total cost of implementation of $6,400. The consensus on interval for replacement of these windows, in a vinyl finish, would be in the region of 30 years but this also somewhat depends on external environmental conditions (Ecoline Windows, 2019) (Feldco Factory Direct, LLC, 2019).

The research team investigated other at-receiver noise reduction approaches that provide a more modest decrease to noise. Caulking and sealing has been shown to provide a reduction of 6–7 dB(A). However, due to the low cost of implementation of approximately $500 per household, it does provide a large benefit with a relatively minimal investment (Craftsman Book Company, 2016). Note that this assumes a two-story residence with three external doors, eight windows, and ground to attic-level sealing (Acoustical Surfaces, Inc., 2019) (Perry, M. J., 2014). Researchers also investigated façade insulations as a means of noise reduction. A study in the Netherlands found that for a detached home, installation of such a feature would cost in the region of $17,000 with an estimated, amortized upkeep of roughly $500 per year (Royal HaskoningDHV, 2013). A literature search was not able to define the useful life for this method.

Layered walls incorporating a cavity between two interior faces, often with an embedded sound absorbing material, can provide performance increases over a solid partition. Simple comparison of a single-layer brick wall and a double-layer brick wall shows as much as a 10 dB(A) reduction at an approximate cost increase of $1.80 per square foot (U.S Department of Transportation - Federal Highway Administration, 2017). Applications are limited to new construction to be financially viable. For an average-sized, detached house in the US, this would result in an incremental investment of $2,800 (Perry, M. J., 2014). Table 55 summarizes the costs for noise reduction method applied along the propagation path.

Table 55: Summary of Cost Analysis for Methods Applied at the Receiver

Mitigation Method	Investment and Maintenance Information			
Description	Initial Investment Cost ($ / Scale Unit)	Process Lifespan (Year)	Annual Maintenance ($ / Scale Unit)	Scale Unit
Windows with a 3 Inch Air Gap	6,400	30	0	Household
Improved Foundation for Vibration and Sound Isolation	14,000	> Track	0	Household
Sound Barriers on Property Boundary Facing Noise Source	1,840,000	30	0	Track Mile
Caulking and Sealing Gaps	500	20	0	Household
Façade Insulation: Low Acoustical Transmission Windows and Walls	17,000	> Track	500	Household
Layered Walls with Hard and Soft Materials to Improve Noise Attenuation	2,800	> Track	0	Household
Vibration-breaking Trenches	57,000	> Track	0	Household

7.4 Summary of Lifetime Costs for Selected Noise Reduction Methods

To apply cost data to specific trains and routes, the development of a normalized method, known as a unit life-cycle cost ($ per dB of noise reduction), was developed. This unit cost is in reference to each track section based on several parameters (e.g., length, number of tunnels, impacted households, and land use designation). The unit lifecycle was employed in the identification of the most effective methods to achieve target noise reductions.

The calculation of the estimated lifecycle cost occurred for each noise reduction method based on estimated values for useful life, with an assumption that the application was applied throughout the average life of a track (assumed to be 35 years) (Campos, J., de Rus, G. J., & Barron, I., 2007). The researchers assumed that an annual maintenance cost is be incurred each year. To simplify the analysis, this project ignored the effects of inflation and time value of money. Table 56 provides a summary of the calculated lifecycle costs for all selected methods, along with an estimate of dollars per dB of expected noise reduction.

Note that the dollars per dB estimate can vary significantly depending upon which scaling method is employed. Using sound barriers and foundation improvements as an example, the cost using the “Track Mile” scaling factor for sound barriers is approximately $2,000,000 per track mile, or $270,000 cost per dB of noise reduction for that length of track. For improved foundations, the cost is $14,000 per house with an approximately $900 per dB of noise reduction for each house. The actual cost will depend upon the length of the track number of houses. Thus, the cost per dB estimate must always be referenced to the scale unit for comparison purposes.

The costs of applying the identified top 30 mitigation methods summarized in Table 56 are in the order of noise reduction effectiveness (see Section 6.4).

Table 56. Summary of Lifecycle Cost and $/dB for Selected Methods

Mitigation Method			Lifecycle Cost		
Location	Description	Noise Reduction (dB)	Total Lifecycle Cost / Unit ($)	Scale Unit	Cost Reduction ($)/ dB
At the Source	Pantograph Fairings & Shields Design	7	21,000	Trainset	3,000
	Skirts	8	79,333	Trainset	9,917
	Spin-slide Control	6	205,333	Trainset	34,222
	Tuned Rail Dampers (Track Based)	6	910,000	Track Mile	151,667
	Under-car Noise Absorption	5	94,500	Trainset	18,900
	Increased Turn Radii	10	53,150,000	Track Mile	5,315,000
	Inter-car Gap Seals	4.5	770,000	Trainset	171,111
	Wheel Dampers and Absorbers (Train Based)	3	627,200	Trainset	209,067
Along Path	Barriers at the Edge of the Right-of-Way	10	4,293,333	Track Mile	429,333
	Sound Absorption Material on the Barrier, Facing the Noise Source	8.5	793,333	Track Mile	93,333
	Tunnel Hoods	8	3,070,000	Tunnel	383,750
	At-grade Ballast	3	5,250,000	Track Mile	1,750,000
	Damping Materials at the Upper Surface of the Slab Tracks	2	924,000	Track Mile	462,000
	Lower Elevation of the Tracks into Trenches	6	210,000	Track Mile	35,000
	Creation / Acquisition of Buffer Zones between Source and Receiver	5	608,000	Track Mile	121,600
	Bridge Beam Supports to Reduce Structure-induced Noise	6	100,000	Bridge	16,667
	Increasing Distance from Source to Receiver	4.5	53,150,000	Track Mile	11,811,111
	Resilient Padding for Slab Track	3.5	116,480	Track Mile	33,280
At Receiver	Windows with a 3 Inch Air Gap	17.5	7,467	Household	427
	Improved Foundation for Vibration and Sound Isolation	15	14,000	Household	933
	Sound Barriers on Property Boundary Facing Noise Source	8	2,146,667	Track Mile	268,333
	Caulking and Sealing Gaps	6.5	875	Household	135
	Façade Insulation: Low Acoustical Transmission Windows and Walls	15.5	34,500	Household	2,226
	Layered Walls with Hard and Soft Materials to Improve Noise Attenuation	3.5	2,800	Household	800
	Vibration-breaking Trenches	4	57,000	Household	14,250

8. Applying Methods on Representative Simplified Tracks

Applying the top 30 train passby noise mitigation methods and associated implementation/operating costs assisted in representing US high-speed rail tracks. The two representative routes are based on: 1) the CAHSR system and 2) the Northeast Corridor High Speed Rail (NEC HSR) segment. The following are the calculation of three comparison parameters: a) total cost of implementation along the track (i.e., in US dollars), b) $ per dB(A) (i.e., for the average noise reduction expected), and c) $ per dB(A) per residents impacted (i.e., based on the total residents impacted around the track).

Researchers chose the two representative track systems because they exhibit significant variations in geometry, adjacent land use designations, construction status, and governance. The CAHSR corridor is currently under construction, with the first segment, located between Merced and Bakersfield, CA, scheduled to begin operations during 2021 (US High Speed Rail Association, 2018). On the other hand, the NEC has been in existence since the 1830s, with continual upgrades and improvements over the years to increase speed and modernize the track (Wikipedia, n.d.). Due to the many differences, the most cost-effective noise mitigation methods vary significantly between the two systems. The reason for this current study was to gain insight into the approaches, costs, and implementation of high-speed rail noise reduction projects. The analysis only addresses the methodology of selecting and applying noise mitigation methods on rail lines. *The analysis does NOT attempt to estimate or define the true cost of applying noise mitigation methods for existing or planned actual high-speed rail lines, which would require a much deeper analysis of the route including specific topographical and other external factors that are outside the scope of the current study*.

8.1 Methodology for Estimating Costs of Compliance

Table 56 summarized the cost estimates. Each method includes a total lifecycle cost per scale unit (e.g., train set, track mile, tunnel, bridge, and building). To enable an estimation of cost of compliance along various track segments, researchers divided all train-related improvement costs by the length of track segments to amortize the costs per mile of track. This allows a consistent comparison of cost drivers across various track segments.

8.1.1 Selection of Noise Reduction Target

From the train noise analysis included in Section 2 of this report, researchers found that currently-available train sets exhibit passby noise levels, based on the US measurement procedures, that range from 81 dB(A) at 160 mph to 97 dB(A) at 220 mph. Also, the typical nighttime and daytime immission noise targets, based on EU, China, Japan, and US local and State regulations, are in the range of 60 dB(A) during the nighttime (i.e., as integrated over the corresponding time period and thus dependent upon the number of passby events) to 70 dB(A) during the daytime period, depending upon land use categories. Thus, a selected target noise reduction of 20 dB was the target for the cost analysis study and is related to achieving the identified receiver immissions noise levels for a typical number of passby events during the specified time categories.

8.1.2 Procedures for Estimating the Cost of Compliance

Researchers identified the key track features for the two selected representative routes. Utilizing these features assisted with scaling the unit costs and estimating the total cost of compliance. Key features of the estimation process are:

1. *Track route and sections*: Identify sections of the track where noise reduction methods can be applied uniformly. The research team divided sections based on representative cities/towns adjacent to the tracks, population densities adjacent to the track, and land use designations. For both representative simplified tracks, the designations for densely populated sections were D1, D2, D3, etc., while the designation for sections with sparse population densities were S1, S2, S3, etc.
2. *Track length*: Defining the lengths of various sections assisted in facilitating scaling of methods applied on a track per mile basis (i.e., including train improvements, which were amortized over the length of track).
3. *Number of tunnels*: This is required for the assessment of tunnel hoods. Calculating the exact number of tunnels across the entire length of track requires detailed track maps and is out of scope for this study. Researchers made an estimate on representative track sections in California and the Northeast regions.
4. *Length of tunnels*: The research team based the estimated total length of tunnels for each designated section on the methodology described in item 3. Subtracting this length from the length of track while applying track-based noise mitigation methods as tunnels, while having separate track construction constraints that are different from open ground-based tracks. Additionally, noise reduction is less applicable in tunnels as the tunnel structure itself can provide noise attenuation.
5. *Number of bridges*: This is required for assessment of beam supports to reduce induced structural noise. As with item 3 above, researchers based the estimation of this number on representative track sections in California and the Northeast regions.
6. *Length of bridges*: The research team based the estimation of the total length of bridges for each designated section on the methodology described in items 3 and 5. Like tunnels, researchers subtracted this distance from each section track length while applying track-based noise mitigation methods, because bridges have separate track construction constraints that are different from open ground-based tracks.

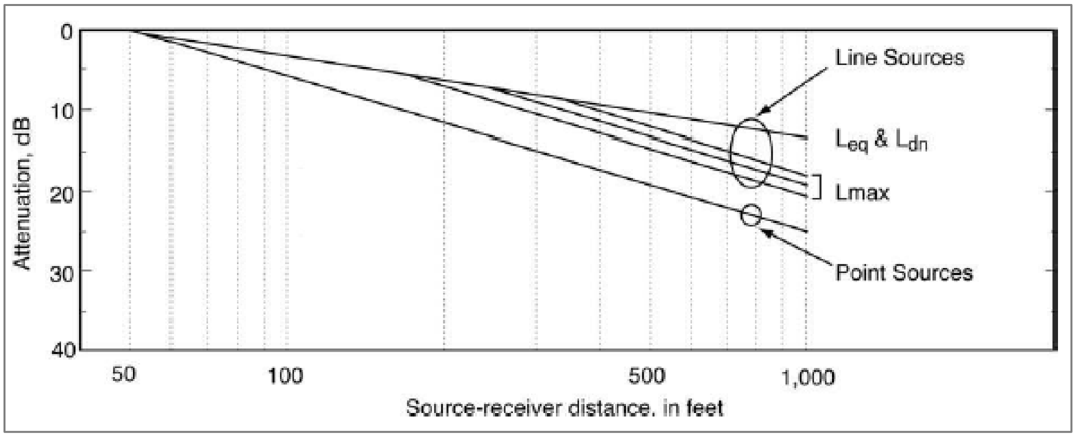
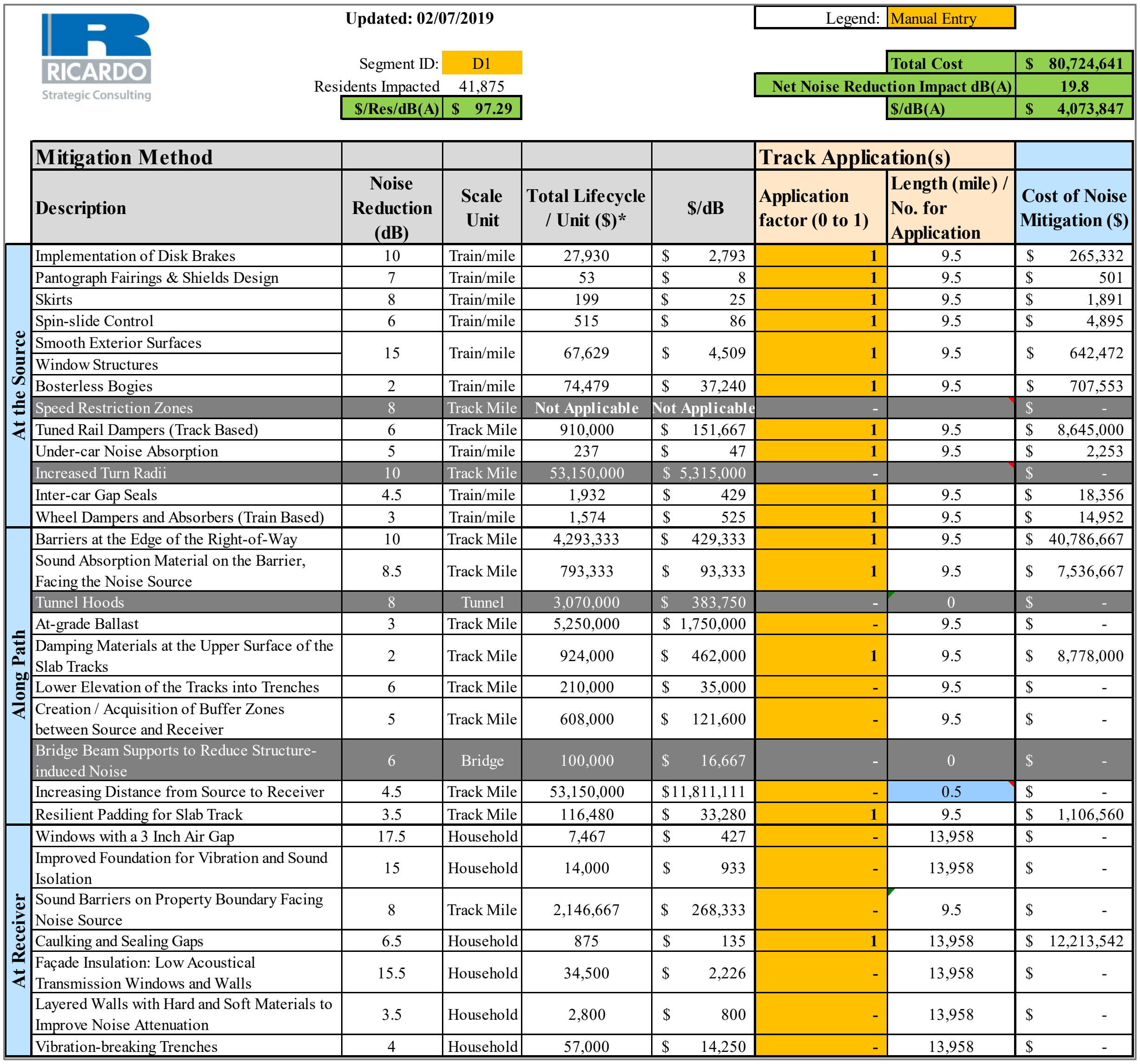


Figure 54: Natural Sound Attenuation Chart

7. *Population density and residents/households impacted*: The current FRA and EPA regulations for noise emissions from passing trains is 90 dB(A) $L_{max(slow)}$ with the microphone located at a distance of 100 ft. from the track centerline and at an elevation of 4 ft. above the top of rail (Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S., 2021). Some train sets emit SPLs higher than this value as discussed in Sections 2 and 3. Based on the natural noise attenuation chart prepared by the Federal Transit Administration (Federal Transit Administration, 2018) (see Figure 54), attenuation of 10 dB due to distance would require open areas having widths over 170 ft. and attenuation equal to 20 dB would require a separation distance of over 0.25 miles. Using the population density charts for the areas adjoining the tracks allowed researchers to calculate the number of residents living within 0.25 miles on each side of the track segment. It is possible, based on train type and speed, residents within this zone could experience noise levels that exceed US regulations. For the current example, researchers established a target noise reduction of 20 dB. The number of affected houses can be estimated by dividing the number of people in the identified zone by three (average persons per house) (Statista, 2019).



Updated: 02/07/2019

Legend: Manual Entry

Segment ID: D1
Residents Impacted 41,875
$/Res/dB(A) $ 97.29

Total Cost $ 80,724,641
Net Noise Reduction Impact dB(A) 19.8
$/dB(A) $ 4,073,847

	Mitigation Method					Track Application(s)		
	Description	**Noise Reduction (dB)**	**Scale Unit**	**Total Lifecycle / Unit ($)***	**$/dB**	**Application factor (0 to 1)**	**Length (mile) / No. for Application**	**Cost of Noise Mitigation ($)**
At the Source	Implementation of Disk Brakes	10	Train/mile	27,930	$ 2,793	1	9.5	$ 265,332
	Pantograph Fairings & Shields Design	7	Train/mile	53	$ 8	1	9.5	$ 501
	Skirts	8	Train/mile	199	$ 25	1	9.5	$ 1,891
	Spin-slide Control	6	Train/mile	515	$ 86	1	9.5	$ 4,895
	Smooth Exterior Surfaces	15	Train/mile	67,629	$ 4,509	1	9.5	$ 642,472
	Window Structures							
	Bosterless Bogies	2	Train/mile	74,479	$ 37,240	1	9.5	$ 707,553
	Speed Restriction Zones	8	Track Mile	Not Applicable	Not Applicable	-		$ -
	Tuned Rail Dampers (Track Based)	6	Track Mile	910,000	$ 151,667	1	9.5	$ 8,645,000
	Under-car Noise Absorption	5	Train/mile	237	$ 47	1	9.5	$ 2,253
	Increased Turn Radii	10	Track Mile	53,150,000	$ 5,315,000	-		$ -
	Inter-car Gap Seals	4.5	Train/mile	1,932	$ 429	1	9.5	$ 18,356
	Wheel Dampers and Absorbers (Train Based)	3	Train/mile	1,574	$ 525	1	9.5	$ 14,952
Along Path	Barriers at the Edge of the Right-of-Way	10	Track Mile	4,293,333	$ 429,333	1	9.5	$ 40,786,667
	Sound Absorption Material on the Barrier, Facing the Noise Source	8.5	Track Mile	793,333	$ 93,333	1	9.5	$ 7,536,667
	Tunnel Hoods	8	Tunnel	3,070,000	$ 383,750	-	0	$ -
	At-grade Ballast	3	Track Mile	5,250,000	$ 1,750,000	-	9.5	$ -
	Damping Materials at the Upper Surface of the Slab Tracks	2	Track Mile	924,000	$ 462,000	1	9.5	$ 8,778,000
	Lower Elevation of the Tracks into Trenches	6	Track Mile	210,000	$ 35,000	-	9.5	$ -
	Creation / Acquisition of Buffer Zones between Source and Receiver	5	Track Mile	608,000	$ 121,600	-	9.5	$ -
	Bridge Beam Supports to Reduce Structure-induced Noise	6	Bridge	100,000	$ 16,667	-	0	$ -
	Increasing Distance from Source to Receiver	4.5	Track Mile	53,150,000	$11,811,111	-	0.5	$ -
	Resilient Padding for Slab Track	3.5	Track Mile	116,480	$ 33,280	1	9.5	$ 1,106,560
At Receiver	Windows with a 3 Inch Air Gap	17.5	Household	7,467	$ 427	-	13,958	$ -
	Improved Foundation for Vibration and Sound Isolation	15	Household	14,000	$ 933	-	13,958	$ -
	Sound Barriers on Property Boundary Facing Noise Source	8	Track Mile	2,146,667	$ 268,333	-	9.5	$ -
	Caulking and Sealing Gaps	6.5	Household	875	$ 135	1	13,958	$ 12,213,542
	Façade Insulation: Low Acoustical Transmission Windows and Walls	15.5	Household	34,500	$ 2,226	-	13,958	$ -
	Layered Walls with Hard and Soft Materials to Improve Noise Attenuation	3.5	Household	2,800	$ 800	-	13,958	$ -
	Vibration-breaking Trenches	4	Household	57,000	$ 14,250	-	13,958	$ -

Figure 55: Sample Worksheet to Estimate Costs for Representative Track Sections

Notes:

1. Speed restriction zones were not applied on any section as indicated in Section 7.1.1.
2. Increased turn radii method was not applied on any section as these representative simplified high-speed tracks were assumed to already have a larger radius to allow trains to turn at higher operating speeds.
3. Tunnel hoods and bridge beam supports are shown as inactive in this sample worksheet as they may only be applied on some sections where bridges and tunnels are assumed to exist.

The costs associated with attaining the target noise reductions included determining the applicability of available noise mitigation methods for each representative track section. Special attention was given to achieving expected noise mitigation results in the most cost-effective way.

This was done by reviewing the $ per dB(A) for each method (see Table 54) and applying lower cost methods first and then moving to more expensive methods until the target reduction is met.

Figure 55 is a sample worksheet illustrating the application of noise mitigation methods to a representative track section. The research team utilized the spreadsheet by selecting the various noise reduction methods (i.e., activated by placing a "1" in the "Application Factor" column) to achieve the target noise reduction, while minimizing the "Total Cost" and "$ per dB(A) per resident" for the subject track section. As each method is applied, the worksheet calculates in real-time, the change to "Total Cost" and "Net Noise Reduction Impact dB(A)." This enables efficient decision-making to select the most effective combination of methods for any section. This analysis only attempts to discuss the methodology of selecting and applying noise mitigation methods on various representative sections. *The analysis does not attempt to estimate or define the true cost of applying noise mitigation methods onto existing or planned actual high-speed rail lines, which would require a much deeper analysis of the full length of the track including specific topographical and other external factors that are outside the scope of this study*.

For the spreadsheet analysis, researchers amortized the cost and noise reduction impact of applying the noise reduction improvements into each designated track section. This enables a consistent estimation of $ per dB(A) and $ per dB(A) per resident across the entire route (all track sections). For this reason, the costs of onboard, train-related improvements have been divided by the length of the track section. The noise reduction impact of the train-related improvements is added to the other "per mile" reductions to determine the total noise reduction expected for each section. The assumption is that the track will not be relocated to increase the distance between the track centerline and nearby occupied structures. Thus, if performing an evaluation occurred regarding increasing the distance to nearby dwellings, the additional distance is to be added on both sides of the representative track.

As described in Section 3, Section 4, and Table 46, the noise reductions associated with each modification are not arithmetically additive. This is because SPLs are expressed in the logarithmic units of decibels (dBs). Thus, to add SPLs and cumulative reductions, they need to be converted to the linear pressure unit of Pascals (Pa). The sums are performed in units of Pa and then converted back to dB as expressed in the following equation (Tontechnik-Rechner Sengpielaudio, n.d.):

$$L_{\Sigma} = 10 \cdot \log_{10}\left(10^{\frac{L_1}{10}} + 10^{\frac{L_2}{10}} + \cdots + 10^{\frac{L_n}{10}}\right) \text{ dB}$$

It is interesting to note that only sound pressures that are similar in order of magnitude to each other have a significant impact when added together. If sound pressures of dissimilar orders of magnitudes are added, the net resulting noise level would be very close to the higher sound pressure decibel level. It is due to this relationship that as observed in later discussion of the results that once a targeted noise reduction is achieved, including additional reduction methods (e.g., at much higher costs, based on the low-to-high cost approach) does not have a significant impact.

After completing all track section worksheets, the research team compiled results for individual segments to estimate the following parameters: the total cost of compliance for the representative simplified track; average noise reduction expected in dB(A) (i.e., calculated as a weighted average based on segment lengths); and the total residents impacted in the vicinity of the track which were $ per dB(A) for the track and $ per dB(A) per resident impacted for the representative simplified track. The research team also compiled methods applied on each representative section in a format that highlights similarities and differences across various track segments.

8.2 Representative Simplified Track for California

The initial segments of the CAHSR tracks are currently under construction in the State's Central Valley. The plan for the first phase route is to connect the Anaheim Regional Transportation Intermodal Center in Anaheim and Union Station in downtown Los Angeles with the Salesforce Transit Center in San Francisco (see Figure 56) (California High-Speed Rail Authority, 2019) in an estimated travel time of 2 hours and 40 minutes (Wikipedia, n.d.).

The plan for future extensions to the CAHSR project (Phase 2) are to connect the cities of San Diego (in the south) and Sacramento (in the north). Additionally, a connection to Las Vegas, NV, from Palmdale, CA, (i.e., where it can connect to the CAHSR track) is also planned by a private company named XpressWest. This will add another 230 miles to the route and would connect Las Vegas to major California cities. In September 2018, the Florida-based Brightline (i.e., involved with high speed rail projects in Florida) purchased all assets and rights for XpressWest (Wikipedia, n.d.).

8.2.1 Introduction to the CAHSR Corridor

The CAHSR project has been described as the most advanced application of high-speed rail in the US with plans to operate trains on dedicated, grade-separated tracks for the entirety of their route between San Jose and Burbank, with speeds of up to 220 mph (Wikipedia, n.d.). The San Francisco to San Jose and Los Angeles to Anaheim sections will be shared with local trains in a "blended system." Though the total length of the track from San Francisco to Anaheim is around 520 miles, the high-speed section between San Jose to Burbank is roughly 400 miles. With the addition of Phase 2, the total length of track from Sacramento to San Diego would exceed 800 miles. The expectation of the first operational section between San Jose and Bakersfield is to begin operations during 2027, while the expectation of the complete first phase is to be operational by 2033.

During February 2019, the governor of California announced a scaling back of this project due to various concerns related to cost overruns, construction delays and lawsuits by property owners and taxpayer groups (Varghese, 2019). At this time, the expectation is to continue construction on only 120 miles of the track from Merced to Bakersfield, while further work has been postponed on rest of the track until further notice (refer to Figure 56).

Figure 56: CAHSR Planned Statewide Alignment

8.2.2 Assumptions for a Representative Simplified Track

Researchers did not intend for the current study to produce detailed noise reduction cost analyses for either the California or NEC projects. Rather, the objective is to use macro level information available in the public domain to develop representative track models that can be used to evaluate the noise reduction methods selection process and to obtain an understanding of the relative costs and magnitudes that may be incurred while achieving noise reduction targets.

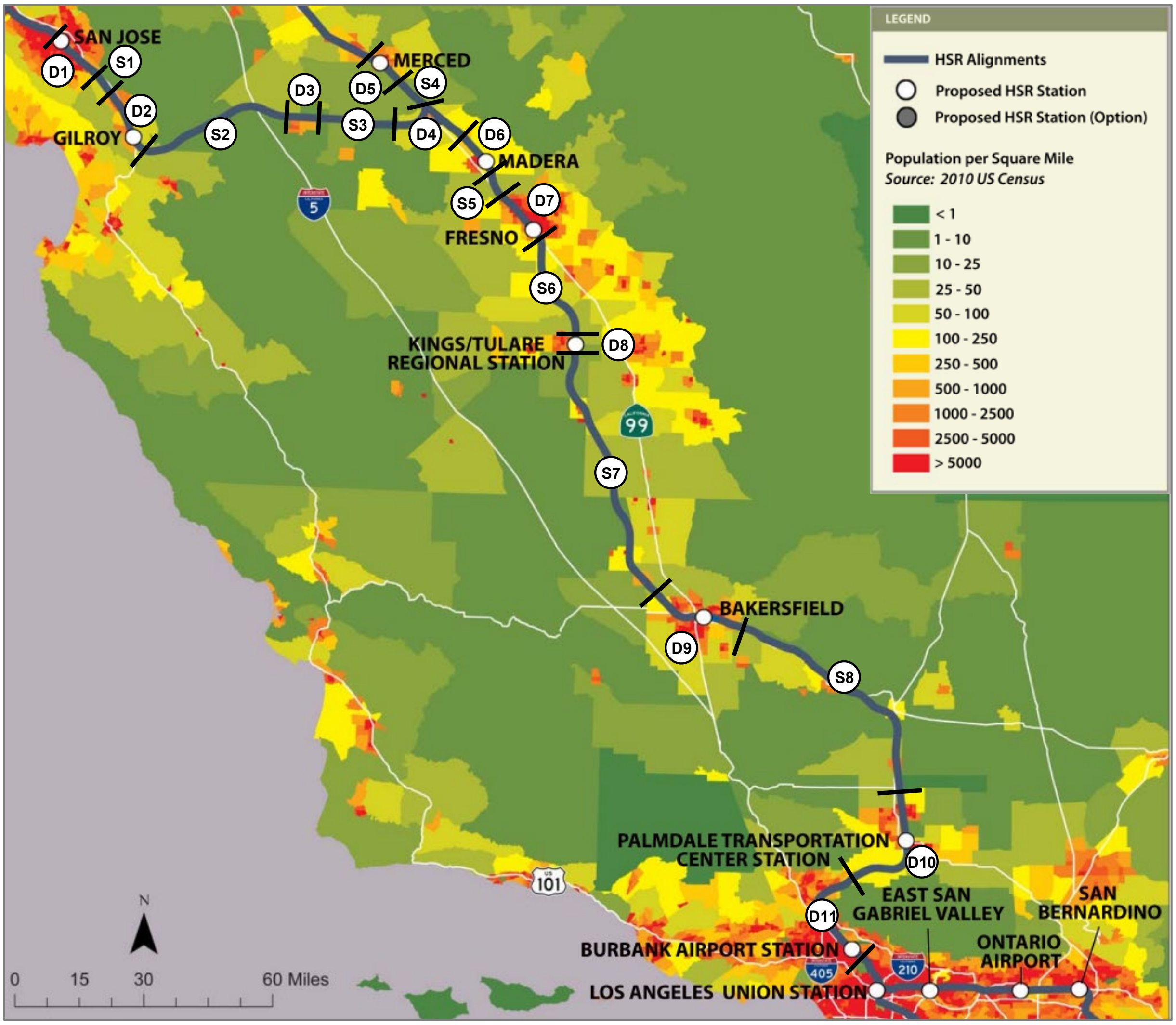


Figure 57: Representative Simplified Track for California with Assumed Sections

Public summary project files made available by CAHSR were employed during the current study to develop the representative track characteristics for the route sections located between San Jose and Burbank (California High-Speed Rail Authority, 2019). The research team evaluated these track sections using the spreadsheet-based cost estimating procedure to determine the most cost effect approaches to achieving target noise reductions. The CAHSRA documents include:

1. *Statewide maps* – provide an overview of the proposed route, along with a summary of topography and population densities along the route provided as a simplified heat map
2. *High-speed rail construction packages* – provide a summary for various phased sections of the track and their corresponding modernization/construction plans
3. *Project section maps* – provide between-station views of each segment of the HSR line. These maps are similar to the statewide maps but provide higher resolution of specific track details around the stations. For example, they include details of both underground and ground- level sections.

4. *Station maps* – provide more detail around stations including a satellite view of each station, planning boundaries, areas for consideration around pedestrian movement, and areas of consideration for excessive noise.

Table 57: Assumptions for sections of California track

Track Sub-Section ID	Length of Track (miles)	No. of Tunnels	Length of Tunnels (miles)	No. of Bridges	Length of Bridges (miles)	Residents Impacted	Households Impacted
D1 San Jose	10	0	0	0	0	41,875	13,958
S1 San Jose-Morgan Hill	8	0	0	0	0	213	71
D2 Morgan Hill-Gilroy	14	0	0	0	0	4,375	1,458
S2 Gilroy-Los Banos	41	0	0	0	0	1,000	333
D3 Los Banos	4	0	0	0	0	2,625	875
S3 Los Banos-Chowchilla	28	0	0	0	0	688	229
D4 Chowchilla-Madera	20	0	0	0	0	3,675	1,225
S4 Merced-Chowchilla	14	0	0	3	1	363	121
D5 Merced	3	2	1	0	0	925	308
D6 Madera	8	0	0	0	0	4,975	1,658
S5 Madera-Fresno	8	0	0	1	3	200	67
D7 Fresno	18	1	1	1	1	77,325	25,775
S6 Fresno-Visalia	22	0	0	2	5	1,438	479
D8 Visalia	6	0	0	1	2	12,000	4,000
S7 Visalia-Bakersfield	69	0	0	6	7	4,750	1,583
D9 Bakersfield	14	0	0	1	12	28,450	9,483
S8 Bakersfield-Palmdale	66	9	15	8	27	3,450	1,150
D10 Palmdale-Burbank	12	1	1	0	0	6,425	2,142
D11 Burbank-Los Angeles	35	5	25	7	2	46,750	15,583
TOTAL	400	18	43	30	60	241,500	80,500

Using these inputs and the methodology described in Section 8.1, the full length of track was divided into subsections. The subsections were chosen so each could be addressed by similar, consistent noise mitigation methods. Figure 57 describes these subsections. The California track was divided into 19 sections running from D1 through D11 for those assumed with a high population density of impacted residents, and from S1 through S8 for sections assumed with a lower density of impacted residents. Track sections assumed to be passing through cities like San Jose, Gilroy, Merced, Madera, Fresno, Kings/Tulare, Bakersfield, Palmdale and Burbank are marked as D sections since their adjoining population densities may exceed 5,000 persons per square mile. For sparse sections, such as those along stretches of the Central Valley, the adjoining population densities are much lower, in some cases less than 1 person per square mile and in others ranging from 100 to 1,000 persons per square mile.

Track features were defined for each segment to determine noise mitigation costs. Table 55 summarizes these features. Because most tracks in the CAHSRA system are relatively new, appropriate planning for crossings has been completed, and thus the assumption is that the cumulative lengths of tunnels and bridges are to be relatively higher than those for the NEC which occupies older rights-of-way and partially updated tracks. When the CAHRSA track passes through relatively smaller cities, the estimated number of impacted residents was determined to be on the order of 240,000 residents and 80,000 households.

8.2.3 Applying Noise Mitigation Methods on Segments

The spreadsheet program illustrated in Table 58 was used to evaluate the noise mitigation effectiveness and costs for each of the CAHSR track section to achieve a target noise reduction of approximately 20 dB(A). As noted above, the approach seeks the target noise reduction level while minimizing the total cost of implementation. In the case where the track passes through long stretches of rural areas, there are fewer constraints to which noise mitigation methods can be applied. This can be compared to the NEC representative track which passes through denser, long established urban and suburban areas, where it is much more difficult to re-route the track, relocate residents, change topography, etc. The specific methods applied for each assumed section can be seen in Table 58 where viable methods have been highlighted in green to enable quick comparison between similar sections.

As identified in Section 4, noise mitigation methods to be applied at the source are the most cost effective since they typically have a higher expected noise reduction, along with a lower cost per dB(A). Also, these methods impact all regions of the train route. The current analysis included all source-based reduction methods and excluded speed restriction zones and increased turning radii methods of noise reduction. The research team applied tuned rail dampers directly to the track and thus scaled with the length of the track. Their cost of $151,667 per dB(A) is also relatively high compared to the other methods to be applied along the path and at receivers. Thus, this method was only used in sections assumed to be densely populated, where the track length was shorter, and the high number of residents impacted made the cost of this approach acceptable.

The cost effectiveness of reduction methods applied along the noise path compared to methods applied at the receiver is dependent on the trade-off between the length of track and the number of residents impacted. For sections that are assumed to be very densely populated (D1 - near San Jose, D7 - near Fresno, D8 - near Kings/Tulare, D9 - near Bakersfield and D11 - near Burbank), the length of track is relatively short and thus applying noise barriers along the rail property boundaries was cost-effective. However, for other sections with longer track lengths, but lower assumed density of population adjoining the track, modifications at the receiver (i.e., in the form of windows with 3-inch air gap and caulking and sealing gaps in houses) was found to be more cost effective. In general, each section of the CAHSR route required implementation of sound path interrupting methods (sound barriers or windows) to achieve the 20 dB(A) noise reduction target in a cost-effective manner.

Table 58: Selected Methods for Assumed California Track Sections

Mitigaton Method		Track Segment																		
		D1	S1	D2	S2	D3	S3	D4	S4	D5	D6	S5	D7	S6	D8	S7	D9	S8	D10	D11
At the Source	Pantograph Fairings & Shields	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Aerodynamic Skirts	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Spin-Slide Control	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Aerodynamic Exterior Surfaces combined with Window Structures	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Tuned Rail Dampers (track based)	1								1					1		1			1
	Under-Car Noise Absorption	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Increased Turn Radii																			
	Inter-Car Gap Seals	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Wheel Dampers and Absorbers (train-based)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Along the Path	Barriers at Edge of Right-of-Way	1											1		1		1			1
	Sound Absorption Material on Barrier, Facing the Noise Source	1											1		1		1			1
	Tunnel Hoods									1			1						1	1
	At-Grade Ballast																			
	Damping Materials at the Upper Surface of Slab Tracks	1				1				1					1		1			
	Lower Tracks into Trenches					1				1										
	Creation/Acquition of Buffer Zones between Source and Receiver					1				1										
	Bridge Beam Supports to Reduce Structure-Induced Noise								1			1	1	1	1	1	1	1		1
	Increasing Distance from Source to Receiver																			
	Resilient Padding for Slab Track	1		1		1				1			1		1		1			1
At the Receiver	Windows with 3-inch Air Gap		1	1	1		1	1	1		1	1		1		1		1	1	
	Improved Foundation for Vibration and Sound Isolation																			
	Sound Barrier on Property Boundary Facing Noise Source					1														
	Caulking and Sealing Gaps	1	1	1	1	1	1	1	1	1	1	1		1		1		1	1	
	Façade Insulation: Low Acoustical Transmission Windows and Walls																			
	Layered Walls with Hard and Soft Materials to Improve Noise Attenuation					1				1										
	Vibration-Breaking Trenches																			

Selected, viable noise mitigation methods are highlighted: 1 each track section

Most of the other sound path interruption methods were less cost effective compared to sound barriers and windows and were included only when required to achieve the 20 dB(A) reduction target. Some methods like tunnel hoods and bridge beam supports were used when segment track features required them. Researchers applied the methods in decreasing order of cost effectiveness to achieve the sound reduction objectives. As indicated in Table 56, at-grade ballast was not selected for any of the route sections. The research team determined that this method is not cost-effective for the CAHSR representative track. Similarly, increasing the distance from source to receiver was either considered impractical (e.g., when passing through dense cities), or too cost prohibitive and was thus not utilized. Additionally, some receiver-based noise mitigation methods were also not utilized due to their high cost, including improved foundations for vibration and sound transmittal, façade insulation and vibration breaking trenches. In practical applications, when there is a requirement for a much higher level of noise attenuation, or based on specific track conditions, these methods may be applied, albeit at a higher total cost of implementation.

8.2.4 Estimated Cost of Compliance

Table 59 shows the results of the noise mitigation cost analysis for the CAHSR representative track. This includes the designated track segments described in Figure 57.

Table 59: Summary of Results for the Assumed California Track

Segment	Estimated Cost ($M)	Average Noise Reduction dB(A)	Assumed Length (miles)	Assumed No. of Residents	$ / dB(A)	$ / Resident / dB(A)
D1 San Jose	$80.7	19.8	10	41,875	$4,073,847	$97.29
S1 San Jose-Morgan Hill	$2.1	21.0	8	213	$98,578	$463.90
D2 Morgan Hill-Gilroy	$16.4	21.1	14	4,375	$775,790	$177.32
S2 Gilroy-Los Banos	$9.8	21.0	41	1,000	$463,898	$463.90
D3 Los Banos	$17.8	19.6	4	2,625	$912,067	$347.45
S3 Los Banos-Chowchilla	$6.7	21.0	28	688	$318,930	$463.90
D4 Chowchilla-Madera	$13.7	21.0	20	3,675	$651,455	$177.27
S4 Merced-Chowchilla	$3.8	21.2	14	363	$181,266	$500.04
D5 Merced	$13.3	19.8	3	925	$675,058	$729.79
D6 Madera	$15.3	21.0	8	4,975	$727,837	$146.30
S5 Madera-Fresno	$2.1	21.2	8	200	$96,915	$484.58
D7 Fresno	$86.9	19.8	18	77,325	$4,381,568	$56.66
S6 Fresno-Visalia	$8.1	21.2	22	1,438	$383,618	$266.86
D8 Visalia	$29.3	19.8	6	12,000	$1,480,093	$123.34
S7 Visalia-Bakersfield	$25.7	21.2	69	4,750	$1,212,417	$255.25
D9 Bakersfield	$20.2	19.8	14	28,450	$1,021,752	$35.91
S8 Bakersfield-Palmdale	$21.7	21.2	66	3,450	$1,026,454	$297.52
D10 Palmdale-Burbank	$23.1	21.3	12	6,425	$1,087,614	$169.28
D11 Burbank-Los Angeles	$71.1	20.0	35	46,750	$3,552,631	$75.99
TOTAL	**$467.8M**	**20.8**	**400**	**241,500**	**$22.44M**	**$92.92**

It can be observed from Table 57 that the estimated total cost to reduce noise by approximately 21 dB(A) is $468,000,000, based on implementation of the methods highlighted in Table 58. This translates to an average $ per dB(A) of $22,400,000. Further, as 241,000 residents are assumed to be impacted by train noise around the track, this translates to an average dollar per dB(A) per impacted resident of $92.91.

Researchers compared the noise reduction cost estimate to CAHSR publicly available EIR/EIS documents. These documents conclude that noise barriers are the most effective means to reduce noise in the vicinity of the track. Noise and vibration analysis results can be found in Section 3.4 of Volume II: Technical Appendices (California High-Speed Rail Authority, 2019), which states the cost of noise mitigation must not exceed $45,000 per resident. For the current analysis of the representative CAHSR track, the total cost per resident for 20.8 dB(A) of noise reduction was estimated to be $2,000. This is much lower than the EIR/EIS threshold, mainly because the noise reduction target was set to 20 dB(A), whereas the actual noise reduction required in some sections of the track may be higher due to the presence of critical buildings, dense cities, etc. Further, specific track topographical and external factors (e.g., grade level and space constraints) were out of scope of the current analysis and may lead to higher costs. It is also possible that the current analysis is much more detailed than the one included in the EIR/EIS documents and thus those documents are based on overly-conservative assumptions.

It is worth noting that the cost per dB(A) per impacted resident varies significantly from $35.91 for segment D9 near Bakersfield to $729.79 for segment D5 near Merced. The key reason for this variation is the relative impact of population density and length of track. In the case of the track section near Bakersfield, the population is relatively dense and the track length relatively short track, so it is cost effective to apply noise barriers. For Merced, population density is lower, and the length of track is shorter. Thus, researchers projected that both noise barriers and windows with an air gap have higher relative costs compared to less effective, lower cost methods.

8.3 Representative Simplified Track for East Coast

The NEC is an electrified track in the Northeastern region of the US (see Figure 60). It runs from Boston, MA, through Providence, RI, New Haven, CT, New York City, NY, Philadelphia, PA, and Baltimore, MD, to Washington, DC. This research did not consider the branches connecting the main corridor part of the NEC, though they are integral to the operation of the corridor (Figure 58) (Wikipedia, n.d.).

8.3.1 Introduction to the NEC

The NEC is the busiest passenger rail line in the US by ridership and train frequency with more than 2,200 trains daily (Wikipedia, n.d.). Though the track is owned by Amtrak and has several Amtrak trains running on it (i.e., including the high-speed Acela Express), most of the corridor also has frequent commuter trains being operated by regional operators such as Massachusetts Bay Transportation Authority (MBTA), Southeastern Pennsylvania Transportation Authority (SEPTA), and New Jersey Transit. Several companies also operate freight trains over sections of the NEC.

Amtrak operates intercity Northeast Regional and Keystone Service trains at up to 125 mph (201 km/h), as well as North America's only currently operating high-speed train, the Acela Express, with speeds up to 150 mph (240 km/h) on a few sections in Massachusetts and Rhode Island (Wikipedia, n.d.). The research shows that the expectation for the next generation of Alstom Avelia trains are to begin operating on this track starting in 2021 and will have a maximum speed capability of 186 mph, although the regulated speed for most sections of the track are speeds of 130 mph or lower due to various safety and noise related considerations. Some sections of the route between Boston and New Haven (Shoreline) have allowable track speeds of up to

150 mph, but these sections are typically in areas with lower population densities to avoid noise disturbances.

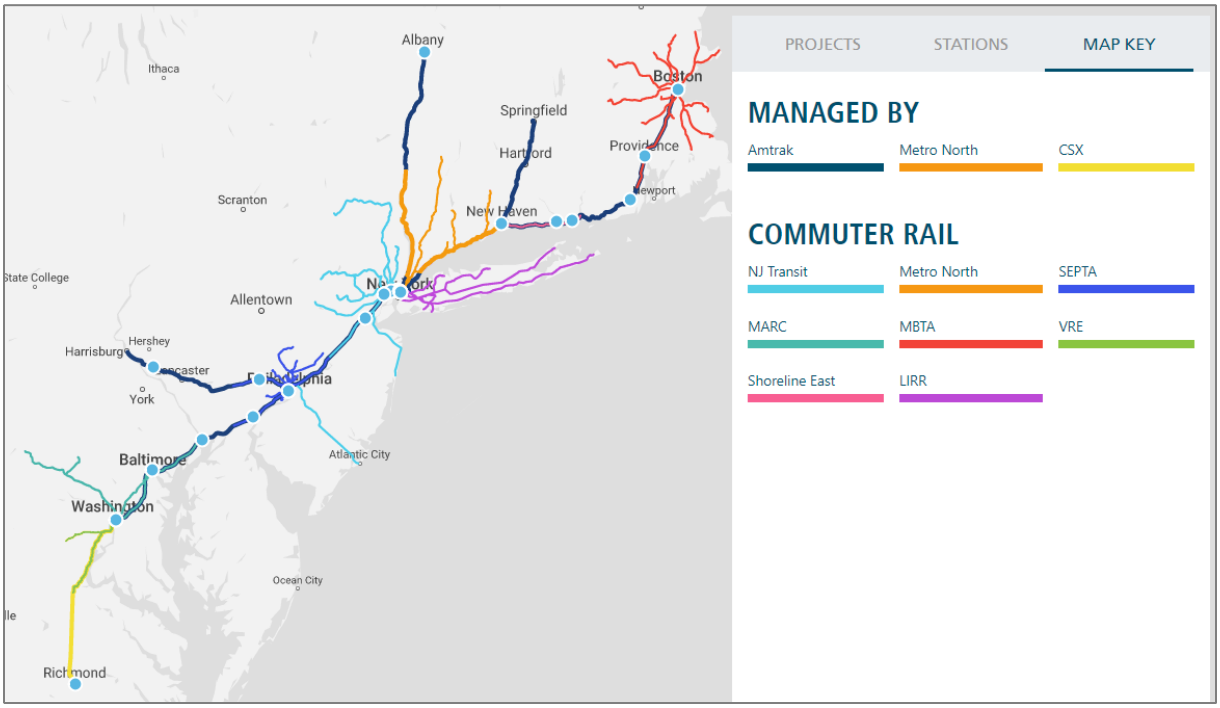


Figure 58: Map of NEC and Connecting Lines (Wikipedia, n.d.)

Construction and operation of the NEC dates to the 1830s and various railroad companies extended it during the intervening years. In the early 1900s, much of the corridor was electrified. By 1976 Amtrak owned the entire NEC except for the Boston to the Rhode Island State line segment which is owned by the Commonwealth of Massachusetts, and the New Haven to the New Rochelle, NY, segment, which is owned by the States of Connecticut and New York (Wikipedia, n.d.). Currently, Amtrak operates and maintains the Massachusetts segment, but the line from New Haven to New Rochelle, NY, is operated by the Metro-North Railroad. This limited control over the full track has somewhat hindered Amtrak's plans to build a full high-speed corridor.

Amtrak continues to upgrade the NEC and bring it up to standards required for high speed service, with the goal of reducing travel times to and from major cities. In 1976, the Federal government authorized the Northeast Corridor Improvement Project, which included safety improvements and modernization of signaling and traffic control systems, thereby allowing more trains to run higher speeds and with shorter inter-train increments. In 1990s, Amtrak began upgrading the line from Boston to New York City to prepare for high speed operation with the Acela trains. The effort eliminated grade crossings, rebuilt bridges, modified curves, added overhead catenary wires, replaced wood ties with concrete ties and led to the implementation of heavier continuous welded rail (CWR) systems (Wikipedia, n.d.). More recently, several projects are underway to expand the system capacity extend high-speed operations throughout the corridor (Amtrak National Railroad Passenger Corporation, 2019). Some key projects are highlighted below:

- *Next-Generation High Speed Trains ($2.45 Billion)* – Amtrak has contracted with Alstom to produce 28 next-generation high-speed trainsets that will replace the equipment used to provide Amtrak's premium Acela Express service. The new trainsets will operate along the NEC initially at speeds up to 160 mph and will be capable of speeds up to 186 mph and thus can take advantage of future NEC infrastructure improvements. The projected timeframe of delivering the first trainset is during 2021 and the expected timeframe of all trainsets to be in service and the current fleet retired is by the end of 2022.
- *New Jersey High Speed Rail Improvement Program ($450 Million)* – Amtrak, with support from the US Department of Transportation (DOT), is upgrading its rail infrastructure to support more frequent high-speed rail service and to improve the reliability of current service between New York and Washington, DC. The project will upgrade electrical power, signal systems, tracks and overhead catenary wires along a 23-mile section of track between Trenton and New Brunswick, NJ, and will allow Amtrak trains to operate at speeds up to 160 mph. The scheduled completion of the project is to be in 2020.
- *Delaware Third Track Project ($71 Million)* – Amtrak and the Delaware Transit Corporation (DelDOT) are partnering to increase capacity between Wilmington and Newark, DE, to fix a two-track bottleneck. The scheduled completion of this project is by 2020.
- *Keystone Corridor ($66 Million)* – Pennsylvania Department of Transportation is making high-speed rail improvements to the 104-mile Keystone Corridor, which Amtrak owns, from Philadelphia to Harrisburg. Though this is not directly a part of the NEC, it helps increase and improve ridership by providing convenient access to the main corridor.
- *Washington, DC, to Richmond Southeast High-Speed Rail (under planning)* – Virginia Department of Rail and Public Transportation (DRPT) and FRA are working to improve passenger rail service between Washington, DC, and Richmond, VA, in a corridor shared by growing volumes of intercity passenger, commuter, and freight rail traffic. This 123-mile corridor is the northernmost segment of the planned Southeast High-Speed Rail (SEHSR) corridor, linking Washington, DC, and Florida.
- *New Haven-Hartford-Springfield Rail Program ($460 Million)* – This program includes design and construction of additional rail capacity on Amtrak-owned infrastructure between New Haven, CT, and Springfield, MA. Like the Keystone Corridor, this is also not directly a part of the NEC but provides benefits in terms of increased access and improved ridership.

8.3.2 Assumptions for a Representative Simplified Track

Presently, all high-speed sections on the NEC track are between Boston and New York City. However, as described above, the New Jersey High Speed Rail Improvement Program is currently in construction and will include upgrades to sections of the track between New York City and Washington, DC, to allow for higher train speeds. Thus, for the current noise mitigation cost study, researchers chose a representative track as the region from Boston to Washington, DC, which includes planned future upgrades. As noted above, obtaining track information containing levels of detail sufficient to estimate or define the true cost of applying noise mitigation methods onto existing or planned actual high-speed rail lines is out of scope of this study. Rather, the objective is to include macro level NEC information, available in the public domain, to define a representative track for which the top noise reduction methods can be applied and their associated costs defined.

As with the CAHSR analysis, the selected NEC route was divided into segments having common characteristics and over which noise mitigation methods can be applied uniformly. This was accomplished through detailed reviews of the track maps, track charts, and population density maps. These documents were not as detailed as those for the CAHSR system. Thus, researchers used an alternate method, ArcGIS, a geographic information system developed by the Environmental Systems Research Institute (Esri) (Esri, n.d.), to map a representative simplified route along the East Coast. The ArcGIS software has an extensive catalog of geodatabases that capture spatial definitions and topography—both for natural formations and infrastructure. Multiple datasets can be layered on top of each other to study their interactions. This capability was very useful for this study where maps for population densities and railway routes can be overlaid to estimate the population density in areas likely to be impacted by railroad traffic. Specifically, the Esri developed "USA Railroad" and "USA Demographic and Boundaries 2018" datasets were overlaid to extract this information. Esri developed the "USA Railroad" dataset with reference to research from Amtrak, FRA and European Petroleum Survey Group (EPSG) amongst others, while the "USA Demographic and Boundaries 2018" makes use of information from the US Census Bureau and Infogroup. The "USA Railroad" dataset had all the railroads mapped in the US and thus manually enhancing the representative East Coast track took place to enable easy identification during segmentation and population assumptions.

After completing the ArcGIS modeling, segmenting the rail routes occurred by reviewing the population densities bordering the track. Figure 59 through Figure 64 visualizes this segmentation.

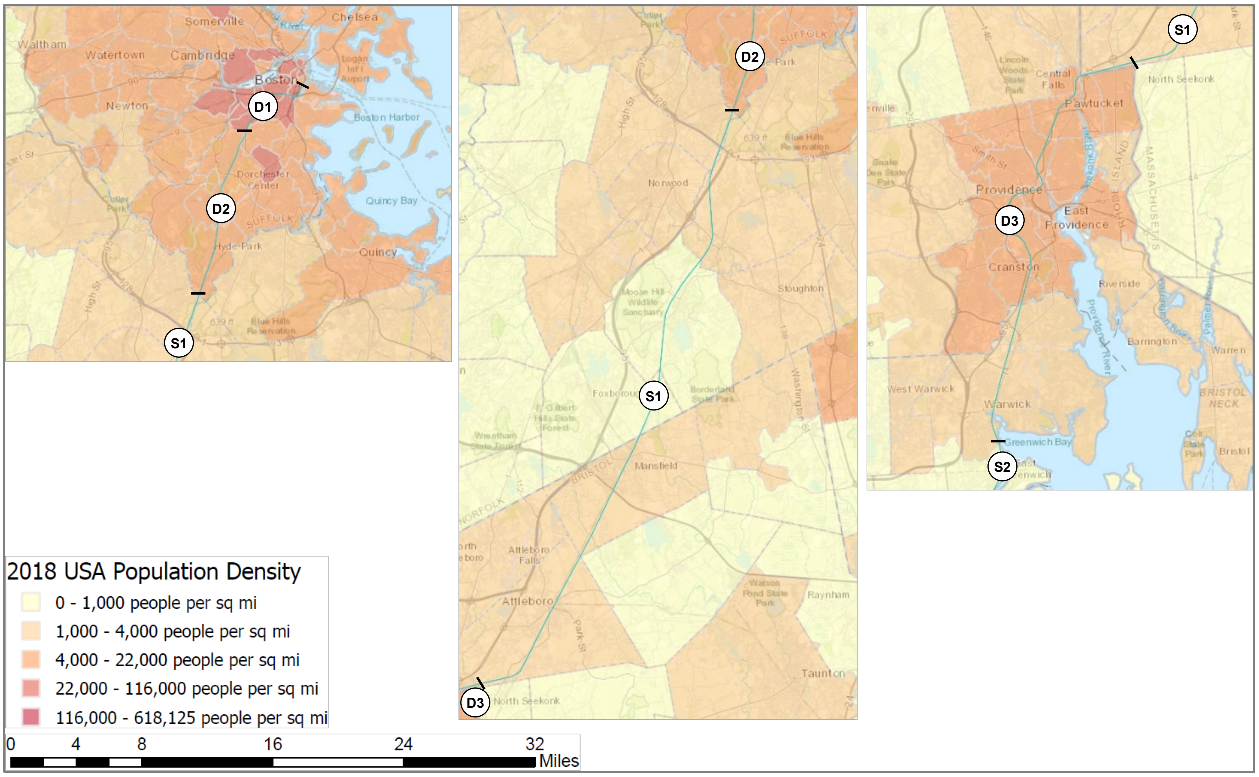


Figure 59: Representative Track for East Coast (part 1 of 6)

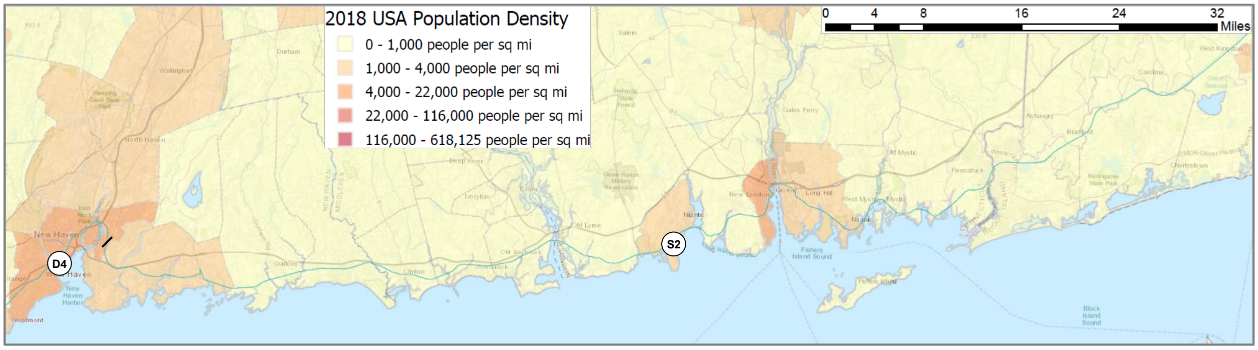


Figure 60: Representative Simplified Track for East Coast (part 2 of 6)

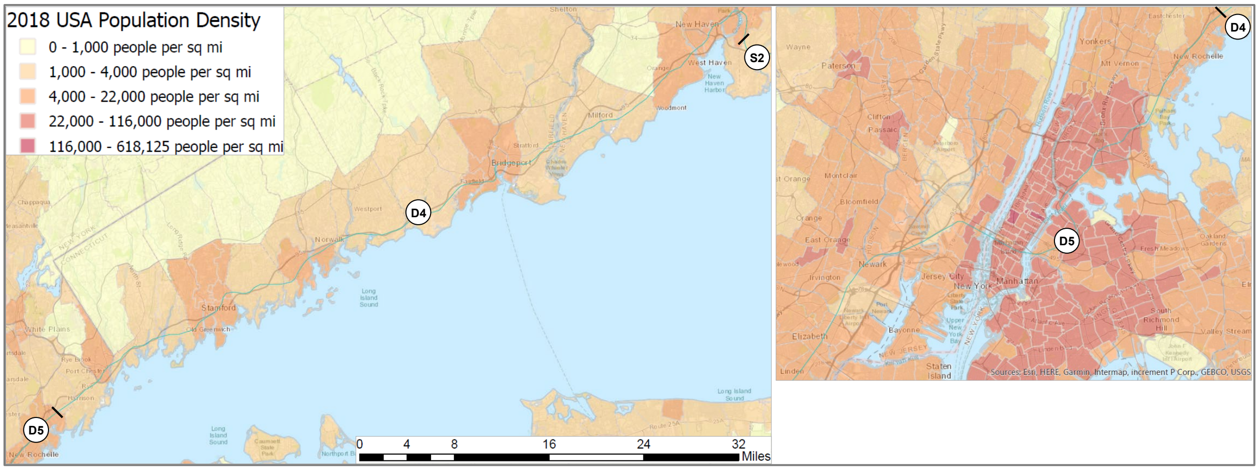


Figure 61: Representative Simplified Track for East Coast (part 3 of 6)

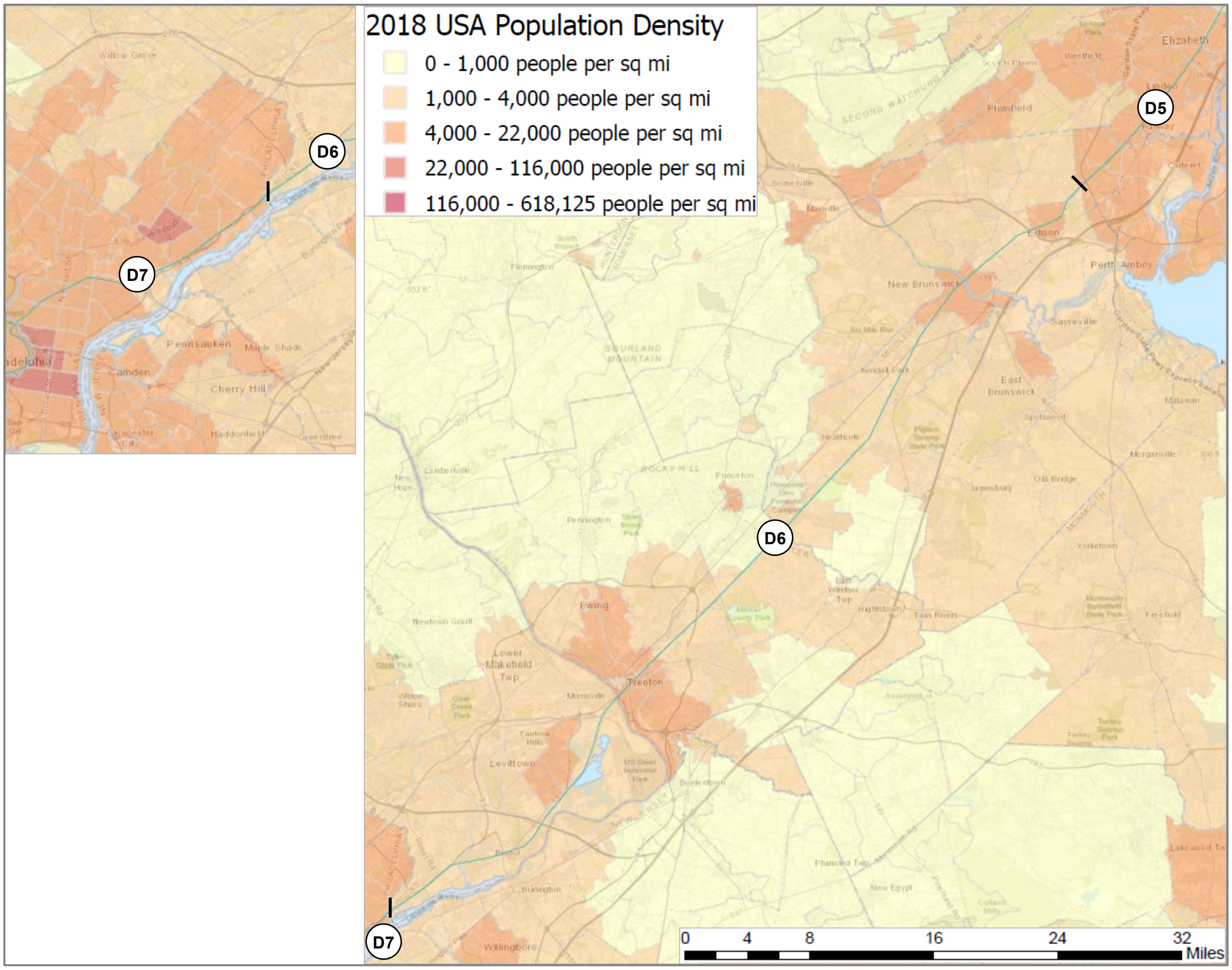


Figure 62: Representative Simplified Track for East Coast (part 4 of 6)

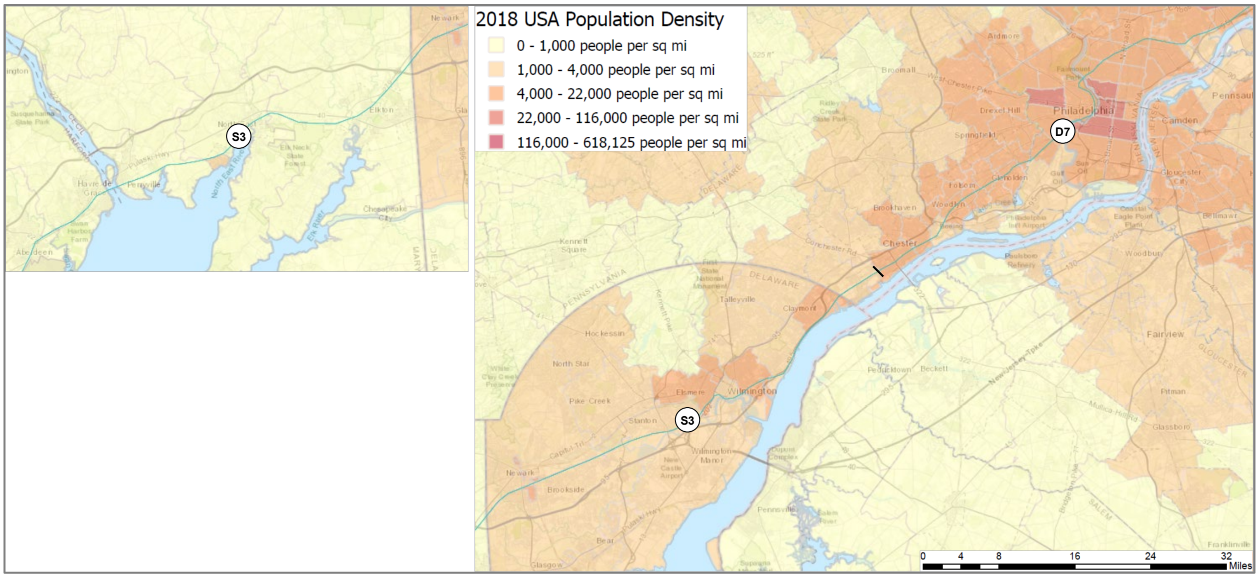


Figure 63: Representative Simplified Track for East Coast (part 5 of 6)

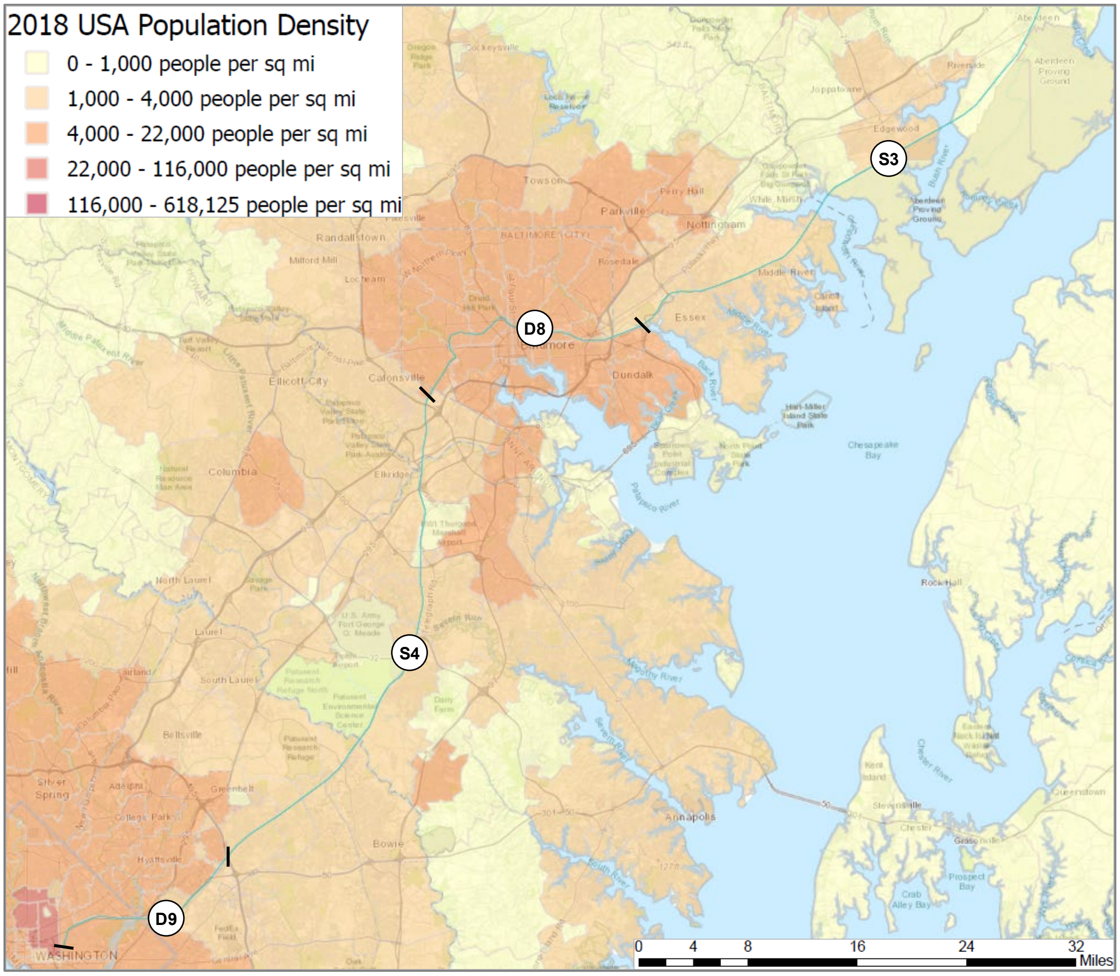
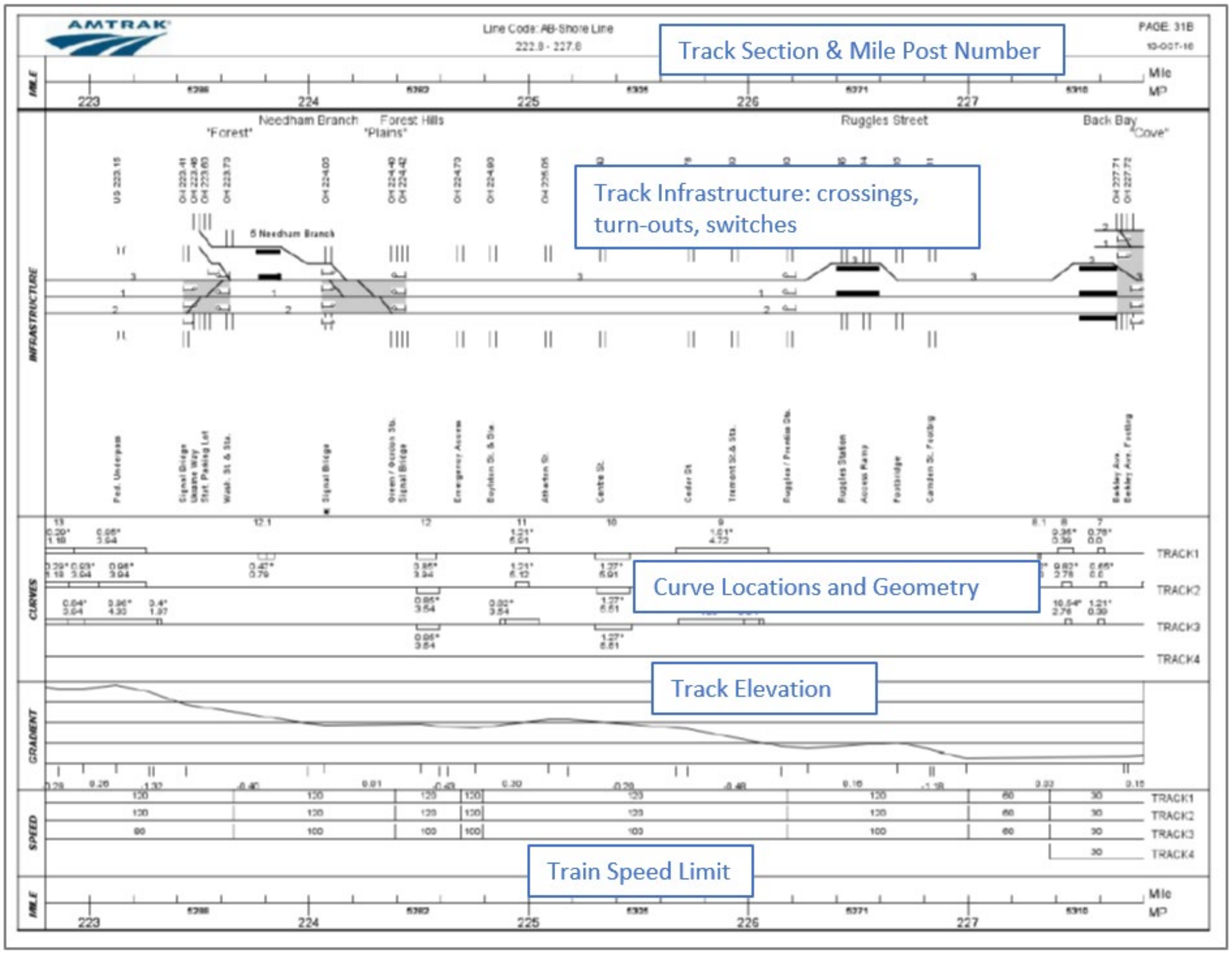


Figure 64: Representative Simplified Track for East Coast (part 6 of 6)

Researchers designated a total of 13 segments with 4 being considered “sparsely populated” (S1 through S4) and 9 being considered “densely populated” (D1 through D9). Further, the cities assumed to be along the representative simplified East Coast track are much larger and therefore much more densely populated. Areas with assumed population densities over 4,000 persons per square mile were dense for implementing noise mitigation methods. Of the densely populated segments, D1 passes near Boston, D3 passes near Providence, D5 passes near New York City, D7 passes near Philadelphia, D8 passes near Baltimore, and D9 passes near Washington, DC, D2, D4 and D6 are unique as they do not pass through densely populated cities, but instead pass through clusters of smaller towns that have medium population densities.

Track features were specific for each representative track segment, including segment length, number and length of tunnels, number and length of bridges (e.g., elevated sections), residents impacted, and households impacted. Amtrak (i.e., a supporter of the current study), provided track charts for most of the NEC routes, except for the section from New Haven to New Rochelle that is operated by Metro-North Railroad. Researchers used the track charts to define key features of the segments, such as number of tracks, locations and lengths of bridges and tunnels, grade crossings, track curves, elevation change, and maximum safe operating speeds (see Figure 65 for a representative track chart on segment D1). Further, these charts provided data for maintenance schedules for the track (see Figure 66 for maintenance schedule for same track chart).



Track Section & Mile Post Number

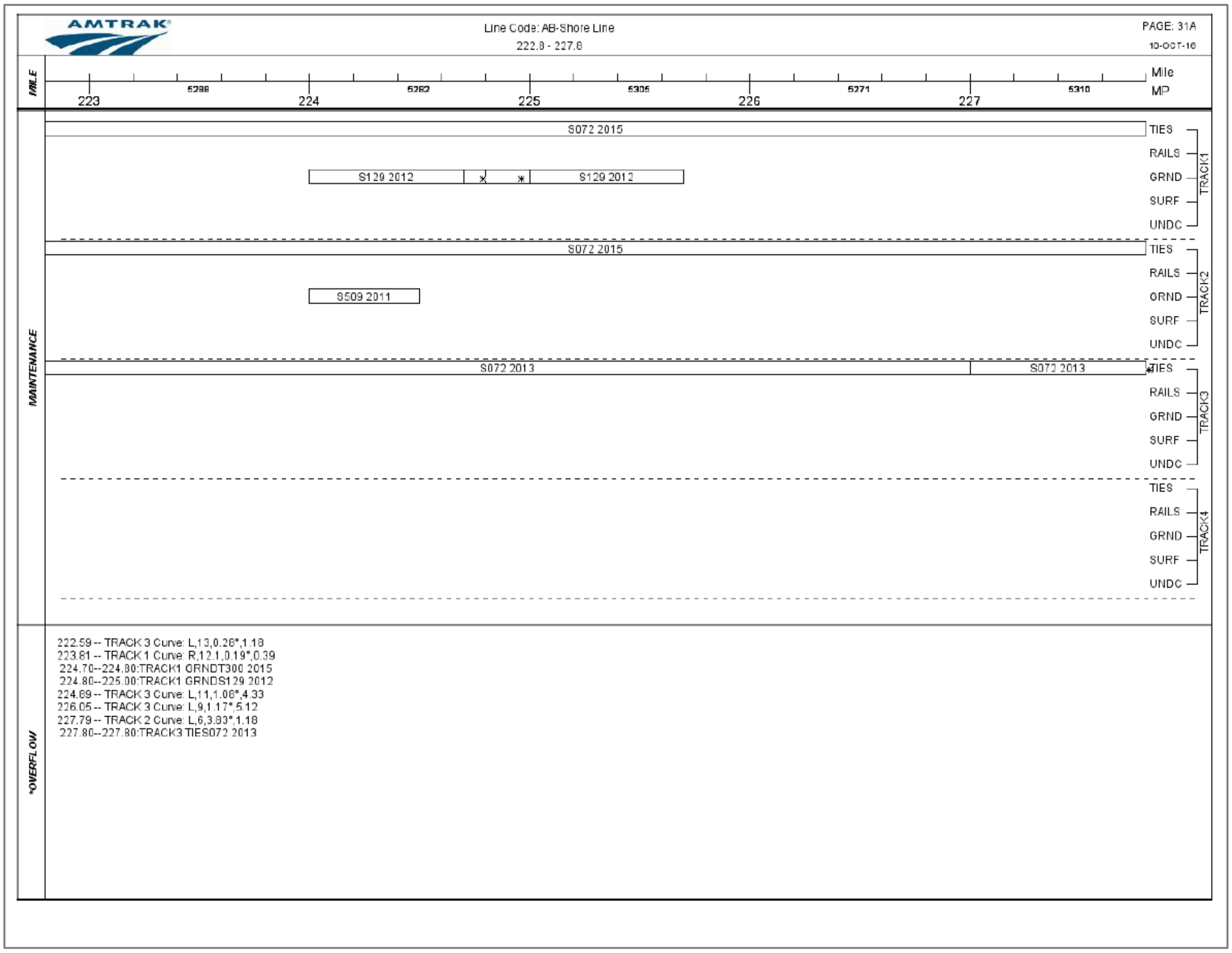
Track Infrastructure: crossings, turn-outs, switches

Curve Locations and Geometry

Track Elevation

Train Speed Limit

Figure 65: Representative Track Chart Showing Track Features



222.59 -- TRACK 3 Curve: L,13,0.28°,1.18
223.81 -- TRACK 1 Curve: R,12.1,0.19°,0.39
224.70--224.80:TRACK1 GRNDT300 2015
224.80--225.00:TRACK1 GRNDS129 2012
224.89 -- TRACK 3 Curve: L,11,1.08°,4.33
226.05 -- TRACK 3 Curve: L,9,1.17°,5.12
227.79 -- TRACK 2 Curve: L,6,3.83°,1.18
227.80--227.80:TRACK3 TIES072 2013

Figure 66: Representative Track Chart Showing Track Maintenance Schedules

Table 60 shows the relevant track features for a representative track for the East Coast region. Comparing these features to the representative California track shown in Table 57, note that both routes have approximately the same length but the East Coast track has a much higher number of tunnels and bridges and the total length of these tunnels and bridges is significantly shorter than those for the California track. Because the location of the NEC is on an older right-of-way, much of it remains at grade level rather than passing over or under other infrastructure. In the case of the California track, a larger section of the track will be elevated to allow room for future crossings when population densities around the track increase.

Table 60: Assumptions for Sections of East Coast Track

Track Sub-Section ID	Length of Track (miles)	No. of Tunnels	Length of Tunnels (miles)	No. of Bridges	Length of Bridges (miles)	Residents Impacted	Households Impacted
D1 Boston	4	2	2	0	0	92,750	30,917
D2 Boston-Hyde Park	6	2	1	0	0	42,250	14,083
S1 Hyde Park-Providence	26	1	1	1	1	25,600	8,533
D3 Providence	20	8	3	0	0	95,250	31,750
S2 Providence -New Haven	97	4	2	4	1	62,400	20,800
D4* New Haven-New York	58	3	1	6	3	200,500	66,833
D5 New York	48	10	4	15	8	819,250	273,084
D6 New York-Philadelphia	52	3	1	6	3	114,250	38,083
D7 Philadelphia	29	5	2	10	5	183,250	61,083
S3 Philadelphia-Baltimore	72	5	1	5	2	77,600	25,867
D8 Baltimore	13	4	1	2	1	84,500	28,167
S4 Philadelphia-DC	25	4	1	0	0	31,250	10,417
D9 DC	10	2	1	3	1	51,250	17,083
TOTAL	**460**	**53**	**21**	**52**	**25**	**1,880,100**	**626,700**

*This section is operated by Metro-North Railroad and thus track charts were not available. This section has been assumed to be similar to section D6. Thus, data for tunnels and bridges has been assumed as D6, but data for length and residents impacted is assumed based on ArcGIS.

8.3.1 Applying Noise Mitigation Methods on Segments

The cost of implementing noise mitigation methods on each selected segment of the representative NEC track, to achieve a noise reduction target of 20 dB(A), while minimizing total cost of implementation, was estimated using the spreadsheet program illustrated in Table 59. As noted above, it was assumed that it is difficult to re-route tracks, relocate residents, and change topography for this track because of the limited land available to make these changes and the current land use regulations in this densely populated region. Thus, methods like lowering track into trenches, creating buffer zones and increasing distance from source to receiver were not included in the noise mitigation cost analysis. Based on these constraints, Table 59 includes the specific methods applied for each designated track section, where active methods have been highlighted in green to enable quick comparison between similar sections.

As was found during the CAHSR analysis, noise mitigation methods applied at the source were found to be most cost effective, including high levels of expected noise reduction and lower $ per dB(A). Thus, all methods to address source noise, specifically train based applications, were applied throughout the NEC track.

Researchers excluded speed restriction zones and increased turning radii from the eligible NEC noise mitigation options. Tuned rail dampers are applied directly to the track and they scale with the length of the track. Thus, this method was only used in sections assumed to be densely populated (all 'D' sections) where the assumed track length was shorter, and the high assumed number of residents impacted kept the total cost reasonable.

Table 61: Selected Methods for Assumed East Coast Track Sections

Mitigaton Method		Track Segment												
		D1	D2	S1	D3	S2	D4	D5	D6	D7	S3	D8	S4	D9
At the Source	Pantograph Fairings & Shields	1	1	1	1	1	1	1	1	1	1	1	1	1
	Aerodynamic Skirts	1	1	1	1	1	1	1	1	1	1	1	1	1
	Spin-Slide Control	1	1	1	1	1	1	1	1	1	1	1	1	1
	Aerodynamic Exterior Surfaces combined with Window Structures	1	1	1	1	1	1	1	1	1	1	1	1	1
	Tuned Rail Dampers (track based)	1	1		1		1	1	1	1		1		1
	Under-Car Noise Absorption	1	1	1	1	1	1	1	1	1	1	1	1	1
	Increased Turn Radii													
	Inter-Car Gap Seals	1	1	1	1	1	1	1	1	1	1	1	1	1
	Wheel Dampers and Absorbers (train-based)	1	1	1	1	1	1	1	1	1	1	1	1	1
Along the Path	Barriers at Edge of Right-of-Way	1	1		1			1	1	1		1		1
	Sound Absorption Material on Barrier, Facing the Noise Source	1	1		1			1	1	1		1		1
	Tunnel Hoods	1	1	1	1	1	1	1	1	1	1	1	1	1
	At-Grade Ballast													
	Damping Materials at the Upper Surface of Slab Tracks	1	1		1		1	1	1	1		1		1
	Lower Tracks into Trenches													
	Creation/Acquition of Buffer Zones between Source and Receiver													
	Bridge Beam Supports to Reduce Structure-Induced Noise			1		1	1	1	1	1	1	1		1
	Increasing Distance from Source to Receiver													
	Resilient Padding for Slab Track	1	1	1	1	1	1	1	1	1		1		1
At the Receiver	Windows with 3-inch Air Gap			1		1					1		1	
	Improved Foundation for Vibration and Sound Isolation													
	Sound Barrier on Property Boundary Facing Noise Source						1							
	Caulking and Sealing Gaps		1	1	1	1	1						1	
	Façade Insulation: Low Acoustical Transmission Windows and Walls													
	Layered Walls with Hard and Soft Materials to Improve Noise Attenuation													
	Vibration-Breaking Trenches													

Selected, viable noise mitigation methods are highlighted: 1 for each track section

	Mitigation Method	**D1**	**D2**	**S1**	**D3**	**S2**	**D4**	**D5**	**D6**	**D7**	**S3**	**D8**	**S4**	**D9**
At the Source	Implementation of Disk Brakes	1	1	1	1	1	1	1	1	1	1	1	1	1
	Pantograph Fairings & Shields Design	1	1	1	1	1	1	1	1	1	1	1	1	1
	Skirts	1	1	1	1	1	1	1	1	1	1	1	1	1
	Spin-slide Control	1	1	1	1	1	1	1	1	1	1	1	1	1
	Smooth Exterior Surfaces	1	1	1	1	1	1	1	1	1	1	1	1	1
	Window Structures													
	Bosterless Bogies	1	1	1	1	1	1	1	1	1	1	1	1	1
	Speed Restriction Zones	-	-	-	-	-	-	-	-	-	-	-	-	-
	Tuned Rail Dampers (Track Based)	1	1	-	1	-	1	1	1	1	-	1	-	1
	Under-car Noise Absorption	1	1	1	1	1	1	1	1	1	1	1	1	1
	Increased Turn Radii	-	-	-	-	-	-	-	-	-	-	-	-	-
	Inter-car Gap Seals	1	1	1	1	1	1	1	1	1	1	1	1	1
	Wheel Dampers and Absorbers (Train Based)	1	1	1	1	1	1	1	1	1	1	1	1	1
Along the Path	Barriers at the Edge of the Right-of-Way	1	1	-	1	-	-	1	1	1	-	1	-	1
	Sound Absorption Material on the Barrier, Facing the Noise Source	1	1	-	1	-	-	1	1	1	-	1	-	1
	Tunnel Hoods	1	1	1	1	1	1	1	1	1	1	1	1	1
	At-grade Ballast	-	-	-	-	-	-	-	-	-	-	-	-	-
	Damping Materials at the Upper Surface of the Slab Tracks	1	1	-	1	-	1	1	1	1	-	1	-	1
	Lower Elevation of the Tracks into Trenches	-	-	-	-	-	-	-	-	-	-	-	-	-
	Creation / Acquisition of Buffer Zones between Source and Receiver	-	-	-	-	-	-	-	-	-	-	-	-	-
	Bridge Beam Supports to Reduce Structure-induced Noise	-	-	1	-	1	1	1	1	1	1	1	-	1
	Increasing Distance from Source to Receiver	-	-	-	-	-	-	-	-	-	-	-	-	-
	Resilient Padding for Slab Track	1	1	1	1	1	1	1	1	1	-	1	-	1
At Receiver	Windows with a 3 Inch Air Gap	-	-	1	-	1	-	-	-	-	1	-	1	-
	Improved Foundation for Vibration and Sound Isolation	-	-	-	-	-	-	-	-	-	-	-	-	-
	Sound Barriers on Property Boundary Facing Noise Source	-	-	-	-	-	1	-	-	-	-	-	-	-
	Caulking and Sealing Gaps	-	1	1	1	1	1	-	-	-	-	-	1	-
	Façade Insulation: Low Acoustical Transmission Windows and Walls	-	-	-	-	-	-	-	-	-	-	-	-	-
	Layered Walls with Hard and Soft Materials to Improve Noise Attenuation	-	-	-	-	-	-	-	-	-	-	-	-	-
	Vibration-breaking Trenches	-	-	-	-	-	-	-	-	-	-	-	-	-

Note that the selected viable noise mitigation approaches are highlighted in green: 1 for each section.

The cost effectiveness of methods applied along the noise path compared to the cost effectiveness of methods applied at the receiver is primarily dependent on the trade-off between the length of track and the number of residents impacted. Thus, for sections assumed to be densely populated (all 'D' sections, except D4), the assumed length of track was relatively lower and applying noise barriers along the right of way was the most cost-effective method to reduce noise. However, for other sections with an assumed longer length of track, but lower assumed density of population adjoining the track, it was much more effective to provide improvements at the receiver in the form of windows with 3-inch air gap and caulking and sealing gaps in houses. Specific to D4, due to the ratio of length of track to number of residents impacted, it was more cost effective to put sound barriers on the property boundaries, supplemented by other methods that can be applied at the receiver, rather than putting sound barriers along the track. Overall, each assumed section required the implementation of one of these highly-effective methods (sound barriers or windows) to achieve the target 20 dB(A) noise reduction in a cost-effective manner.

As was found during the analysis of the representative California track, most of the other noise reduction methods were less effective compared to sound barriers and windows and its use was primarily to further decrease noise levels to achieve the target reduction. Researchers used tunnel hoods and bridge beam supports where appropriate. Applying methods in decreasing order of cost effectiveness took place to achieve the sound reduction objectives (e.g., researchers favored cost effective solutions with high rankings). Table 61 observed that methods like at-grade ballast, improved foundation isolation materials, façade insulation, layered walls and vibration breaking trenches were not cost-effective solutions and thus not utilized for any of the designated track sections. When a much higher level of noise attenuation is required in practical cases, these methods may be applied, albeit at a higher total cost of implementation.

8.3.2 Estimated Cost of Compliance

Table 62 summarizes the results of the NEC track noise reduction cost analysis. Table 61 showed the projected total cost to reduce noise levels by approximately 21 dB(A), as measured according to US regulations, is \$2.2 billion, based on implementation of the methods. This translates to an average dollar per dB(A) of \$104,000,000. Since approximately1.9 million residents are impacted by train noise in the vicinity of the representative NEC track segments, the projected cost of the noise reduction measures translates to an average \$ per dB(A) per impacted resident of \$55.40.

The total cost of noise mitigation methods for the representative NEC track is approximately five times higher than those for the CAHSR representative track, even though both tracks are approximately the same length. However, the average cost per impacted resident is much lower at \$55.40 for the NEC track and \$92.91 for the California track due primarily to the NEC region having about 10 times more residents in the impacted zone than does the California region.

The cost per dB(A) per impacted resident for the NEC track varies from \$10.86 for D1 near Boston to \$158.17 for S2 near Shoreline, though these costs are still much lower than seen in California. Once again, the key reason for the variation is the trade-off between population density and length of track. While Boston has high population density with a relatively shorter track (4 miles), the Shoreline is much longer (97 miles) and passes through very sparse population zones with densities mostly under 1,000 persons per square mile. Thus, it is very effective to apply noise barriers to obtain large noise reductions at relatively low cost near Boston, while for the rest of the Shoreline area, it is more effective to reduce noise at the receivers.

Table 62: Summary of Results for the Assumed East Coast Track

Segment	Estimated Cost ($Million)	Average Noise Reduction, dB(A)	Assumed Section Length (miles)	Assumed Number of Residents	$ / dB(A)	$ / Resident / dB(A)
D1 Boston	$20.0	19.9	4	92,750	$1,007,183	$10.86
D2 Boston-Hyde Park	$61.7	20.1	6	42,250	$3,069,384	$72.65
S1 Hyde Park-Providence	$81.4	21.5	26	25,600	$3,795,341	$148.11
D3 Providence	$173.5	20.1	20	95,250	$8,636,187	$90.67
S2 Providence -New Haven	$211.6	21.5	97	62,400	$9,865,687	$158.17
D4 New Haven-New York	$297.8	19.8	58	200,500	$15,047,264	$75.05
D5 New York	$302.0	20.1	48	819,250	$15,047,940	$18.37
D6 New York-Philadelphia	$354.7	20.1	52	114,250	$17,671,474	$154.67
D7 Philadelphia	$177.0	20.1	29	183,250	$8,816,929	$48.11
S3 Philadelphia-Baltimore	$220.0	21.2	72	77,600	$10,360,095	$133.46
D8 Baltimore	$86.9	20.1	13	84,500	$4,331,140	$51.26
S4 Philadelphia-DC	$103.0	21.3	25	31,250	$4,844,146	$155.01
D9 DC	$61.4	20.1	10	51,250	$3,057,162	$59.65
TOTAL	**$2,151.1 M**	**20.7**	**460**	**1,880,100**	**$104.16M**	**$55.40**

9. Summary – Cost of Noise Compliance Procedures

This section of the report contains a summary of the outcomes and conclusions for the Cost of Compliance for Noise Mitigation Procedures tasks.

This research defined key parameters to assess the effectiveness of over 70 noise reduction methods highlighted in FRA's study (Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S., 2021). These parameters included noise reduction potential, technology readiness level, practicality to implement, industry acceptance and level of cost or investment, and were ranked using a 3-point scale (low = 1, medium = 2, high= 3) and parameter weighting system. Using the resulting score allowed for the selection of 30 methods for detailed analysis from generating an effectiveness ranking. Industry stakeholders, including rail operators, technical service providers, and vehicle manufacturers discussed interim results, ensured that project research was addressing industry needs, assessed practicality of identified reduction methods, and gathered input for the analysis.

The noise reduction methods were divided into three categories: 1) source reduction (e.g., related to noise generated by the train, including mechanical equipment, aerodynamic effects, underbody and wheels, and the wheel/rail interface), 2) interruption of noise path (e.g., barriers, deflectors, and sound absorbing materials), and 3) reduction at receiver (e.g., barriers and building modifications). The top 30 noise reduction methods summarized in Table 63 use the ranking procure as selected and presented in order of assessed effectiveness.

Researchers estimated lifecycle costs for each of the top 30 noise reduction methods and included initial investment, capital and construction, labor and materials, permits and operating expenses, and maintenance costs. Data sources included literature reviews, discussions with industry stakeholders, manufacturer information sheets, and price build up procedures. The research team identified or estimated the life span of each noise reduction method as input to the lifecycle cost analysis. Costs were calculated in units of dollars/train set, maintenance costs/year, dollars per track feature (i.e., tunnel or bridge), and dollars per mile of track.

Source noise reduction costs ranged from a high of $50,000,000/track mile for increasing track curve radii to a low of $18,000/train set for adding pantograph fairings. Other notable reduction method costs included $68,000/train set for side skirts, and $780,000/track mile for tuned rail dampers.

Costs for reduction methods applied along the noise path range from a high of $50,000,000/track mile for increasing the distance to the edge of the railroad property to a low of $133,000/track mile for adding resilient padding to slab track. Other noise path mitigation method costs include $3,700,000/track mile for barriers at the edge of the right of way, $3,000,000 each for tunnel entrance hoods, $689,000/track mile for application of sound absorbing materials on existing noise barriers, and $210,000/mile to lower tracks into trenches.

Costs for reducing noise levels at the receiver range from a high of $1,800,000/track mile for sound barriers at property boundaries to a low of $500/dwelling for caulking and sealing gaps. Other reduction method costs applied at the receiver include $57,000/dwelling for vibration-breaking trenches, $17,000/dwelling for façade insulation, $14,000/dwelling for foundation vibration and sound insulation, $6,400/dwelling for windows with 3-inch air gap, and $2,800/dwelling for in-wall noise attenuation systems.

Table 63: Mitigation Methods Ranked by Noise Reduction Effectiveness

Category	Rank	Method
At Source	1	Improved composite disk brakes
	2	Pantograph fairings & shields design
	3	Skirts
	4	Spin-slide control
	5	Smooth exterior surfaces
	6	Window structures
	7	Bolsterless bogies
	8	Speed Restriction Zones
	9	Tuned rail dampers (elastomers)
	10	Under-car noise absorption
	11	Increased turn radii
	12	Inter-car gap seals
	13	Wheel dampers and absorbers
Along Path	1	Sound Absorption Material on the Barrier, Facing the Noise Source
	2	Barriers at the Edge of the Right-of-Way
	3	Tunnel Hoods
	4	At-grade ballast
	5	Damping materials at the upper surface of the slab tracks
	6	Lower elevation of the tracks into trenches
	7	Creation / acquisition of Buffer Zones between source & receiver
	8	Bridge beam supports to reduce structure-induced noise
	9	Increasing distance from source to receiver
	10	Resilient padding for slab track
At Receiver	1	Windows with a 3-inch air gap
	2	Improved foundation for vibration and sound isolation
	3	Sound barriers on property boundary facing noise source
	4	Caulking and sealing gaps
	5	Façade Insulation: Low acoustical transmission windows and walls
	6	Layered walls with hard and soft materials to improve noise attenuation
	7	Vibration-breaking trenches

To allow the cost data to be applied to specific trains and routes, a normalized method, known as a unit lifecycle cost ($ per dB of noise reduction), was developed. This unit cost is referenced to each track section based on a number of parameters (e.g., length, number of tunnels, impacted households, and land use designation). The unit lifecycle cost was employed in the identification of the most effective methods to achieve target noise reductions. Table 64 shows the top five most cost-effective noise reduction methods in each category.

The calculated costs and ranked noise reduction effectiveness results were applied to representative routes to determine the cost of compliance for meeting target reduction levels consistent with US regulations. The two representative routes are based on 1) the CAHSR system and 2) the NEC HSR segment. To enable an estimation of cost of compliance along various track segments, all train-related improvement costs ($/dB reduction) were divided by the length of track segments to amortize the costs per mile of track. This allows consistent comparison of cost drivers across various track segments. These features were utilized to scale the unit costs and estimate the total cost of compliance. Key features of the estimation process are track route and sections, track length, number of tunnels, length of tunnels, number of bridges, length of bridges, and population density and number of residents and households impacted.

Table 64: Most Cost-Effective Noise Reduction Methods

Category	Scale Unit	Mitigation Method	Lifecycle Cost ($/dB reduction)
At the Source	Per Train Set	Pantograph Fairings and Shields	$3,000
		Skirts	$9,917
		Undercar Noise Absorption	$18,900
		Spin Slide Control	$34,222
		Tuned Rail Dampers	$151,667
Along Path	Per Track Mile	Lower Track into Trenches	$35,000
		Sound Absorption Material on Barriers	$93,333
		Creation of Additional Buffer Zones	$121,600
		Barriers at Edge if Right-of-Way	$429,333
		Damping Materials on Slab Track	$462,000
At Receiver	Per Dwelling	Caulking and Sealing Gaps	$135
		Windows with 3 inch Air Gap	$427
		Layered Noise Attenuation Walls	$800
		Foundation Insulation	$933
		Façade Insulation	$2,226

Researchers developed a spreadsheet-based method to facilitate the assessment of mitigation method costs along the selected NEC and California track sections. The spreadsheet is utilized by interactively selecting the noise reduction methods to achieve an accumulated target (20 dB reduction was chosen for the comparison analysis), while minimizing the “Total Cost” and “$ per dB(A) per resident” for the subject track section. As each method is applied, the worksheet calculates in real-time, the change to “Total Cost” and “Net Noise Reduction Impact dB(A).”

The current study is not intended to produce detailed noise reduction cost analyses for either the California or NEC projects. Rather, the objective is to use macro level information available in the public domain to develop representative track models that can be used to evaluate the noise reduction methods selection process and to obtain an understanding of the relative costs and magnitudes that may be incurred while achieving noise reduction targets.

The CAHSR representative analysis modeled the section of track between San Jose and Burbank. The track was divided into 19 segments, each having common characteristics that could be addressed using similar sets of noise mitigation methods, with key differentiators being population density adjacent to the rail line and segment track length. The total length of the representative California track was assumed to be 400 miles. The noise reduction analysis indicated noise reduction methods applied at the source were the most cost effective, with 10 determined to be cost effective. Noise reduction methods applied along the noise path were the second most effective category, with eight being applied, and the receiver-based methods were found to be the lease cost effective with four being applied. The result of the cost effectiveness analysis for the California representative track system indicates a noise reduction of 21 dB, as measured according to US rail noise regulations, could be obtained along the entire length of the track for a lifecycle cost of $468 million. This translates to an average cost per dB reduction of $22.4 million. Based on the estimated population of 241,000 residents in the affected region of the tracks, the cost per dB reduction per impacted resident is $92.91. The variation in cost per resident varies from $35.91 in the highly populated region near Bakersfield to $729.79/resident in the rural area near Merced.

Researchers conducted a similar cost study for the representative NEC track, which was divided into 13 segments for the region between Boston and Washington, DC. In comparing the NEC representative track to the NEC representative track, note that both routes have approximately the same length, but the NEC track has a much higher number of tunnels and bridges. The total length of these tunnels and bridges is significantly shorter than those for the California track, the population density along the NEC track is much higher than that along the California track, and options for track-related modifications along the NEC track, such as increased noise buffer zones as curve radius increases, are fewer than for the California track. The projected total cost to reduce noise levels by approximately 21 dB(A) along the NEC track, as measured according to US regulations, is $2.2 billion. This translates to an average $ per dB(A) of $104,000,000. Since the train noise in the vicinity of the representative NEC track segments impacted approximately1,900,000 residents, the projected cost of the noise reduction measures translates to an average dollar per dB(A) per impacted resident of $55.40 and varies from $10.86 per dB per impacted resident near Boston to $158.17 per impacted resident near Shoreline.

The total cost of noise mitigation methods for the representative NEC track is approximately five times higher than those for the CAHSR representative track, even though both tracks are approximately the same length. However, the average cost per impacted resident is much lower at $55.40 for the NEC track and $92.91 for the California track due primarily to the NEC region having about 10 times more residents in the impacted zone than does the California region.

The cost effectiveness of high-speed train noise reduction methods applied along the noise path compared to the cost effectiveness of methods applied at the receiver is primarily dependent on the trade-off between the length of track and the number of residents impacted. Thus, for sections assumed to be densely populated, researchers determined the length of track was relatively lower and applying noise barriers along the right of way was to be the most cost-effective method to reduce noise. However, for lower population sections for which track lengths are greater, it was much more effective to provide improvements at the receiver in the form of windows with 3-inch air gaps and caulking and sealing gaps in houses. In some cases, depending upon the ratio of length of track to number of residents impacted, it was more cost effective to install sound barriers on the property boundaries, supplemented by other methods that can be applied at the receiver, rather than installing the sound barriers along the track. Overall, each analyzed track section for both the NEC and California high speed rail systems, required the implementation of sound barriers or windows to achieve the target 20 dB(A) noise reduction in a cost-effective manner.

Most of the other identified noise reduction methods were less effective compared to sound barriers and windows but were required to achieve the selected target reduction of 20 dB. These methods were applied in decreasing order of cost effectiveness for each representative segment. Methods such as at-grade ballast, improved foundation isolation materials, façade insulation, layered walls and vibration breaking trenches were found to not be cost-effective solutions and thus were not utilized for any of the designated track sections. When a much higher level of noise attenuation is required in practical cases, these methods may be applied, albeit at a higher total cost of implementation.

10. Conclusion

Conclusions related to train noise metrics and regulations comparisons:

1. A common reference approach is required for comparisons of noise regulations because of the wide variation in metrics, measurement locations, train operating conditions (e.g., speed) and measurement procedures.
2. For the three train types included in the CONTRAST library, the Chinese CRH3 series train set is predicted to have passby SPLs that would exceed US noise limits at speeds above 350 km/hr (217.5 mph). The Thalys PBKA train set is predicted to exceed the US noise limits at speeds above 300 km/hr (185.4 mph) and the Korean HEMU-430X train set is expected to exceed the limit at speeds above 200 km/hr (124.3 mph). A train set that exhibits SPLs that correspond to the maximum allowed EU TSI levels, would produce an SPL that is 4.8 dB lower than the US maximum for locomotive classification trains operating at 250 km/hr. Similarly, the same train set operating at 350 km/hr and classified in the locomotive category would exceed the US noise limit by 1.6 dB. If the common reference train set is classified as a rail car under US regulations, it would meet the maximum allowed SPL specified by those regulations for all speeds up to 350 km/hr (218 mph).
3. Not all train sets in the CONTRAST library are capable of meeting US regulations at speeds above 300 km/hr (185 mph).
4. In Japan, for Zone I (residential) land use, the maximum value of L_{Amax} is 70 dB(A) and the Zone II (commercial/industrial) maximum L_{Amax} value is 75 dB(A). The common reference data set (based on scaled SPLs for a European train set) exhibits SPLs that vary from 69.8 dB(A) at 80 km/hr to 91.1 dB(A) at 350 km/hr for microphone position 3 (microphone 25 m from track centerline) and thus exceed the limit at higher speeds, requiring the application of noise mitigation methods. Two noise metrics are associated with Japan rail noise regulations, $L_{eq(hour)}$ and L_{Amax}. The $L_{eq(hour)}$ regulation is readily met with existing train set designs and no wayside mitigation methods. Because the L_{Amax} measurements are based on the maximum SPLs obtained for 20 consecutive passby events, they are much more stringent. For the Zone I land use designation, the maximum allowed value of L_{Amax} is 70 dB(A). The common reference data set train set exhibits SPLs that vary from 69.8 dB(A) at 80 km/hr to 91.1 dB(A) at 350 km/hr and thus exceed the limit. For Zone II, the maximum value of L_{Amax} is 75 dB(A) and is exceeded at speeds above 80 km/hr for the common reference data set. Thus, the train associated with the common reference data set would require significant application of mitigation methods, both onboard and wayside, to meet the L_{Amax} 20-passby event noise regulation in Japan. At the current Japan train speeds of 270 to 320 km/hr on the main lines and 130 km/hr to 160 km/hr on local lines, the L_{Amax} noise limit would be exceeded by all the train types included in the CONTRAST library if no wayside barriers were installed. The Shinkansen trains have undergone significant modifications to reduce onboard noise emissions and 3 m high straight and L-type wayside barriers have been installed to reduce noise levels to meet the Lmax regulation.
5. It is unlikely that the Chinese noise limits would be exceeded due to the limited night time train activity and the limited number of passby events. With the measurement

uncertainty of ±3 dB(A), it appears the L_n limit does not pose a serious threat to current and future night time operations of the Chinese high speed rail system. The Chinese day time high speed train noise limits are relatively easy to achieve, even without the use of wayside sound mitigation installations, such as noise barriers. With the current maximum average number of day time train passby events at 7, there is significant room for expansion of train frequency. Even at 25 trains per hour, at a speed of 350 km/hr (the upper part of the current China train speeds), the value for L_d is projected to be 16 percent lower (1.6 dB) than the 70 dB(A) limit.

The conclusions related to noise mitigation costs:

1. Source noise reduction costs ranged from a high of \$50,000,000/track mile for increasing track curve radii to a low of \$18,000/train set for adding pantograph fairings. Other notable \$68,000/train set for side skirts, and \$780,000/track mile for tuned rail dampers.
2. Costs for reduction methods applied along the noise path range from a high of \$50,000,000/track mile for increasing the distance to the edge of the railroad property to a low of \$133,000/track mile for adding resilient padding to slab track. Other noise path mitigation method costs include \$3,700,000/track mile for barriers at the edge of the right of way, \$3,000,000 each for tunnel entrance hoods, \$689,000/track mile for application of sound absorbing materials on existing noise barriers, and \$210,000/mile to lower tracks into trenches.
3. Costs for reducing noise levels at the receiver range from a high of \$1,800,000/track mile for sound barriers at property boundaries to a low of \$500/dwelling for caulking and sealing gaps. Other reduction method costs applied at the receiver include \$57,000/dwelling for vibration-breaking trenches, \$17,000/dwelling for façade insulation, \$14,000/dwelling for foundation vibration and sound insulation, \$6,400/dwelling for windows with 3-inch air gap, and \$2,800/dwelling for in-wall noise attenuation systems.
4. The total cost of noise mitigation methods for the representative NEC track is approximately five times higher than those for the CAHSR representative track, even though both tracks are approximately the same length. However, the average cost per impacted resident is much lower at \$55.40 for the NEC track and \$92.91 for the California track due primarily to the NEC region having about 10 times more residents in the impacted zone than does the California region.
5. The cost effectiveness of high-speed train noise reduction methods applied along the noise path compared to the cost effectiveness of methods applied at the receiver is primarily dependent on the trade-off between the length of track and the number of residents impacted.
6. Each analyzed track section for both the NEC and California high speed rail systems, required the implementation of sound barriers or windows to achieve the target 20 dB(A) noise reduction in a cost-effective manner. Other identified noise reduction methods were less effective compared to sound barriers and windows but were required to achieve the selected target reduction of 20 dB.
7. Methods such as at-grade ballast, improved foundation isolation materials, façade insulation, layered walls and vibration breaking trenches were found to not be cost-effective solutions and thus were not utilized for any of the designated track sections.

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12. Appendix. CONTRAST Spreadsheet

Paul, J. C., Neeraj, V., & Foyle, J. (2022). Comparison Of Noise for TRAin STandards Spreadsheet. Washington, DC: U.S. Department of Transportation, Federal Railroad Administration.

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
ASJ	Acoustical Society of Japan
AHJ	Agency Having Jurisdiction
ANSI	American National Standards Institute
APTA	American Public Transportation Association
APL	Axles per Length (number of rail car axles divided by car length)
BSI	British Standards Institute
CAHSRA	California High Speed Rail Authority
CHSTS	California High-Speed Train System
EPB	China: Local Environmental Protection Bureaus
MEP	China Ministry of Environmental Protection
SEPA	China State Environmental Protection Administration
CARS	Chinese Academy of Railway Sciences
CTRL	Channel Tunnel Rail Link
CFR	Code of Federal Regulations
CER	Community of European Railway and Infrastructure Companies
CTL	Community Tolerance Levels
CWR	Continuous Welded Rail
CR	Conventional Rail
CEQ	Council on Environmental Quality
dB(A)	Decibels, A-Weighted Scale, Sound Pressure Level Measurement Unit
DMU	Diesel Multiple Units
RMR	Dutch Noise Level Calculation Procedure
EBA	Eisenbahn Bundesamt (German Federal Rail Agency)
EMU	Electric Multiple Units
Esri	Environmental Systems Research Institute
AEIF	European Association for Railway Interoperability
ESPG	European Petroleum Survey Group
EN	European Standards - Engineering
ERA	European Union Agency for Railways
END	European Union Environmental Noise Directive

ACRONYMS	EXPLANATION
ERTMS	European Rail Transport Management System
ETCS	European Train Control Systems
EU	European Union
TSI	European Union Technical Specifications for Interoperability
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
GPP	Geluidsproductieplafonds (Netherlands) or Noise Production Ceilings
DE	Germany
HSL	High Speed Line
HSR	High Speed Rail
HST	High Speed Train
IEEE	Institute of Electrical and Electronics Engineering
ICE	Intercity Express Trains (Europe)
ICNG	Intercity Next Generation Trains (Europe)
ICA	International Congress on Acoustics
IEC	International Electrotechnical Commission
I-INCE	International Institute of Noise Control Engineering
ISO	International Organization for Standardization
UIP	International Union of Wagons Keepers
ISO DIS	ISO Draft International Standard
MITTI	Japanese Agency of Industrial Science and Technology
JIS	Japanese Industrial Standard
LCC	Lifecycle Costs
MBTA	Massachusetts Bay Transportation Authority
NL	Netherlands
NS	Nederlandse Spoorwegen: Netherlands passenger railway operator
NOEMIE	Noise Emission Measurement Campaign for HS Interoperability in Europe
NEC	Northeast Corridor
NEC HSR	Northeast Corridor High Speed Rail
OTM	On Track Machine
Pa	Pascals (sound pressure level measurement unit)

ACRONYMS	EXPLANATION
PRIIA	Passenger Rail Investment and Improvement Act
PPP	Public Private Partnership
RGS	Railway Group Standards (European Union)
RMV	Reken en Meet voorschrift, Dutch Noise Calculation and Measurement Instructions
SEL	Sound Exposure Level
SEHSR	Southeast High-Speed Rail
SEPTA	Southeastern Pennsylvania Transportation Authority
SPL	Sound Pressure Level
TRL	Technology Readiness
CEN	The European Committee for Standardization
TEL	Transient Exposure Level
TGV	Train à Grande Vitesse (French High Speed Train)
TSI NOI	TSI Noise Regulation Number 1304/2014
UIC	Union International des Chemis de fer (International Union of Railways)
UK	United Kingdom
RSSB	UK Rail Safety Standards Board
USDA	US Department of Agriculture
DOL	US Department of Labor
DOT	US Department of Transportation
EPA	US Environmental Protection Agency
FTA	US Federal Transit Administration
GAO	US Government Accountability Office
NEPA	US National Environmental Policy Act
OSHA	US Occupational Safety and Health Administration
DRPT	Virginia Department of Rail and Public Transportation
VT	Virtual Testing