MODELING THE EFFECTS OF RAIL NOISE PROPAGATION ON PEDESTRIANS IN NORTH CAROLINA RAILROAD ENVIRONMENTS




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NORTH CAROLINA AGRICULTURAL AND TECHNICAL STATE UNIVERSITY

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RESEARCH & DEVELOPMENT

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16. Abstract

With more than three thousand miles of railroad tracks, North Carolina has about two percent of the national total railroad track mile, but its share of trespassing incidents/accidents consistently exceeded that share in most years during the past decade, ranging from two to four percent, while death rates remained above two percent during most year. Many entities worked together to educate the public, invest in warning devices, and enforce trespassing laws to eliminate preventable death and keep the public safe. However, little research has examined the relationship between sound propagation and its effect on rail trespass strikes. Yet studies show that 95% of rail related deaths involve drivers going around warning devices or people walking on railroad tracks.

In our effort to assist NCDOT in investigating the relationship between sound propagation and rail trespass strikes, the NCAT team, led by Dr. Rongfang (Rachel) Liu and supported Acoustic Spectrum Acoustics (CSA), Inc., has defined the characteristics of rail noise propagation and assessed the awareness of railroad trespassing laws through literature review and online survey. Then, the research team has identified a comprehensive list of factors that affect rail noise propagation and selected a key set to be evaluated in field data collection and acoustic models. Working with the NCDOT Rail Safety staff and Project Steering and Implementation Committee (StIC), the NCAT team has collected field data, generated sound propagation models, tested various scenarios based on factors identified earlier and visualized the sound propagation/decomposition processes. The research result will not only help engineers to improve safety design and preventive measures but also can be used to educate the public about the dangers of rail trespassing behavior.

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I am grateful for the assistance from the administrators and supporting staff at North Carolina A & T State University, College of Business and Economics, as well as Transportation Institute while I am responsible for errors and/or omissions, if any, in the report.

North Carolina Department of Transportation
Research Project 2023-10
Final Report

MODELING THE EFFECTS OF RAIL NOISE PROPAGATION ON PEDESTRIANS IN NORTH CAROLINA RAILROAD ENVIRONMENTS

Submitted

By

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1. INTRODUCTION

Each day in the United States, an average of three people are killed or injured while traversing railroad properties, which resulted in 715 pedestrian fatalities in 2023 alone (National Safety Council 2024). With more than 190,000 miles of tracks, railroads operate in 49 states in America and affect almost every corner of the country. The economic and social costs of railroad fatality and injury can be compounded to the billions of dollars each year. The urgency and importance of understanding pedestrian and railroad safety can't be overemphasized.

With more than three thousand miles of railroad tracks, North Carolina ranks 23rd in the nation for total miles of railroad (Association of American Railroad 2021). However, its ranking for pedestrian casualties in and around railroad properties, Trespassing Casualty in FRA terms, is 12th - far higher than its ranking in railroad mileage. As shown in Figure 1, the railroad miles in North Carolina are about two percent of the national total, but its share of trespassing incidents/accidents consistently exceeded that share in most years during the past decade, ranging from two to four percent, while death rates remained constant at two percent except in 2012.

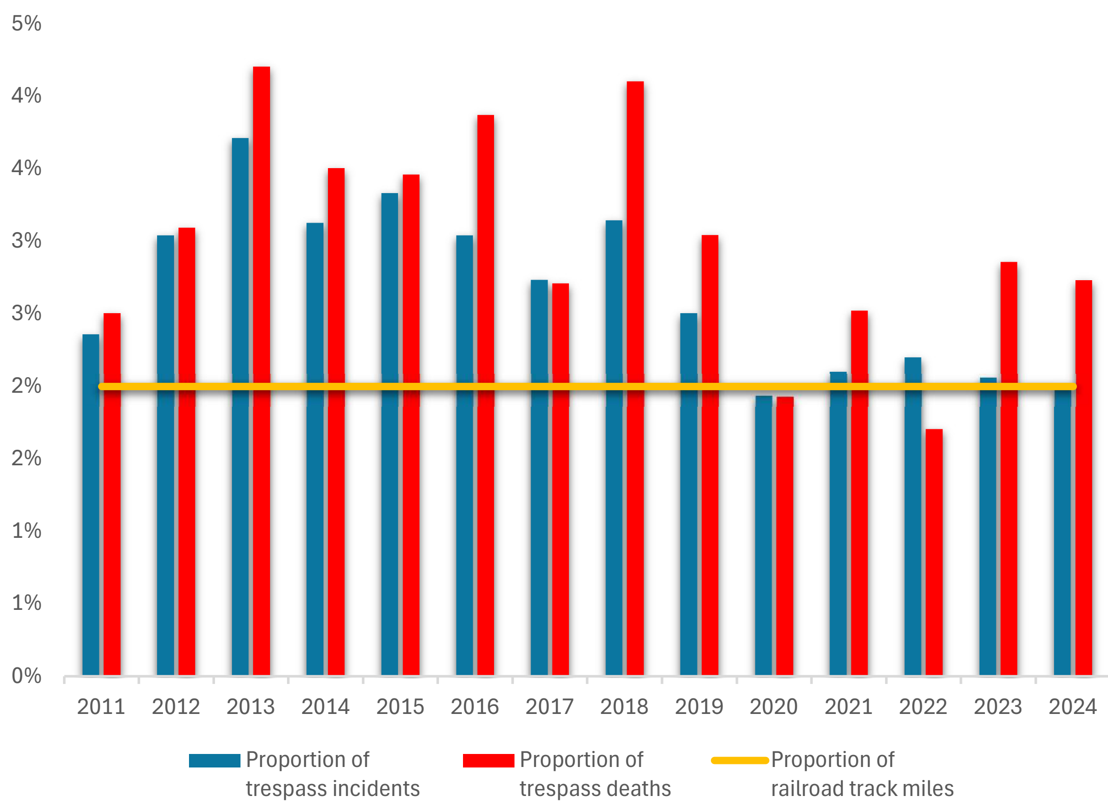


Figure 1. NC Shares of Railroad Miles, Incidents, & Fatalities over National Total

Many entities, such as state, local and federal agencies, safety organizations, railroad owners/tenants, and technology companies, worked together to educate the public, invest in warning devices, and enforce trespassing laws to eliminate preventable death and keep the public safe. However, little research has examined the relationship between sound propagation and its effect on rail trespass strikes. Yet studies show that 95% of rail-related deaths involve drivers going around warning devices or people walking on railroad tracks (AAR 2021).

As the direct result of a universal belief “that people walking on the tracks should hear or feel the train with adequate advanced warning to avoid being stuck,” a recurring theme has often been observed: “most humans were never aware of the train approaching or made a realization far too late to take life-saving action.” The observation is often confirmed by railroad safety professionals, but the existing literature has seldomly addressed the issue nor explored the reasons behind the observations.

In our effort to assist NCDOT in investigating the relationship between sound propagation and rail trespass strikes, Dr. Rongfang (Rachel) Liu, PI, has led a team of rail safety, travel behavior, and community outreach experts to accomplish the objectives set out for this research. Cross Spectrum Acoustics (CSA), Inc., a nationally recognized expert in acoustic modeling and a longtime advisor to FRA, has supported the research effort in sound propagation modeling and visualizations.

This final report documents the research approaches undertaken by the NCAT research team. After establishing a baseline scenario on public beliefs and attitudes about the danger of railroad environments, the research team has defined the characteristics of rail noise propagation and assessed the awareness of railroad trespassing laws through literature review and online survey. Then, the research team has identified a comprehensive list of factors that affect rail noise propagation and selected a key set to be evaluated in field data collection and acoustic models.

Working with the NCDOT Rail Safety staff and Project Steering and Implementation Committee (StIC), the NCAT team has collected field data, generated sound propagation models, tested various scenarios based on factors identified earlier, and visualized the sound propagation/decomposition processes. The research result will not only help engineers to improve safety design and preventive measures, but also can be used to educate the public about the dangers of rail trespassing behavior.

2. BENCHMARKING

After receiving the Notice to Proceed (NTP) from NCDOT, the NCAT research team conducted a detailed, in-depth literature review, which serves as the knowledge baseline on rail trespass strikes and highlights the critical areas that need further investigation. Due to the limited quantity and scope of existing studies and the time lag of formal publications, the research team also examined alternative sources, such as unpublished project reports, conference presentations, as well as personal communications and project experiences. A detailed literature review is summarized in **Appendix 1.**

Confirming our initial assessment, the first task proved that little research has investigated the relationship between sound propagation and its effect on rail trespass strikes. In fact, many studies focused on reducing rail noise, promoting quiet zones, and proving annoyance of train noise (Lambert et al., 1996), which all had the common goal of reducing rail noise but also the inadvertent effect of increasing rail trespass strikes.

The effort to control rail noise in the U.S. dates back to the 1960s and intensified in the 1970s when a special interest group in Florida sought ways to ban train whistles from residential areas (FRA 1995). Many alternatives, such as Wayside Auditory Warning, train bells, and/or Quiet Zones, have been studied and implemented in many railroad and highway crossing locations (Multer 1994, Hummer and Jafari 2003, and U.S Government Accountability Office 2017). Together with technological improvements, such as continuous welding rails (CWR), dampening devices on wheels, and overall reduction on the friction of steel wheel on steel rails, rail operations got much quieter, which may please nearby urban dwellers, but also invalidated the belief that "people walking on the tracks should hear or feel the train..."

As the first steps to accomplish the overall research objectives, the NCAT team has established the baseline definition of trespassing incidents, developed in-depth understanding of rail danger awareness by surveying the public, and identified key factors that have the potential to affect or alternate rail noise propagation. The following section documents the baseline findings of those tasks.

2.1 Definition of Trespassing Incident

It is commonly accepted that rail trespassers are individuals illegally on private railroad property. They are most often pedestrians who walk across or along railroad tracks as a shortcut to another destination. In reality, there are various definitions and interpretations of "trespass," "trespasser," and "trespassing incidents." For example, the Federal Railroad Administration (FRA) defines trespassers as "persons who are on the part of railroad property used in railroad operation and whose presence is prohibited, forbidden, or unlawful" (FRA 2011). Meanwhile, the Federal Transit Administration (FTA) dictates that "trespass" is "the unauthorized entry of transit-owned land, structure, or other real property not intended for public use" (FTA 2020).

As the main source of railroad safety data, the injury-illness summary database by FRA has a separate category for trespasser/trespassing, while FTA does not separate "trespasser" from other types of persons in the incident report. In the National Transit Database (NTD), there is no specific reporting category for a person who is walking along or across rail transit tracks, along the right-of-way, or in a station environment. Those discrepancies and inconsistencies made it difficult, if not impossible, to compare and analyze the causes of trespassing in various locations, types of rail facilities, and other environmental conditions based on reported data.

To establish a baseline for further investigation of trespassing behavior, the research team has adapted the definition of trespasser as "**an unauthorized individual on railroad or rail transit property that is not intended for public use**." A trespasser may be a rail passenger who ventures into off-limit territory. A trespassing incident occurs whenever a pedestrian enters these restricted areas, and a trespassing accident occurs when a pedestrian suffers bodily injury or is killed as a direct result of his or her presence on railroad or rail transit properties.

This report employs the words "trespass," "trespasser," and "trespassing" to describe events of pedestrians on railroad or rail transit property illegally, largely based on the commonly accepted terminology in the transportation safety arena. It is important to note that the connotation of inherent criminality in the term "trespass" may obscure the actor/victim in a trespassing incident from being fully understood.

Striving for a deeper understanding of trespassing behavior and the range of factors affecting those behaviors, the NCAT team has dived deep into the complicated matrix of those causal relationships. For example, the research team has examined the impact of demographic and socioeconomic status; Safety education on the awareness of dangers associated with railroad operations; and the effects of land use, natural environments, and various warning devices on rail noise propagation, which may have played key roles in trespass strikes.

With significant efforts to mitigate railroad casualties and improve crossing safety during the past half century, the overall rate of railroad injury and fatality has been decreasing, as shown in Figure 2. While total annual incidents are decreasing, especially during the two most recent decades, annual fatalities are decreasing at a slower pace, which resulted in an increased fatality rate from 3% in 1975 to 13% in 2024 when comparing yearly railroad fatalities to annual incidents.

On the other hand, trespassing behavior has not changed much during the past half century, as shown in Figure 3. Placing trespasser fatalities in the context of total trespassing incidents, the yearly fatality rate ranges between 37 to 52 percent. The more worrisome trend is that the highest fatality rates occurred more recently in 2022, at 52%.

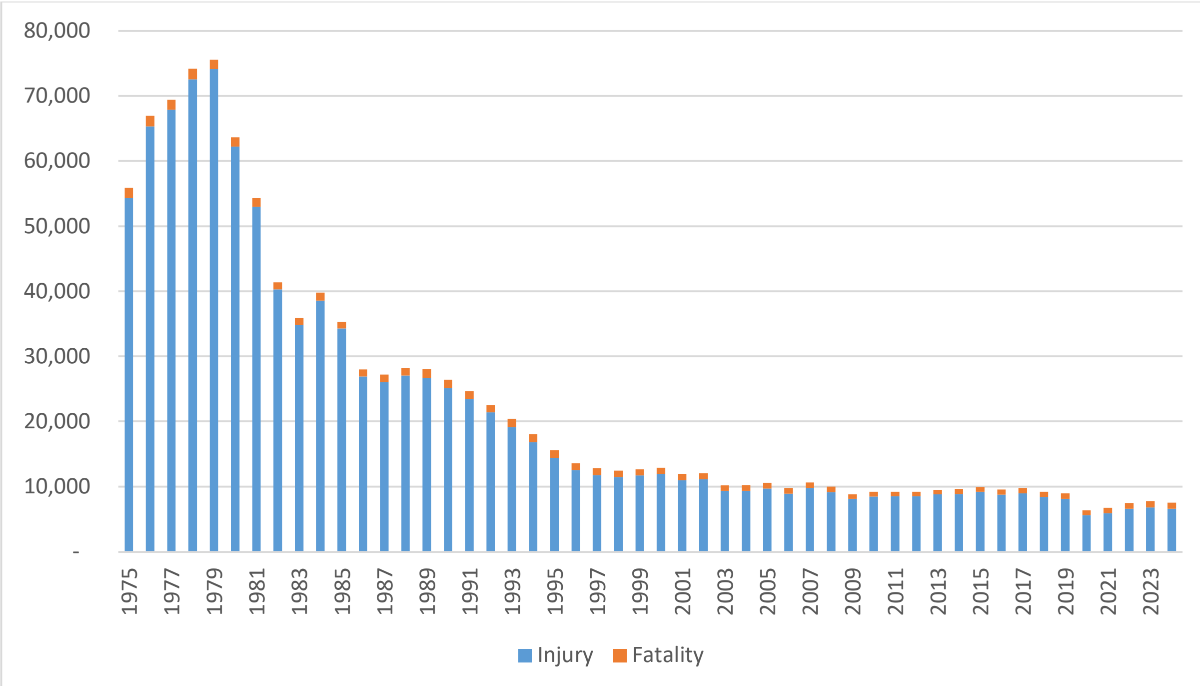


Figure 2. Railroad Injury and Fatality, 1975-2024

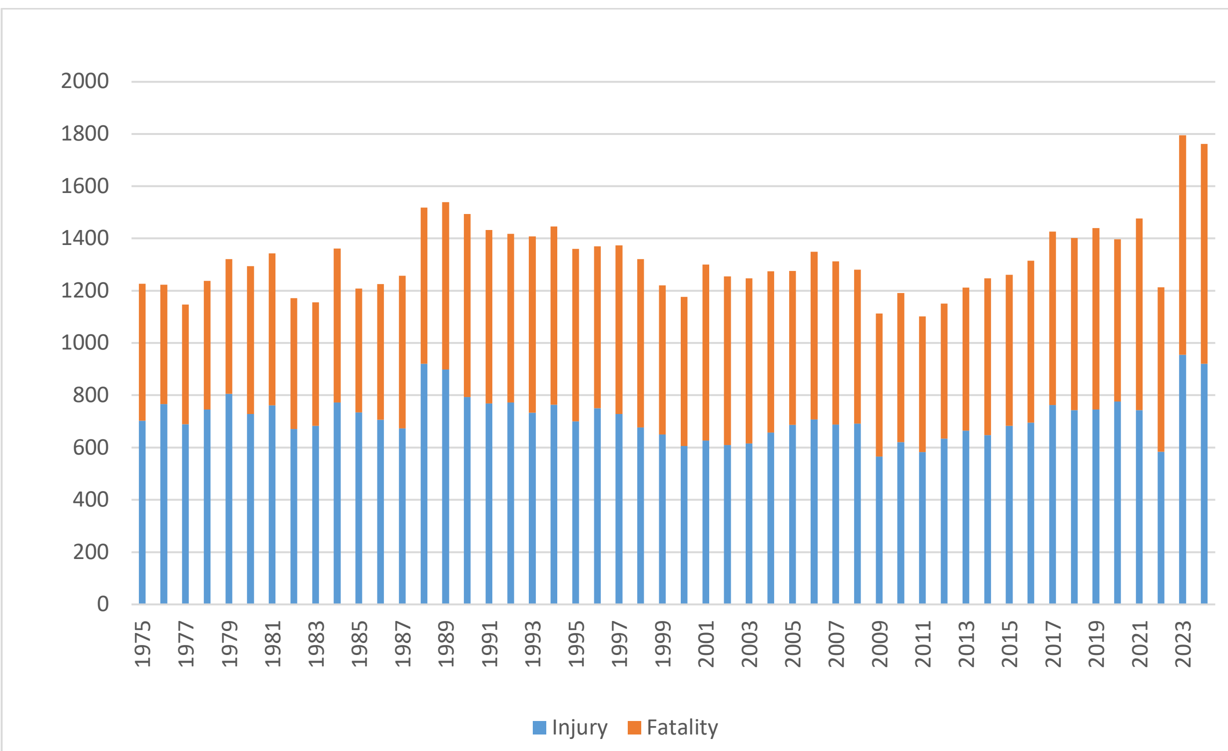


Figure 3. Trespasser Injury and Fatality, 1975-2024

The prevalence of railroad trespassing is well-documented, both by mandatory data reporting of incidents and by sensor and camera studies conducted to identify local hotspots. Trespassing is the leading cause of both accidental railroad-related deaths and all railroad-related deaths—about 44% of all railroad casualties, according to earlier studies (Sumwalt, 2019; Laffey, 2019).

2.2 Awareness of Railway Danger

There is little work in the existing literature to understand trespasser behavior around railroad or transit properties in advance of strike incidents. As noted earlier, a person’s understanding of rail danger and his or her motivation for traversing the railroad environment are essential factors to develop effective strategies to reduce or eliminate trespass strikes.

Some research efforts have focused on determining trespasser demographics and the reason for their trespassing behavior by isolating self-harm from others using accident data collected from official reports. Other work has added to the body of literature around pedestrian behavior. It is important to note that very few studies support the efficacy of any measures to modify trespasser behavior, although Waterson et al. (2017) did document teenage trespass perceptions and how teenagers perceived the efficacy of various interventions.

An additional under-researched aspect of the rail strike problem is the emerging study of perceived versus measured noise input, currently applied to personal exposure assessment in noise and air pollution (Marquart et al., 2021). The researchers established that measurable noise and air pollution did not always match perceived levels and were confounded by variables like knowledge, embodied experience, life situations, and activities. It has been established that perceived risks and noise both influence behavior and route choices for active mode travelers (Gössling et al., 2019), so it begs the question of how perceived risk (or lack thereof) is not only influencing trespasser behavior, but also their actual ability to discern emergency warnings from trains.

Furthermore, popular beliefs from long ago and current social media trends do not help warn of the potential danger of railroad environments. For example, while media depictions of trains typically portray them as dangerous, the hero nearly always escapes the tracks in time. What’s more, trains are portrayed as quite loud, from the noise of carts rattling along rails to the signature long, loud warning whistle, which is virtually never absent, implying that it can always be heard. In reality, rail technology has come a long way since the wild west, driven by the idea that quieter trains are better for society. Interestingly, the inherent danger of quieter trains is not widely discussed, even within the industry.

In order to develop a current, deeper understanding of rail danger awareness, the NCAT team has conducted a survey, which was executed via both online and in-person settings. The survey is designed to establish a baseline understanding of the public’s awareness of rail danger and gauge their overall interactions with the rail network. As a key component of this research, public awareness about risks associated with crossing railroad tracks and general rail operations may play a significant role in understanding how North Carolinians are interacting with railroad operations, particularly as it relates to their expectation of encountering a train during trespassing incidents.

2.2.1. Survey Design

Working with NCDOT staff and various stakeholders, the NCAT team has developed a survey comprised of four unmarked sections, totaling 29 questions, as shown in **Appendix 2**. The first section gathered information on people's experiences, observations, and perceptions of rail trespassing danger. The second section gleaned information on the perceived impact of various parameters, such as time of day, weather conditions, urban versus rural, and other physical environmental factors. The third section collected information on public exposure to rail safety education and the effectiveness of various approaches. The last section of the survey asked for general demographic and socioeconomic information about the respondent.

Aided by an outreach package including a QR code, a website banner, and a poster, as shown in **Appendix 3,** the survey was disseminated between March 1 and June 30, 2023, and shared widely among the research team's network and with help from external partners. Included in these efforts were the Center for Advanced Transportation Mobility's public newsletter distribution list, local government newsletters and bulletins, and the public networks of a variety of rail stakeholders nationwide who attended a November 2022 FRA rail safety workshop in Raleigh, North Carolina. In addition to the online format, the research team also took advantage of in-person workshops organized by NCDOT BeRailSafe Program.

2.2.2 Data Analysis

When the survey was completed, a total of 2,030 survey attempts were recorded via the Qualtrics system. Of the 2,030 attempts, 1,925 respondents, representing 95%, went through all the survey questions, while 105 respondents abandoned the exercise at various points after starting. This includes 35 respondents who didn't expressly consent to participating in the survey.

As shown in Figure 4, the demographics of survey respondents loosely correlate with the demographic data of the United States at large. The majority of survey respondents (79%) were between 25-44. Since our survey excluded minors, the youngest group, 18-24 is slightly larger than the older groups, 55-64 and 65+, but the general distribution still resembles a bell curve similar to the overall US population distribution. The gender breakdown skewed slightly toward male, 53% of survey respondents as opposed to 49.5% of the U.S. population. The majority of survey participants, 77%, are white, which closely correlates with the share of the U.S. population, 75.5%. About 18% of survey respondents noted that they had a disability or a history of disability, while only 8.7% of the U.S. population under 65 identifies with disability status.

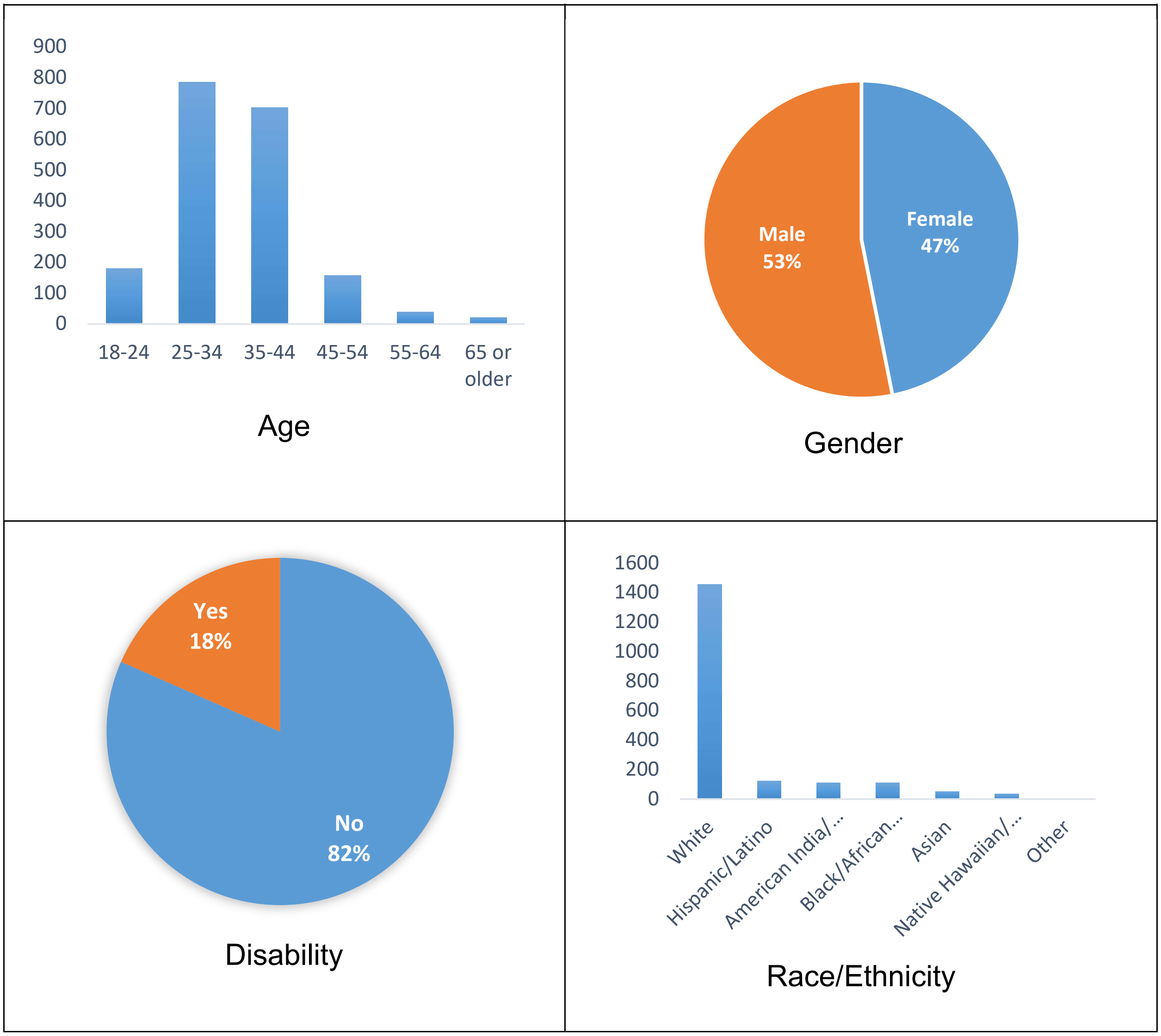
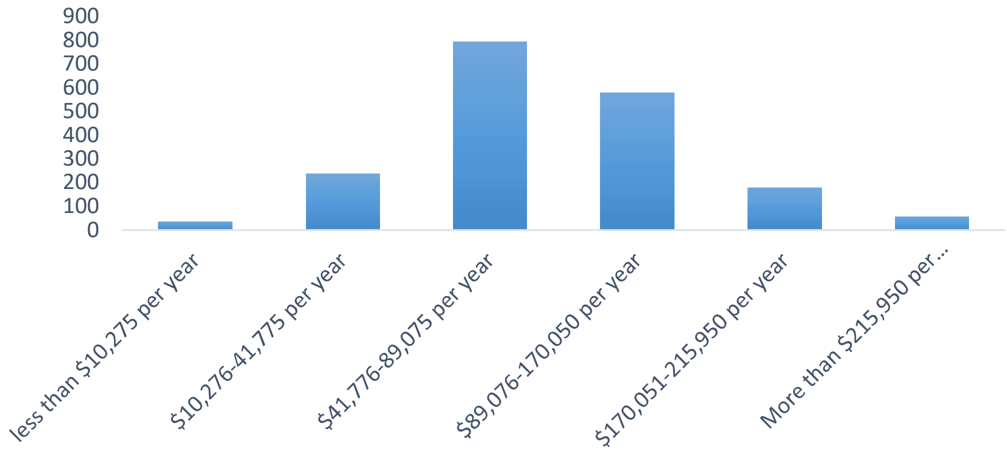
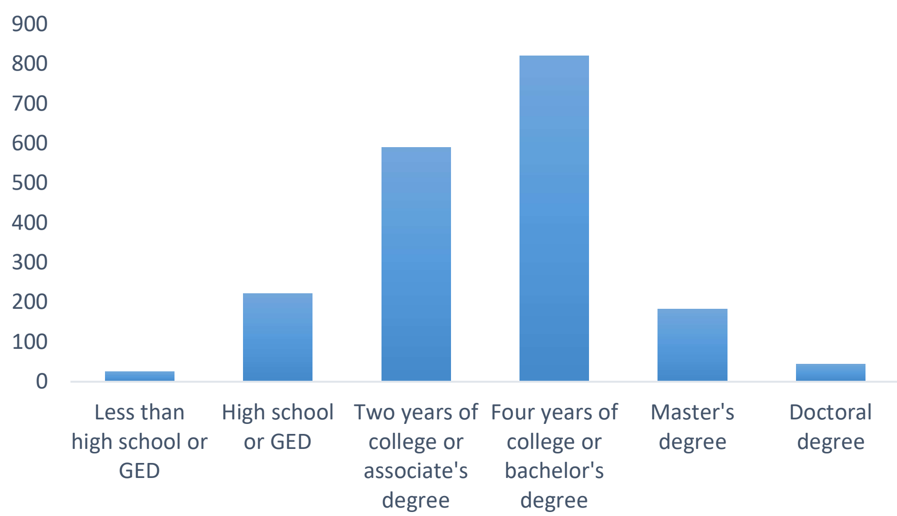


Figure 4. Demographic Characteristics of Survey Participants

Figure 5 documents the socioeconomic backgrounds of survey participants, which differ from the general distribution of the U.S. population. While the U.S. population's education and income levels both skew with significantly higher numbers at the lower income/education levels, the survey participants were more normally distributed across income and education levels with a plurality of participants falling in the same range as the U.S. median individual income, $41,776-$89,075, and having achieved a bachelor's degree. The BeRailSafe/FRA workshops were targeted at working professionals in the three largest metropolitan areas of North Carolina, and it stands to reason that transportation professionals tend to have higher income and education levels than the general public.



A. Household Income of Respondents



B. Education Levels of Respondents

Figure 5. Social Economic Status of Survey Participants

When asked about their rail safety education experiences, the majority of respondents, 91%, were familiar with the signage around railroad rights-of-way warning against illegal crossing and trespassing, and 65% have attended a rail safety education course of some kind, as shown in Figure 6A and 6B. Of those who attended a course, the vast majority, 85%, took the course within the past 3 years, as shown in Figure 6C. Participants favored in-person demonstrations, and the perceived efficacy of other delivery modes decreases along the categories of TV/movies, webinars, social media, and radio, as demonstrated in Figure 6D.

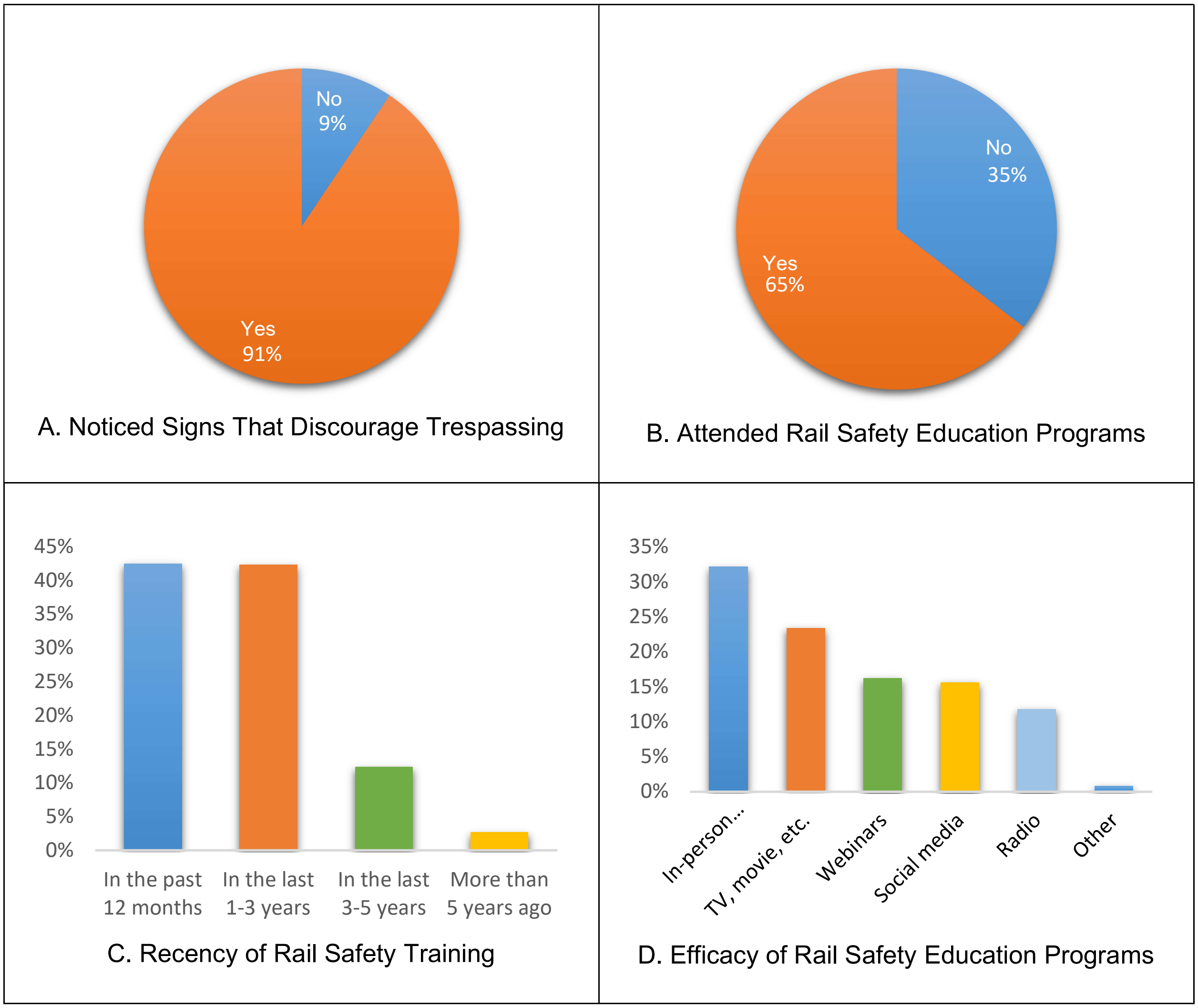


Figure 6. Rail Safety Education/Knowledge

Figure 7 shows participants' perceptions of right-of-way danger in a variety of environments. The survey required them to use a sliding scale to choose which of the two environmental factors represented in each graph they felt created a more dangerous rail environment. The first four graphs show predictably increased danger perception of night over day, snow over sun, rain over sun, and fog over sun. While some respondents felt that daytime and sunny weather was more dangerous than their counterparts in the question, the overwhelming majority chose increased danger in environments that are typically perceived as more dangerous. The last two graphs demonstrate ambivalent perceptions of the rural versus city and the fall versus spring dichotomies. Further research into safety perceptions and the environment would be necessary to understand these mixed responses.

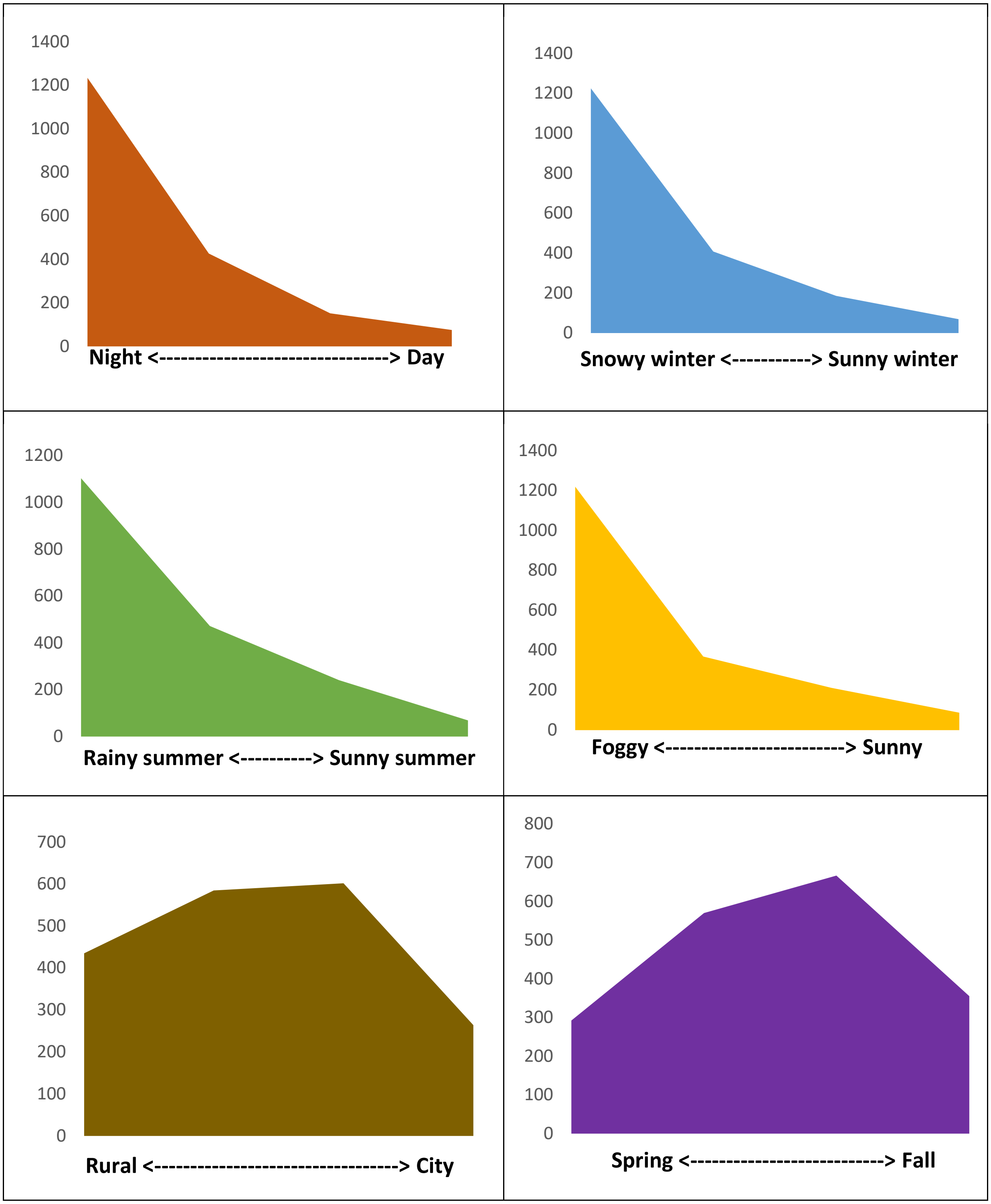


Figure 7. Respondents' Perception of Danger for Environmental Conditions

When it comes to train operations and mechanics, the majority, 75%, of the survey respondents believed that trains ran on a fixed, regular schedule, which might help to explain some pedestrian behavior in the railroad environment. More than half of the survey participants, 58%, felt that it was impossible to get electrocuted by tracks under any circumstances, while 42% of the participants felt that some railroad tracks did present electrocution danger, as shown in Figure 8. The overwhelming majority, 82%, of respondents believed that train wheels and engines make enough noise to be heard by pedestrians on the tracks. Respondents were divided, however, on whether or not they thought that all trains produced equal levels of noise, exhibited in the right-most bar in Figure 8.

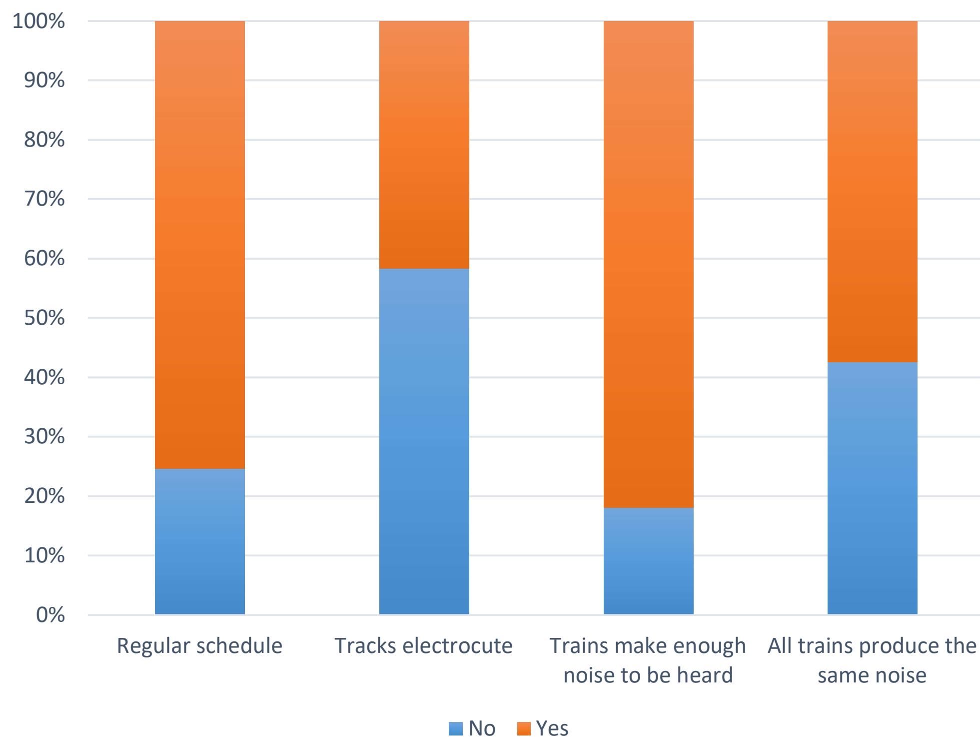


Figure 8. Rail Mechanics and Logistics

The survey contains a number of questions about train noise and how it may affect pedestrian behavior. Documenting perceptions is a vital step in understanding public awareness of modern train environments and developing effective interventions. The first of these questions illustrates which aspect of rail operations was responsible for noise creation. While multiple selections were allowed, the largest swathe of answers credited steel wheels on steel tracks as the main source of the rail noises. The “Other” selections on this question were left blank by all respondents, as shown in Figure 9.

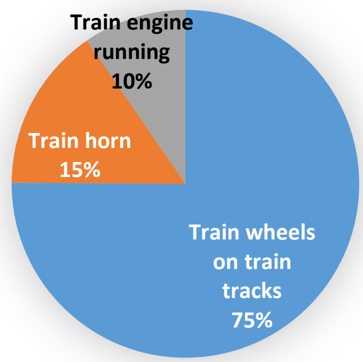


Figure 9. Sources of Train Noise

Figure 10 represents question 10 in the survey, which employed Qualtrics "display logic," only appearing if the respondent chose "no" for question 9 ("Do you believe that all types of trains produce the same types/levels of noise?"). Respondents who chose "yes" for question 9 advanced to question 11 automatically. Less than half of respondents thought that different kinds of trains would make a perceptible difference in noise production. Those who did advance to question 10 were asked to rank various rail modes from loudest to quietest.

As shown in Figure 10, freight was by far considered the loudest rail mode and light rail the quietest, while passenger (intercity), commuter (intracity), and subway trains fell somewhere in between the two. In general, these perceptions matched the reality of wayside or platform rail noise during a locomotive pass by, with freight measuring the highest at 97 dB (Office of Railroad Policy and Development, 2012) and light rail the quietest, ranging from 76-88 dB (Metropolitan Council, 2015). Intercity passenger rail, such as Amtrak, followed freight in loudness at 92 dB (Office of Railroad Policy and Development, 2012), and commuter rail was close behind, measuring between 90-92 dB (Hanson, 2006). Subway noise varies wildly from 73-90 dB (Neitzel et al., 2009), with some independent data collectors reporting up to 119 dB (Guralnick, 2018).

Despite the correctness of the general trends, many respondents reported incorrect answers that ran the gamut of possible interpretations. One possible explanation for this stems from the fact that the survey question text made no delineations between the types of rails. "Passenger," "commuter," and "light rail" could have easily been confused by laypersons who took the survey. While this limitation to our data doesn't lend itself to a clear understanding of public perceptions of those particular modes, it does illustrate one facet of the public's ignorance about rail—the average pedestrian probably doesn't see railroad tracks or trains and perceive a great deal of nuance that might alter their behavior. To them, tracks are tracks and trains are trains. The somewhat random spectrum of answers in Figure 10 speaks to a level of guesswork by respondents.

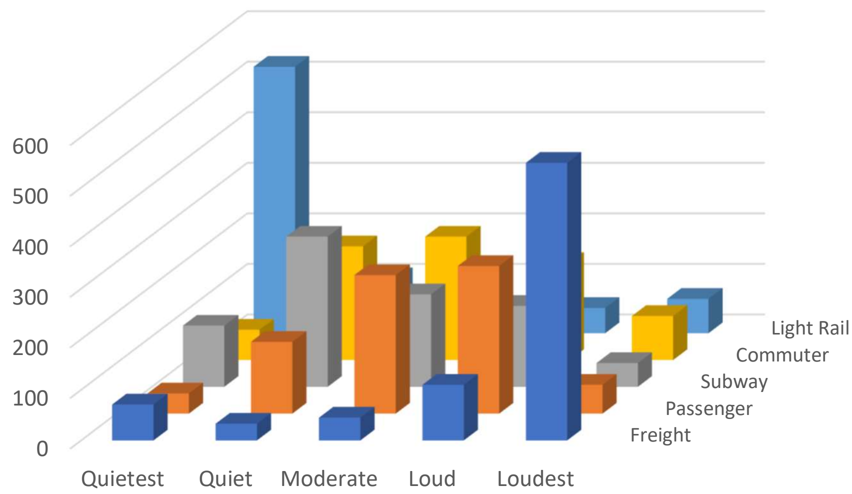


Figure 10. Train Types and Their Perceived Noise Levels

Awareness of the kinds of rail activity that occur within respondents' home states is represented in Figure 11. While the general recognition of train operations is consistent with the actual situation in each state, incorrect numbers may be attributed to a lack of awareness or confusion about the types of rails that do exist. For example, 61% of North Carolina respondents believe that subways exist in North Carolina even though there is no subway or commuter rail currently operating in the state. Confusion about train and rail types that operate locally is suggestive of wider ignorance about rail operations but also may contribute to dangerous behavior patterns in rail environments. For example, if a person believes that quiet rail modes don't operate in their state, they will assume trains are always loud and can be heard.

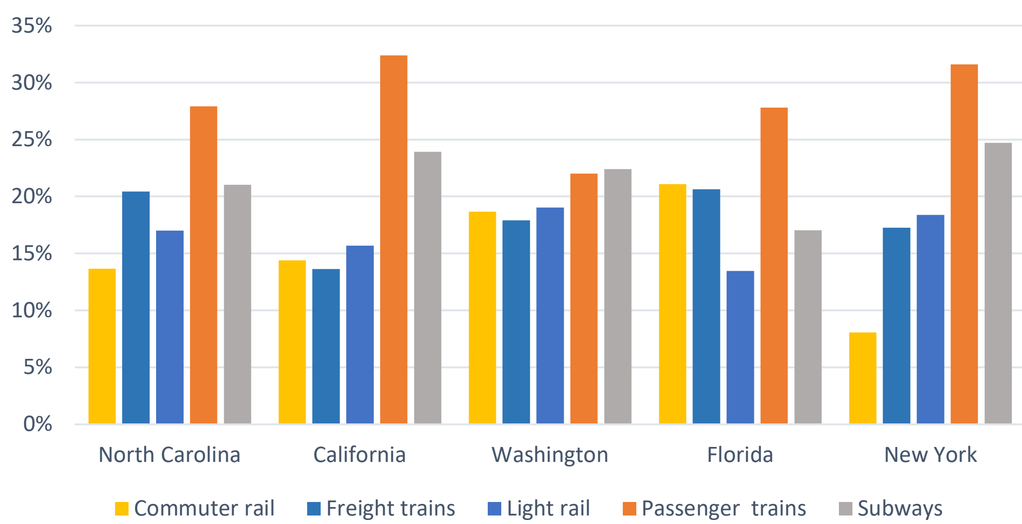


Figure 11. Perceived Rail Service Types by State

The survey responses on pedestrian interaction with trains are key metrics in understanding why rail incidents still occur with high frequency today. As proven by national accident statistics and anecdotal evidence in North Carolina, pedestrians often do not see or hear a train in time to take lifesaving action. However, the majority of survey respondents thought that pedestrians would have time to move to safety in either scenario, as demonstrated in Figure 12.

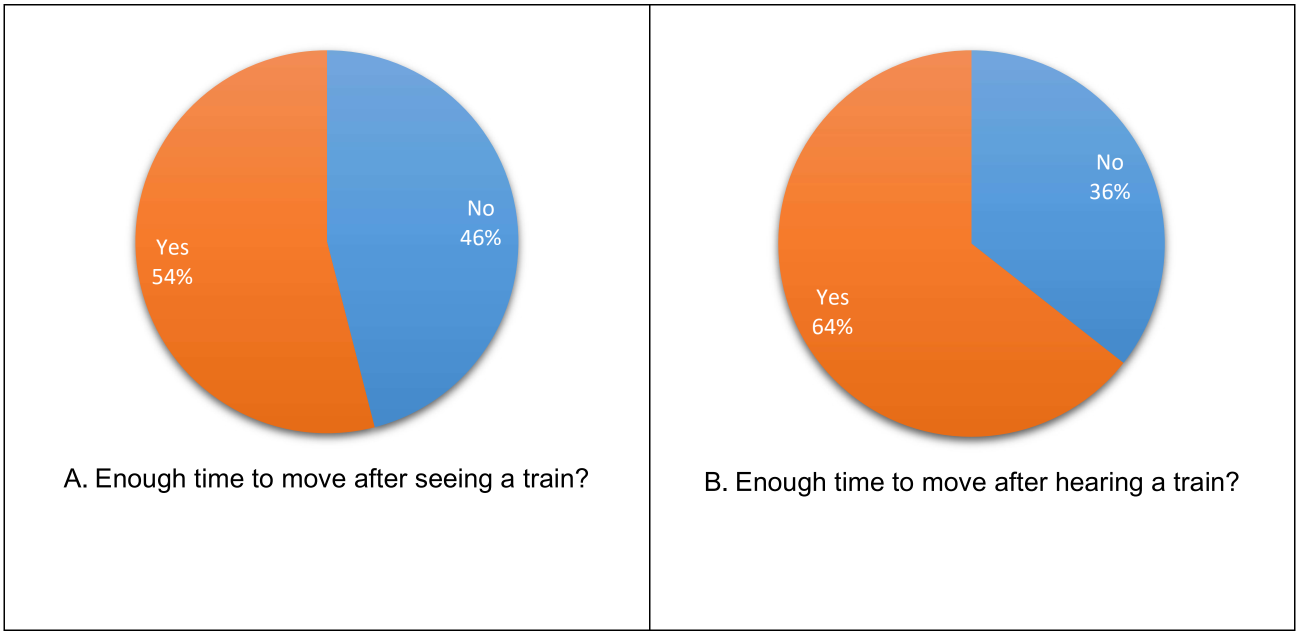


Figure 12. Perceived Pedestrian Response Time

While more than half, 57%, of the respondents claimed that they would never cross railroad tracks illegally to save time, the number of respondents who would, depending on how much time they would save, is still staggering. As exhibited in Figure 13, only a small portion of people would cross the railroad tracks illegally if it saves five minutes of their travel time. The share increased to five percent when it saves 10 minutes and 14% when 30 minutes of travel time is saved. Since all the "yes" answers are stacked, the data shows that if a person will cross the railroad tracks illegally when it saves five minutes of travel time, he or she will certainly do the same if more time, say 20 or 30 minutes of travel time, can be saved by crossing the railroad tracks illegally. This observation is confirmation that illegal right-of-way trespassing is a matter of convenience, perhaps more than it is a matter of criminal intent.

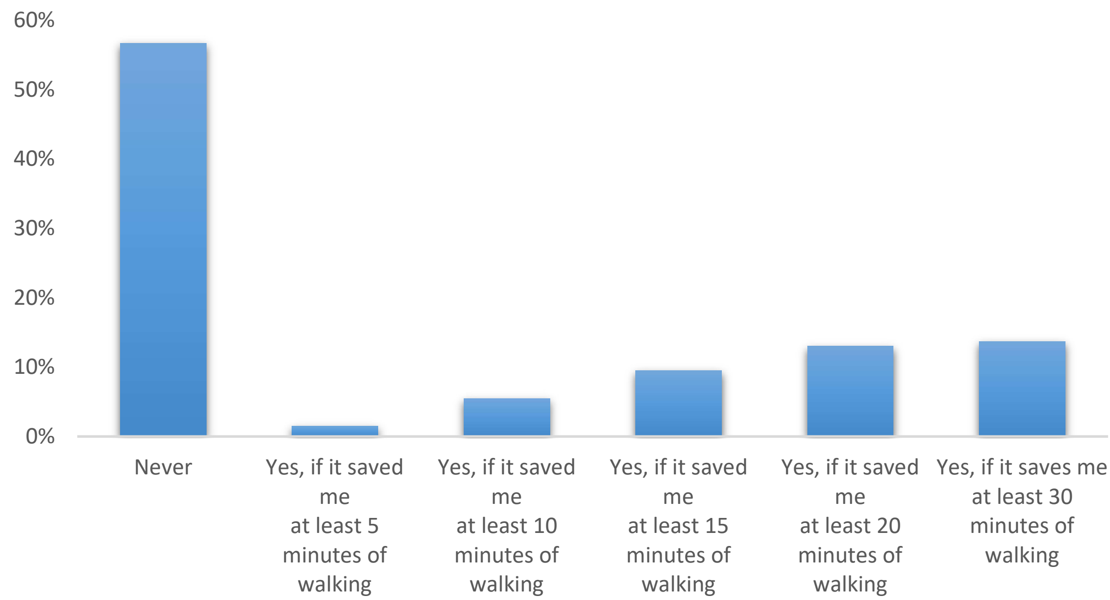


Figure 13. Respondents' Willingness to Cross Train Tracks

Interestingly, ambiguity exists in the public consciousness about the legality of crossing over train tracks. While most participants believe it is illegal to cross railroad tracks at non-designated locations, about 22% of the survey participants were not sure, and 17% believe it is legal to cross over train tracks at non-designated locations, as shown in Figure 14. Although awareness is relatively high, there is enough doubt in the public's awareness to open the possibility of incidents.

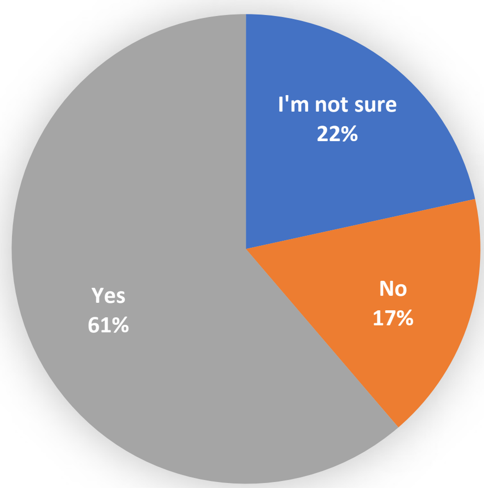


Figure 14. Answers to Illegal Crossing over Railroad Tracks

Additionally, survey participants demonstrated a surprising willingness to overcome obstacles in order to save time by crossing the railroad tracks illegally. While 62% of respondents would never use a faster route across the tracks, 18% would be willing to jump a fence, 11% would be willing to climb a steep hill, five percent of the respondents would climb through bushes, and about two percent would jump over a ditch to save some time as documented in Figure 15.

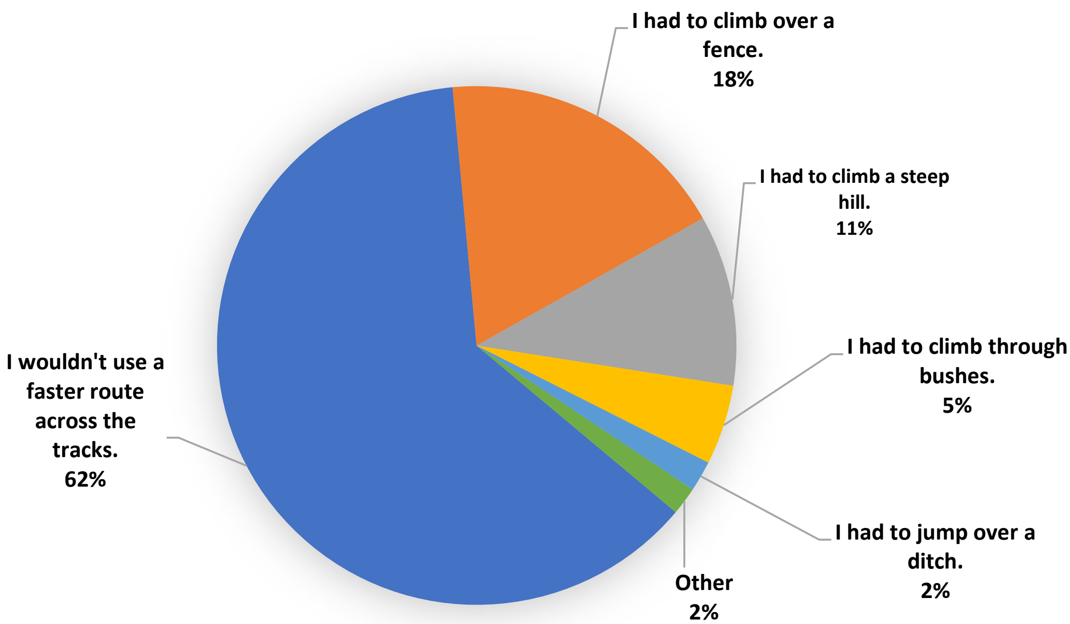


Figure 15. Willingness to Use a Faster Route across Train Tracks

Seven out of 10 respondents think it isn't safe to cross over or walk on railroad tracks for various reasons, mostly because of injuries and fatalities that could occur. Conversely, of the respondents who perceived railroad tracks to be safe, more than half thought the tracks posed no danger as long as there were no trains around. Details of this public perception are shown in Figure 16.

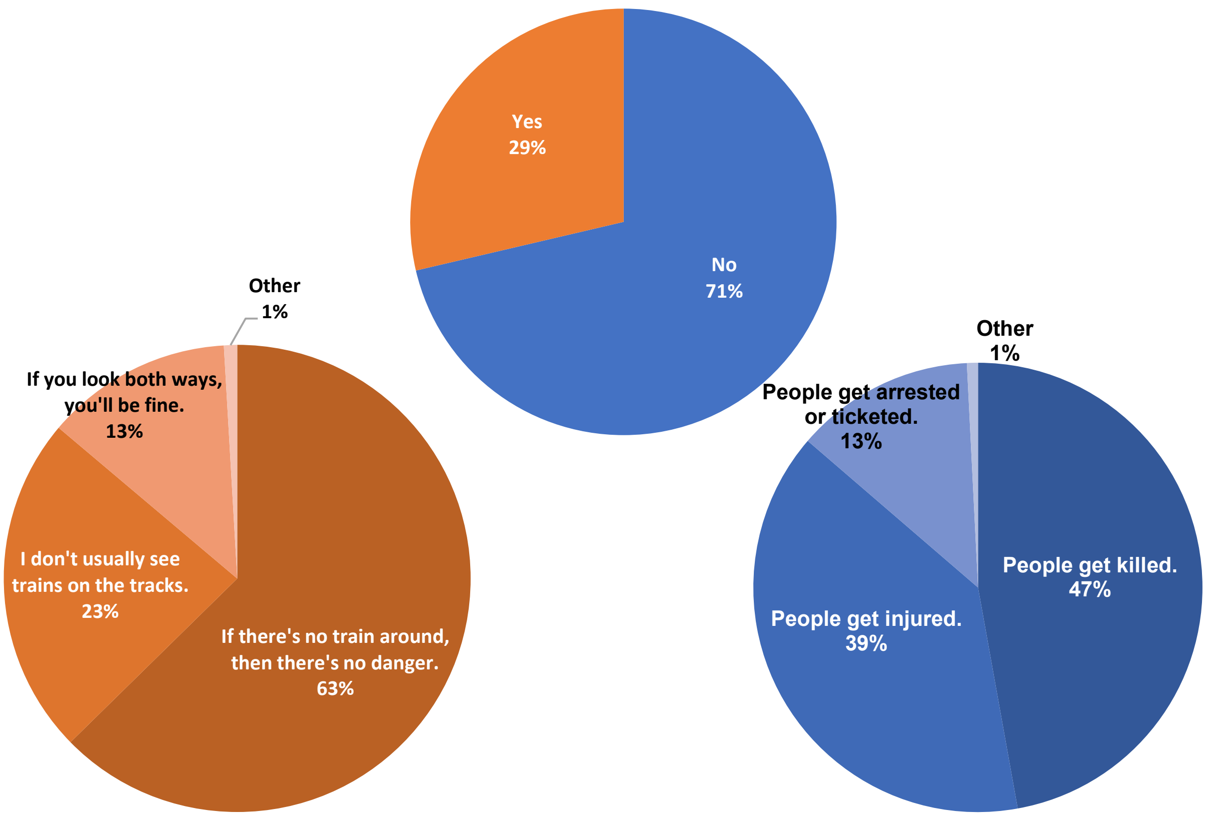


Figure 16. Reasons for "Safe/Unsafe" Beliefs about Crossing Railroad Tracks

Additionally, nine out of 10 respondents have done or seen at least one of the following in the past year: crossing train tracks at non-crossings, walking on tracks, or hanging out around the tracks for leisure activities, as documented in Figure 17.

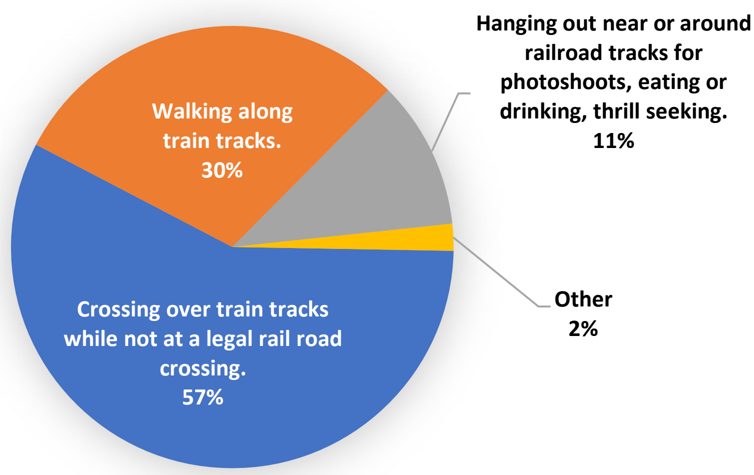


Figure 17. Rail Trespassing Activities

2.2.3 Impact Analysis

Diving deep into the relationship between people's beliefs, experiences, knowledge of railroad operations, and their respective socioeconomic backgrounds, the NCAT team has explored potential connections and/or impacts on their decision-making behavior at non-designated railroad crossings. Using respondents' beliefs of whether it is safe to cross a railroad track as the dependent variable, the research team has assessed various hypotheses by calibrating different regression models and identified a few significant variables that may affect people's perceptions and their decisions at railroad crossing locations.

Applying regression analysis and machine learning techniques, the research team has identified nine variables/features that significantly affect an individual's safety perception of railroad crossings. As shown in Table 1, three demographic variables and six rail operations knowledge variables have a significant impact on their belief about railroad crossing safety.

Table 1. Analysis of Maximum Likelihood Estimates

Effects	Maximum Likelihood Estimate	Odds Ratio Estimate	P-value
Regular schedule	0.370	1.856	0.028
Tracks electrocute	0.340	1.817	0.005
Move_after_seeing	1.802	4.723	0.000
Move_after_hearing	0.864	2.801	0.000
Time saving	0.029	1.029	0.002
Illegal to cross	-0.263	0.763	0.041
White	-1.195	0.261	0.001
Disability	1.309	2.501	0.000
Education	-0.119	0.872	0.001

The estimates of the odds ratio obtained from the logistic regression are used to judge the likelihood of an individual perceiving it safe to cross rail tracks.

- Demographics: There is a lower chance that an individual will think it is safe to cross railroad tracks if they are white. Also, people with lower levels of education are more likely to perceive it as safe to cross rail tracks. Lastly, it was also discovered that the likelihood of an individual perceiving it safe to cross railroad tracks increases if that person has a form of disability.

- Knowledge of operations: The likelihood of an individual saying it is safe to cross railroad tracks is higher if they think they have enough time to flee from the tracks after hearing or seeing a train approach. The same goes for individuals who use rail tracks as shortcuts to their destination, even if it will save them just 5 minutes of travel time. Lastly, individuals who believe that trains run on a regular schedule are also more likely to think it's safe to cross the rail tracks.

Respondents' perceptions of rail safety show some relationship to other factors in the survey. As commonly understood, disability may have a significant impact on how respondents view and interact with the world they get around in. Additionally, targeted efforts need to be made in order to reach lower-income groups and racial minorities. The data found that these groups are more likely to think it is safe to cross railroad tracks and subsequently are more at risk of trespassing and being struck by a train. A number of factors could be at play at the root of their increased risk, from educational disparities, environmental and housing injustice, attitudes about the law and government (National Institute of Justice, 1999). While further studies may shed light on trespass motivations and provide a more robust dataset for analysis, it is clear that trespass prevention needs to be focused on specific groups.

2.3 Factors Affecting Rail Noise Propagation

If the survey helps us understand how rail noise was perceived and/or received, then the combined knowledge of noise and vibration basics, rail noise sources, and the paths of rail noise propagation should help us to understand how rail noise is produced, measured and altered. For a detailed narrative of noise and vibration basics, please refer to **Appendix 4.**

As illustrated in the existing literature and past studies, there are a wide range of factors/environments that affect the rail noise propagation. It is ideal to examine all possible factors but certainly not practical. Given the restrictions of budget, time, and scope, this study focused on those critical and measurable ones after a thorough review of all potential factors, which have guided our next step: field data collection, model calibration, and evaluations.

Ambient noise levels do not affect noise propagation, but they do affect the perceptibility of train noise at a given location. Locations with higher existing noise environments can provide sound masking, meaning that transient or intermittent noise sources would need to be louder to be distinguished above the background noise. Ambient noise typically increases with population density and with proximity to transportation sources such as busy roads and highways, railroad corridors, and airports.

Noise from railroad systems is influenced by the types and consists of trains, operations schedules, train speeds, and track construction and condition. Some diesel locomotives create more noise than others, and some trains operate with multiple locomotives. Locomotive engine noise typically increases with increasing throttle setting when trains are accelerating or traveling up a steep incline. Train speed increases correspond to increased wheel-rail noise from rail cars and passenger coaches. Any irregularities in the rail or wheel surfaces can cause increases in train noise. Trains traveling over rail joints, damaged/unsmooth sections, rough rails, or through special trackwork at turnouts and crossovers will generate additional noise. Wheel flats on rail cars and passenger coaches will also generate additional noise. Curved sections of track can lead to wheel squeal. EWD's near at-grade crossings can significantly affect the noise in a rail environment. Train horns on FRA regulated rail corridors are required to have horns that produce a minimum sound level of 96 dBA and a maximum of 110 dBA at a position 100' forward of the locomotive and the horns must be sounded 15-20 seconds prior to and not more than ¼ mile in advance of a train's arrival at the at-grade crossing. Therefore, the proximity of a receiver to an at-grade crossing will significantly affect the noise exposure. These are some of the real-world factors that affect rail noise sources.

The acoustical divergence of the sound wave due to the propagation distance has a significant effect on the noise levels at a receiver location. For receiver locations near the railroad right of way (ROW), the noise level will naturally vary from moment to moment as a train's position changes. Also consider that in a railroad corridor with multiple tracks, one train operating closer to a receiver location than another could be louder and therefore provide some temporary sound masking, making it more difficult for a receiver to hear a second train potentially approaching.

Acoustical shielding from topography, barriers, and buildings can have a significant effect on rail noise propagation. Typically, any impervious material (with sufficient density to block sound transmission) that blocks the line-of-sight between a noise source and a receiver will provide at least 5 dB of attenuation. The location of specific noise sources is important. For example, consider the elevation of the wheel-rail interface, the height of a locomotive engine and exhaust stack, and the typical position of a locomotive warning horn mounted on top of the cab. Noise barriers, berms, buildings, and relatively small undulations in the ground elevation can block the sound path and provide reductions in rail noise.

The ground coverage in the path between the sound source and receiver location can be an important factor in rail noise propagation. For example, ballasted track along the path between a train and a receiver location near or in the ROW could result in noticeably lower noise levels compared to a location where the ground along the sound path was hard and reflective, such as a paved parking lot.

Atmospheric effects, including wind speed and direction, or temperature gradients, can significantly affect rail noise propagation. These effects are typically greater at farther propagation distances, but they can still be significant at distances within a few hundred feet.

The effects of forests and foliage and atmospheric absorption are typically less significant than the other factors discussed in this section at the closer distances of concern for this study.

In short, the critical factors affecting rail noise propagation are (1) characteristics of the noise source and relation to the ambient noise environment; (2) distance between the source and receiver; and (3) excess attenuation due to shielding from topography and intervening structures, and to a lesser degree, due to ground and atmospheric effects.

3. METHODOLOGY

Having worked closely with the NCDOT rail safety and steering committee, the NCAT research team developed a methodology to model the various identified train noise sources of concern and their propagation to sensitive receivers at potential pedestrian crossing locations. Starting with critical factors defined earlier, the research team has developed an approach to conduct acoustical modeling of train noise propagation events under various operating conditions, utilizing field-collected data. Multiple factors that affect noise propagation are included in the acoustical models, which demonstrate pedestrian experiences as trains are approaching and passing pedestrian receiver locations near and within railroad rights-of-way (ROW).

3.1 Noise Model Calibration

The NCAT team has adopted the noise modeling approach that conforms to the methodology used by the Federal Railroad Administration (FRA) and Federal Transit Administration (FTA) for predicting noise from rail and transit noise sources. Additional information included in the FRA's Horn Noise Model and CREATE Freight Noise Model was incorporated as needed (FRA, 2000). The industry-standard SoundPLAN Essential acoustical modeling software was used to generate noise level result figures.

The FRA Horn Noise Model is a spreadsheet model that is commonly used as a tool to predict noise and assess noise impacts from train horns near highway-rail grade crossings. It includes reference noise levels for freight trains based on data collected throughout the country and train horns based on FRA regulations and measured noise data.

The CREATE Freight Noise Model is another spreadsheet used to predict noise and assess noise impacts from moving and stationary railroad and highway noise sources. It is based on the Federal Transit Administration (FTA) General Transit Noise Assessment spreadsheet model. (FTA, 2018) It includes reference sound level information for freight locomotives and various types of freight cars based on data collected across the country.

The SoundPLAN Essential modeling software differs from the FRA Horn Noise Model and the CREATE Noise Model in that it is a three-dimensional modeling program. It allows users to input various types of moving and stationary noise sources and construct a digital ground model that more closely matches a real-world site. Numerous types of elements that affect the propagation of noise can be included in the modeling, such as buildings, walls, ground type, and terrain features.

Noise models for this research include diesel locomotive-hauled passenger trains and freight trains consistent freight operations in North Carolina. The NCAT team collected noise measurement data in various railroad environments as part of the study. The acoustic models are based on the railroad noise environments where field measurements were conducted. A three-dimensional acoustic model is constructed for each site where field noise measurements are conducted. The models include ground elevation information and terrain features that affect noise propagation; large buildings or walls; ground type; and vegetation.

The noise measurement data are used to validate the noise models by comparing the measured sound levels of Amtrak and freight trains to the results from SoundPLAN. The standard practice in noise modeling is to use significant noise sources based on available reference levels or measured data with significant environmental factors as benchmarks, either by predicting results at specific locations or comparing predicted results to known measurement data. It is common to refine the models as necessary when comparing results to measured noise data.

3.2 Noise Model Validation

The base acoustical models simulating the field noise measurement sites are constructed to reflect the physical environment of the sites. Operating conditions of measured trains at the sites were entered in the models, and receiver locations were placed within the models where the microphones were located at the measurement sites.

The noise models were adjusted as necessary in order to validate them against the actual measured noise levels. This iterative process is a standard step when developing acoustical models. Once the noise models are shown to be in acceptable agreement with the measurement results, various factors can be added, removed, or changed to document their effect.

3.3 Modeling Key Factors Affecting Noise Propagation

The key factors affecting noise from trains near or in the ROW are:

1. Characteristics of the noise source, such as freight vs passenger trains;
2. Relation of the noise source to the ambient noise environment, which may include urban, suburban, and rural areas or proxies like busy commercial districts, residential neighborhoods and remote sites etc.;
3. Distance between the source and receiver, mainly based on speed of approaching train;
4. Excess attenuation due to shielding from topography, intervening structures, ground effects, and atmospheric effects.

The noise models were based on the different environments found at the selected noise measurement sites. The key factors that affect the noise levels at receiver locations were then varied and measured. The goal is to determine the approximate range of effect different variables have on the A-weighted sound level. For example, some factors affected the sound level by significantly greater amounts (> 10 dB) while others were much less (<= 1 dB). The maximum noise level of a train is typically proportional to

30*Log(speed), so the difference in noise level between a train moving at 20 mph and 80 mph could be approximately 18 dB. A building, noise barrier, or terrain feature that blocks the line-of-sight between a noise source and a receiver could potentially reduce sound levels by 5 to 15 dB. Table 2 below includes factors that are considered within the noise models.

It is noted that the length of the train affects the cumulative noise levels, but it may affect the maximum noise levels much less. Because noise levels combine logarithmically, multiple noise sources of similar level, such as multiple rail cars, can combine to cause a higher Lmax, but if one source is significantly louder than another, such as a locomotive compared to a rail car, then the addition of the quieter source may not noticeably increase the noise from the louder source. From the operation's perspective, more trains over a given period of time will increase the cumulative noise but not the maximum noise level unless two trains pass a receiver position at the same time.

Table 2. Key Factors Affecting Train Passby Sound Levels

Key Factors	Details
Characteristics of Noise Source	
Type of Train	Passenger vs freight
Train consists	Train configuration: position and number of locomotives and railcars
Operations	Schedule
Train speed	
Acceleration/deceleration	Up/down grade
Train wheel condition	Wheel flats
Horn noise	Proximity to at-grade crossing
Ambient Noise Environment	
Ambient noise levels	Noise measurements
Rural/Suburban/Urban	
Quiet zone	
Crossing bells	Proximity to bells/gates
Distance Between Source and Receiver	
Distance	Train speed
	Train approach time
	Pedestrian reaction time
Excess Attenuation	
Curved track	Small radius: wheel squeal
	Large radius: affecting line-of-sight
	Ground cover for sound path
	Trees/other shielding for sound path
Track construction	Ballast & tie
Atmospheric conditions	Wind speed & direction
	Temperature inversion condition
	Humidity, rain, snow
Terrain features	Hills, berms
Shielding	Buildings, barriers
Reflections	Buildings

4. DATA COLLECTION

Representing a novel approach in noise data collection approaches, the field data collection in this study placed acoustic devices as close as possible to railroad tracks, which was designed to emulate pedestrian presence on railroad rights-of-ways in order to model how oncoming train noise propagates and decays from the perspective of a human being. Rather than documenting the noise levels of a location over a long period of time or documenting a noise model of a single moment in time, the data uses multiple models to document the evolution of rail noise during a locomotive pass-by, demonstrating key moments that need to be understood from first warning to the train's intersection with a pedestrian's path across the railway. This data is key in understanding the experience of pedestrians in the right-of-way and solving the problem of unnecessary strikes in North Carolina.

4.1 Site Selection

Site selection was initiated by examining the high concentration of trespassing locations in North Carolina. Using the FRA accident data (1997 - 2021), the NCAT research team examined rail incident distributions in various counties in North Carolina, as shown in Figure 18. Focusing on the trespassing incidents by county, Figure 19 highlights the top five counties with the highest fatal and non-fatal trespassing incidents in North Carolina.

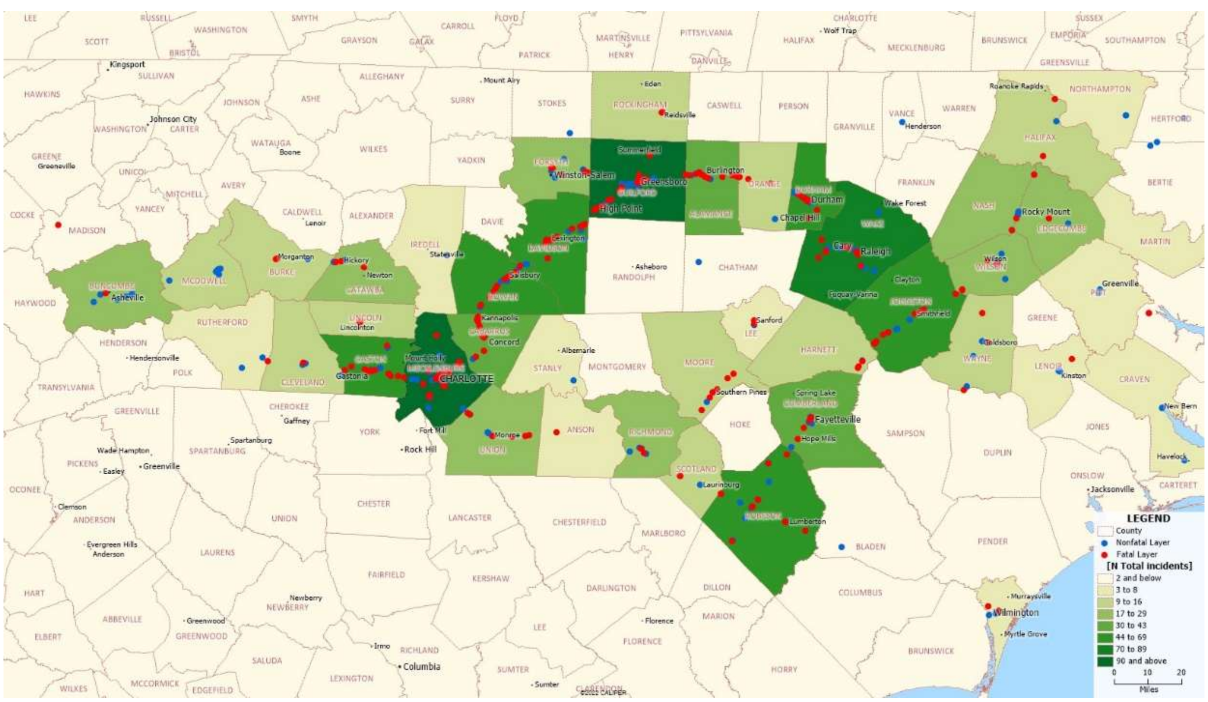


Figure 18. Rail Accident Distributions in NC 1997-2021
Source: FRA 2022

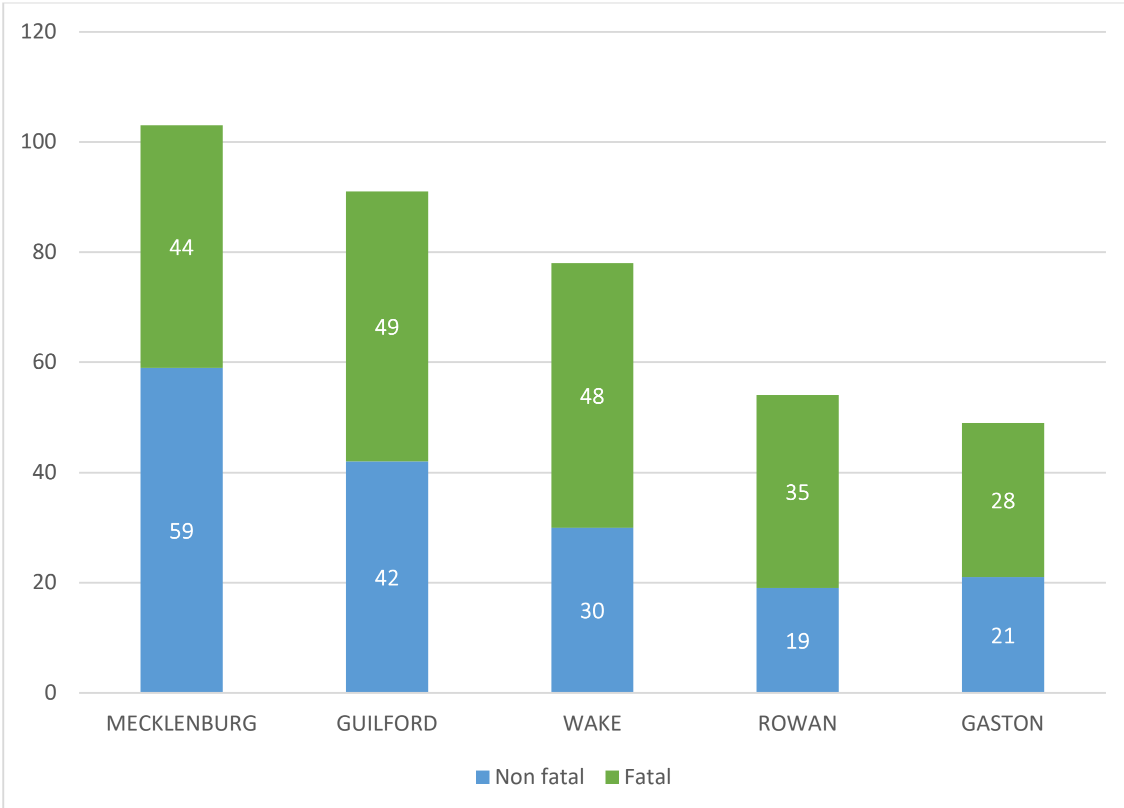


Figure 19. Top Five Counties for Trespassing Incidents Since 1997

Additionally, the data was further processed into heat maps illustrating the most concentrated rail accident locations in each of the top four metropolitan areas. Each county or metro area has a cluster of rail accidents along one particular stretch or segment of railroad tracks, which serve as our starting points for further narrowing down and selecting potential sites for field data collection.

Consulting a trespass hotspot list generated by NCDOT Project 2019-08 and a qualitative review of the sites, the research team tried to evaluate potential field data collection locations. Prioritizing a diverse mix of potential locomotive types and geographical characteristics while accounting for safety and potential accessibility by foot, the research team identified eleven potential locations for field evaluation. Figure 20 shows the preliminary field data collection sites based on accident data analysis and previous studies.

Further vetting by satellite imaging helped determine the accessibility of each location and the general layout of the site. Due to the nature of unattended site measurements, it was important to find accessible locations with relatively low usage to minimize the risk of passersby meddling with the equipment. Additionally, the satellite images helped the team narrow down locations for factors such as the presence of buildings, trees, shrubs, and grade crossings; the curvature of the tracks; and overlap with Quiet Zones.

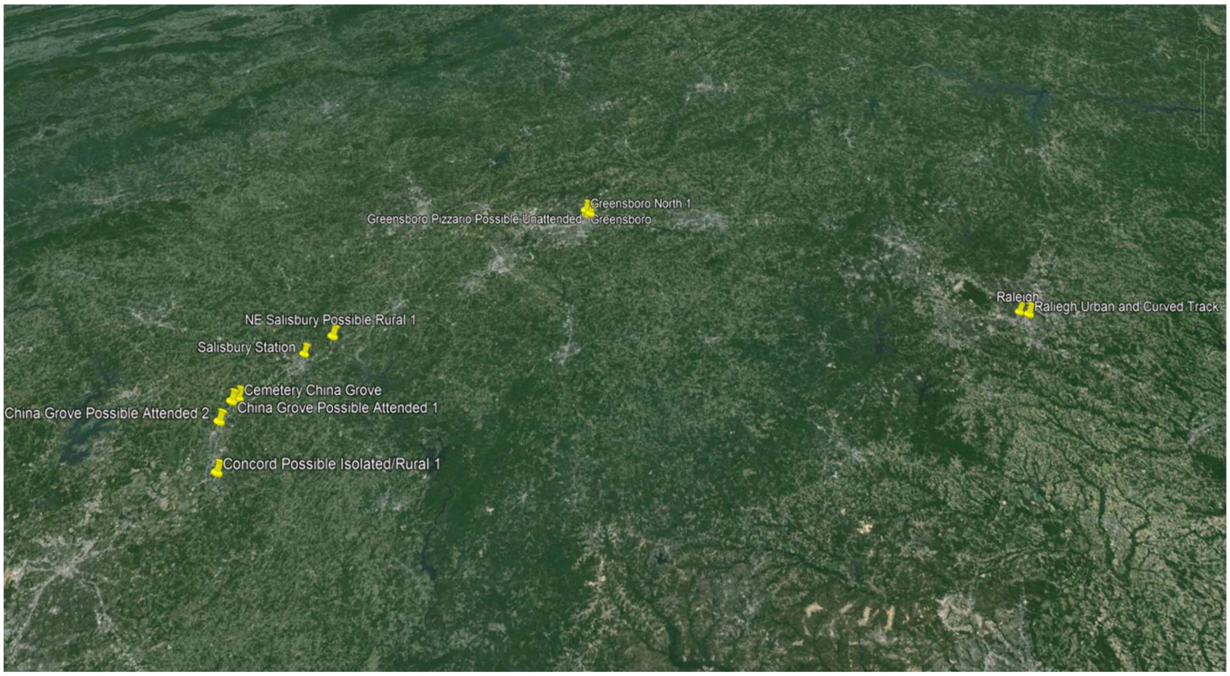


Figure 20. Preliminary Field Data Collection Locations

Continuous discussions between NCAT researchers and the NCDOT StIC ensured the potential locations, quantity, and representing factors will align with the project scope, optimize the resources allocated, and meet the expectations of the NCDOT StIC. Equipped with ample knowledge of potential field data collection sites and various questions and/or uncertainties with some locations, the NCAT researchers have visited those potential sites via three separate day trips to finalize the site selection. When possible, the research team spoke with local residents about the nature and frequency of train passing as well as pedestrian activities. Some sites were eliminated due to accessibility difficulties or proximity to wayside homeless encampments.

Incorporating feedback from the NCDOT StIC and discoveries through the field outings, the NCAT team finalized the field data collection locations for the subcontractor, Cross-Spectrum Acoustics Inc. to install the field measurement equipment and collect noise propagation data. As documented in Table 3, a total of six sites, two of each located in three of the highest rail accident concentrated counties/metro areas. The sites comprised locations with multiple train types operating at various speeds, different degrees of track curvature, diverse environmental characteristics, such as vegetation, adjacent buildings, and background noises. Both Quiet Zones and non-Quiet Zones locations are included in those sites, so the noise levels between train horn and bell can be compared. All those locations had high trespassing activities as documented by the data analysis and previous studies. Satellite images of each site are available in **Appendix 5.**

Table 3. Data Collection Sites and Environmental Factors

Site #	Location	Coordinates	Environmental Factors	Quiet Zone
N1a/ N1b	China Grove	35°33'23.25"N 80°35'35.34"W 35°33'23.53"N 80°35'35.12"W	• Rural/small town • Trees along both sides of tracks • Large radius track curve one direction	Yes
N2	China Grove	35°34'11.29"N 80°34'45.65"W	• Small town • Trees along one side of tracks • Large radius track curve both directions	Yes
N3	Greensboro	36° 4'16.75"N 79°46'21.12"W	• Urban • Trees along both sides of tracks • Auxiliary track noise	No
N4	Greensboro	36° 4'9.55"N 79°46'59.66"W	• Urban • Trees along both sides of tracks • Auxiliary track noise • Adjacent building	No
N5	Raleigh	35°46'53.88"N 78°39'39.72"W	• Urban • Trees along both sides of tracks • Adjacent building	No
N6a/N 6b	Raleigh	35°47'34.08"N 78°41'16.44"W 35°47'34.02"N 78°41'16.50"W	• Suburban • Trees along both sides of tracks • Adjacent building	No

4.2 Field Noise Data Collection

The field noise data collection was carried out during the week of October 9-13, 2023, and resulted in more than 100 train pass-by measurements. Both attended and unattended measurements were collected at each locale: China Grove, Greensboro, and Raleigh. Attended measurements included miles-per-hour measurements for each train and were usually at a setback distance that was closer to the tracks and therefore slightly more representative of the experience of the pedestrian fouling the tracks. Unattended measurements were typically recorded farther from the right-of-way and therefore represent the experience of pedestrians approaching the tracks, usually at an at-grade non-designated crossing location. The measurement procedures, locations, and results are described in the subsections below.

4.2.1 Noise Measurement Procedures

The noise measurement program consisted of both long-term (24-hour or greater) unattended and short-term (0.5 to 2.5-hour) attended monitoring of the A-weighted sound level at sites that were selected to represent a range of conditions. The noise measurements were conducted in a manner consistent with standard FRA and FTA methodology for measuring noise from train operations and as narrated above.

The noise measurements were performed using NTi Audio model XL2 noise monitors that conform to American National Standards Institute (ANSI) Standard S1.4 for Class 1 (Precision) sound level meters. Calibrations, traceable to the U.S. National Institute of Standards and Technology (NIST), were carried out in the field before and after each set of measurements using an acoustical calibrator. In all cases, the measurement microphone was protected by a windscreen and supported on a tripod at a height of approximately five feet above the ground surface, as shown in Figure 21. When possible, during the short-term attended measurements, the train consist (number and position of locomotives and railcars) was noted, and the train speeds were measured with a radar speed detector.

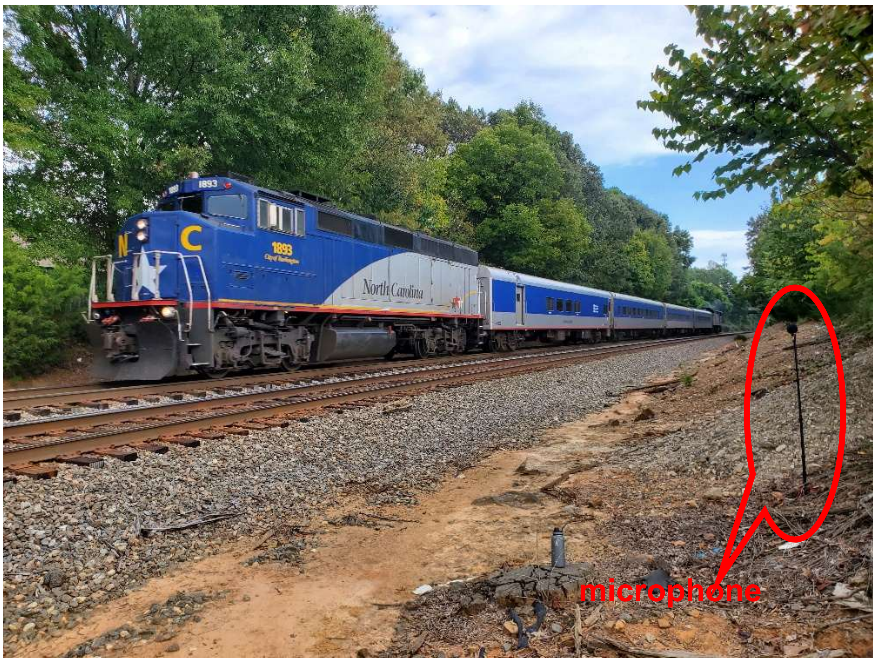


Figure 21. Sample Microphone Installations

4.2.2 Noise Measurement Locations

Three main areas were identified for noise data collection in China Grove, Greensboro, and Raleigh. The China Grove section is within a quiet zone and is a fairly rural environment with relatively high train speeds. The downtown Greensboro section is a more urban environment with horn noise and moderate to lower train speeds. The Raleigh section is an urban/suburban environment with horn noise and generally lower train speeds.

Table 4 summarizes the noise measurement locations. Sites N1a, N1b, and N2 were located in China Grove, sites N3 and N4 were located in Greensboro, and sites N5, N6a, and N6b were located in Raleigh. The table includes a description of each measurement location, the measurement start date, start time, and duration.

Table 4. Summary of Noise Measurement Locations

Site #	City	Location Description	Start of Measurement		Measurement Duration	# of Trains	Type
			Date	Time			
N1a[1]	China Grove	Green Lawn Cemetery	10/9/23	2:46 PM	3 days, 34 minutes	~60	Unattended
N1b[1]	China Grove	Green Lawn Cemetery	10/13/23	11:41 AM	1 hour, 14 minutes	2	Attended
N2	China Grove	East Centerview Dr. Grade Crossing	10/13/23	10:50 AM	25 minutes	1	Attended
N3	Greensboro	Behind Pizzario Grill & Subs off E. Market St.	10/11/23	2:58 PM	1 day, 30 minutes	~14	Unattended
N4	Greensboro	East of Amtrak Station & Murrow Blvd.	10/11/23	3:44 PM	1 hour, 14 minutes	2	Attended
N5	Raleigh	Behind Multi-family Residential Building at 426 Park Ave.	10/10/23	11:20 AM	1 day, 20 hours, 48 minutes	~35	Unattended
N6a[2] N6b[2]	Raleigh	Royal St. Grade Crossing	10/10/23	12:58 PM	2 hours, 22 minutes	4	Attended

[1]Sites N1a and N1b were both located in Green Lawn Cemetery. The N1b microphone was placed in a slightly different location to collect additional train pass-by noise measurement data at this location.
[2] Sites N6a and N6b were both located at the Royal St. grade crossing. The microphone was moved partway through the measurement period to the N6b location.

4.3 Data Descriptions

Located in three different counties in North Carolina and representing diverse factors that affect the rail noise propagation, the field data collection sites have very different characteristics and represent a wide range of relevant noise propagation factors.

4.3.1 Relevant Noise Propagation Factors

With both freight and passenger trains passing through, the China Grove site serves as a good candidate to measure various environmental factors, such as trees and vegetation on both sides of the tracks, a bridge crossing (Coach Deal Dr. to the west of N1), large-radius track curves, and relatively close buildings (at N2). The ambient noise environment includes marginally complicating factors, such as overhead aircraft, intermittent traffic, and some insect background noise, which is typical of rural environments. Table 5 gives a complete description of all the relevant site factors.

The Greensboro collection sites provided data that expands upon the baseline dataset collected in China Grove. By using locations with urban environmental traits, the data collected features increased background noise in the form of vehicular traffic, industrial equipment, and auxiliary train noise, all of which are potentially problematic ambient factors for pedestrians.

Table 5. Noise Propagation Factors

Site #	Rail Noise Sources	Ambient Noise Environment	Noise Propagation Factors
N1a N1b	• Amtrak (>70 mph) • freight (>50 mph) • 2 tracks, CWR, B&T[1] • quiet zone	• rural / small town environment • distant traffic on local roads • aircraft overflights • insects	• large radius track curve to east • short rail bridge to west • trees along both sides of tracks • calm/clear conditions
N2	• Amtrak operations (>70 mph) • freight operations (>50 mph) • 2 tracks, CWR, B&T[1] • grade crossing bells • quiet zone	• small town environment • traffic on local roads • grade crossing: traffic crossing rails when gates up & crossing bells and vehicles idling when gates down • distant lawn maintenance equipment	• large radius track curve both directions • trees along 1 side of tracks east & west • some small buildings set back ~50-75 feet of tracks • calm/clear conditions
N3	• Amtrak operations (~50 mph) • freight operations (~50 mph) • 1 track, CWR, B&T[1] • train horns	• urban environment • traffic on local roads • birds • nearby rooftop mechanical equipment & power plant boiler • freight trains on other nearby tracks	• tangent track • trees along both sides of tracks • small buildings, mostly 50 (feet) set back from tracks • sunny/light breeze conditions
N4	• Amtrak operations (25-40 mph) accelerating/decelerating at passenger station • freight operations (~20-40 mph) • 2 tracks, CWR, B&T[1] • train horns • passenger station noise/train gong at platform	• urban environment • traffic on local roads • freight trains on other nearby tracks visible to north and wheel squeal from curved track section	• tangent track • trees along both sides of tracks • large building adjacent to tracks 45 feet east of microphone • Amtrak station platform to west • overcast/light breeze conditions
N5	• Amtrak operations (25-35 mph) • freight operations (~20-35 mph) • 3 tracks, 2 main tracks CWR & B&T, 3rd siding track jointed rail	• urban environment • traffic on local roads • distant train horns at other grade crossings • occasional stopped/idling freight trains/air brakes • nearby mechanical building • aircraft overflights • birds	• tangent track • trees along both sides of tracks • large building on one side of tracks ~ 125 feet set back • initially clear conditions, some rain overnight
N6a	• Amtrak (>70 mph) • freight (~20 mph) • 2 tracks, CWR, B&T[1] • train horns • grade crossing bells	• suburban environment • traffic on local roads • distant train horns at other grade crossings • aircraft overflights	• tangent track • trees along both sides of tracks, open at grade crossing • large building on one side of tracks ~ 90 feet set back • calm/clear conditions

CWR = continuous welded rail. B&T = ballast and tie track construction.

The Raleigh collection sites provide further examples of suburban and urban right-of-way environments to augment the Greensboro sites. As summarized in Table 5, the data features tangential tracks, buildings at various setback distances, treed and treeless right-of-way sections, and distinct ambient noise interference.

4.3.2 Noise Measurement Results

As the first step of data collection/processing, the NCAT team has downloaded the time history of the plot as shown in Figure 22, which is a snapshot of all the noise levels recorded at the long-term unattended site. This graph only shows the first 12 hours of about 3 total days of noise data in China Grove. The train pass-bys are readily identifiable by the periodic peaks of noise levels.

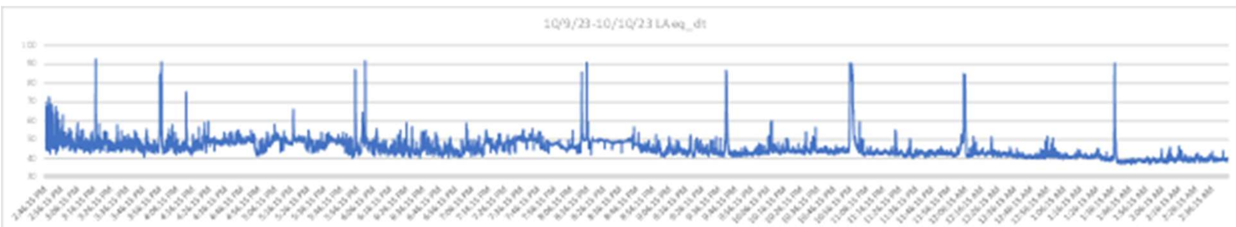


Figure 22. Site N1a Time History Plot - First 12 Hours

Figure 23 shows a few zoomed-in samples of pass-by time histories at sites N1a and N1b, including 50’ and 66’ setbacks for both freight and Amtrak trains. General ambient noise levels are evident as well as train approach times, which demonstrate just how sudden the main noise event of a train pass-by is. It also demonstrates how noise propagates differently for freight and passenger trains.

Figure 24 illustrates a pass-by time history at site N2 with a 27’ setback and several adjacent noise pass-bys for comparison. Note that none of the figures for China Grove illustrate a train horn due to the Quiet Zone restriction.

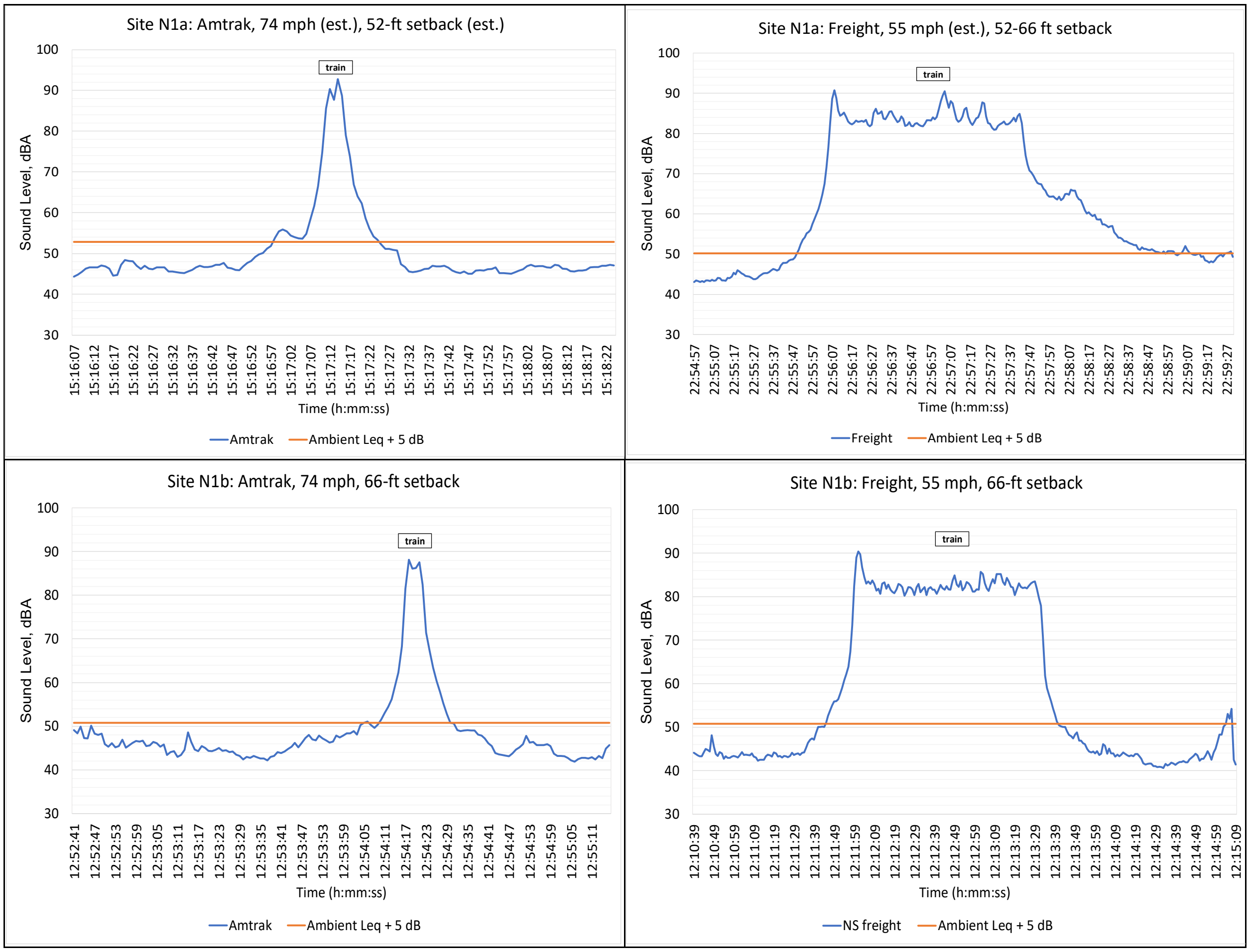


Figure 23. Site N1 Sample Pass-by Data

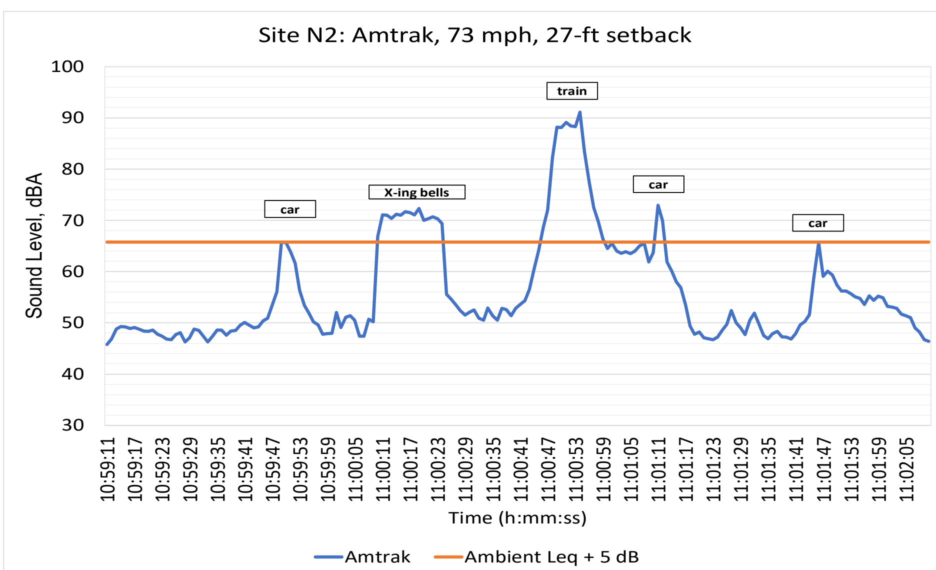


Figure 24. Site N2 Amtrak Pass-by Time History

The China Grove data collection sites demonstrate a rural to semi-rural environment under relatively calm, clear conditions and include roughly 60 pass-bys comprising both freight and Amtrak trains in a Quiet Zone. Subsequently, the time history samples do not show train horn noise, but do demonstrate other adjacent sounds, such as at-grade crossing warning bells and vehicular pass-bys. These measurements are important for establishing baseline train noise without the interference of train horns or urban environments that are documented at other sites in this study.

Similar noise measure results for the other sites located in Greensboro and Raleigh are documented in detail in the Technical Memorandum but not repeated here as they are utilized and elaborated in the simulation models**.** The Greensboro data collection sites illustrate train pass-bys in urban environments under generally calm conditions and include about 15 pass-bys comprising both freight and Amtrak trains and EWD blasts. The sample time histories show train horn noise relative to train pass-by noise as well as ambient noise levels before and after pass-bys. The Raleigh data collection sites provide further granularity to urban and suburban rail environments. The collected pass-by data includes freight and Amtrak pass-bys, associated EWD blasts, train wheel noise, and other information like crossing bells and airplane pass-bys. These measurements deepen the dataset’s ability to illustrate rail propagation in urban environments and provide useful comparisons for further analysis.

5. MODELING OF RAIL NOISE PROPAGATION

Using the field-collected noise propagation data, the NCAT team has calibrated acoustical models to reflect the train noise propagation effects in the North Carolina railroad environments. Numerous factors that affect the propagation of noise from moving trains were incorporated into the acoustical models. The modeling results show the changing noise levels as trains are approaching pedestrian receiver locations near and within the railroad rights-of-way (ROW).

5.1 Model Construction

Three-dimensional models were constructed of the six sites using the SoundPLAN Essential acoustical modeling software. The models constructed a digital ground model that closely matched the real-world sites based on imported terrain elevation information. Undulations in the ground can cause relatively significant changes in noise propagation when the sound paths between noise sources and receiver locations are impeded by small amounts. Sound diffracts over the top of terrain features.

Existing railroad track centerlines were imported and overlaid on the digital terrain models. Large buildings adjacent to the railroad ROW were digitized into the models where appropriate. Sound reflections of building facades can affect noise propagation. Large buildings also provide sound attenuation, functioning like a noise barrier, where they block the path of the sounds between source and receiver locations. Sound diffracts over the top and around the sides of building structures.

Sections of trees and dense foliage were included in some locations in the acoustical models where appropriate. Trees often do not provide much attenuation of overall A-weighted sound levels; however, they can reduce sound levels somewhat when the path between the source and receivers travel through significant lengths of foliage. For example, a relatively narrow section of foliage between railroad tracks and wayside properties may not provide much sound attenuation, but the path of noise from a train traveling on a curved section of track may travel through a much greater distance of foliage to a receiver position adjacent or in the ROW in front of an approaching train.

Most conventional noise prediction methodology and models used to assess noise from railroads and train operations are based on the total sound energy of a passing train and the maximum noise level (Lmax) of a train pass-by event. The Lmax of a train pass-by event can be combined with operating characteristics and site information to predict the energy of the event, using metrics such as the sound exposure level (SEL), equivalent sound level (Leq), or day-night sound level (Ldn). These metrics are used by agencies such as the Federal Railroad Administration (FRA) and Federal Transit Administration (FTA) to assess potential noise impacts because they are closely related to adverse community reactions to noise.

The FTA and FRA's noise and vibration guidance manuals for assessing rail and transit impact assessments are based on extensive reference level information, which is measured by the Lmax and the sound energy of passing trains at the point of closest approach of the train. Applying the same principles, none of FRA horn noise models and the CREATE freight noise models include a detailed methodology to predict the noise level from approaching trains before they arrive at a receiver or listener position.

There are theoretical ways to predict the noise level of approaching trains that are based on the difference in the angles between a receiver position and the front and back of an approaching train. However, these calculations can quickly become cumbersome when considering quickly moving trains, resulting in rapidly changing relative angles between receiver position and front/back of trains. Consider also that the trains themselves include multiple types of noise sources. The locomotives and railcars of an Amtrak train all produce wheel-rail noise that changes based on speed, which can be modeled as a discrete-length line source. The noise from locomotive engines and exhaust noise sources or train horns functions more as moving point sources approaching the receiver position. All would need to be calculated individually at specific moments in time for an approaching train.

The SoundPLAN Essential software package includes reference sound level information for various train configurations that are consistent with the FTA/FRA methodology approaches. However, the specific software package is limited to only being able to provide results based on the typical metrics used nationally, based on the Leq and Ldn, and not specifically the Lmax of the trains before reaching the receiver positions.

SoundPLAN Essential software does, however, include the ability to model stationary point sources or line sources with levels defined by the user. The noise modeling conducted for this study utilized this functionality and modeled approaching trains at numerous distinct locations as discrete-length line sources. Reference noise level information was calculated for each modeled train type, at each site, at each unique approaching train position, based on the detailed analysis of the noise measurement data collected in the field. The line sources representing trains were modeled at heights of 8 feet above the tracks, which is a reasonable assumption accounting for the combination of the wheel-rail propulsion noise sources consistent with FTA methodology.

The noise measurement program collected the time-varying noise levels of numerous approaching train pass-by events. Attended noise monitoring included observations of train consists and measurement of train speeds. With this data, unique reference noise levels at the microphone receiver locations were used in conjunction with train speeds and lengths to calculate where trains were located (i.e., how far down the tracks from the receiver position) at various moments in time prior to the maximum noise level occurring as the trains passed the microphone/receiver locations.

These unique reference noise levels were used to validate the noise models at all six sites, consistent with the collected noise measurement data for each measured train type and condition. The models were run and checked relative to the measured noise levels at each site, train type, and position. Where necessary, the reference levels were adjusted to provide consistency with the actual measured noise levels.

The models all produced results consistent with the measured noise levels. However, it should be noted that this validation process essentially “tuned” the models to be most accurate at the desired receiver locations, representing potential pedestrian crossing locations across the ROW. Therefore, the modeled noise level results for the wayside of the tracks are potentially not as accurate. In some cases, showing noise levels to the wayside above or below what would theoretically have been measured at those locations. Tuning the models further or perhaps investigating other modeling options could possibly be researched further in other studies.

5.2 Model Calibration

The noise measurement program collected data on between one and approximately 60 passing trains at each of the six sites. The data were analyzed, and all the train pass-by noise levels were compared to one another. Individual train pass-by events were identified at each site as candidates for noise modeling based on the measured noise levels. These sample train pass-by events had train speeds and maximum noise levels approximately meeting the averages across all recorded events. The sites cover a range of different types of environments from rural to urban and many combinations of conditions affecting noise propagation. The modeled train operations are based on the field noise measurement at each site. The measurement results were used to validate the noise models at each site.

Figure 25 shows noise level contours from an approaching Amtrak train at site 1, located at the Green Lawn Cemetery in China Grove, NC. The modeled Amtrak train travels westbound at a speed of 74 mph. The maximum noise level at the receiver location increased above the ambient Leq + 5 dB (Lmax of 52 dBA) when the approaching Amtrak train was approximately 868 feet from the receiver, which corresponds to a time of approximately 8 seconds before the leading locomotive passed the receiver.

The maximum noise level of the approaching Amtrak train, approximately midway between the ambient + 5 dB time and passing the receiver, was 68 dBA. The midway location was 217 feet from the receiver, corresponding to a time of approximately 2 seconds from the receiver location. The maximum noise level of the Amtrak train as it passed the receiver location was 88 dBA.

The noise modeling results are shown graphically in Figure 25, illustrating the noise level contours at distinct moments in time as the trains approach the receiver location, approximating the pedestrian crossing location. Each type of train modeled at each site includes three figures illustrating an approaching train. The top figure shows the train before it reaches the receiver location at the time when the maximum noise level (Lmax) from the approaching train was approximately equal to the ambient Leq at that site plus 5 dB. This baseline of the ambient noise level + 5 dB has been identified as the minimum ambient noise background for an approaching train to be audible for this study.

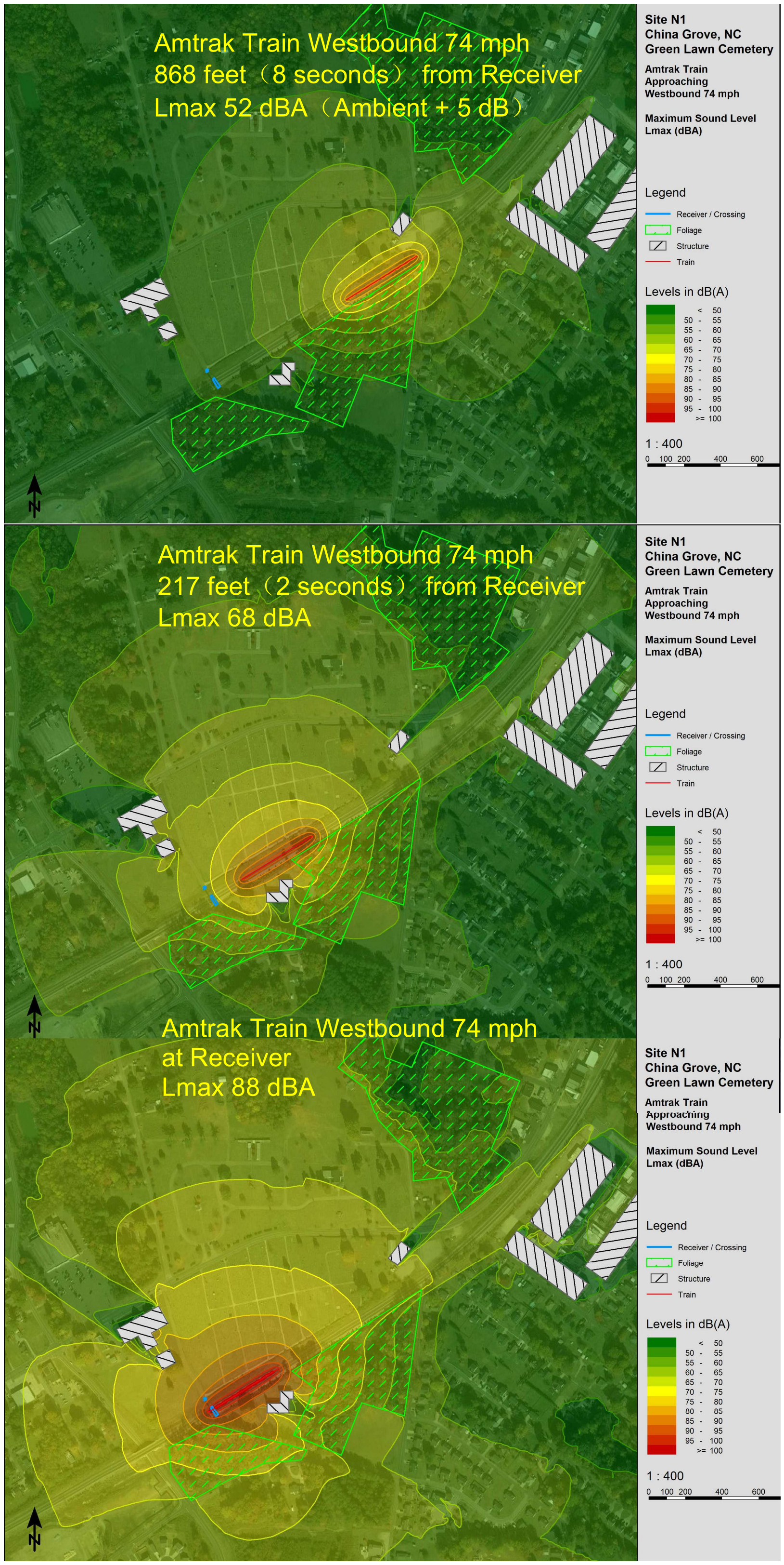


Figure 25. Amtrak Train Noise Model at China Grove

The middle figure illustrates the noise level contours from the approaching train at a position closer to the receiver when the Lmax was approximately in the middle of the upward slope of the measured time history data between when the noise level first exceeded the ambient + 5 dB and when the maximum noise level occurred as the train reached the receiver location. The bottom figure illustrates the noise level contours when the leading locomotive of the train reached the receiver location, resulting in the maximum noise level of the train pass-by event. Together, the sets of three figures show the increasing noise levels at the receiver locations from the approaching trains at each site for each modeled train type.

As illustrated in Figure 25, noise level contours were superimposed over aerial images at each site. The noise levels are illustrated over a gradient from dark green (noise levels less than 50 dBA) transitioning to dark red (noise levels greater than 100 dBA). The model at each site is based on ground elevation data imported from Google Earth. The train locations are shown by red lines in the figures. Amtrak trains were modeled as 460-foot-long sources, corresponding to 2 locomotives (each 60 feet long) and 4 railcars (each 85 feet long), consistent with the train consists observed in the field.

The receiver locations are shown on the figures as blue points and lines indicating the pedestrian crossing locations. These locations are the starting points where the approaching train distances and times were calculated from. Large buildings in the vicinity of each site were specifically included in the noise models and are shown in the figures as white polygons with black diagonal lines through them. Generally, only buildings taller than 15 to 20 feet were specifically included in the noise models. These tall buildings cause noise reflections off their facades, provide acoustical shielding from the train noise sources, and cause sound to diffract around them. These effects can be visually seen in the noise level contour results in each figure. Large areas of trees and foliage adjacent to the railroad tracks were also included in the noise models where appropriate. These areas provide some additional noise attenuation where the sound path travels through the attenuation areas.

Accompanying each noise modeling result figure is a plot of the sample measured train pass-by event noise level time history used to validate each noise model, as shown in Figure 26. Those plots show the measured noise level of the trains passing the receiver/microphone location. The yellow lines show the ambient Leq + 5 dB. The red boxes highlight the small portion of the train pass-by that are of concern for this study, included in the noise modeling. Each set of 3 modeled train noise figures occurs within the area highlighted in the red boxes in the time history plots.

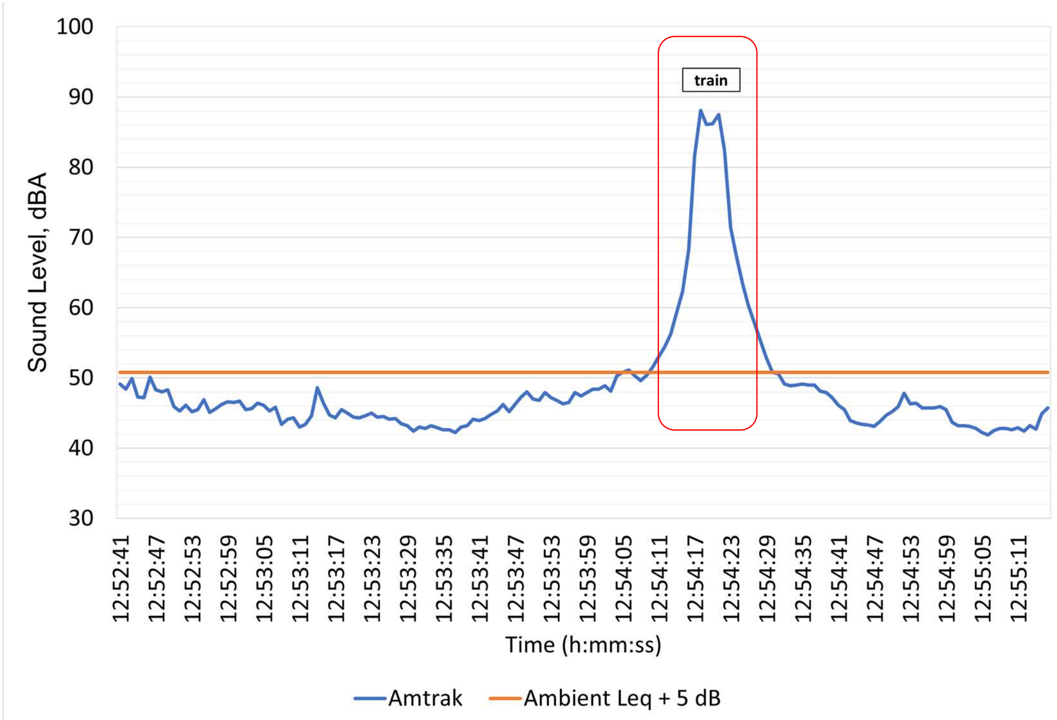


Figure 26. Amtrak Train Pass-by Time History at China Grove

A separate approaching freight train was modeled via a similar procedure and presented in the same framework. The modeled freight train is traveling westbound at a speed of 55 mph. As documented in Figures 27 and 28, the maximum noise level at the receiver location increased above the ambient Leq + 5 dB (Lmax of 51 dBA) when the approaching freight train was approximately 1,291 feet from the receiver, which corresponds to a time of approximately 16 seconds before the leading locomotive passed the receiver. Freight trains observed in the field typically consisted of up to 3 locomotives and approximately 100 railcars. Since the study is focused on approaching trains, freight trains were modeled as long as necessary to cover the focused study area at each site as necessary.

Simulation models were calibrated for all six sites and multiple train sets but not repeated here. For completed model information, please refer to **Appendix 6**. Each noise modeling figure includes information identifying the site location and the modeled train conditions, including the train type, direction of travel, and speed. Additional information specifying the distance from the leading locomotive to the receiver location and the corresponding amount of time before the train reached the receiver location are included in the figure captions.

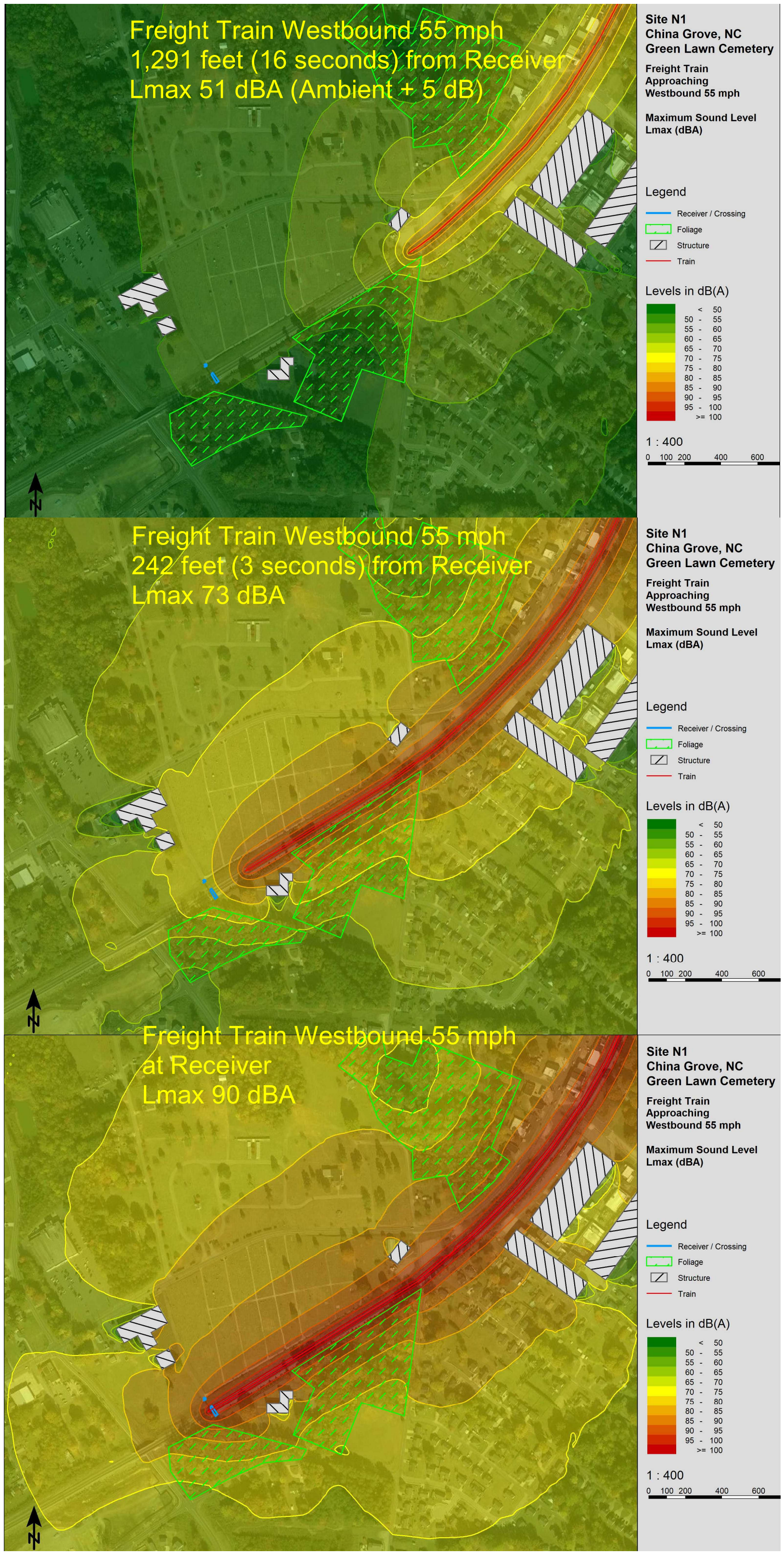


Figure 27. Freight Train Noise Model at China Grove

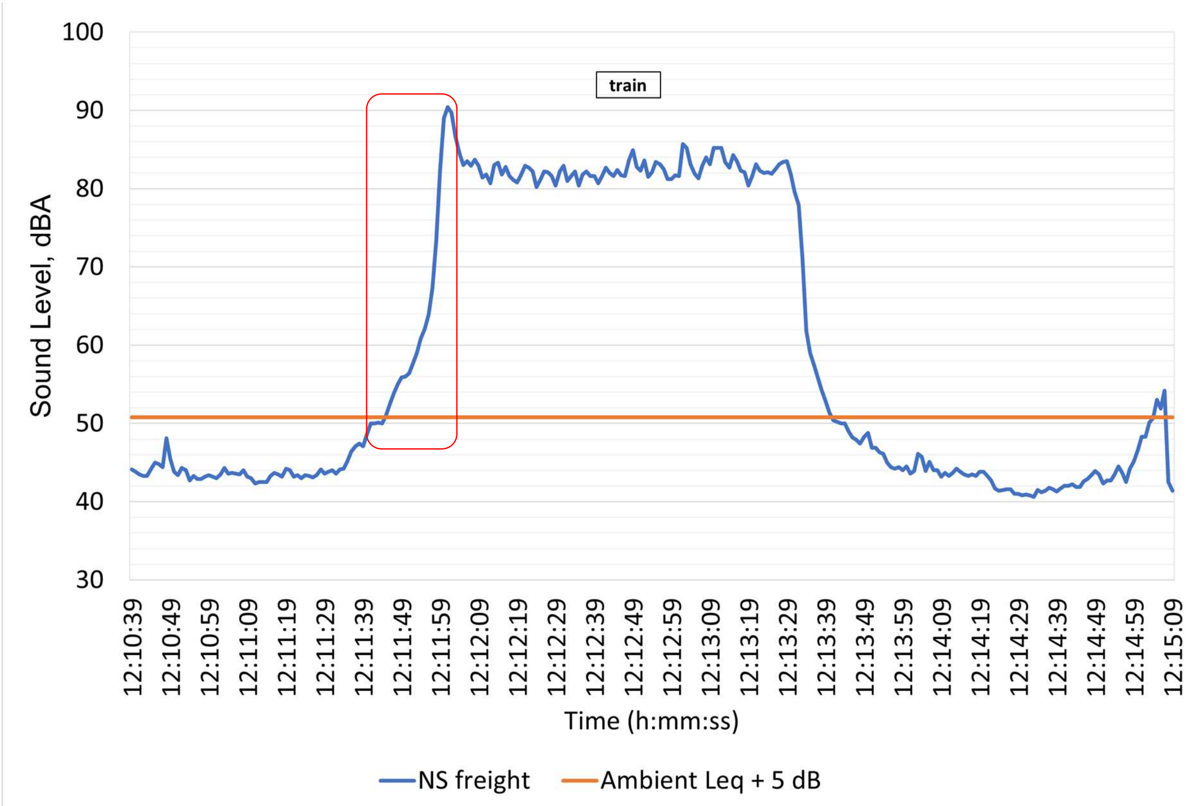


Figure 28. Freight Train Pass-by Time History at China Grove

5.3 Model Result Summary

Table 6 provides a summary of the modeled train noise results at each site for each modeled train type and speed. The maximum noise level, distance from the receiver position, and time from the receiver position are included for the modeled trains at the ambient + 5 dB position, the position midway to the receiver, and at the receiver position.

The rail noise propagation models provide visual representations of the noise levels at receiver and pedestrian crossing locations from approaching Amtrak and freight trains at multiple moments in time prior to the trains passing the receiver positions. The models cover an extensive range of different railroad environment conditions affecting the perceived audibility of approaching trains in North Carolina.

Table 6. Train Profiles for Noise Modeling

Site #	Train Type	Train Speed (mph)	Train at Ambient + 5 dB position			Train Midway between Ambient + 5 dB Position and Receiver			Train at Receiver Position
			Lmax (dBA)	Dist. to Rec. (ft)	Time to Rec. (sec)	Lmax (dBA)	Dist. to Rec. (ft)	Time to Rec. (sec)	Lmax (dBA)
N1	Amtrak	74	52	868	8	68	217	2	88
	Freight	55	51	1,291	16	73	242	3	90
N2	Amtrak	73	64	964	9	82	642	6	91
N3	Amtrak	50	60	587	8	75	147	2	94
	Freight	50	58	293	4	69	73	1	87
N4	Amtrak	43	59	252	4	80	189	3	102
N5	Amtrak	28	57	363	9	74	81	2	90
	Freight	20	57	587	20	74	147	5	91
N6	Amtrak	74	57	543	5	74	217	2	90
	Freight	17	64	1,820	73	79	848	34	104

6. HIGH-RISK ENVIRONMENTS FOR UNDETECTED RAIL NOISE

Utilizing field-collected data and simulation software, the NCAT team has evaluated the impact of various factors on rail noise propagation. The modeling results have assisted the research team in identifying an extensive set of conditions that contribute to higher risk environments for undetected train noises. These findings are critical for understanding how environmental and operational factors influence pedestrian awareness of approaching trains.

6.1 Evaluation of Various Factors

The modeling result summary presented in Table 6 serves as a comparative tool for evaluating how different site conditions influence noise detectability. For example, at high-speed sites like N1 and N6, Amtrak trains traveling at 74 mph became audible to pedestrians only 5–8 seconds prior to arrival, highlighting the potential hazard posed by limited reaction time. In contrast, low-speed freight trains, such as those observed at Site N6, provided as much as 73 seconds of auditory lead time when sounding horns - demonstrating how operational practices and train speed dramatically alter risk levels.

Working with the NCDOT and other railroad safety stakeholders, NCAT researchers have reviewed the results of the noise modeling, compared the conditions of various sites, and evaluated the risks associated with diverse environments that may create higher risk for pedestrian crossings depending on how well and/or how fast the train noises are detected. Individual factors and their associated environmental and/or operational conditions are elaborated in the following sections.

6.1.1 Train Speed

Train speed is one of the most significant determinants of noise detection not only because the train movement speed affects the noise-producing dynamics, but also the train traveling speed dictates how much time there is between noise detection and train arrival. As demonstrated in Figure 29, High-speed trains, such as Amtrak services operating at 70–74 mph, e.g., Sites N1, N2, and N6, produce a rapidly increasing sound profile that often becomes distinguishable from ambient noise less than 10 seconds before arrival. This short warning period limits pedestrian reaction time and significantly increases risk, particularly at unauthorized/illegal crossings where visual cues may also be limited.

On the other hand, slower freight trains, especially those operating at speeds below 20 mph, e.g., Site N3 freight operations, provide much longer detection times - up to 75 seconds, as shown in Figure 30, allowing pedestrians a greater margin to respond. These differences underscore the importance of accounting for operational speeds when evaluating trespass risk. Faster trains reduce the time available for pedestrians to recognize and react, which increases the likelihood of unsafe crossings. Slower trains, by contrast, provide a wider reaction window but may create a false sense of security, encouraging risky behaviors such as attempting to cross in front of them. For this reason, operational speed should be a key factor not only in risk assessments but also in the development of public outreach strategies.

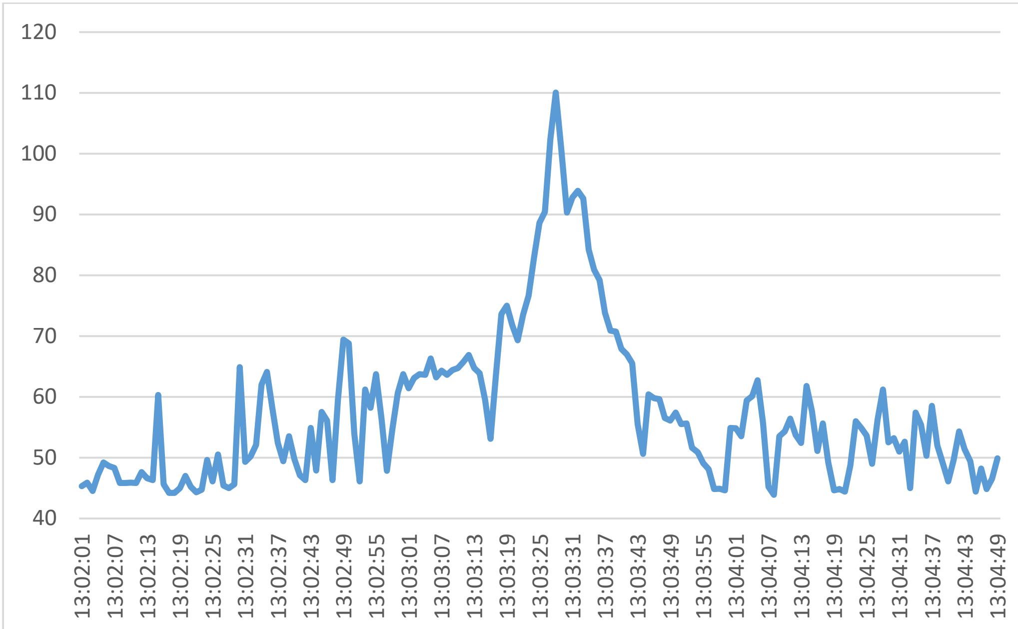


Figure 29. Noise Propagation Profile for Sample Passenger Train
Source: Site N6a: Amtrak @73-75 MPH

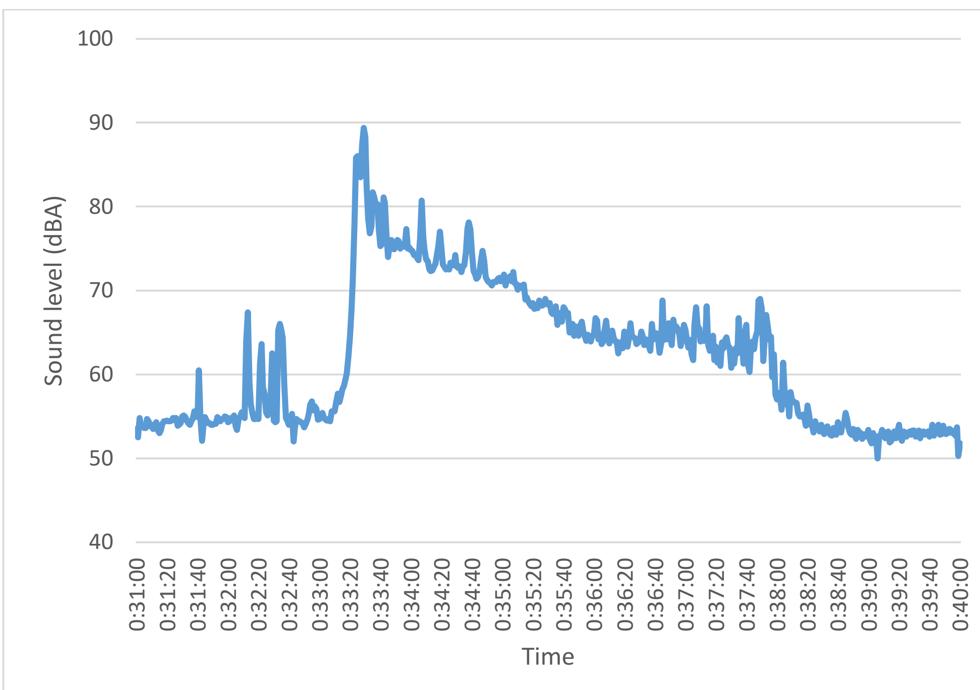


Figure 30. Noise Propagation Profile for Sample Freight Train
Source: Site N3 Freight Train

6.1.2 Ambient Noise

Ambient noise levels heavily influence the threshold at which train noise becomes perceptible. In urban settings like Greensboro and Raleigh, ambient noise levels (Leq) frequently exceed 60 dBA, due to road traffic, mechanical systems, and human activity. At these sites, train noise had to exceed 64 dBA (Leq + 5 dB) to be detectable -often providing only a few seconds of advance notice.

In contrast, rural environments such as China Grove (Site N1) exhibited much lower ambient levels (~51–57 dBA), improving the signal-to-noise ratio and enabling earlier detection. These findings support prior research that identifies high ambient noise as a critical risk factor in masking approaching train sounds (FTA, 2018).

Figure 31 shows the ambient noise levels in three different locations from rural to suburban and urban during various time periods. It is clear that the ambient noise levels in urban settings are consistently higher than those at rural areas. Zooming into the noise patterns of each location, it is possible to identify certain noise level fluctuations associated with human activity patterns. For example, the China Grove, Site N1, located in a residential area, exhibited higher noise levels during morning and evening time periods, which may indicate the residents returning from work and carrying out various activities near our data collection sites. In contrast, the Greensboro site is located in downtown, which has a slightly higher noise level in the morning around 6 AM, then the noise levels peak around noon, afternoon, and evening hours. Those background noise levels are most likely associated with morning and afternoon commuting activities, mealtime traffic, and evening recreational activities in Greensboro. Representing suburban conditions, the Raleigh site does not have a predominant peak, while the noise level is fairly high throughout the day.

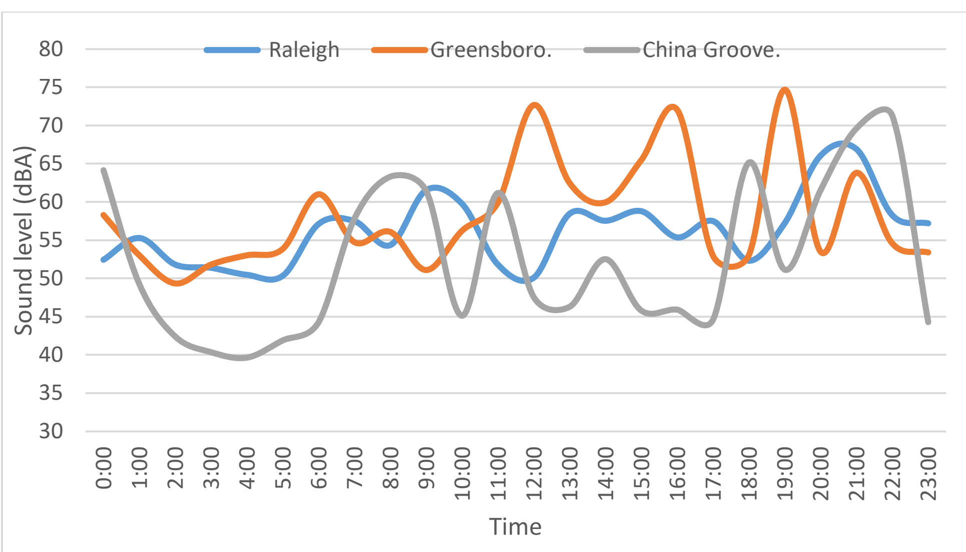


Figure 31. Ambient Noise Levels at Various Locations Throughout the Day

6.1.3 Warning Horns

Train horns are one of the most effective auditory warnings for pedestrians. Field data show that horn use dramatically increases Lmax levels and the distance at which a train becomes audible. For instance, the freight train at Site N6, traveling at 17 mph with its horn activated, was detectable 1,820 feet (73 seconds) before arrival - far exceeding the detection distance of similar-speed trains without horn use. Figure 32 shows the differential effect of train horn versus ambient noises and longer distances provided to notice the incoming train.

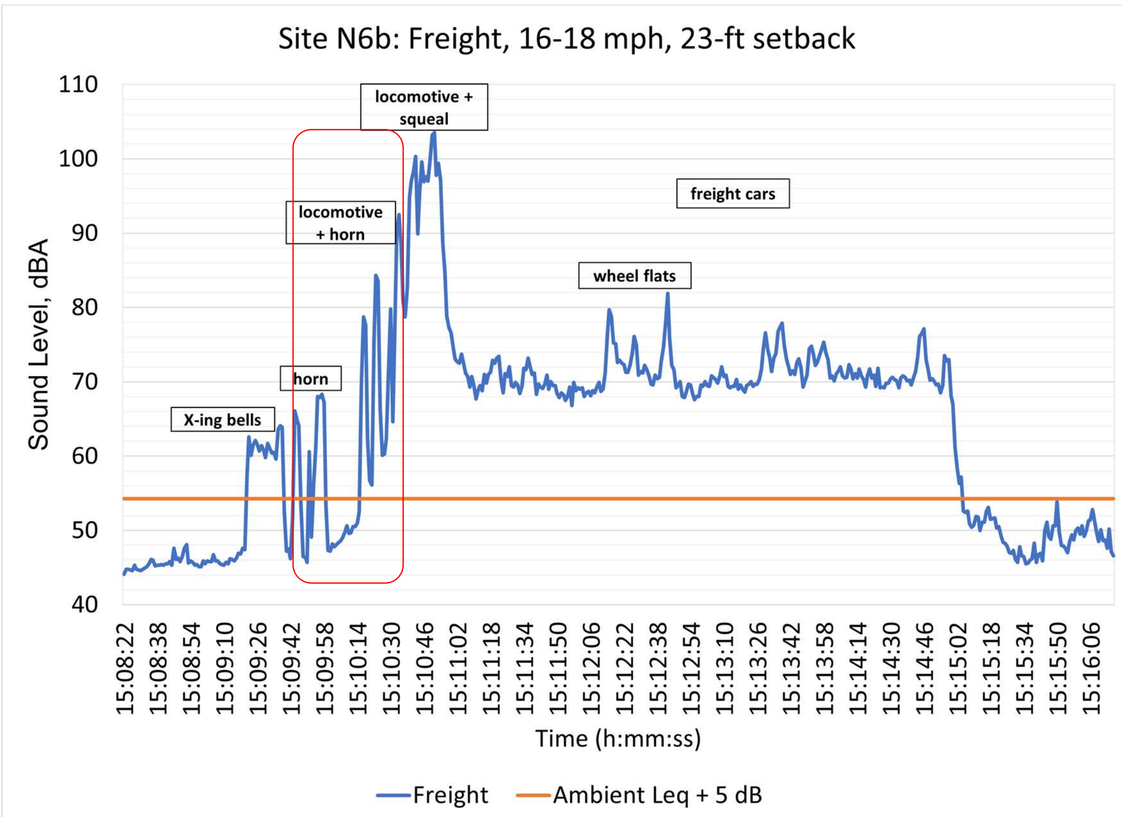


Figure 32. Noise Propagation Profiles for Freight Train Using Horn
Source: Site N6 Freight @16-18 MPH

However, in Quiet Zones (e.g., Sites N1 and N2), where horns are not routinely used, the risk increases significantly, particularly when paired with high-speed operations and ambient noise. As documented in Figure 33**,** the incoming train at Site N1a was only detectable when it was 16 seconds from the impacted location, with a lack of warning signal or sounds, as compared to approximately 45 seconds before arrival at Site N3, where a horn is used to provide a warning. The findings confirm Federal Railroad Administration (FRA) guidance that horn absence must be offset by other mitigation measures, such as visual signals or fencing, to ensure safety (FRA, 2006).

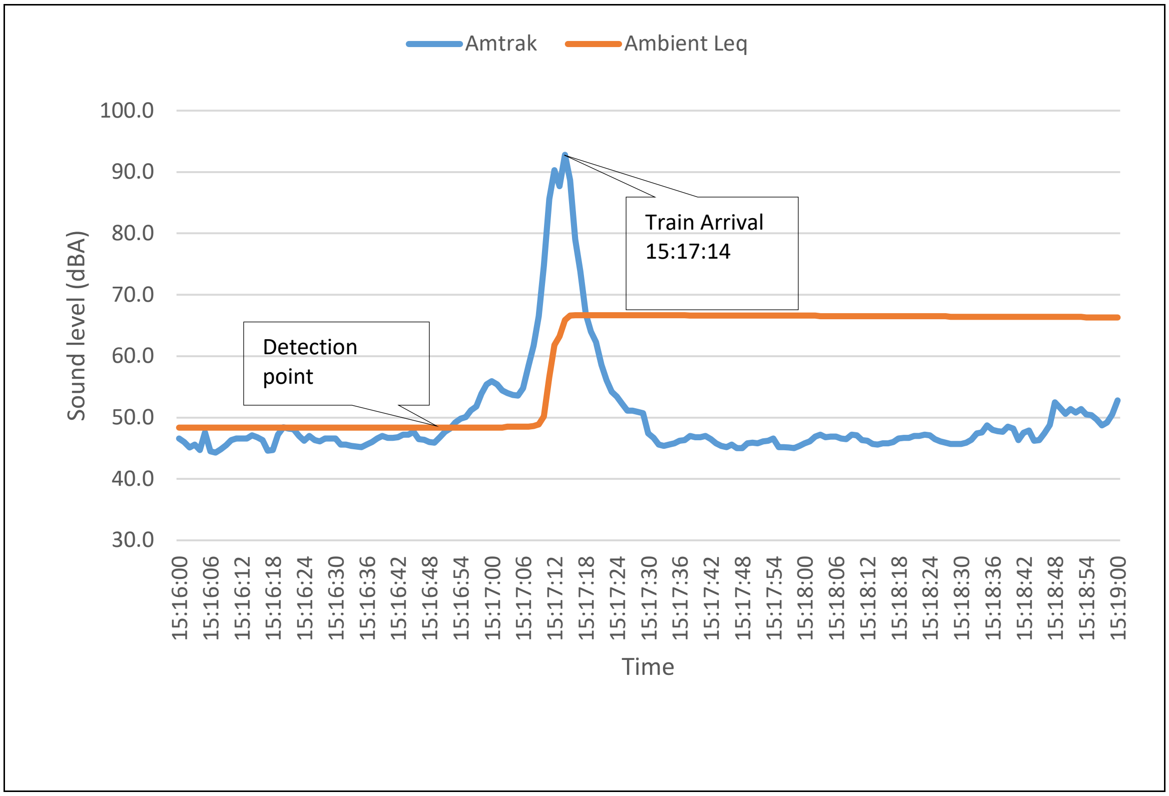


Figure 33. Delayed Detection of Incoming Train in Quiet Zone
Source: Site N3: Amtrak @ 50mph and Site N1a: Amtrak @74MPH

6.1.4 Track Alignment

Track geometry influences how sound propagates toward a pedestrian receiver. Tangent (straight) tracks, common at several sites, allow direct line-of-sight for both visual and acoustic cues. However, the absence of barriers or topographic variation also means that noise rises sharply and reaches the listener with minimal advance buildup, as seen at Sites N3 and N4. As shown in Figure 34, the noise propagation is not impeded when straight tracks are utilized in Site N3, while the train speed may also be higher.

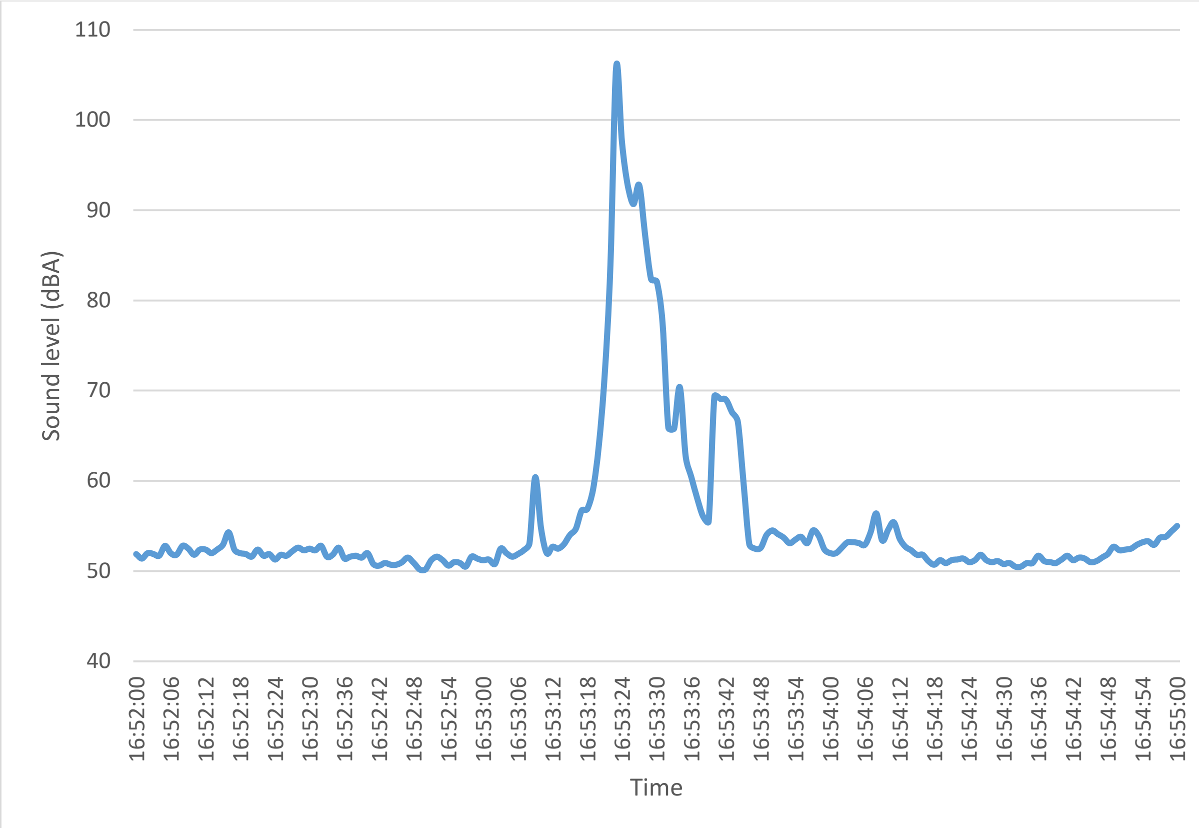


Figure 34. Noise Propagation along Straight Track
Source: Site N3: Amtrak @50MPH

Curved track sections, on the other hand, may allow sound to travel through more reflective or absorptive terrain, e.g., vegetation or buildings, potentially increasing the audible warning distance. For example, the noise propagation at Site N2, shown in Figure 35, includes curved track segments where noise was detectable earlier than at comparable tangent sections. Curvature should be considered in modeling for more realistic pedestrian risk assessment.

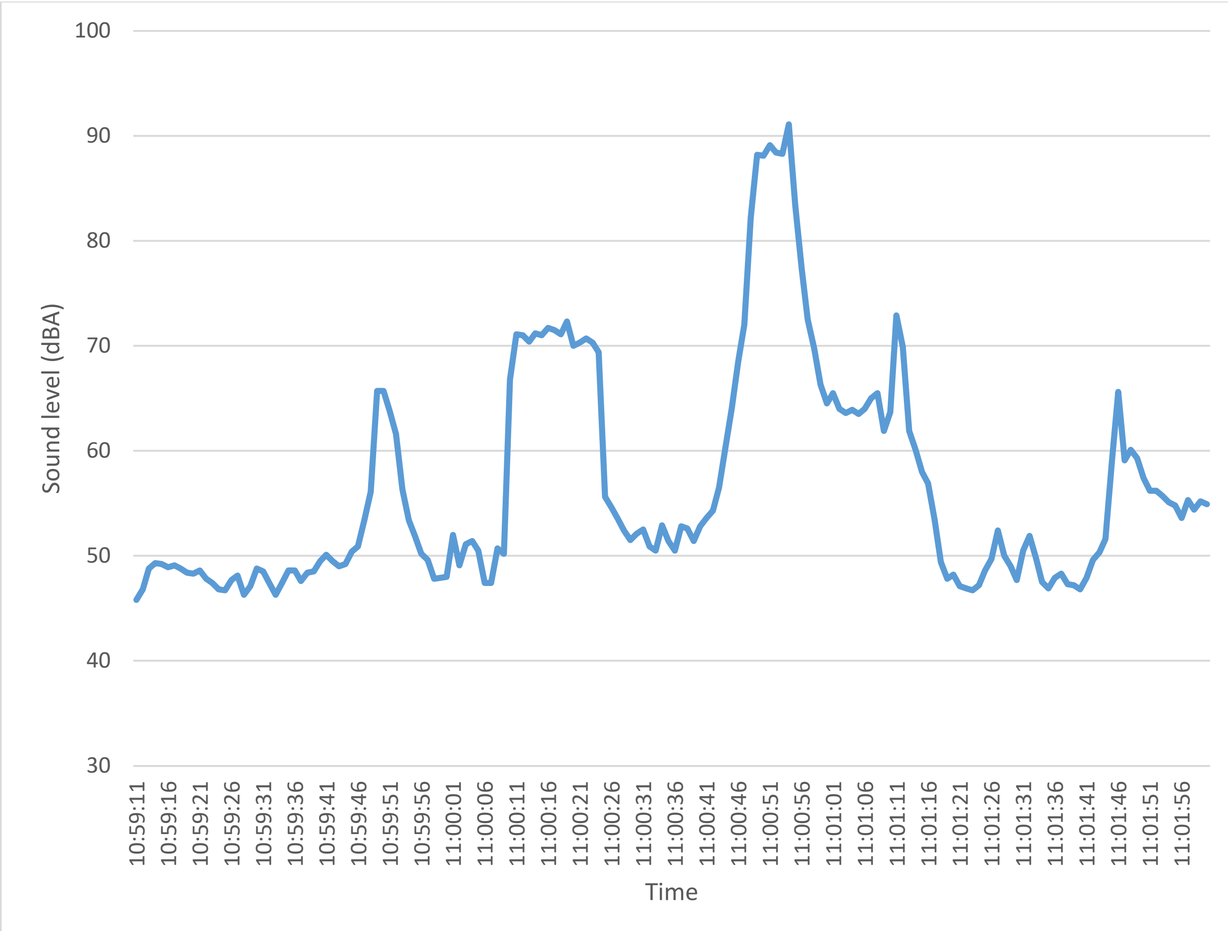


Figure 35. Noise Propagation along Curved Track
Source: Site N2: Amtrak @73MPH

6.1.5 Vegetation / Trees

Vegetation has a limited but variable impact on noise attenuation. Trees and shrubs between the tracks and pedestrian locations were modeled at all sites, but results show that unless the vegetation belt is dense and extends for significant distances, its attenuation effect is minimal—typically no more than 2–3 dBA, which is also confirmed in studies (Fang, 2005). At Sites N3 and N5, where trees lined both sides of the track, see Figure 36, the perceived noise difference was negligible when compared to open areas. Moreover, vegetation can introduce a false sense of security or sound blockage while failing to provide meaningful auditory shielding. Therefore, reliance on vegetation alone is insufficient to mitigate noise detection risk.

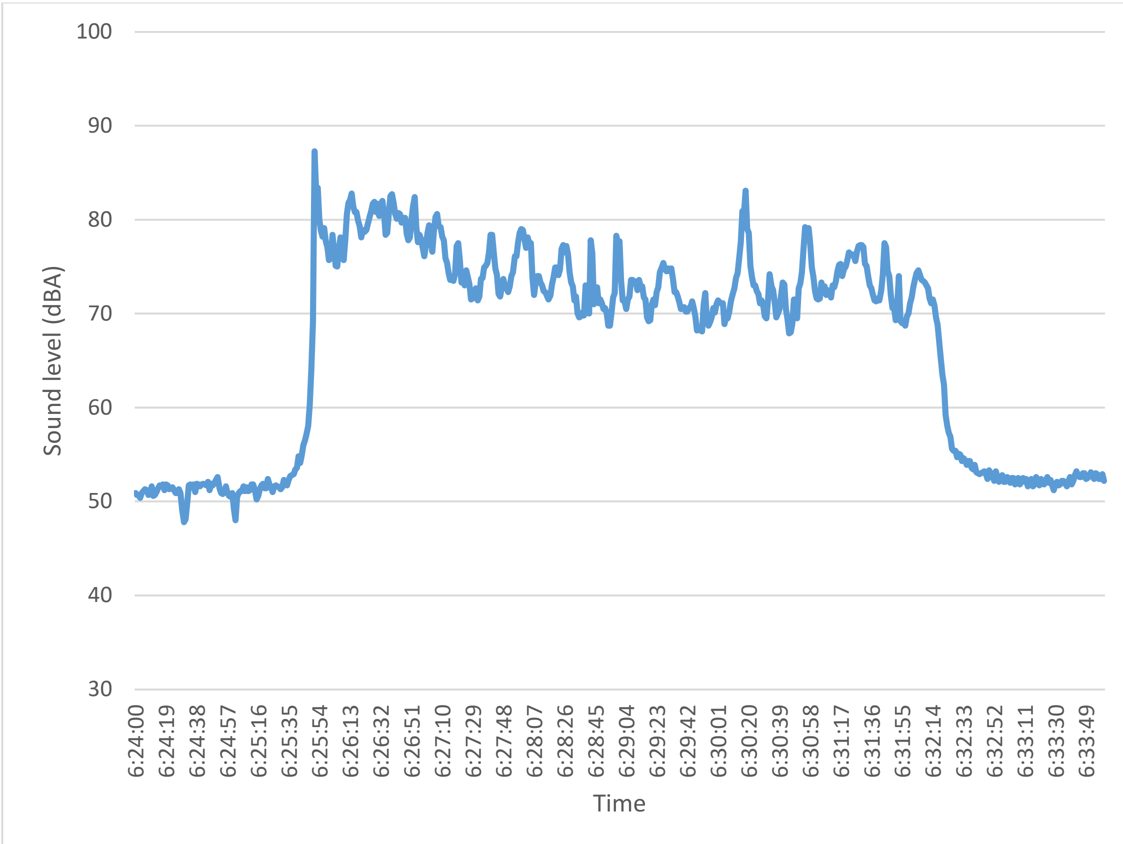


Figure 36. Noise Propagation for Freight Train Traveling along Tree Lined Track
Source: Site N3: Freight Train

6.1.6 Building/Structure Barriers

Large buildings and structural barriers have a more pronounced effect on noise propagation than vegetation. Their presence can both attenuate and reflect sound, depending on location, orientation, and material. As shown in Figure 37, a large building located 45 feet from the tracks at Site N4 served as a sound barrier, reducing forward propagation but increasing lateral reflections that could mislead pedestrians about the train's direction.

In modeling, buildings generally contributed up to 10 dBA in noise reduction under certain configurations - enough to affect detectability based on the threshold principle that sources 10 dBA lower than dominant ones contribute minimally to perceived sound. However, in some cases, this attenuation can delay detection and increase risk if not coupled with other warnings.

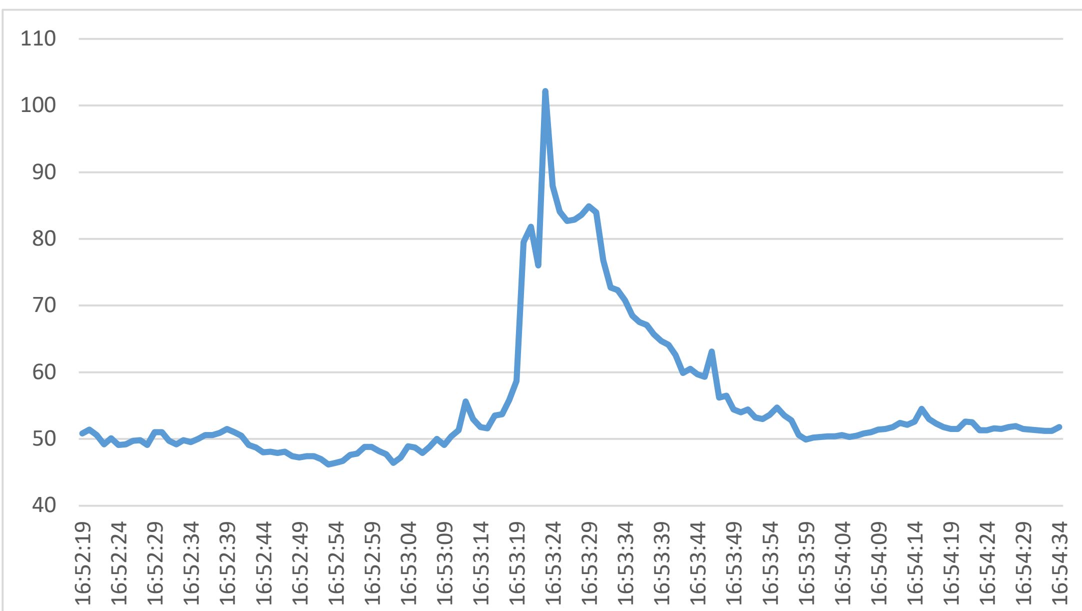


Figure 37. Building Barrier and Sound Propagation
Source: Site N4: Amtrak @37-43 MPH

6.1.7 Environmental Noise

Aside from ambient background levels, specific localized noise sources, such as HVAC systems; idling locomotives; mechanical blowers; and crossing bells, can significantly interfere with train detection. At urban sites, such as N3 and N5, rooftop mechanical equipment and auxiliary freight activity were frequently cited as interfering factors. Figure 38 exhibits certain background noises, which are often higher than ordinary ambient noises and can mask the noises associated with incoming trains. Additionally, intermittent noises like aircraft overflights and nearby vehicular traffic can create sudden masking events, especially in environments where the pedestrian is already relying on limited auditory cues. Such overlapping noise events are particularly problematic when trains do not sound their horns.

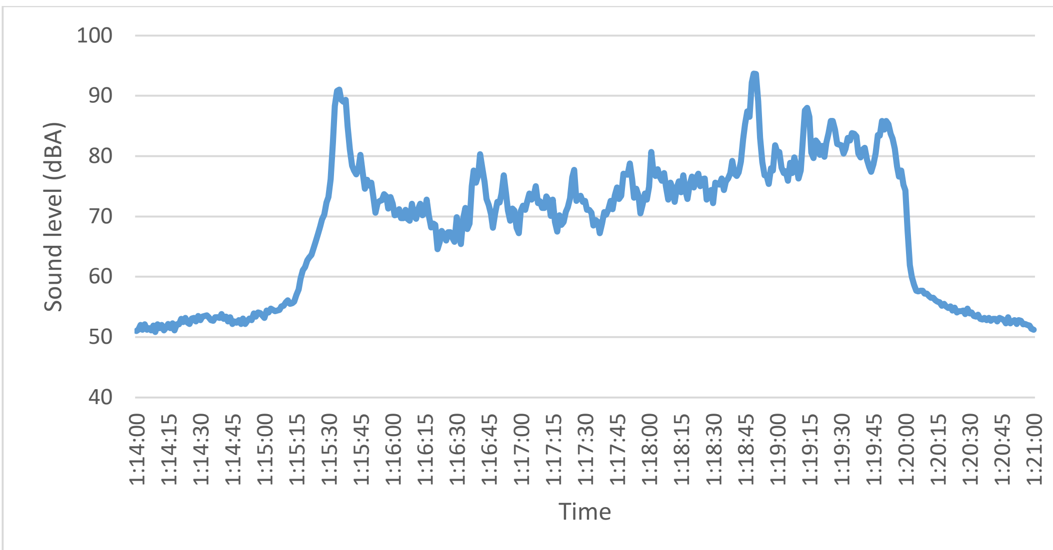


Figure 38. Environmental Noises at Site N5
Source: Site N5: Freight Train @20-25 MPH

6.1.8 Distance to Tracks

The relative distance between a pedestrian and the tracks at the time of detection plays a crucial role in determining effective warning time. Field data from attended and unattended measurements reveal that detection time is closely linked not only to ambient noise and train speed, but also to how close pedestrians are positioned to the right-of-way. As shown in Figure 39, the noise levels are rapidly reduced when the distance from the track center increases.

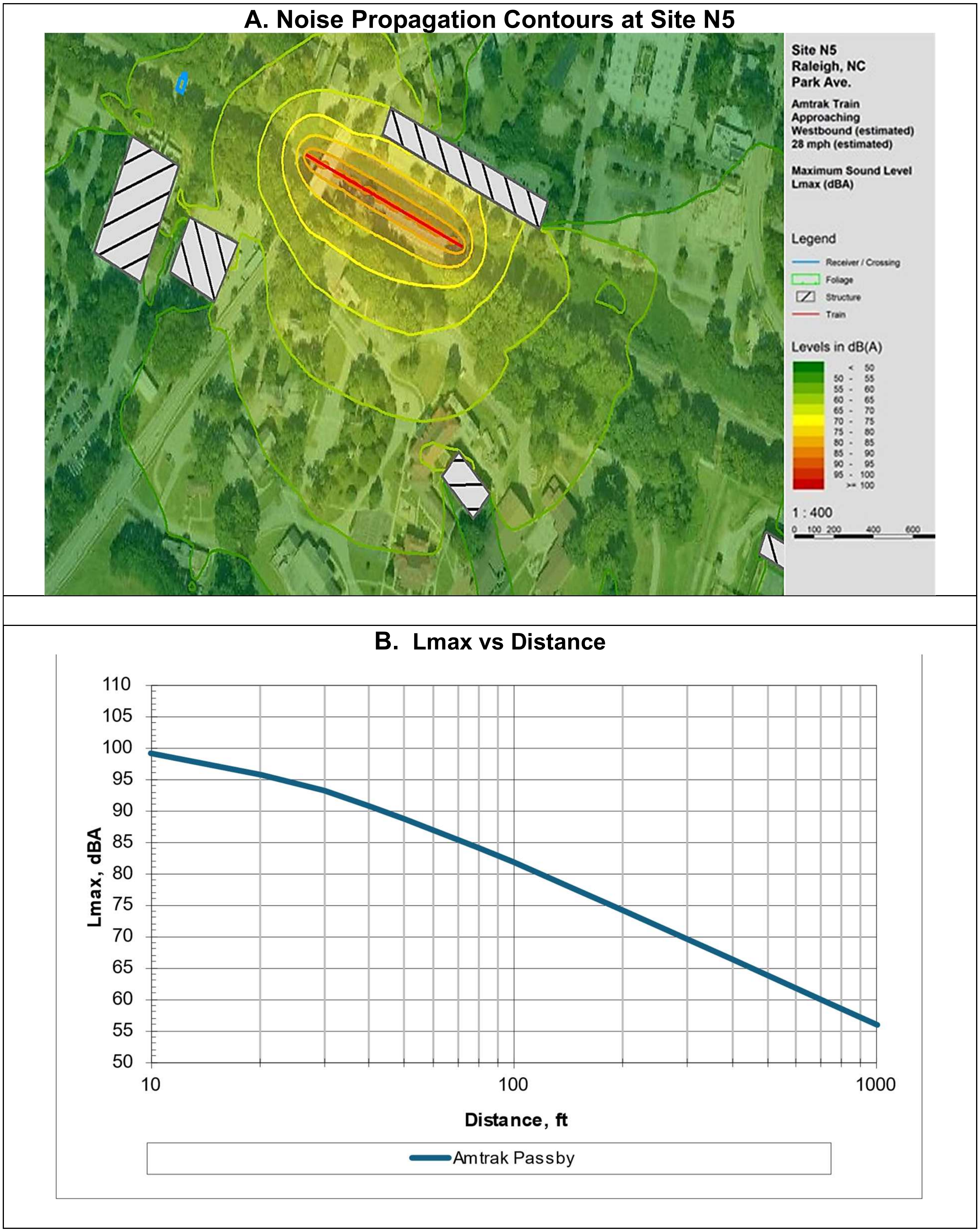


Figure 39. Rail Noise Propagation Contour and Crossing Distances
Source: Site N5: Amtrak @28 MPH

At unauthorized/illegal crossings or locations where pedestrians approach from behind buildings or parked freight cars, the delay in sound arrival and buildup may be compounded. In contrast, designated crossings with direct exposure offer better acoustic transparency and situational awareness. These findings highlight the importance of managing access and designing pathways to ensure pedestrians are exposed to train noise cues early and directly.

6.2 Risk Levels of Various Environments

To systematically evaluate the conditions under which train noise may go undetected by pedestrians, the NCAT team has developed the qualitative matrix capturing the environmental and operational factors that influence the audibility of approaching trains. As documented in Table 7, the matrix synthesizes insights gained through field observations, calibrated noise modeling, and a review of site-specific characteristics, providing a clear framework to classify and compare high-risk and low-risk conditions for noise detection.

Table 7. Environmental and Operational Conditions Impacting Train Noise Detection

Category	High-Risk Conditions (Noise Likely Undetected)
Train Speed	High-speed trains (>70 mph) reduce warning time to <10 seconds before arrival
Ambient Noise	High ambient levels, such as urban zones, 60–64 dBA, mask approaching train noise
Warning Horns	Quiet Zones or distant crossings—no horns used
Track Alignment	Straight tracks limit diffraction and increase risk when paired with obstructions
Vegetation / Trees	Sparse or narrow vegetation strips provide minimal attenuation
Buildings / Barriers	Obstructive buildings can block noise, especially at low frequencies, reducing early detection
Environmental Noise	Industrial/mechanical sounds (HVAC, idling freight, auxiliary rail activity) can mask key acoustic cues
Distance to Tracks	Pedestrians far from tracks (e.g., illegal crossings behind buildings) have delayed or distorted perception

Each factor included in the matrix - such as train speed, ambient noise level, track geometry, warning device usage, and physical obstructions - has been identified as a key variable affecting how and when pedestrians perceive oncoming trains. For instance, trains operating at high speeds through areas with elevated ambient noise, e.g., traffic-heavy urban corridors, present a significantly greater risk for undetected noise compared to low-speed freight trains operating in quieter, rural environments. In some cases, high background noise levels combined with the absence of train horns (as found in Quiet Zones) can reduce a pedestrian's auditory warning time to less than ten seconds.

The matrix also distinguishes between propagation-related factors that amplify or diminish risk, such as vegetation buffers, building-induced sound diffraction, and the presence or absence of line-of-sight to the tracks. Notably, the matrix incorporates the principle that noise sources producing levels at least 10 dBA lower than dominant sources contribute minimally to overall perceived sound - underscoring the limited value of some environmental barriers unless they provide substantial attenuation.

By highlighting these factors with high risks, the matrix serves as both an analytical tool and a practical reference for rail safety professionals. It enables a more informed assessment of designated crossing locations, illegal pathways, and high-incident zones, guiding the prioritization of safety enhancements and public outreach strategies. Additionally, the matrix may be adapted for use in training programs or incorporated into safety audit checklists to assist in identifying locations where auditory warning cues may be insufficient, thus supporting proactive risk mitigation efforts along rail corridors.

The structured presentations of these parameters allow stakeholders to identify high-risk locations where pedestrians may not receive sufficient auditory warning, especially in areas with elevated background noise or limited use of train horns. Moreover, summary results can be referenced to design context-sensitive countermeasures such as targeted signage, acoustic alerts, and crossing design enhancements. It also underscores the importance of incorporating noise propagation dynamics into safety evaluations and trespass mitigation planning along rail corridors.

7. SUMMARY

Blazing the trails of railroad safety research, this study is the first, as evident in existing literature, effort to examine railroad noise propagation from the perspective of pedestrians. The rail noise propagation data was collected at locations as close as possible to railroad tracks, which resembles the environment where pedestrians cross railroad tracks at non-designated locations.

This approach is different from all previous studies, which often focus on the impact of rail noise on the surrounding neighborhood and/or establishment. The goal of which is often to reduce or mitigate the rail noise, especially in high-density downtown areas or residential neighborhoods.

7.1 Research Conducted

Setting the objective of examining rail noise propagation to understand its impact on pedestrians, the NCAT team has combined field data collection and computer simulation modeling to explore and quantify the impact of various factors on rail noise propagation and its end results on pedestrians who are attempting to cross railroad tracks at locations that may or may not be designated crossings.

Ultimately, this dataset and accompanying matrix not only illustrate the physical behavior of train-generated sound in varied environments but also provide actionable insight into how rail operators, planners, and policymakers can develop interventions to reduce the occurrence of preventable trespasser incidents. In the context of pedestrian safety along rail corridors, the ability to detect the approach of a train through audible cues is a critical factor in preventing collisions. Train horns, engine noise, and wheel–rail interaction sounds often serve as the primary warning signals for pedestrians, especially in areas without dedicated barriers or active warning devices. This highlights the need to carefully evaluate the role of auditory detection in safety planning, while also supplementing it with visual warnings, physical barriers, and educational initiatives to reduce dependence on sound alone.

7.2 Implementation and Technology Transfer

This study has produced several implementable research products:

- A model that demonstrates how propagated train noises interacts with external factors;
- A prioritized list of high-risk environments resulting from the conditions that enable noise propagation to go undetected by individuals on the railroad right-of-way;
- Scientific evidence to explain why individuals, who trespass on the railroad right-of-way, are caught “off-guard” by trains approaching;
- Awareness, knowledge, and guidance for highway and rail design engineers to ‘design out’ pedestrian ease of access to rail environments.

Based on the findings from this study, NCDOT will be able to pinpoint high-risk areas of train noise-detection. This information can be used to demonstrate where noise-related safety countermeasures can be implemented to obviate rail trespass strikes related to individuals being caught off-guard, see figure below. BeRailSafe will implement the findings with public and public safety stakeholders through local, state, and national rail safety awareness networks. In addition, the research findings will be shared with highway and rail design engineers to 'design out' ease of access by pedestrians to rail environments.

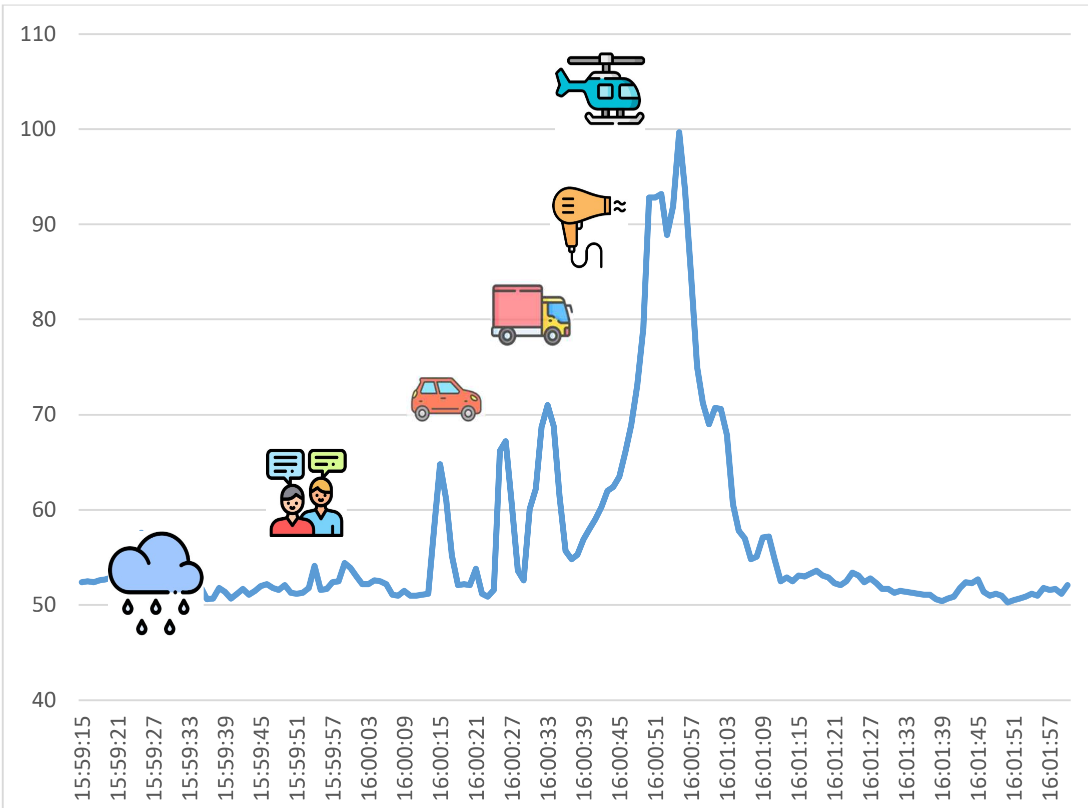


Figure 40. Rail Noise Comparison with Daily Activities

7.3 Further Research

The data collection and simulation analysis performed in this study is extensive, but it is still limited to a few selected sites located in three regions of North Carolina. A large sample size and more diverse locations will help confirm our findings and provide more generalized conclusions. Further studies may include reexamining rail incident data to test the categories of high and low risk environments; isolating and evaluating various factors and their correlation to trespasser casualties included in the existing data; and developing and/or modifying mitigation approaches to reduce trespassing casualties in the railroad environment.

REFERENCES

Association of American Railroad, 2021. Total Rail Miles by State: 2020. https://www.aar.org/wp-content/uploads/2021/02/AAR-State-Rankings-2019.pdf. Accessed in Sept 2021.

Fang, Chih-Fang and Der-Lin Ling, 2005. "Guidance for Noise Reduction Provided by Tree Belts." Landscape and Urban Planning 71(1): 29–34. https://doi.org/10.1016/j.landurbplan.2004.01.005.

Federal Railroad Administration, 2011. A Guide for Preparing Accident/Incident Reports, 2011.

Federal Railroad Administration, 2006. "Current 49 CFR Part 222: Use of Locomotive Horns at Public Highway-Rail Grade Crossings". Electronic Code of Federal Regulations. https://www.ecfr.gov/current/title-49/subtitle-B/chapter-II/part-222

Federal Railroad Administration, 2000. Horn Noise MS Excel Spreadsheet Model. https://railroads.dot.gov/elibrary/horn-noise-ms-excel-spreadsheet-model

Federal Railroad Administration, 1995. Nationwide Study of Train Whistle Bans, https://railroads.dot.gov/elibrary/nationwide-study-train-whistle-bans; /common/images/covers/large/453591.png. Accessed in Sept 2021.

Federal Transit Administration, 2020. National Transit Database, 2020.

Federal Transit Administration, 2018. *Transit Noise and Vibration Impact Assessment Manual (FTA Report No. 0123).* U.S. Department of Transportation. Accessed June 2025. https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/research-innovation/118131/transit-noise-and-vibration-impact-assessment-manual-fta-report-no-0123_0.pdf

Gössling, S., Humpe, A., Litman, T., & Metzler, D. 2019. Effects of perceived traffic risks, noise, and exhaust smells on bicyclist behavior: An economic evaluation. *Sustainability*, *11*(2), 408. https://doi.org/10.3390/su11020408

Guralnick, A. J. 2018. "Subway noise can harm your hearing. Hearing Health Foundation. " Accessed Dec 2023 via https://hearinghealthfoundation.org/subway#:~:text=And%2C%20with%20maximum%20readings%20actually,is%20likely%20an%20auditory%20minefield.

Hanson, C. E. 2006. *Create Railroad Noise Model User Guide 1–6*. Burlington, MA; Harris Miller, Miller & Hanson Inc.

Hummer, J and Jafari, M. 2003. Railroad Crossing Wayside Horn Evaluation. https://connect.ncdot.gov/projects/research/RNAProjDocs/2003-11FinalReport.pdf. 2003.

Laffey, S., 2019. Railroad fatalities in the United States 2012-2017. *TR News,* July-August 2019, Transportation Research Board.

Lambert, J., Champelovier, P., & Vernet, I., 1996. Annoyance from high speed train noise: A social survey. *Journal of Sound and Vibration*, *193*(1), 21–28. https://doi.org/10.1006/jsvi.1996.0241

Marquart, H., Ueberham, M., & Schlink, U., 2021. Extending the dimensions of personal exposure assessment: A methodological discussion on perceived and measured noise and air pollution in traffic. *Journal of Transport Geography*, *93*, 103085. https://doi.org/10.1016/j.jtrangeo.2021.103085

Metropolitan Council. 2015. *Southwest LRT Noise Fact Sheet*. Minneapolis, MN; Metropolitan Council. Retrieved January 3, 2024, from https://metrocouncil.org/getattachment/1c8f21d0-e29a-41b2-b618-c57eb96db743/Southwest-LRT-Noise-Fact-Sheet.aspx

Multer, J., 1994. Field Study of a Way Side Auditory Warning for Motorists. Proceedings for Third International Symposium of Railroad-Highway Grade Crossing Research and Safety. Pp 203-215. 1994.

National Institute of Justice, 1999. “Attitude toward Crime, Police, and the Law: Individual and Neighborhood Differences.” US Department of Justice, Office of Justice Programs. Accessed in Dec 2023. https://www.ojp.gov/pdffiles1/fs000240.pdf.

National Safety Council, 2024. Railroad Deaths and Injuries” Safety Topics. Accessed in July 2025 via https://injuryfacts.nsc.org/home-and-community/safety-topics/railroad-deaths-and-injuries/.

Neitzel, R., et al, 2009. “Noise levels associated with New York City’s Mass Transit Systems.” *American Journal of Public Health*, *99*(8), 1393–1399. https://doi.org/10.2105/ajph.2008.138297.

Office of Railroad Policy and Development, 2012. *High-speed ground transportation noise and Vibration impact assessment: Final report 1–248.* Washington, DC; Office of Railroad Policy and Development.

Sumwalt, R., 2019. Toward railroad trespassing solutions. *TR News,* July-August 2019, Transportation Research Board.

U.S Government Accountability Office, 2017. Railroad Safety: Quiet Zone Analyses and Inspections Could Be Improved. http://www.gao.gov/assets/690/688079.pdf; /common/images/covers/large/1487193.png; http://www.gao.gov/assets/690/688080.pdf. Accessed in Sept 2021.

Waterson, P. E., Kendrick, V. L., & Underwood, P. J., 2017. Teenage trespass on the railways – A systems approach. *Proceedings of the Institution of Civil Engineers - Transport*, *170*(5), 287–295. https://doi.org/10.1680/jtran.16.00012

APPENDIX 1. LITERATURE REVIEW SUMMARY

1. INTRODUCTION

As mentioned in the NCDOT RFP (2023-017) and confirmed in our initial literature review during the proposal preparation stages, little research has investigated the relationship between sound propagation and its effect on rail trespass strikes. In fact, many studies focused on reducing rail noise, promoting quiet zones, and proving annoyance of train noises (Lambert et al., 1996), which all had the common goal of reducing rail noise but also the inadvertent effect of increasing rail trespass strikes.

After receiving the Notice to Proceed (NTP) from NCDOT, the NCAT research team conducted a detailed, in-depth literature review, which serves as the knowledge baseline on rail trespass strikes and highlights the critical areas that need further investigation. Due to the limited quantity and scope of existing studies and the time lag of formal publications, the research team also examined alternative sources, such as unpublished project reports, conference presentations, as well as personal communications and project experiences.

2. DEFINITION OF TRESPASSING INCIDENT

It is commonly accepted that rail trespassers are individuals illegally on private railroad property. They are most often pedestrians who walk across or along railroad tracks as a shortcut to another destination. In reality, there are various definitions and interpretations of “trespass,” “trespasser,” and “trespassing incidents.” For example, the Federal Railroad Administration (FRA) defines trespassers as “persons who are on the part of railroad property used in railroad operation and whose presence is prohibited, forbidden, or unlawful” (FRA 2011). Meanwhile, the Federal Transit Administration (FTA) dictates that “trespass” is “the unauthorized entry of transit-owned land, structure, or other real property not intended for public use” (FTA 2020).

As the main source of railroad safety data, the injury-illness summary database by FRA has a separate category for trespasser/trespassing while FTA does not separate “trespasser” from other types of persons in the incident report. In the National Transit Database, there is no specific reporting category for a person who is walking along or across rail transit tracks, along the right-of-way, or in a station environment. Those discrepancies and inconsistencies made it difficult, if not impossible, to compare and analyze the causes of trespassing in various locations, types of rail facilities, and other environmental conditions based on reported data.

To establish a baseline for further investigation of trespassing behavior, the research team has adapted the definition of trespasser as “an unauthorized individual on railroad or rail transit property that is not intended for public use." A trespasser may be a rail passenger who ventures into off-limits territory. A trespassing incident occurs whenever a trespasser willfully enters into these restricted areas and a trespassing accident occurs when a trespasser suffers bodily injury or is killed as a direct result of his or her presence on railroad or rail transit properties.

This report employs the words "trespass," "trespasser," and "trespassing" to describe events of pedestrians on railroad or rail transit property illegally, largely based on the commonly accepted terminologies in the transportation safety arena. It is important to note that the connotation of inherent criminality in the term "trespass" may obscure the actor/victim in a trespassing incident from being fully understood. Striving for a deeper understanding of trespassing behavior and the range of factors affecting those behaviors, the NCAT team will dive deep into the complicated matrix of those causal relationships. For example, the research team will examine the impact of demographic and socioeconomic status; English proficiency on the awareness of dangers associated with railroad operations; and the effects of land use, natural environments, and various warning devices on rail noise propagation, which may play a key role in trespass strikes.

With significant efforts to mitigate railroad casualties and improve crossing safety during the past half century, the overall rate of railroad injury and fatality has been decreasing as shown in Figure 1. While total annual incidents are decreasing, especially during the two most recent decades, annual fatalities are decreasing at a slower pace, which resulted in an increased fatality rate from 2% in 1975 to 13% in 2021 when comparing yearly railroad fatalities to annual incidents.

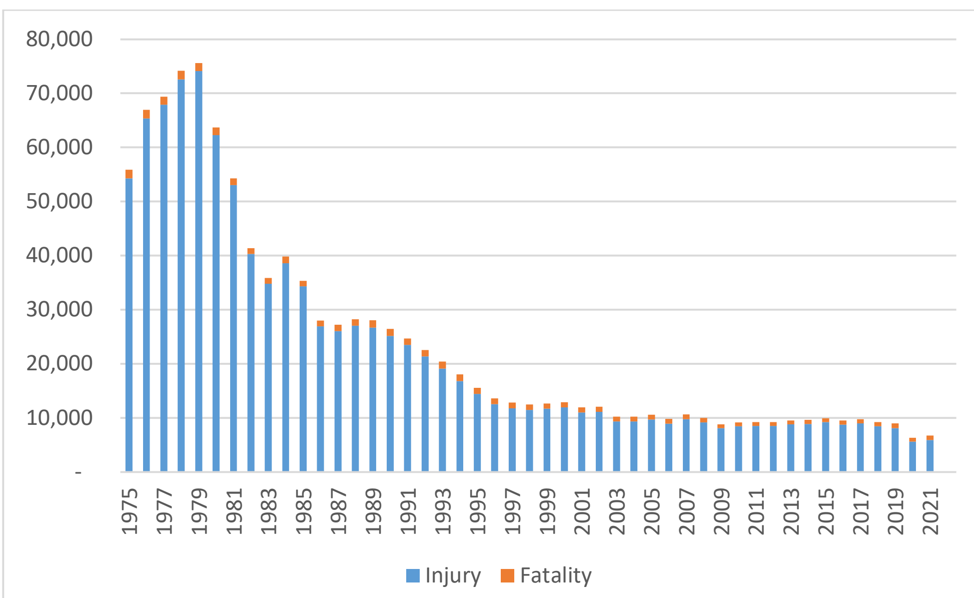


Figure 1. Railroad Injury and Fatality, 1975-2021

On the other hand, trespassing behavior has not changed much during the past half century, as shown in Figure 2. Placing trespasser fatalities in the context of total trespassing incidents, the yearly fatality rate ranges between 37 to 52 percent. The more worrisome trend is that the highest fatality rates occurred last year, 2021, at 52%. The prevalence of railroad trespassing is well-documented, both by mandatory data reporting of incidents and by sensor and camera studies conducted to identify local hotspots. Trespassing is the leading cause of both accidental railroad-related deaths and all railroad-related deaths—about 44% of all railroad casualties according to earlier studies (Sumwalt, 2019; Laffey, 2019).

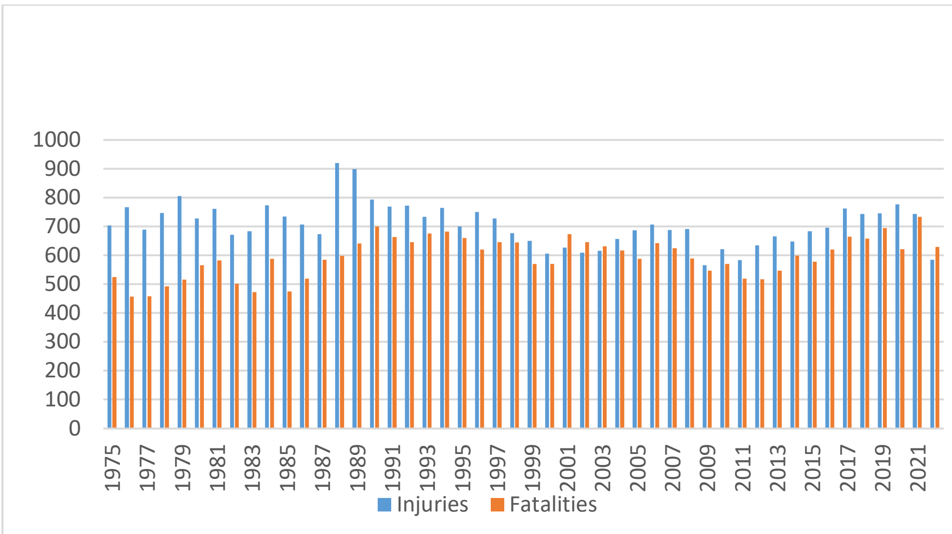


Figure 2. Trespasser Injury and Fatality, 1975-2021

3. AWARENESS OF RAILWAY DANGER

There is little work in the existing literature to understand trespasser behavior around railroad or transit properties in advance of strike incidents. As noted earlier, a person's understanding of rail danger and his or her motivation for traversing the railroad environment are essential factors to develop effective strategies to reduce or eliminate trespass strikes. Some research efforts have focused on determining trespasser demographics and the reason for their trespassing behavior by isolating self-harm from others using accident data collected from official reports. For instance, Kidda et al. (2020a) applied Trespasser Intent Determination and Evaluation (TIDE) criteria created by FRA to sort accidents into three categories: probably suicide, probably accident, and inconclusive. While this work is useful in standardizing determination criteria and data collection methods, it doesn't provide the nuanced understanding of trespasser behavior necessary to preempt trespasses, especially for those trespassers who do not intend to harm themselves.

Silla and Luoma (2008) laid the groundwork for the kind of research that would have better preemptive capabilities by interviewing trespassers at problematic trespass locations in Finland. The research revealed that trespassing is most often motivated by more expedient pedestrian routes, even when a legal crossing was within 1,000 feet of the trespass site. Furthermore, the study revealed that half of Finnish trespassers regarded trespassing as safe and 15% regarded it as legal. While age diversity exists in the research's sample, it lacks the socioeconomic status, demographic background, and cultural context necessary in an analysis of American trespassers. It is necessary to learn a great deal more about trespassers and their behaviors in order to craft effective countermeasures and intervention strategies.

An additional under-researched aspect of the rail strike problem is the emerging study of perceived versus measured noise input, currently applied to personal exposure assessment in noise and air pollution (Marquart et al., 2021). The researchers established that measurable noise and air pollution did not always match perceived levels and were confounded by variables like knowledge, embodied experience, life situation, and activities. It has been established that perceived risks and noise both influence behavior and route choices for active mode travelers (Gössling et al., 2019), so it begs the question of how perceived risk (or lack thereof) is not only influencing trespasser behavior, but their actual ability to discern emergency warnings from trains.

Other work has added to the body of literature around pedestrian behavior. The FRA has constructed demographic and behavioral profiles to better understand who dies in trespass strikes by utilizing decedent data, but the study naturally excludes trespassers who were not involved in an accident (Office of Railroad Safety, 2013). Stanchak and daSilva (2014) conducted a similar review of various data sources, leading them to categorize risk factors into individual, such as disregard for grade crossing warnings, intoxication, and use of electronic devices; and location, which includes time of day and year, grade crossing, stations, schools, yards, bridges, and population density.

Geospatial analyses of trespass incidents showed that 74% of trespass casualties occur within 1,000 feet of a grade crossing (FRA, 2018). Chaudhary et al. (2011) spearheaded efforts to predict "hotspot" locations with high incident potential. Kidda et. al (2020b) expanded on these predictors by delineating time of year, time of day, and age of victims for newer data sets. Oswald Beiler and Filion (2021) mapped Amtrak's trespasser data from 2011-2019 to find significant national hotspots. These studies provide a useful foundation for further research in categorizing risk factors and localizing intervention efforts, but more work is needed to understand the public's perception of rail environments and their motivations behind trespassing.

It is important to note that very few studies support the efficacy of any measures to modify trespasser behavior, although Waterson et al. (2017) did document teenage trespass perceptions and how teenagers perceived the efficacy of various interventions. Despite a dearth of evidence-based studies to support interventions, evidence does suggest that most measures share interdependent “effect mechanisms” and work better together (Harvârneau, 2017). And indeed, Jacobini and daSilva (2021) demonstrated the effectiveness of the CARE model, which requires diverse stakeholder collaboration and collective resources to maximize overall effectiveness.

Furthermore, popular beliefs from long ago and current social media trends do not help warn of the potential danger of railroad environments. For example, while media depictions of trains typically portray them as dangerous, the hero nearly always escapes the tracks in time. What’s more, trains are portrayed as quite loud from the noise of carts rattling along rails to the signature long, loud warning whistle, which is virtually never absent, implying that it can always be heard. In reality, rail technology has come a long way since the wild west, driven by the ideal that quieter trains are better for society. “Noise and vibration reduction is crucial to achieve greater social benefits” (Ortega et al., 2018) may just be the unspoken mantra that has allowed so many unnecessary rail fatalities. Indeed, the literature contains an abundance of research in pursuit of reduced rail noise, especially regarding ground vibration and noise pollution (Ortega et al., 2018; Ouakka et al., 2022; Wen et al., 2020).

Interestingly, the inherent danger of quieter trains is not widely discussed, even within the industry. Volpe National Transportation Systems Center (Fleming, 2021) did not mention the unintended consequences of decreased rail noise in their review of rail noise implications, despite the steady rate of strikes. Rather than this being a critique, the article illustrates the blind spot in the public consciousness about the magnitude of trespassing and the danger of rail noise “improvements.” The fact is, while the train noises fade away, railroad trespass strikes become much more frequent and prevalent.

4. EXISTING STANDARDS, REGULATIONS, AND PRACTICES

The latest development, the FRA’s *High-Speed Ground Transportation Noise and Vibration Impact Assessment* (Hanson et al., 2012) and the FTA’s *Transit Noise and Vibration Impact Assessment Manual* (Quagliata et al., 2018) guidance manuals establish methodology for the evaluation of noise from passenger and freight trains. High speed rail noise concerns are thoroughly addressed by federal standards and regulations (Paul et al., 2021). Those guidelines superseded earlier manuals and procedures (Boeker et al., 2009) and will be used to identify the types of noise sources and factors that influence noise propagation in railroad environments.

Government handbooks exist for standardizing metrics of noise, measurement techniques, and relevant noise thresholds (Hanson et al., 2006, 2012; Quagliata et al., 2018; Canadian Transportation Agency, 2011). *The Handbook for Railroad*

Noise Measurement and Analysis, however, compiled the most thorough review of noise measurement procedures with specific regard to train horns and federal compliance with emergency warning standards. With the intent to mitigate noises around railroad operation, the handbook requires that measurement instruments be positioned at least 10 feet from the track center line (page 8). Similarly, the handbook encourages testers to avoid conducting measurements within ¼ mile of a grade crossing "to avoid noise contamination from the horn and crossing bells" (page 14). Finally, the handbook details "clear zone requirements" for all measurements, stating that "measurement site(s) must be free of large, reflecting objects such as buildings, hills, signposts, bridges, parked vehicles, railroad cars and locomotives" to avoid reflections that could increase sound levels. As narrated earlier, most railroad noise measurement standards and regulations are developed to abate noise levels, which may create a gap in understanding true rail noise propagation and its impact on trespass behavior.

Railroad horn systems are historically well-vetted (Keller and Rickley, 1993) and many aspects of train noise have been addressed to some degree, from ambient noise to curve squeal (Shimizu, 2022). Relevant studies include more complex data like flow structure and far-field noise (Zhuo-ming et al., 2022). Wayside horns have been extensively studied as Quiet Zones grew in popularity, but Ngamdung and daSilva (2020) found that the creation of quiet zones did not create a statistically significant change in trespassing incidents. Accidents could be expected to remain steady in Quiet Zones as well, owing to the fact that engineers may still sound their horns at pedestrians and trespassers in Quiet Zones. Bravo, et al. (2002) examined the influence of air layers and damping layers on sound transmissions. Hemsworth (1977) investigated the effect of topography on propagation of railway noise. Acoustic modeling research will combine these factors to document the decomposition of rail noise on North Carolina rights-of-way.

A study by Volpe Transportation Research Center (Keller and Rickley, 1993) has evaluated the characteristics of several types of railroad horn system by collecting field data at four separate locations in Iowa, Florida, Massachusetts, and Nebraska. The data collection approach can be of reference for the proposed study, but the train horn systems may or may not be used today, therefore, new data collection and assessment is needed. Noise and vibration prediction methods have also been established and vetted in the literature (Colaço et al., 2022; Hohenwarter, 1990; Lei, 2019; Thompson et al., 2019).

5. EMERGING APPROACHES TO IMPROVE RAILWAY SAFETY

The effort to increase rail danger awareness and mitigate trespassing is interdisciplinary and crosses agency boundaries (Aducci et al., 2008; Harrison and daSilva, 2012). Recent publications have detailed rail trespassing behavior and evaluated relevant strategies for mitigation (Warner et al., 2022a and 2022b). Both volumes of *Strategies for Deterring Trespassing on Rail Transit and*

Commuter Rail Rights-of-Way serve as foundational texts to understand rail trespass and develop cutting edge survey content. As part of a National Trespass Prevention Strategy, training has been created, particularly around suicide prevention (Sherry and Pusavat, 2021). Horton and Foderaro (2016) documented best practices for law enforcement agencies to employ to reduce trespass risk factors. Ngamdung and daSilva (2019) demonstrated that anti-trespass guard panels could reduce trespassing incidents (38% in this case) at highway-grade crossings. The efficacy of other evidence-based suicide interventions has also been analyzed (Barker et al. 2016). Lobb et al. (2003) examined a multi-faceted trespass intervention approach involving public awareness, education, punishment, and reinforcement in school-age children. Despite the multi-faceted nature of the literature, rail trespass strikes have not been significantly mitigated.

As the rail industry advances, so too have approaches to rail safety, albeit with some lag. Work with technology, particularly camera systems, to document trespasser prevalence and in some cases warn trespassers to evacuate the right-of-way (daSilva et al., 2006) has been undertaken for more than 20 years. Smailes et al. (2007) demonstrated that effective real-time monitoring systems could be accomplished with non-intrusive commercial-off-the-shelf equipment. Baron and daSilva explored the use of police-operated camera systems to detect trespass hotspots and outlined the technological difficulties therein (2020). As part of the NCDOT research program, Searcy et al. (2019, 2020) examined the extent of pedestrian trespassing activities using improved static thermal camera systems. The preliminary modeling results with adjusted R-Square in the range of 0.2-0.3 may not be ready to be used to predict and/or profile trespassing candidates, but the hot-spot location data will be very useful to the NCAT team in selecting case study sites and examining the impact of rail noise propagation in the following tasks.

Similar research by daSilva and Carroll (2011) further proved the necessity for effective on-train warning devices by finding that 66% of the trespass incidents recorded by their train-mounted cameras occurred along the right-of-way at non-crossing locations. Equipment reliability remains a concern, but for the most part technology has advanced to the point of being able to detect trespassing accurately. Nonetheless, costs and right-of-way coverage remain problematic given the small area of coverage that static cameras can provide. Additionally, the prevalence of pedestrians on the right-of-way is well-established; it is yet unclear, however, how to increase pedestrian awareness and successfully give advance warning about approaching trains in order to prevent strikes. Progress is being made in this regard, although best practices have yet to be established. In keeping with this research purpose, it is apparent that effective train-mounted emergency warning systems will be the most reliable, least expensive, and provide the most complete coverage of active rights-of-way.

The latest, most authoritative research on Emergency Warning Devices (EWD) funded by FRA (Campbell et al., 2019, 2021a, and 2021b) has not only demonstrated the importance of preventing rail trespassing casualties but also of paying attention to the other spectrum of rail noises—the sound or startle effect of train horns or warning signals may save lives. Charged to develop an Emergency Warning Signal (EWS) to improve safety for railroads and warn trespassers, the researchers evaluated an array of EWS devices by measuring detectability, sense of urgency, startle effects, and the identification/association of the sound with a train. Having completed the first part of phase three, the preliminary results show that an EWS could maintain its indication of a train approaching, improving detectability, and providing more time to persons wearing headphones to vacate the tracks. However, the on-going study has not finalized its recommendations for Acoustic Warning Devices as EWS. The research is not scoped to evaluate the impact of environmental factors on sound propagation and its effect on rail trespassing strikes; therefore, the urgency and necessity of the proposed research remains.

A considerable body of research provides other useful background information. English and Moore (2004) tested the effectiveness of various locomotive horns at various speeds and various positions on the train in live field conditions. Their research was inspired by a pedestrian incident similar to those that have catalyzed this research: a pedestrian was struck after the train horn did not become audible in time for the individual to take life-saving action. Their work sets up useful considerations, best practices, and areas for expanded testing in regard to the influence of speed on horn output, the influence of wind and temperature gradients on sound refraction, and the importance of horn placement for pedestrian safety. Campbell et al. (2022) performed similarly useful research in their investigation into the use of acoustical warning devices for locomotive horns, but their research is limited by the lack of human factor analysis and variable, real world conditions.

While there is a useful body of literature involving human factor analysis of audible noises in real world conditions, its focus on rail is limited and its focus on rail pedestrians and trespassers is nearly non-existent. A search of "perception-reaction rail" on the TRID database of the Transportation Research Board yielded 12 records, none of which pertain to rail pedestrians/trespassers. Dolan and Rainey (2005) and Rapoza and Raslear (2001) conducted useful work defined by the minimum warning distance required for automobile drivers to initiate life-saving action in a potential strike scenario. Similarly, Zhao and Rilett (2017) and Long and Nitsch (2008) presented research related to automobile driver perception-reaction time (PRT) at highway-rail grade crossings at the Transportation Research Board's Annual Meeting. These efforts represent a body of work about PRT that leads to one general conclusion: despite the law's definition of a single PRT (2.5 seconds in the U.S.), there is actually no single PRT (Green, 2021). Time to respond varies greatly across tasks and conditions, the most important variable being driver (or subject) expectation (Green, 2000), which ties back to perceived versus measured noise input discussed in Section 3. These methodologies need to be retooled for a slew of pedestrian scenarios and combined with research about horn directivity, soundwave refraction, and the effects of train speed on noise loss in order to fully understand how pedestrians react to train horns and interact with rail rights-of-way.

6. SUMMARY

As expected, there is little work in the existing literature that investigates the rail noise propagation and its impact on trespass strikes. However, gleaning through the limited publications still provides the research team a basic context for much-needed understanding of rail noise propagation, how it is affected by the natural and/or built environment and how it is received by people in close proximity to rail transportation facilities. Limited research on how people perceive rail danger also motivates the NCAT team to dive deeper into the topic by conducting surveys and/or dialogues with general public to understand the best approach to reduce or eliminate trespass strikes.

REFERENCES

Adduci, B., Mottley, F., & Haines, M. (2009). *Row fatality and trespass reduction workshop 2008, summary of results*. FRA. Retrieved November 15, 2022, from https://railroads.dot.gov/elibrary/row-fatality-and-trespass-reduction-workshop-2008-summary-results

Barker, E., Kolves, K., & De Leo, D. (2016). Rail-suicide prevention: Systematic literature review of evidence-based activities. *Asia-Pacific Psychiatry*, *9*(3). https://doi.org/10.1111/appy.12246

Baron, W., & daSilva, M. (2020). *Trespasser detection systems on railroad rights-of-way*. FRA. Retrieved November 15, 2022, from https://railroads.dot.gov/elibrary/trespasser-detection-systems-railroad-rights-way

Boeker, E., Fleming, G., Rapoza, A., & Barberio, G. (2009). *Handbook for Railroad Noise Measurement and analysis*. FRA. Retrieved November 21, 2022, from https://railroads.dot.gov/elibrary/handbook-railroad-noise-measurement-and-analysis

Bravo, J. M., Sinisterra, J., Uris, A., Llinares, J., & Estelles, H. (2002). Influence of air layers and damping layers between gypsum boards on sound transmission. *Applied Acoustics*, *63*(10), 1051–1059. https://doi.org/10.1016/s0003-682x(02)00028-2

Campbell, T., Parida, B., & Ross, J., Acoustical warning devices as emergency warning systems, phase 1 (2019). Washington, DC; Federal Railroad Administration.

Campbell, T., Parida, B., & Ross, J., Acoustical warning devices as emergency warning systems, phase 2 (2021a). Washington, DC; Federal Railroad Administration.

Campbell, T., Parida, B., & Ross, J., Acoustical warning devices as emergency warning systems, phase 3: performance evaluation on a locomotive (2021b). Washington, DC; Federal Railroad Administration.

Campbell, T., Parida, B. K., & Ross, J. C. (2022). *Acoustical warning device for locomotive horns*. FRA. Retrieved November 7, 2022, from https://railroads.dot.gov/elibrary/acoustical-warning-device-locomotive-horns

Canadian Transportation Agency. (2011). *Railway noise measurement and reporting methodology*. Canadian Transportation Agency. Retrieved

November 21, 2022, from https://otc-cta.gc.ca/eng/railway_noise_measurement

Chaudhary, M., Hellman, A. D., & Ngamdung, T., Railroad right-of-way incident analysis research (2011). Washington, DC; U.S. Dept. of Transportation, Federal Railroad Administration, Office of Railroad Policy and Development.

Colaço, A., Castanheira-Pinto, A., Alves Costa, P., & Fernández Ruiz, J. (2022). Combination of experimental measurements and numerical modelling for prediction of ground-borne vibrations induced by railway traffic. *Construction and Building Materials*, *343*. https://doi.org/10.1016/j.conbuildmat.2022.127928

daSilva, M., Baron, W., & Carroll, A. (2006). Highway Rail-Grade Crossing Safety Research: Railroad Infrastructure Trespassing Detection Systems Research in Pittsford, New York 1–50. Cambridge, MA; U.S. Department of Transportation; Federal Railroad Administration.

daSilva, M., & Carroll, A. (2011). Preliminary results of the Trespass Prevention Research Study in West Palm Beach, Florida. *2011 Joint Rail Conference*. https://doi.org/10.1115/jrc2011-56091

Dolan, T. G., & Rainey, J. E. (2005). Audibility of train horns in passenger vehicles. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *47*(3), 613–629. https://doi.org/10.1518/001872005774859999

English, G. W., & Moore, T. N. (2004). Locomotive Horn Effectiveness at operating speeds. *Transportation Research Record: Journal of the Transportation Research Board*, *1880*(1), 165–173. https://doi.org/10.3141/1880-20

Federal Railroad Administration (2018, October). *Report to Congress: National Strategy to Prevent Trespassing on Railroad Property.* U.S. Department of Transportation, Washington, DC.

Federal Railroad Administration, 2011. A Guide for Preparing Accident/Incident Reports, 2011.

Federal Transit Administration, 2020. National Transit Database, 2020.

Fleming, G. G. (2021, June 15). *Trains, planes, and Automobiles: Transportation Noise in the United States*. NAE Website. Retrieved November 4, 2022, from https://www.nae.edu/19579/19582/21020/255782/255847/Trains-Planes-and-Automobiles-Transportation-Noise-in-the-United-States

Green, M. (2000). "how long does it take to stop?" methodological analysis of driver perception-Brake Times. *Transportation Human Factors*, *2*(3), 195–216. https://doi.org/10.1207/sthf0203_1

Green, M. (2021). *Driver Reaction Time*. Driver reaction time. Retrieved November 8, 2022, from https://www.visualexpert.com/Resources/reactiontime.html

Gössling, S., Humpe, A., Litman, T., & Metzler, D. (2019). Effects of perceived traffic risks, noise, and exhaust smells on bicyclist behaviour: An economic evaluation. *Sustainability*, *11*(2), 408. https://doi.org/10.3390/su11020408

Hanson, C. E., Ross, J. C., & Towers, D. A. (2012, September). *High-speed ground transportation noise and Vibration impact assessment*. FRA. Retrieved November 21, 2022, from https://railroads.dot.gov/elibrary/high-speed-ground-transportation-noise-and-vibration-impact-assessment

Hanson, C. E., Towers, D. A., & Meister, L. D., Transit noise and Vibration impact assessment (2006). Washington, DC; U.S. Department of Transportation, Federal Transit Administration, Office of Planning and Environment.

Harrison, J., & daSilva, M. (2012). *2012 right-of-way fatality and trespass prevention workshop*. FRA. Retrieved November 14, 2022, from https://railroads.dot.gov/elibrary/2012-right-way-fatality-and-trespass-prevention-workshop

Havârneanu, G. M. (2017). Behavioural and organisational interventions to prevent trespass and graffiti vandalism on railway property. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, *231*(10), 1078–1087. https://doi.org/10.1177/0954409716675004

Hemsworth, B. (1977). Rapporteur's report, session 4: Propagation of railway noise; effect of topography; barrier design. *Journal of Sound and Vibration*, *51*(3), 399–401. https://doi.org/10.1016/s0022-460x(77)80082-5

Hohenwarter, D. (1990). Railway Noise Propagation Models. *Journal of Sound and Vibration*, *141*(1), 17–41. https://doi.org/10.1016/0022-460x(90)90510-7

Horton, S., & Foderaro, F. (2016). *Law enforcement strategies for preventing rail trespassing*. FRA. Retrieved November 16, 2022, from https://railroads.dot.gov/elibrary/law-enforcement-strategies-preventing-rail-trespassing

Jacobini, F. B., & daSilva, M. (2021). Trespass Prevention Research Study - Worcester, MA. *Research Results*, *21*(08).

https://doi.org/https://railroads.dot.gov/elibrary/trespass-prevention-research-study-worcester-ma

Keller, A., & Rickley, E. J. (1993). *The safety of highway-railroad grade crossings: Study of the acoustic characteristics of Railroad Horn Systems*. FRA. Retrieved November 21, 2022, from https://railroads.dot.gov/elibrary/safety-highway-railroad-grade-crossings-study-acoustic-characteristics-railroad-horn

Kidda, S., Chase, S., & Hiltunen, D. (2020a). *Trespasser intent determination and evaluation (tide) criteria*. Trespasser Intent Determination and Evaluation (TIDE) Criteria. Retrieved November 4, 2022, from https://railroads.dot.gov/elibrary/trespasser-intent-determination-and-evaluation-tide-criteria

Kidda, S., Chase, S., & Hiltunen, D. (2020b, January). *Fatal trespasser strikes in the United States: 2012-2017*. Fatal Trespasser Strikes in the United States: 2012-2017. Retrieved November 4, 2022, from https://railroads.dot.gov/elibrary/fatal-trespasser-strikes-united-states-2012-2017

Laffey, S. (2019) Railroad fatalities in the United States 2012-2017. *TR News,* July-August 2019, Transportation Research Board.

Lambert, J., Champelovier, P., & Vernet, I. (1996). Annoyance from high speed train noise: A social survey. *Journal of Sound and Vibration*, *193*(1), 21–28. https://doi.org/10.1006/jsvi.1996.0241

Lei, X. (2019). Methods for predicting the ambient vibration and noise resulting from Rail Transit. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, *234*(9), 1054–1067. https://doi.org/10.1177/0954409719881860

Lobb, B., Harré, N., & Terry, N. (2003). An evaluation of four types of railway pedestrian crossing safety intervention. *Accident Analysis & Prevention*, *35*(4), 487–494. https://doi.org/10.1016/s0001-4575(02)00026-x

Long, G., & Nitsch, A. (2008). Effect of Head Turning on Driver Perception-Reaction Time at Passive Railroad Crossings. Retrieved November 8, 2022, from https://trid.trb.org/View/848853

Marquart, H., Ueberham, M., & Schlink, U. (2021). Extending the dimensions of personal exposure assessment: A methodological discussion on perceived and measured noise and air pollution in traffic. *Journal of Transport Geography*, *93*, 103085. https://doi.org/10.1016/j.jtrangeo.2021.103085

Ngamdung, T., & daSilva, M. (2019). *Effect of anti-trespass guard panels on pedestrian behavior*. FRA. Retrieved November 16, 2022, from https://railroads.dot.gov/elibrary/effect-anti-trespass-guard-panels-pedestrian-behavior

Ngamdung, T., & daSilva, M. (2020). *Trespass risk in quiet zones*. FRA. Retrieved November 16, 2022, from https://railroads.dot.gov/elibrary/trespass-risk-quiet-zones

Ortega, A., Blainey, S., Preston, J., Thompson, D., Squicciarini, G., Ntotsios, E., & Armstrong, J. (2018). Noise reduction for ballasted tracks: A socio-economic assessment. *WIT Transactions on The Built Environment*. https://doi.org/10.2495/cr180411

Oswald Beiler, M. R., & Filion, E. (2021). Amtrak rail trespasser analysis using a GIS space-time approach. *Public Works Management & Policy*, *26*(4), 310–336. https://doi.org/10.1177/1087724x211003249

Ouakka, S., Verlinden, O., & Kouroussis, G. (2022). Railway Ground Vibration and mitigation measures: Benchmarking of Best Practices. *Railway Engineering Science*, *30*(1), 1–22. https://doi.org/10.1007/s40534-021-00264-9

Office of Railroad Safety, June 2013. (2013). *Rail Trespasser Fatalities Demographic and Behavioral Profiles, June 2013*. Office of Railroad Safety. Retrieved November 4, 2022, from https://railroads.dot.gov/elibrary/rail-trespasser-fatalities-demographic-and-behavioral-profiles-june-2013

Paul, J. C., Bubna, P., de Grauw, H., Wolf, M., & Jain, S. (2021). *High Speed Rail Noise Standards and regulations | FRA - transportation*. FRA. Retrieved November 21, 2022, from https://railroads.dot.gov/elibrary/high-speed-rail-noise-standards-and-regulations

Quagliata, A., Ahearn, M., Boeker, E., Roof, C., Meister, L., & Singleton, H. (2018). *Transit noise and Vibration impact assessment manual (report 0123)*. Transit Noise and Vibration Impact Assessment Manual (Report 0123) | FTA. Retrieved November 21, 2022, from https://www.transit.dot.gov/research-innovation/transit-noise-and-vibration-impact-assessment-manual-report-0123

Rapoza, A. S., & Raslear, T. G. (2001). Analysis of railroad horn detectability. *Transportation Research Record: Journal of the Transportation Research Board*, *1756*(1), 57–62. https://doi.org/10.3141/1756-06

Searcy, S., Cunningham, C., Vaughan, C., Coble, D., & Avr, A., Rail Corridor Trespass Severity Assessment (2019). Raleigh, NC; North Carolina Department of Transportation.

Searcy, S., Vaughan, C., Coble, D., Poslusny, J., & Cunningham, C., Rail Network Trespass Statewide Severity Assessment and Predictive Modeling (2020). Raleigh, NC; North Carolina Department of Transportation.

Sherry, P., & Pusavat, A. (2021). *Trespasser and Suicide Prevention Training for Rail Transportation Workers*. TRB TRID Database. Retrieved November 17, 2022, from https://rip.trb.org/view/1881400

Shimizu, Y., Sueki, T., Kawaguchi, T., Kitagawa, T., Kanemoto, H., & Kuzuta, M. (2022). Experimental Study on Curve Squeal Noise with a Running Train. *Quarterly Report of RTRI*, *63*(1), 44–49. https://doi.org/10.2219/rtriqr.63.1_44

Silla, A., & Luoma, J. (2008). Trespassing on finnish railways: Identification of problem sites and characteristics of trespassing behaviour. *European Transport Research Review*, *1*(1), 47–53. https://doi.org/10.1007/s12544-008-0005-y

Smailes, J., Ries, R., & Raslear, T. (2007). Trespass on Railroad Rights-of-Way. *Research Results*, *07*(19). https://doi.org/https://railroads.dot.gov/sites/fra.dot.gov/files/fra_net/2550/rr0719_v2.pdf

Stanchak, K., & daSilva, M. (2014). Trespass Event Risk Factors. Retrieved November 4, 2022, from https://railroads.dot.gov/elibrary/trespass-event-risk-factors

Sumwalt, R. (2019). Toward railroad trespassing solutions. *TR News,* July-August 2019, Transportation Research Board.

Thompson, D. J., Kouroussis, G., & Ntotsios, E. (2019). Modelling, simulation and evaluation of ground vibration caused by rail vehicles. *Vehicle System Dynamics*, *57*(7), 936–983. https://doi.org/10.1080/00423114.2019.1602274

Warner, J. E., Lee, D., Trueblood, A. B., Cline, J. C., Johnson, N. A., & Christjoy, A. (2022a). *Strategies for deterring trespassing on rail transit and commuter rail rights-of-way, Volume 1: Guidebook*. Transportation Research Board.

Warner, J. E., Lee, D., Trueblood, A. B., Cline, J. C., Johnson, N. A., & Christjoy, A. (2022b). *Strategies for deterring trespassing on rail transit and commuter rail rights-of-way*, *Volume 2 Research Overview*. Transportation Research Board.

Waterson, P. E., Kendrick, V. L., & Underwood, P. J. (2017). Teenage trespass on the railways – A systems approach. *Proceedings of the Institution of Civil Engineers - Transport*, *170*(5), 287–295. https://doi.org/10.1680/jtran.16.00012

Wen, Y., Chen, D., Wu, A., & You, H. (2020, June). *Vibration Reduction and Noise Suppression for Urban Railways with a Wheelset Dynamic Vibration Absorber*. Retrieved November 17, 2022, from https://www.researchgate.net/publication/342532683

Zhao, L., & Rilett, L. R. (2017, February 23). Dynamic Model of Driver Approaching Behaviors at Highway-Rail Grade Crossings. Retrieved November 8, 2022, from https://trid.trb.org/View/1439295.

Zhuo-ming, L., Qi-liang, L., & Zhi-gang, Y. (2022). Flow structure and far-field noise of high-speed train under Ballast Track. *Journal of Wind Engineering and Industrial Aerodynamics*, *220*, 104858. https://doi.org/10.1016/j.jweia.2021.104858

APPENDIX 2. RAIL SAFETY SURVEY QUESTIONNAIRE

Default Question Block

Welcome. Study Title: Public Perceptions of Railroad Environments
Principal Investigator: Dr. Rongfang Liu

This research project is funded by the North Carolina Department of Transportation. The procedure involves completing a survey that will take approximately 5 minutes. The survey questions will be about rail safety. You must be at least 18 years old to participate. To protect your confidentiality, the survey will not contain information that will personally identify you and you will not be asked for your name. All information collected in this study will be kept completely confidential to the extent permitted by law. There are no anticipated risks from participating in this research. Your email address or phone number will be requested so that we can conduct a drawing for a $100 gift card. However, it will be stored separately from any data collected in the study.

This project has been approved by the Institutional Review Board (IRB) at North Carolina A&T State University. Your participation is voluntary and there is no penalty if you do not participate. You may stop the survey at any time or skip any questions you do not wish to answer. If you have any questions about completing the questionnaire or about being in this study, you may contact Nicholas Allen at nrallen1@ncat.edu. If you have any study-related concerns or any questions about your rights as a research study participant, you may contact the Office of Research Compliance and Ethics at North Carolina A&T State University at (336) 285-3179 or email rescomp@ncat.edu.

By completing this survey, you are indicating that you at least 18 years old, have read this document, have had any questions answered, and voluntarily agree to take part in this research study. You may print a copy of this consent agreement for your records.

Please answer all of the following questions and proceed to the next survey in order to be entered into a drawing for a $100 gift card.

***Q0.* Please click "I agree" to give your consent to participate in this survey and continue.**

- ◯ I agree.
- ◯ I do not consent.

***Q1.* Do you think it is safe to cross over or walk on railroad tracks?**

- ◯ Yes
- ◯ No

Q2. Why do you think it's dangerous?

- [ ] People get killed.
- [ ] People get injured.
- [ ] People get arrested or ticketed.
- [ ] Other

Q3. Why do you think it's safe?

- [ ] If there's no train around, then there's no danger.
- [ ] I don't usually see trains on the tracks.
- [ ] If you look both ways and you don't spend very long on the tracks, you'll be fine.
- [ ] Other

Q4. Have you done or seen any of the following during the past year?

- [ ] Crossing over train tracks while not at a legal rail road crossing.
- [ ] Walking along train tracks.
- [ ] Hanging out near or around railroad tracks for photoshoots, eating or drinking, thrill seeking.
- [ ] Other

Q5. Do you believe trains always run on a set, regular schedule?

- ○ Yes
- ○ No

Q6. Do you believe that you can be electrocuted by touching any railroad tracks?

- ○ Yes
- ○ No

Q7. Where do you think train noise comes from?

- [ ] Train wheels on train tracks
- [ ] Train horn
- [ ] Train engine running
- [ ] Other

_Q8._ Do you think that train wheels and engines make enough noise to be heard by pedestrians on the tracks?

- ◯ Yes
- ◯ No

_Q9._ Do you believe that all types of trains produce the same types/levels of noise?

- ◯ Yes
- ◯ No

_Q10._ Rank the quietest (1) to the loudest (5) types of trains from the following list:

- [ ] Freight trains
- [ ] Passenger intercity trains
- [ ] Subways
- [ ] Commuter rail
- [ ] Light rail

_Q11._ Which of these types of trains do you believe operate in your state?

- [ ] Freight trains
- [ ] Passenger intercity trains
- [ ] Subways
- [ ] Commuter rail
- [ ] Light rail

_Q12._ What state do you live in?

Q13. **Do you think that pedestrians on the tracks have enough time to move to safety after they *SEE* a train?**

◯ Yes

◯ No

Q14. **Do you think that pedestrians on the tracks have enough time to move to safety after they *HEAR* a train?**

◯ Yes

◯ No

Q15. **Would you cross train tracks on foot at a location that is not a designated crossing?**

◯ Never

◯ Yes, if it saves me at least 30 minutes of walking

◯ Yes, if it saved me at least 20 minutes of walking

◯ Yes, if it saved me at least 15 minutes of walking

◯ Yes, if it saved me at least 10 minutes of walking

◯ Yes, if it saved me at least 5 minutes of walking

Q16. **Do you think it is illegal to cross over train tracks?**

◯ No

◯ I'm not sure

◯ Yes

Q17. **I would use a faster route across the tracks even if...**

☐ I wouldn't use a faster route across the tracks.

☐ I had to climb over a fence.

☐ I had to climb a steep hill.

☐ I had to climb through bushes.

☐ I had to jump over a ditch.

☐ Other

_Q18._ Select where the danger level falls in the following scenarios:

It's more dangerous to be on rail road tracks...

At night	○	○	○	○	During the day
When it's snowing in the winter	○	○	○	○	When it's sunny in the winter
When it's raining in the summer	○	○	○	○	When it's sunny in the summer
In the spring	○	○	○	○	In the fall
In a rural area	○	○	○	○	In a city
When it's foggy outside	○	○	○	○	When it's sunny outside

_Q19._ Have you ever noticed any signs around rail road tracks to discourage crossing or trespassing?

○ Yes

○ No

_Q20._ Have you ever attended a rail safety education program or course?

○ Yes

○ No

_Q21._ How long ago did you attend?

○ In the past 12 months

○ In the last 1-3 years

○ In the last 3-5 years

○ More than 5 years ago

_Q22._ What format is most effective in rail safety education?

○ In-person demonstrations

○ Webinars

○ TV, movie, etc.

○ Radio

- Social media
- Other

Block 1

Q23. What is your age?

- 18-24
- 25-34
- 35-44
- 45-54
- 55-64
- 65 or older

Q24. How do you identify your gender?

- Female
- Male
- Other

Q25. What is your race/ethnicity?

- American India/Alaskan Native
- Asian
- Black/African American
- Hispanic/Latino
- Native Hawaiian/Pacific Islander
- White
- Other

Q26. Do you have a disability or a history of having a disability?

- Yes
- No

Q27. **What is your household income?**

- ◯ less than $10,275 per year
- ◯ $10,276-41,775 per year
- ◯ $41,776-89,075 per year
- ◯ $89,076-170,050 per year
- ◯ $170,051-215,950 per year
- ◯ More than $215,950 per year

Q28. **What is the highest level of education you have completed?**

- ◯ Less than high school or GED
- ◯ High school or GED
- ◯ Two years of college or associate's degree
- ◯ Four years of college or bachelor's degree
- ◯ Master's degree
- ◯ Doctoral degree

APPENDIX 3. SURVEY OUTREACH PACKAGE

The Transportation Institute's research team at NC A&T State University is a wide-reaching survey to document the U.S. public's opinions about rail safety, rail environments, and pedestrian activity in the railroad right-of-way.

We would be deeply grateful if you would share this survey widely using the enclosed poster and links. Survey participants will be entered into a drawing for a $100 gift card as a thank you for their time. Their information will *only* be used if they are selected as a winner. All other survey information collected is completely anonymous.

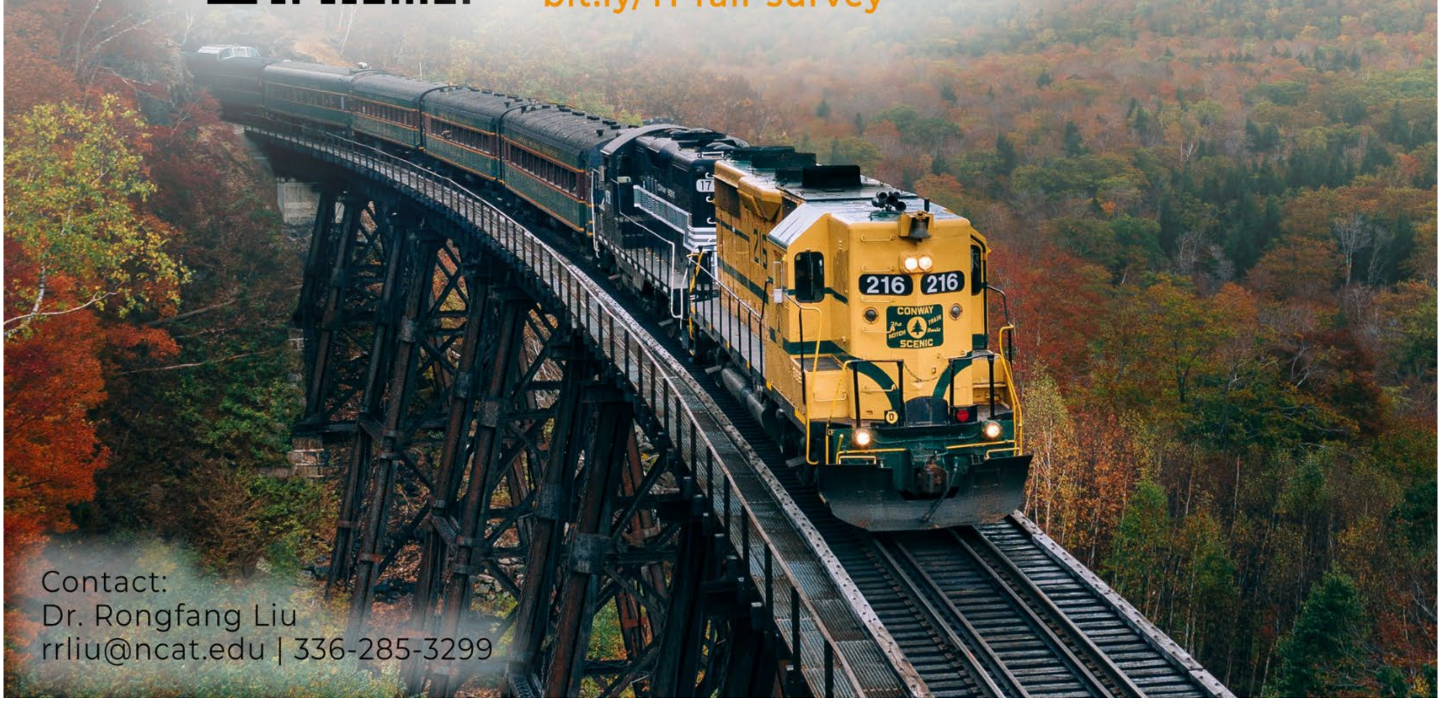
North Carolina Agricultural and Technical State University

TRANSPORTATION INSTITUTE | WILLIE A. DEESE COLLEGE OF BUSINESS AND ECONOMICS

WHAT DO YOU THINK ABOUT RAIL SAFETY?

Take our 5-minute survey to make your voice heard and be entered into a drawing for a $100 gift card! You'll also be helping make railroads safer.

Use the QR code or visit bit.ly/TI-rail-survey



Contact:
Dr. Rongfang Liu
rrliu@ncat.edu | 336-285-3299


WHAT DO YOU THINK ABOUT RAIL SAFETY?
Tell us your opinion of rail safety to be entered for a drawing for a $100 gift card!
bit.ly/TI-rail-survey
216 216
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APPENDIX 4. NOISE AND VIBRATION BASICS

Noise from a railroad system is analyzed in terms of a “source-path-receiver” framework. The “source” generates noises while the levels of the noises are directly related to type of sources, such as rolling noise from the interaction of steel wheels and rails, and its operating characteristics. The “receiver” is the person(s), noise-sensitive buildings, or land uses exposed to noise from the source. In between the source and the receiver is the “path” where the noise is reduced by distance, intervening buildings, and topography.

1. Noise Fundamentals and Descriptors

Noise is typically defined as unwanted or undesirable sound, where sound is characterized by small air pressure fluctuations above and below the atmospheric pressure. The basic parameters of environmental noise that affect human subjective response are (1) intensity or level, (2) frequency content, and (3) variation with time.

The first parameter is determined by how greatly the sound pressure fluctuates above and below the atmospheric pressure and is expressed on a compressed scale in units of decibels, which are logarithmic values of the ratio of the pressure produced by the sound wave to a reference pressure, 20 Micro Pascals. By using this scale, the range of normally encountered sound can be expressed by values between 0 and 120 decibels. On a relative basis, a 3-decibel change in sound level generally represents a barely noticeable change outside the laboratory, whereas a 10-decibel change in sound level would typically be perceived as a doubling, or halving, in the loudness of a sound.

Because decibels are logarithmic quantities, sound pressure levels do not combine, or add, as we might expect. For example, combining two sound sources that each generate a sound pressure level of 40 dB individually causes a total sound pressure level of 43 dB, not 80 dB. Every doubling of source strength results in an increase of 3 dB, so that four 40-dB sources have a combined sound pressure level of 46 dB, eight 40-dB sources have a combined sound pressure level of 49 dB, etc. A tenfold increase in either the source strength or number of equivalent sources causes the sound pressure level to increase by 10 dB. Because of the non-linear characteristics of human hearing, a doubling in the source strength is not perceived by humans as a doubling of loudness.

The frequency content of noise is related to the tone or pitch of the sound and is expressed based on the rate of the air pressure fluctuation in terms of cycles per second, called Hertz and abbreviated as Hz. The human ear can detect a wide range of frequencies from about 20 Hz to 17,000 Hz. However, the human hearing system does not respond equally to all frequencies; it is more sensitive to mid-band frequencies, e.g., 500 to 2,000 Hz. Thus, when describing sound and its effects on a human population, “A-weighting system” is commonly used when measuring environmental noise to provide a single number descriptor that correlates with human subjective response by de-emphasizing the low and very high frequency components of the sound. Sound levels measured using this weighting system are called "A-weighted" sound levels and are expressed in decibel notation as "dBA." The A-weighted sound level is widely accepted by acousticians as a proper unit for describing environmental noise. Figure 1 shows examples of typical A-weighted sound levels for both rail transit and non-transit noise sources.

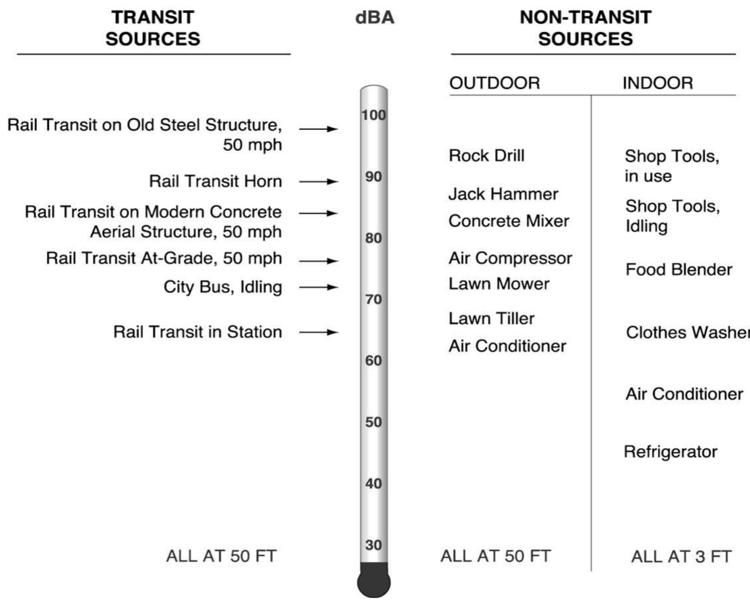


Figure 1. Typical A-weighted Sound Levels
Source: U.S. Federal Transit Administration, 2018

Because environmental noise changes continuously, it is sometimes convenient to describe a particular noise event or source in terms of its maximum sound level, L_{max} or maximum A-weighted sound level, L_{Amax}. While the maximum sound level is useful in describing one aspect of an event or noise source, it provides no information on the duration of the event or the cumulative exposure to a noise source. A common way to account for the cumulative exposure is to express the energy-average of the actual time-varying sound level over a period of time as a single number, called the “equivalent” sound level, L_{eq} or L_{Aeq}. The L_{eq} is the constant or “equivalent” sound level that would contain the same amount of sound energy as the time-varying sound level over the same period. Due to the logarithmic addition of noise sources described above, L_{eq} is influenced strongly by the loudest events that occur during a particular period. Because the L_{eq} represents the changing sound level over a specific interval, such as one hour, an eight-hour workday, or the nine-hour nighttime period from 10:00 PM until 7:00 AM, it is important that the time period be expressed or understood when using the metric.

Often the L_{eq} values over a 24-hour period are used to calculate cumulative noise exposure in terms of the Day-Night Sound Level (L_{dn}). L_{dn} is the A-weighted L_{eq} for a 24-hour period with an added 10-decibel penalty imposed on noise that occurs during the nighttime hours, between 10:00 PM and 7:00 AM. Many surveys have shown that L_{dn} is well correlated with human annoyance, and therefore this descriptor is widely used for environmental noise impact assessment. Figure 2 provides examples of L_{dn}'s for freight and rail transit sources and typical noise environments. While the extremes of L_{dn} are shown to range from 35 dBA in a wilderness environment to 85 dBA in noisy urban environments, L_{dn} is generally found to range between 55 dBA and 75 dBA in most communities.

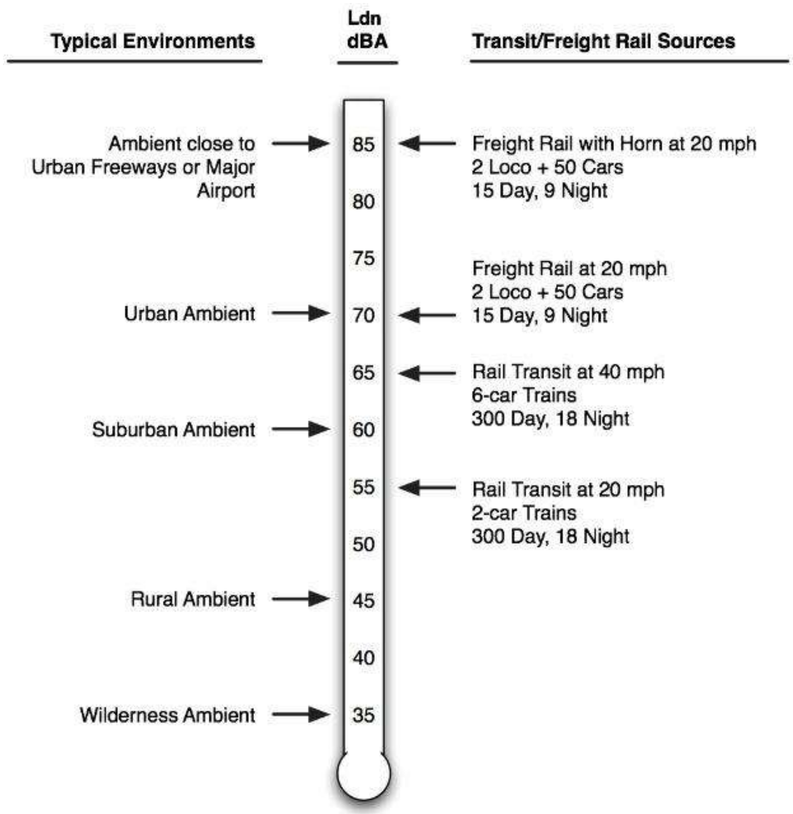


Figure 2. Typical Ldn's
Source: CSA, 2023

Environmental noise can also be viewed on a statistical basis using percentile sound levels, L_n, which refers to the sound level exceeding "n" percent of the time. For example, the sound level exceeded 90 percent of the time, denoted as L_{90}, is often taken to represent the "background" noise in a community. Similarly, the sound level exceeding 33 percent of the time, L_{33}, is often used to approximate the L_{eq} in the absence of loud, intermittent sources such as aircraft and trains.

Table 1 compares different noise source in terms of decibel levels and perceived loudness, helping to illustrate the impact of environmental noise. To connect the train noise propagation along it traveling path with daily activities, Figure 3 has transformed individual noise levels to various everyday activities, such as rain dropping, car running and jet flying noise to provide more relatable measures to the lay persons.

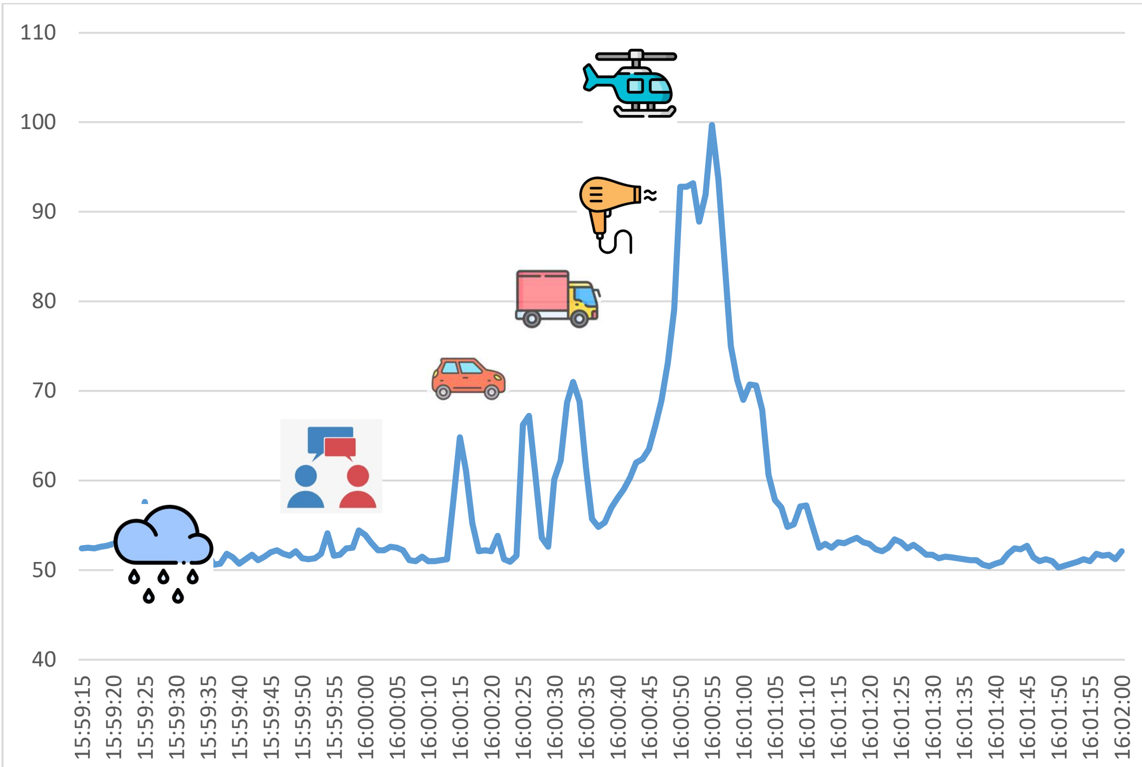


Figure 3. Noise Level Along with a Typical Train Path

Table 1. Comparative Noise Levels

Noise Source	Decibel Level	Decibel Effect
Jet take-off (at 25 meters)	150	Eardrum rupture
Aircraft carrier deck	140	
Jet aircraft take-off from aircraft carrier at 50 ft	130	
Thunderclap, chain saw. Oxygen torch.	120	Painful. 32 times as loud as 70 dB.
Auto horn at 1 meter. Riveting machine (110 dB); live rock music (108 - 114 dB).	110	Average human pain threshold. 16 times as loud as 70 dB.
Use of outboard motor, motorcycle, farm tractor, jackhammer, garbage truck.	100	8 times as loud as 70 dB. Serious damage possible in 8 hr exposure.
Power mower (96 dB); motorcycle at 25 ft (90 dB). Newspaper press (97 dB).	90	4 times as loud as 70 dB. Likely damage in 8 hour exposure.
Garbage disposal, dishwasher, average factory, freight train (at 15 meters). Car wash at 20 ft (89 dB); diesel truck 40 mph at 50 ft (84 dB); diesel train at 45 mph at 100 ft (83 dB). Food blender (88 dB); milling machine (85 dB); garbage disposal (80 dB).	80	2 times as loud as 70 dB. Possible damage in 8 hour exposure.
Passenger car at 65 mph at 25 ft (77 dB); Living room music (76 dB); radio or TV-audio, vacuum cleaner (70 dB).	70	Arbitrary base of comparison. Upper 70s are annoyingly loud to some people.
Conversation in restaurant, office, background music, Air conditioning unit at 100 feet.	60	Half as loud as 70 dB. Fairly quiet.
Quiet suburb, conversation at home. Large electrical transformers at 100 feet.	50	One-fourth as loud as 70 dB.
Library, bird calls (44 dB); lowest limit of urban ambient sound	40	One-eighth as loud as 70 dB.
Quiet rural area.	30	One-sixteenth as loud as 70 dB. Very Quiet.
Whisper, rustling leaves	20	
Breathing	10	Barely audible

Source: https://www.iacacoustics.com/blog-full/comparative-examples-of-noise-levels

2. Vibration Fundamentals and Descriptors

Vibration from a rail transit system is analyzed in terms of a “source-path-receiver” framework. The “source” is the train rolling on the tracks which generates vibration energy transmitted through the supporting structure under the tracks and into the ground. Once the vibration gets into the ground, it propagates through the various soil and rock strata, the “path”, to the foundations of nearby buildings, the “receivers”. Ground-borne vibrations generally decrease with distance depending on the local geological conditions. A “receiver” is a vibration-sensitive building, such as residence, hospital, or school, where the vibrations may cause perceptible shaking of the floors, walls and ceilings and a rumbling sound inside rooms. Not all receivers have the same vibration-sensitivity. Consequently, vibration criteria are established for the various types of receivers.

Ground-borne vibration (GBV) is the oscillatory motion of the ground that can be described in terms of displacement, velocity, or acceleration. The ground oscillates away from a static position. The response of humans, buildings, and equipment to vibration is most accurately described using velocity or acceleration. Human sensitivity to ground-borne vibration typically corresponds to the amplitude of vibration velocity within the low-frequency range of most concern for environmental vibration (roughly five to 100 Hz.) Therefore, velocity is the preferred measure for evaluating ground-borne vibration from rail systems.

The most common measure used to quantify vibration amplitude is the Peak Particle Velocity (PPV), defined as the maximum instantaneous peak of the vibratory motion. PPV is typically used in monitoring blasting and other types of construction-generated vibration, since it is related to the stresses experienced by building components. Although PPV is appropriate for evaluating building damage, it is less suitable for evaluating human response, which is better related to the average vibration amplitude. Thus, ground-borne vibration from trains is usually characterized in terms of the "smoothed" root mean square (RMS) vibration velocity level, in decibels (VdB), with a reference quantity of one micro-inch per second. VdB is used in place of dB to avoid confusing vibration decibels with sound decibels. Like noise, VdB is related to a reference quantity; in this case, 1 micro-inch per second. Vibration is a function of the frequency of motion measured in Hz. Ground vibration of concern for transportation sources generally spans from 4 to 160 Hz. The overall vibration is the combined energy of ground motion at all frequencies.

Vibration attenuates as a function of the distance between the source and the receptor because of geometric spreading and inherent damping in the soil that absorbs energy of the ground motion. Ground-borne vibration from rail systems is caused by dynamic forces at the wheel/rail interface. It is influenced by many factors, which include the rail and wheel roughness, out-of-round wheel conditions, the mass and stiffness of the rail vehicle truck and its suspension components, the mass and stiffness characteristics of the track support system, and the local soil conditions.

Vibration transmitted through the rail system structure, such as at-grade ballast and tie track, radiates energy into the adjacent soil in the form of different types of waves that propagate through the various soil and rock strata to the foundation of nearby buildings. Buildings respond differently to ground vibration depending on the type of foundation, the mass of the building, and the building interaction with the soil. Once inside the building, vibration propagates throughout the building with some attenuation with distance from the foundation, but often with amplification due to floor resonances. The basic concepts for rail system-generated ground vibration are illustrated in Figure 4.

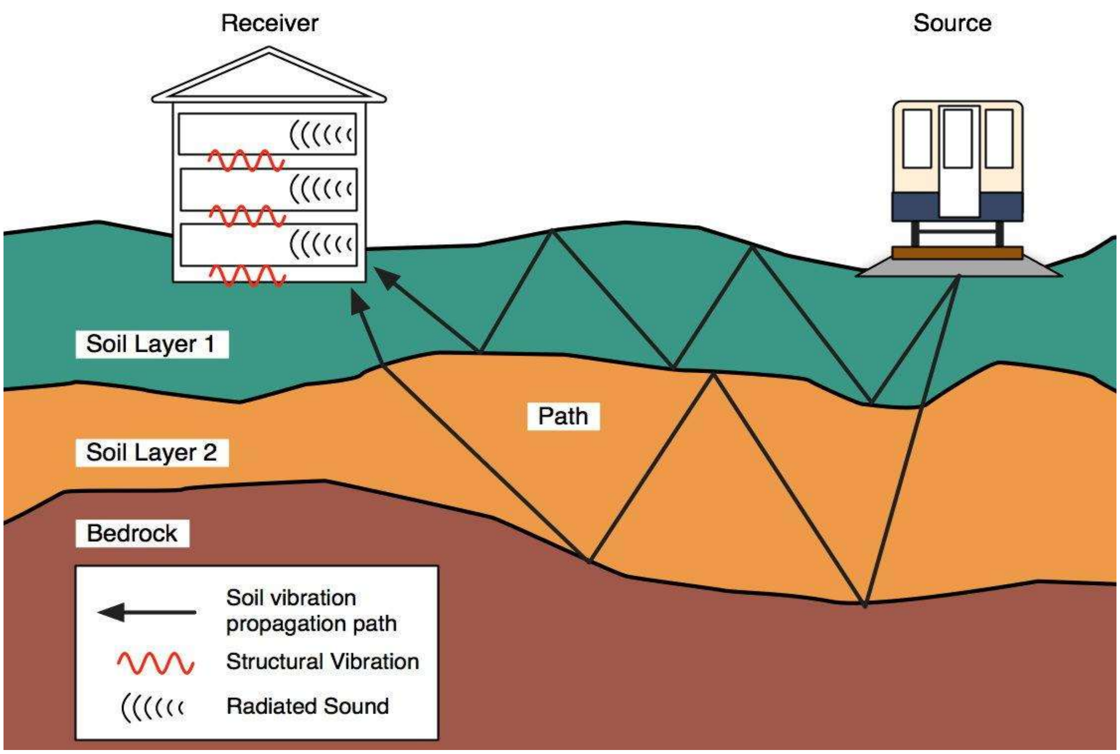


Figure 4. Basic Concept of Rail Generated Ground-Borne Vibration
Source: CSA, 2023

Figure 5 illustrates typical ground-borne vibration levels for common sources as well as criteria for human and structural response to ground-borne vibration. As shown, the range of interest is from approximately 50 to 100 VdB, from imperceptible background vibration to the threshold of damage. Although the approximate threshold of human perception to vibration is 65 VdB, annoyance is usually not significant unless the vibration exceeds 70 VdB.

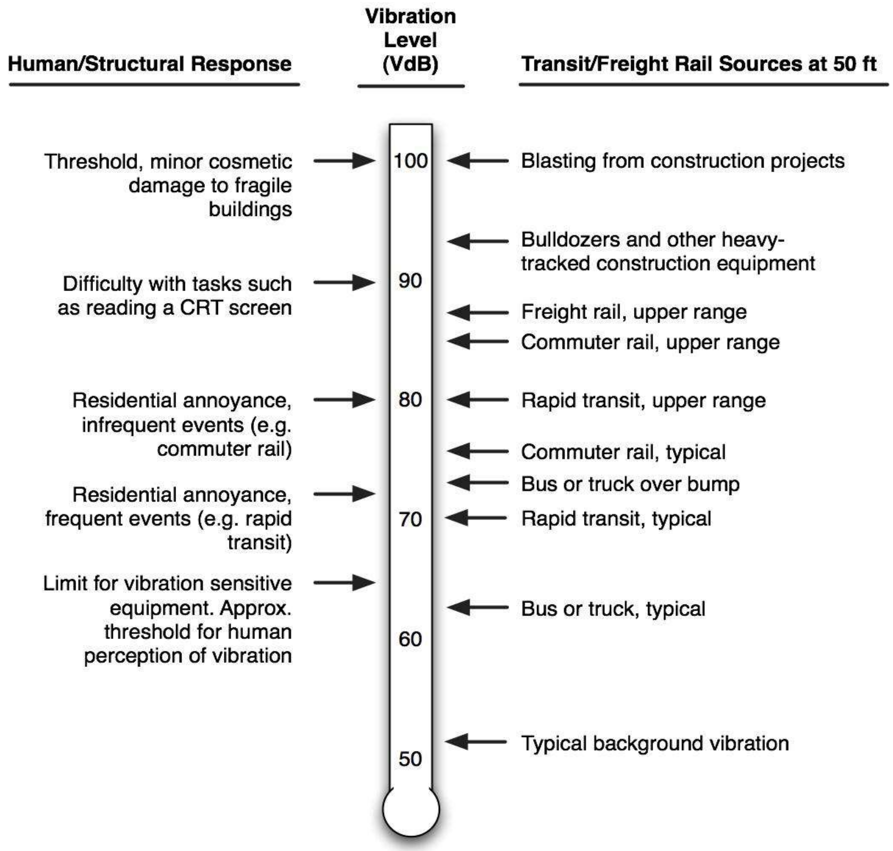


Figure 5. Typical Levels of Ground-Borne Vibration
Source: CSA, 2023

Ground-borne noise is a secondary phenomenon of ground-borne vibration. When a building structure vibrates, noise is radiated into the interior of the building. Typically, this low-frequency sound would be perceived as a low rumble. The magnitude of the sound depends on the frequency characteristic of the vibration and the manner in which the room surfaces in the building radiate sound. Ground-borne noise is quantified by the A-weighted sound level inside the building.

3. Sources of Rail Noises

The dominant noise sources in a conventional railroad environment are well known and typically include engine or propulsion noise from locomotives, noise from the interaction of the steel wheels and steel rails, auxiliary equipment, and warning signals, such as train horns and wayside at-grade audible warning devices. All of these noise categories are generally regarded as unwanted noise and have been subjected to ongoing and widespread efforts to reduce and control them. For example, warning signals are closely regulated and their mandated usage is increasingly reduced by quiet zones and at-grade crossing closures.

A guidance manual has been developed by the U.S. Federal Transit Administration (FTA) for predicting and assessing noise and vibration impact from conventional rail systems (FTA 2018). The U.S. Federal Railroad Administration (FRA) has developed a complementary guidance manual for high-speed rail systems. For conventional train speeds up to approximately 125 mph, propulsion and mechanical wheel-rail noise are sufficient to describe the total wayside noise. Aerodynamic noise resulting from airflow moving past the train begins to be an important factor at speeds exceeding approximately 160 mph (FRA 2012).

3.1 Propulsion Noise from Locomotives

Train propulsion technologies have been steadily evolving since the advent of the steam locomotive and even beyond the still-common diesel engines. Despite advancing technologies and noise abatement strategies, these are still a significant source of rail noise.

Early efforts have focused on reducing noises and making trains much quieter to meet strict EPA noise standards. For example, Goding (1980) focuses on reducing rail engine noise through the development of exhaust silencing hardware and a quieter radiator cooling fan. These advancements have successfully achieved locomotive sound levels that comply with the Federal EPA noise regulations. Ongoing development programs aim to further improve fuel economy by introducing low backpressure silencers specifically designed for turbocharged and roots blown engine locomotives. Additionally, efforts are being made to develop a compact exhaust silencer suitable for turbocharged engine export locomotives with limited available space. Goding's work also highlights the importance of addressing rail engine noise to reduce the overall environmental impact of locomotives. The research emphasizes the significance of meeting federal noise regulations set by the EPA, as excessive noise can contribute to noise pollution and negatively impact communities near rail lines. By implementing exhaust silencing hardware and quieter cooling fans, the study aims to create a more pleasant and sustainable rail transportation system. The ongoing research and development programs signify a commitment to continuously improving the fuel economy and noise emissions of locomotives, ultimately striving for a quieter and more environmentally friendly rail industry.

3.2 Noises from the Interaction of Steel Wheels and Steel Rails

In the United States, most unwanted rail noises come from standard railroads operating locomotives and rail cars over steel tracks, commonly referred to as rolling noise. Significant strides have been made to understand rolling noise and the related ground vibrations that emanate from rights-of-way. Rolling rail noise is affected by the composition of ties and ballast, track surface roughness and waviness, flange squeal and more.

The design and material make-up are significant factors in how rolling noise and vibration propagate in rail environments. Many technological advances have focused on ballast and tie design as a means of mitigating unwanted noise. Zhai et al. (2004), address the issue of railway ballast vibration and its impact on track maintenance costs. They highlight the lack of well-established methods for analyzing and testing ballast vibration. In their study, the authors proposed a five-parameter model to analyze ballast vibration, based on the hypothesis that load transmission from a tie to the ballast follows a cone distribution. The model incorporates the concepts of shear stiffness and shear damping to account for the interlocking behavior of ballast granules. To validate their model, a full-scale field experiment was conducted to measure ballast acceleration caused by moving trains. The theoretical simulation results were found to closely match the measured results, confirming the validity of the proposed ballast vibration model. This research contributes to the understanding of ballast behavior and provides a framework for analyzing and predicting ballast vibration in railway tracks.

Theyssen's (2020) numerical model for predicting noise produced by trains on slab tracks illustrates the differences in parameters influencing sound radiating from ballasted and slab tracks. Wenjing et al. 's (2020) systematic comparison of various tracks on a single network included embedded tie blocks, ballasted track, and embedded rails. Zhiping et al. (2023) conducted a similar investigation into the vibration mitigation characteristics of ballasted track, but their focus was on rubber composite ties compared to the older concrete sleepers. Jones et al. (2006) centered their investigation on the noise generation mechanisms associated with decay rates of vibration along the rail and their impact on track noise performance. Recently, Thompson et al. (2021) showed the effect of ground height and equivalent flow resistivity on sound propagation and as affected by different track types. Various track types significantly affect sound propagation and work in concert with the steel wheel and rail contact of the rolling cars.

Rail's distinct design of steel wheels on steel rails has a significant effect on rolling noise, particularly as it relates to the maintenance cycle and lifecycle of the components. Heutschi et al. (2016) discussed the noise generation mechanisms of road and rail vehicles and explored noise abatement measures. They also discussed noise reduction strategies specifically focusing on rail vehicles. The study provided an overview of the fundamental noise generation mechanisms in rail vehicles and highlighted the importance of noise abatement measures. The manuscript emphasized the potential of various strategies to mitigate rail noise. While the paper provided a comprehensive overview of rail noise reduction strategies, it also discussed the current policy and legislation regarding rail noise in the EU and different European countries.

Thompson (2000) documented that the vertical excitation of wheels and rails is the foremost source of rolling noise. Two key noise mechanisms are wheel-rail contact noise, which occurs due to the interaction between the wheel flange and the rail, resulting in vibrations and sound radiation; and rail roughness noise, caused by irregularities or imperfections on the rail surface that lead to vibrations and noise generation when the wheel passes over them. The effects of rail roughness were further demonstrated by Kuffa et al. (2016), whose novel rail grinding finishing strategy proved that smoother tracks were quieter than rough tracks. The research on this aspect of rail noise is well-established (Lutzenberger, 2008; Wu, 2008; Croft et al., 2008; Nielsen, 2008). Wheel contact with the steel rails is not limited, however, to the main rolling surface of the wheel.

The final component of rail's unique wheel design is the wheel flange, which makes contact with the side of the rail as a steering and alignment mechanism. This noise is commonly called curve squeal or flange squeal. Luo et al. (2023) investigated the mechanism of wheel-rail flange squeal from a contact perspective. They utilized measurements and numerical simulations to establish a connection between the observed squeal noise and contact forces. The researchers developed an integrated transient model that incorporated genuine 3D surface irregularities to simulate the flange squeal phenomenon under different speed levels. By considering both global dynamics and local contact status, the model accurately reproduced the features of flange squeal observed in in-situ experiments. The study proposed a generation mechanism for flange squeal based on measurement observations and confirmed its validity through the proposed model, taking into account multiple influencing factors. This work contributes to a better understanding of the mechanisms behind wheel-rail flange squeal and provides insights into mitigating this noise issue.

Compared to the common noises described above, ground-borne noise and vibration is much more complex and less examined but may have potential to affect noise propagation and awareness by pedestrians. Thompson, Kouroussis and Ntotosios (2019) have focused on highlighting the complexity of ground vibration and exploring evaluation criteria, prediction methods, and mitigation strategies to address the negative environmental consequences of noise and vibration in rail networks. The authors emphasized the importance of developing rail networks as sustainable transportation options while acknowledging the negative environmental consequences of noise and vibration. They highlighted the complexity of ground vibration compared to airborne noise, as ground properties vary significantly across locations. Ground-borne vibration, although generally not causing structural or cosmetic damage, can be perceived as feelable whole-body vibration or low-frequency noise, impacting buildings and sensitive equipment.

The evaluation of noise and vibration in rail networks involves the use of various methodologies to assess and mitigate their impact. This includes establishing evaluation criteria for vibration and noise levels, employing empirical and numerical prediction methods to estimate their effects, considering factors such as vehicle characteristics and track parameters, and understanding the properties of the ground. These methodologies aim to ensure the comfort and well-being of individuals near railway lines and minimize negative environmental effects. Additionally, past standards like ISO 14837-1 and ISO 4866 have been utilized to evaluate vibration perception and potential damage to buildings. It is important to recognize that whole-body vibration can have adverse effects on health. Overall, these approaches provide a comprehensive understanding of rail-related noise and vibration and help develop effective strategies for mitigation.

3.3 Noises Generated by Warning Signals

Keller et al (1993) conducted a study to evaluate the effectiveness of railroad horn systems and their impact on the community noise environment. Measurements were taken on different horn systems, including three-chime and five-chime horns, as well as a prototype Automated Horn System (AHS). The analysis revealed that the five-chime horn, generating a broadband signal with higher frequencies, was more effective at attracting motorists' attention by overcoming background noise. The placement of horn systems on the locomotive affected their sound output and directivity, suggesting that positioning them at the front and higher up maximized their effectiveness in warning motorists. The AHS, designed to face oncoming traffic, showed a different frequency spectrum and directivity pattern, indicating that increasing the number of horns could enhance the warning effectiveness by broadening the sound bandwidth. These findings provide insights for improving warning signals and wayside at-grade audible warning devices while minimizing community noise impact.

The research conducted by Rapoza et al. (1999) aims to evaluate the effectiveness of various methods in reducing accidents and casualties at highway-railroad grade crossings. The study focused on warning signals and wayside at-grade audible warning devices as noise sources. The research investigated the detectability of horn systems used as audible warnings for motorists at grade crossings and their impact on the community noise environment. The findings align with previous reports, indicating that horns have significantly reduced accidents, with rates as high as 69 percent. The study also presented acoustic data for a conventional three-chime horn system on moving locomotives, considering factors such as sound attenuation effects of buildings and vegetation along the right-of-way. The research addressed the sound insulation characteristics of motor vehicles and determined the necessary sound level of the warning signal to effectively alert motorists. Furthermore, the study evaluated the probability of detecting warning signals for different crossing scenarios, including passive crossings, active crossings, and active crossings equipped with wayside horn systems located directly at the crossing. The work also explored the possibility of changing the warning signal duration to reduce the community noise impact.

English et al (2004). conducted a comprehensive study aimed at evaluating the placement and sound characteristics of locomotive horns to ensure adequate warning for safety purposes and address concerns regarding loudness from crews and nearby residents. The research involved laboratory investigations to identify desirable warning characteristics, field measurements to assess how horn position affects its effectiveness at operating speeds, and an in-service evaluation of alternative horns. The study emphasized safety effectiveness considerations for pedestrians, trespassers, drivers stopped at grade crossings, and drivers approaching grade crossings. While no specific details on warning signals and wayside at-grade audible warning devices are provided, the study aimed to provide recommendations to optimize warning signals and address the noise-related aspects of locomotive horns to enhance safety and minimize disruptions for both the railway industry and local communities.

The work by Dolan and Rainey (2005) investigated the sources and characteristics of rail noise with a specific focus on freight trains. The study incorporated detailed measurements and analyses of different noise components, including rolling noise, impact noise, and aerodynamic noise, generated by various freight train operations. The authors discussed the influence of factors such as train speed, wheel condition, track roughness, and train weight on the generation and propagation of rail noise. The study provided insights into the dominant noise sources and their contributions to overall noise levels. The findings emphasized the importance of understanding and managing rail noise sources to minimize environmental impacts and improve the quality of life for communities near rail corridors. The research contributed to the understanding of rail noise sources and provided valuable information for developing noise mitigation strategies in freight train operations. The study also examined the importance of train horns as warning signals for motorists at railroad crossings. The researchers aimed to determine the levels of horn sounds necessary for detection by motorists. They recorded horn sounds in test vehicles and presented them to 20 normal-hearing listeners in different noise conditions, including quiet, engine idling with and without ventilation fan, and vehicle moving at 30 mph with and without fan. The thresholds of horn sounds were measured using an adaptive procedure. The study found that the lowest thresholds were observed in quiet conditions, while the highest thresholds were associated with the vehicle moving at 30 mph with the fan on. Despite variations in noise conditions, the horn thresholds remained more than 10 dB below the overall level of vehicle interior noise. The findings contributed to understanding the auditory component of the motorist's detection task and can aid in establishing signal-to-noise ratio requirements for horn sound detection at highway-rail crossings.

According to Tuzik (2019), urban rail transit systems are consistently plagued by the issue of noise. Factors such as vehicle and track design, condition of wheels and rails, as well as the age and design of infrastructure, all contribute to the propagation and public perception of noise and vibration. Unlike freight railroads, rail transit systems carry a substantial number of passengers daily, sometimes reaching tens of thousands in certain cities. Consequently, transit management places significant importance on addressing noise and vibration issues. While to the average rider or resident, noise is simply noise and vibration is vibration, for transit and acoustics professionals, these represent intricate engineering, maintenance, acoustic, and political challenges. The causes and solutions for these challenges are diverse and multifaceted, presenting formidable obstacles in their resolution. Warning signals, including train horns and wayside at-grade audible warning devices, play a crucial role in urban rail transit systems, but they also contribute to the overall noise levels experienced by passengers and nearby residents. Tuzik (2019) acknowledged that noise and vibration issues in rail transit systems are multifaceted, and addressing these challenges requires a comprehensive approach that includes the management of warning signals. The design and use of train horns and wayside audible warning devices must strike a balance between ensuring effective safety alerts for pedestrians, motorists, and other road users, while also minimizing excessive noise disturbance to the surrounding environment. The study considered factors such as the placement and sound characteristics of the warning devices, their impact on nearby communities, and the perception of noise by residents and passengers. Transit management teams and acoustics professionals need to work together to develop innovative solutions that enhance safety without unduly burdening urban areas with excessive noise from warning signals. Efforts to mitigate noise from warning signals may involve exploring alternative horn designs, optimizing placement strategies, implementing sound barriers or enclosures, and adopting advanced technologies to control and reduce noise levels. Additionally, continuous monitoring and evaluation of noise emissions from warning signals are necessary to identify areas for improvement and ensure compliance with noise regulations. By addressing noise issues associated with warning signals, urban rail transit systems can enhance overall passenger experience and foster harmonious coexistence with the surrounding communities.

Costanza et al (2022) focuses on the significant impact of railway noise on urban environments, particularly in the region straddling Campoleone and Aprilia near Rome, Italy. This area is influenced by a railway infrastructure that disrupts the urban fabric due to unauthorized constructions and lack of coherent development. The study evaluated sound levels generated by this railway and proposed strategies for noise mitigation. A few scenarios were developed, including moving a railway section near the station underground, managing new building designs, and constructing acoustic barriers. These scenarios were simulated using SoundPLAN software, and the most effective solution was determined based on both urban and technical considerations, supported by an economic analysis. The study emphasized the need for optimizing railway services to reduce noise pollution and improve the urban environment in tandem with expansion plans.

Kumar and Chowdury’s (2023) focused on the monitoring and evaluation of a noise pollution hotspot at a railway level crossing, where various transportation-related activities contribute to the noise levels. The study examined the effectiveness and impact of train horns, which are used to alert road users but often regarded as a nuisance by nearby residents. The research included a comprehensive noise monitoring survey and the development of an artificial neural network (ANN)-based railway noise prediction model. The results indicated that train horns produce impulsive sound signals in high-frequency bands, causing significant annoyance to residents near the railway. The proposed ANN models provided accurate predictions of maximum and equivalent noise levels, offering valuable insights for railway noise abatement, and informing urban planning and development authorities on strategies to mitigate urban environmental noise.

4. The Paths of Rail Noise Propagation

The path of the noise from the various sources to the receiver locations greatly affects the noise levels. The terrain topography and any intervening physical objects will affect the noise propagation. Examples include noise diffraction over hills or earthen berms, or around and over noise barriers or buildings. Large amounts of vegetation in the noise path can affect the frequency and level of noise at a receiver location. Ground cover will also affect the propagation of train noise based on how absorptive it is, such as undergrowth in wooded areas, tall grass, or ballast in the railroad right-of-way, or how reflective it is, such as paved roads, parking lots, and bodies of water.

According to Embleton (1996), the propagation of sound outdoors follows all other wave propagation mechanisms such as geometrical spreading, molecular absorption, turbulence, and scattering. Further, sound pressure levels change significantly due to refraction caused by wind and temperature gradients in the atmosphere. The Canadian Transportation Agency (2011), which provides a framework for the measurement of rail noise, also found wind as a contributor to the increase in sound pressure levels outdoors. Other factors highlighted by Embleton (1996) include the shape of the ground and its acoustic impedance. The general definition of acoustic impedance of a material is the product of the density of the material and speed of sound in that material. Sound waves close to the ground, or any other surface therefore propagate differently due to the varying acoustic properties of the different types of surfaces.

A formula for finding the sound pressure level at an observation point was derived by Bies & Hansen (2009). The observed sound is a function of the power of the sound at the source, the geometrical spreading property of the sound, the directional properties of the source, and an excess attenuation factor. For a single source, the relation is given by:

$$L_p = L_w - K + DI_M - A_E \qquad (1)$$

Where:

L_p represents the sound pressure level at the point of observation,

L_w is the power of the sound at the source,
K is the geometric spreading factor,
DI_m represents the directivity index of the source, and
A_E is the excess attenuation factor.

There is no uniformity in the radiation of general sound in all directions due to the presence of reflective surfaces such as walls. According to Crocker and Arenas (2021), most sound sources become directional at high frequencies while some sources can propagate in all directions at low frequencies, if the source dimension is smaller than its wavelength. This variation is accounted for by a parameter called the directivity index (DI_m) in calculating the observed sound at any point. Noise from trains, however, does not radiate equally in all directions due to complex interactions involved during the noise generation (Hanson et. al., (1993).

Embleton (1996) found that there is a decrease in sound-pressure by 6 dB at any receiving point that is twice the distance from the source due to geometrical spreading. Studies by Rathe (1977) have shown that noise from rail vehicles as a result of wheel-rail interaction can be modeled as a line source with dipole directivity. That is, much of the noise is propagated on either side of the moving train compared to the front, rear, or above the train. Bies & Hansen (2009) went a step further to derive a relation for computing the geometric spreading factor of sound sources that are above the ground and sources at ground level.

For a line source, the geometric spreading factor is given by:

$$K = 10log\left(4\frac{\pi rD}{\alpha}\right) \quad \dots\dots.. \quad (2)$$

Where:
r is the distance from the source to the point of observation,
D represents the length of the line source,
α is the angle subtended by the source at the observation point.

The propagation of noise away from a source depends on how the sound attenuates en route to the receiver. The ground, atmosphere, geometric divergence, foliage, diffraction from noise barriers as well as reflection from buildings all contribute to the attenuation of the sound (Murphy & Douglas, 2018; Bies & Hansen, 2009). The parameter for the excess attenuation factor (A_E) is obtained from the relation:

$$A_E = A_a + A_{bhp} + A_f + A_g + A_m \quad \dots.. \quad (3)$$

The terms on the right of the equation (3) are attenuation factor due to air absorption (A_a), barriers and houses (A_{bhp}), forests and foliage (A_f), reflection in the ground plane (A_g), and attenuation due to meteorological effects such as wind and temperature gradients (A_m). The effect of ground reflection and meteorological factors on noise propagation may contribute to gains in the noise level rather than a loss (Bies & Hansen, 2009; Embleton 1996). The above equations are a more generalized version of those outlined in ISO 9613-2 (1996). The ISO standard makes provision for more complex noise environments, considering different meteorological effects as well as different types of grounds and other barriers. The mechanism in which noise propagates through these media is discussed in the following sections.

4.1 Atmospheric Absorption

Atmospheric absorption is an important feature of noise propagation as found by Embleton (1996) and prior to that Sutherland et al. (1974). Since the sound waves from the rail vehicles are propagated outdoors, the waves are absorbed by the molecules in the atmosphere. During molecular absorption a fraction of the energy from the sound waves are converted into vibrations of oxygen and nitrogen molecules. This conversion process is significantly affected by temperature and the concentration of water vapor in the atmosphere, thus the relative humidity (Sutherland and Bass, 1979; Embleton, 1996). Atmospheric pressure and the frequency of the sound also contribute to the sound absorption in the atmosphere (Hanson et al.1993). Also, the loss of sound energy due to molecular absorption is directly proportional to the sound pressure (Bass et al., 1996)

The formula for calculating air absorption was derived by Sutherland et al., (1974). The air absorption (A_a) for noise propagating over a distance, X, is given by:

$$A_a = mX \quad \dots\dots.. \quad (4)$$

Where *m* is the absorption rate given the frequency of the noise. This approach calculates air absorption with an accuracy of ±10% from 10°C to 40°C and provides the best approximation, according to Gill (1980a).

Hanson et al. (1993) presented a procedure for roughly estimating atmospheric absorption of noise. According to the report, under standard day conditions, where temperature is 59°F and relative humidity is 70 percent, the atmosphere absorbs 1 dBA of noise for every 1,000 ft. This rough estimate holds for noise frequencies between 500 and 1000 Hz. Bass et al., (1996) also estimated that for noise frequencies above 500 Hz, at least 2 dB is lost per kilometer (3280 ft) due to molecular absorption and this increases very rapidly with increasing noise frequency. For noise frequencies below 200Hz, molecular absorption is negligible except when the atmosphere is extremely dry.

4.2 Barriers, Houses, and Equipment

Remillieux et al. (2012) simulated the effects of noise from aircraft flying over buildings in an urban environment using a numerical tool. The tool adopted is a combination of the geometrical-acoustic and Biot-Tolstoy method of predicting sound propagation on isolated and multiple-building configurations. The study found that in areas where buildings are closely spaced, the propagation mode of the noise is mainly through reflection between the buildings. Refraction is present but its effect is negligible. Also, the elevation of the noise source above ground as well as its frequency highly influences the distribution of the sound pressure. The noise distribution is however independent of the azimuth of the sound wave.

According to a report by Hanson et al. (1993), noise barriers used in transportation systems attenuate 5-15 dBA of noise at the receiver. Factors that contribute to the attenuation include the elevation of the source and the receiver, distance between source and receiver, the height and length of the barrier. The frequency of the noise was also found to be directly proportional to the attenuation by the barrier. The report also found that barriers placed very close to the source in most cases serve as reflection surfaces for the noise rather than attenuation. This can be remedied by increasing the height of the barrier or using an acoustically absorptive material on the source side of the barrier. The attenuation factor is therefore an arithmetic sum of attenuations due to large barriers, houses, and process equipment, if present (Bies and Hansen, 2009).

$$A_{bhp} = A_b + A_h + A_p \qquad (5)$$

4.3 Forests and Foliage

Studies regarding the effect of forests and foliage along noise propagation paths are limited. Notable studies include Hoover (1961), Huisman and Attenborough (1991), and ISO 9613-2 (1996). Hoover (1961) derived a relation for estimating the excess attenuation due for forests and foliage, a method which has been applied quite extensively to date. The relation is given by:

$$A_f = 0.01 r_f \, f^{\frac{1}{3}} \quad \ldots\ldots \quad (6)$$

Where:

f is the frequency of the propagating sound and
r_f is the distance sound moves through the forest.

Huisman and Attenborough (1991) focused on the reverberation and attenuation of sound in a pine forest using stochastic numerical modeling. Among the findings of the authors is that, for a 100 meters distance, there is no change in the attenuation of sound in the pine forest even with variation in meteorological profiles. Also, high frequency sounds at elevations below the foliage canopy propagate by multiple scatterings among trees and trunks. The model, however, couldn’t verify the dependency of attenuation of sound on the height of the trees.

According to ISO 9613-2 (1996), the effect of foliage on the attenuation of noise is not significant unless the foliage is dense enough to block view along the propagation path. Foliage of trees and shrubs located anywhere between a noise source and a receiver can attenuate sound proportional to the density of the foliage close to the source and the receiver.

4.4 Ground Effects

In a review regarding common schemes used in outdoor noise measurement, Embleton (1996) identified six features that influence the path of propagation of sound due to ground:

- Proximity of source to the ground;
- Interference between direct and reflected waves;
- Acoustic ground waves;
- Ground impedance;
- Flow resistivity of ground surface;
- Acoustic surface waves.

To calculate the attenuation of noise due to ground effects, Manning (1981) provides a rough estimation procedure for two types of grounds: acoustically hard surfaces and soft grounds. The author in the study considered grounds that are common in rural and urban areas, usually flat and undulating land. For acoustically hard surfaces such as concrete, asphalt, or water, noise levels increase by 3 dB for all frequency bands and distances. Soft grounds such as those covered with grass have no effect on the noise level. Therefore, the simplest approximation of attenuation due to ground (A_g) is –3dB or 0dB.

ISO 9613-2 (1996) outlines the procedure for calculating the effect of the ground on the propagation of noise in the worst-case scenario. The distance between the source and the receiver split into three zones: source, middle and receiver zones. For a given octave band, the ground attenuation for each of these three zones is calculated separately, then summed up. The relation is given by:

$$A_g = A_s + A_m + A_r \quad \ldots\ldots. \quad (7)$$

Each of the attenuation components is calculated taking into consideration the ground factors for that zone (G_s, G_m, and G_r), which ranges from 0 to 1. Hard grounds such as pavement, water, or concrete take a value of zero and porous grounds such as grass take a value of 1. This method incorporates meteorological effects such as severe wind and temperature gradients, which therefore do not need to be considered separately when calculating the attenuation of noise. This procedure yields results that are only moderately accurate.

4.5 Meteorological Effects

Manning (1981) conducted a study to understand how noise from petroleum and petrochemical complexes propagate to the neighboring communities. One of the several findings was that wind velocity and atmospheric temperature gradients contribute to the refraction of sound and consequently affect the pressure level of sound observed. The study further established six categories of weather conditions for the usual octave bands and defined them based on the vector wind velocity and atmospheric temperature gradient. This enables the calculation of the noise level in communities based on climatic data provided by local meteorological offices.

Another study was conducted by Trikootam and Hornikx (2019) aimed at measuring the effect of wind on the propagation of sound in an urban area in Eindhoven, Netherland. Sound from an uncontrolled source with a high elevation was continuously measured downwind from the source up to 527 meters away. The authors found that sound pressure level increases with increasing wind speed for one-third of the frequencies in the octave band. Additionally, the effect of wind on sound propagation varies with frequency and was observed to be larger at lower sound frequencies. The effect of wind was also found to be larger as one moves further away from the source.

Menge et al. (2014) studied the effects of wind and temperature gradients on ground transportation noise propagation. Wind speed and direction and temperature gradients with changing altitude were found to have a significant effect on sound propagation. The speed and direction of wind can increase or decrease the amount of sound energy at a receiver location relative to a calm wind condition due to the refraction of the sound toward the ground in a downwind case or upward in the upwind case. Wind effect differences under strong wind conditions relative to calm conditions were found to be approximately +15 dB to -10 dB at 400 feet from the source and +15 dB to -20 dB at 1,600 feet from the source. Temperature gradients with altitude cause sound speed to vary with distance from the ground. Inversion or lapse conditions due to temperature gradients were found to cause differences relative to calm conditions of +10 dB to -5 dB at 400 feet from the source and +15 dB to -15 dB at 1,600 feet from the source.

5. Measurements of Rail Noises

In-depth analyses and methodologies have been developed to measure and document factors affecting diesel engine noise (Narayan, 2015; Schaberg and Priede, 1990; Saad and El Sabai, 1999). Tiwari (2017) compiled a thorough delineation of all the noise-producing elements of a diesel engine.

Over the years, researchers have developed rail noise emission and propagation models. These models are popular in European countries (Komorski et. al. 2022). Switzerland for instance uses the SonRAIL and SonTRAM simulation software to calculate rail and tram noise (Thron & Hecht, 2010). The model calculates the sound power levels of a rail vehicle in motion across a frequency band of 100-8000 Hz. The model also calculates the propagation of sound according to the standards set out in ISO 9613. This standard (ISO 9613-2:1996) outlines the methods of calculating the attenuation of sound during propagation outdoors.

Germany uses a similar model to the Swiss, but the model calculates the acoustic power level of the moving train per meter of rail track. The German model is also implemented in line with the ISO 3095 standard, which outlines the procedures in measuring noise emitted by rail-bound vehicles. The model used in Slovakia applies statistical techniques such as correlation and regression analysis to describe the propagation of acoustic waves emitted by trams in the city (Mandula et al, 2002). This model is limited to the description of the propagation of tram noise and therefore cannot be used to describe source emissions.

Similar models exist in the United States. The Bureau of Transportation Statistics' National Transportation Noise Map estimates localized rail noise for stakeholders and policymakers, but assumptions in the model allow for a wide margin of error that is likely exposed during highly localized strike incidents. The map does not consider atmospheric effects, ground type, or terrain, which can all affect rail noise to varying degrees (Volpe National Transportation Systems Center, 2020). Furthermore, no equivalent to the noise maps exists for ground-borne vibration (Thompson et al., 2019).

Lotz (1977) studied sound pressure levels near passing trains, which is crucial for estimating noise impact and selecting appropriate noise abatement design options in railroad or rail transit systems. Using reported measurements of noise emission from locomotives and railcars, the study found that locomotive noise levels typically range from 75 to 95 dB(A) at a distance of 30 meters (100 feet) for all speeds. The data suggested that A-weighted sound levels of various railcars on tie and stone ballast track increase uniformly with speed, even reaching speeds up to 400 km/h (250 miles/h) based on available data. At a given speed, the noise level data typically exhibits a range of 15 dB. The findings indicate a lower bound for noise among current steel wheels on steel rail.

Moellar and Hegarten (1982) evaluated literature, examined measurements, and focused on rail noise sources. Detailed sound measurements were performed on locomotives and passing trains to gather data on rail noise. The study not only identifies the existing sources of noise in rail transportation but also offers practical suggestions for mitigating noise issues in both new and old diesel locomotives. By conducting detailed sound measurements on locomotives and passing trains, the researchers gather valuable data to better understand the nature and extent of rail noise. This research serves as a foundation for developing effective strategies and technologies aimed at reducing noise levels and improving the overall acoustic environment associated with rail systems. Through their comprehensive analysis and recommendations, Moellar and Hegarten's work contributed to the practices in the field of rail noise reduction and management.

Polak and Korzeb (2021) focused on investigating the main sources of noise generated by railway vehicles operating at speeds of 200 km/h. The research involved the identification of testing areas, selection of measurement equipment, and the development of a measurement methodology for assessing noise on curved and straight tracks. Specifically, electric multiple units of the Pendolino, Alstom type ETR610 series ED25 trains, were examined. The measurements were conducted using a Bionic S-112 microphone camera positioned 22 m away from the track axis. The experimental research revealed that the dominant source of sound was the noise produced by vibrations occurring at the wheel-rail contact or rolling noise. This study provides valuable insights into the sources of rail noise and contributes to the understanding and management of railway noise issues.

In their work to effectively analyze the propagation of railway noise using point source sound propagation theory, Jonasson and Zhang (2001), represented the train/track system as a series of distinct point sources. The primary objective was to investigate the sound propagation patterns exhibited by real trains. By combining sophisticated sound propagation theory with different source models and conducting thorough comparisons between calculations and measurements obtained from multiple receiver positions, it became possible to evaluate the assumptions made regarding the number and positions of point sources selected to describe the train's noise emission accurately.

Other approaches developed to measure or estimate noise for other modes may be of reference value also. For example, Cutler-Wood et al. (2022) measured drone noise data in Liberty, NC and Cape Cod, MA with a special focus on documenting the directional noise properties of drone operations. A detailed analysis of microphone setup for measuring directional noise levels provided a good starting point for applying this methodology to rail operations.

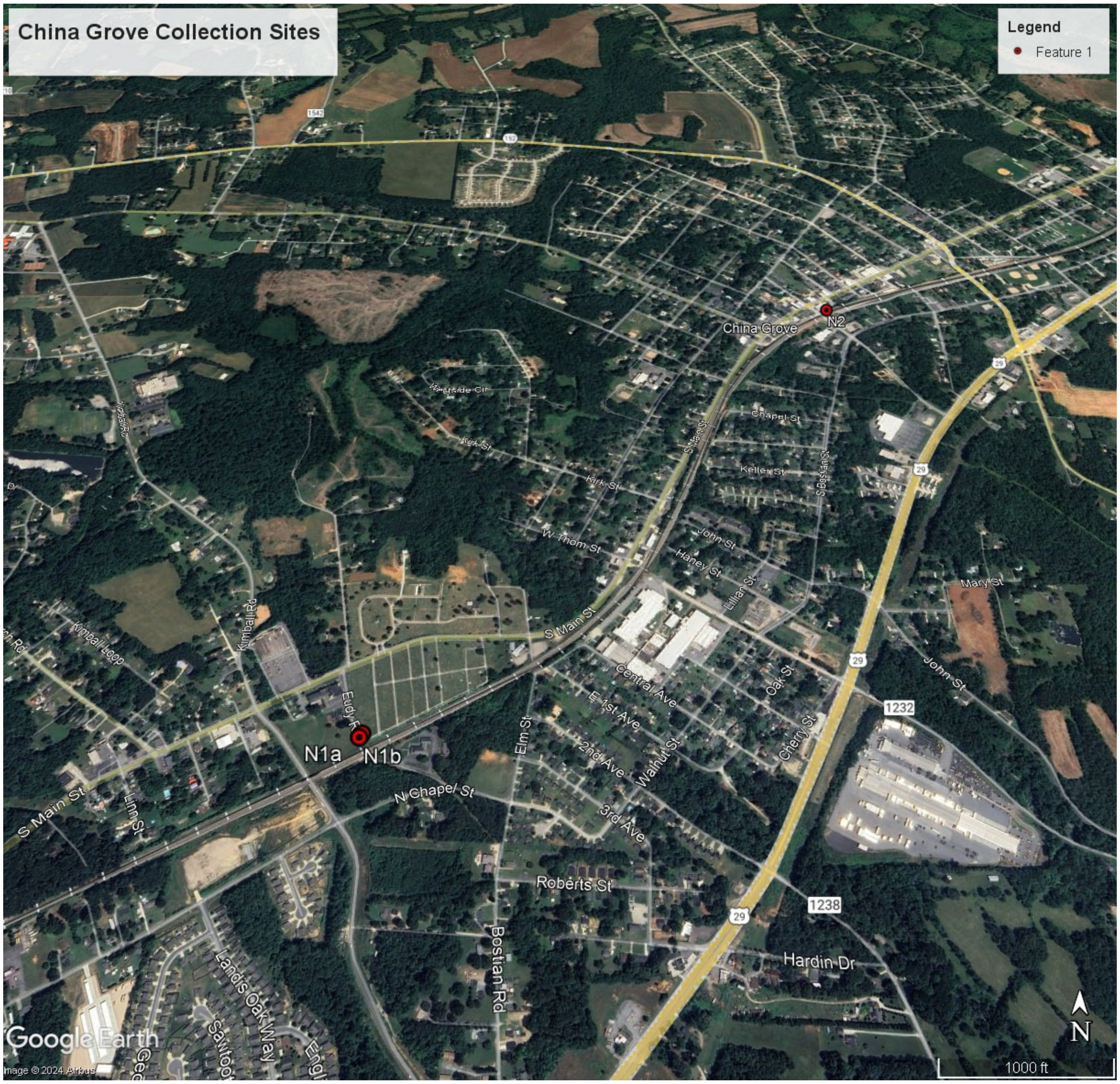
Wayside measurements are usually used in measuring freeway noise levels, as demonstrated by Hastings and Kaye (2022). However, their work incorporated variations in time of day for measurements, accounts for meteorological data, and attempts to rectify the differences between perceived sound and measured sound in their methods and analysis. This kind of methodology lays a strong foundation for our work in which perception plays a key role as well as the actual performance versus tested performance in controlled environments. Boeker et al. (2010) wrote the handbook on measuring rail noise in the United States, but its precautionary stipulations to prevent interference from external factors helped create the research niche that this project will fill: external factors affect rail noise in meaningful ways and it's important to fully understand them in light of the national track record of rail incidents.

Thompson et al. (2019) presented evaluation criteria for both feelable vibration and ground-borne noise, empirical and numerical prediction methods, the main vehicle and track parameters that affect the vibration levels and a range of possible mitigation methods. Li et al. (2018) enhanced methods of determining and predicting vibration and noise parameters caused by wheel-rail combined roughness from field measurements. Similarly, Li and Dwight (2018) validated the indirect track decay rate measurement method as a suitable alternative to direct measurement for determining total effective roughness of wheels and rails. Wang (2021) investigated if rail unevenness and corrugation could be measured using the dynamic response of the angle box and bogie with some success.

Theyssen (2020) developed a model for predicting the high-frequency vibration of rolling noise on concrete slab-supported tracks. Some important work has been done to apply various external factors to noise measurement, but none has been applied to the rail environment or EWDs yet. The FTA noise and vibration guidance manual (FTA 2018) includes procedures and methodology for measuring and modeling noise and vibration from rail systems.

As recognized in the larger background to rail safety and noise reduction, many approaches have been implemented to reduce various noises and mitigate their negative impact but hardly any assessment on its unintended results in reduced warnings for pedestrians in the railroad right of way or tracks.

APPENDIX 5: SITE LOCATIONS VIA GOOGLE EARTH PRO MAP




Greensboro Collection Sites
Legend
Feature 1
N3
N4
Greensboro
CUMBERLAND
TOLBERT
LOGAN
SOUTHSIDE
GORRELL ST. COMMUNITY
ASHEBORO COMMUNITY
BENJAMIN BENSON
FISHER PARK HISTORIC DISTRICT
IDLEWOOD
LATHAM PARK
ROSEWOOD
PHILLIPS AVE
E Gate City Blvd
Gorrell St
E Market St
E Friendly Ave
E Lindsay St
E Bragg St
Douglas St
Julian St
Broad Ave
E Whittington St
S Elm St
Arlington St
Vance St
Bellevue St
Martin St
Macon St
Omaha St
Sevier St
Reid St
Bennett St
High St
Hargett St
Law St
Logan St
S Benbow Rd
Rugby St
Burbank St
Duke St
S O Henry Blvd
Lincoln St
Rex Ct
JC Price Ln
Bilbro St
Ashe St
Eugene St
S Spring St
N Greene St
2000 ft
N
Google Earth

Raleigh Collection Sites
Legend
Feature 1
N6a
N6b
N5
RIDGE PARK
HIGHLAND GARDENS
BUDLEIGH
WAYLAND HEIGHTS
COUNTRY CLUB VILLAS
BLOOMSBURY
SUNSET HILLS
RALINA
RIDGEWOOD
FIVE POINTS
HAYES BARTON
OBERLIN
UNIVERSITY PARK
GLENWOOD
WILMONT
BAGWELL
METHOD
WEST RALEIGH
GLENWOOD SOUTH
NORTH BOYLAN
BOULEVARD PARK
ST MARYS TOWNHOMES
GORMANS-BURT
KIRBY-BILYEU
BOYLAN HEIGHTS
MARTIN HOMES
Centennial Pkwy
Avent Ferry Rd
Western Blvd
Hillsborough St
W Morgan St
Clark Ave
Google Earth
3000 ft

APPENDIX 6. TRAIN NOISE SIMULATION MODELING

The following Figures show the results of the noise modeling at each of the six sites. The sites cover a range of different types of environments from rural to urban and many combinations of conditions affecting noise propagation. The modeled train operations are based on the field noise measurement at each site. The measurement results were used to validate the noise models at each site.

The noise measurement program collected data on approximately 60 passing trains at each of the six sites. The data were analyzed, and all the train passby noise levels were compared to one another. Individual train passby events were identified at each site as candidates for noise modeling based on the measured noise levels. These sample train passby events had train speeds and maximum noise levels approximately meeting the averages across all recorded events.

The noise modeling results are shown graphically in figures illustrating the noise level contours at distinct moments in time as the trains approach the receiver location, approximating the pedestrian crossing location. Each type of train modeled at each site includes three figures illustrating an approaching train. The first of these sets of figures shows the train before it reaches the receiver location at the time when the maximum noise level (Lmax) from the approaching train was approximately equal to the ambient Leq at that site plus 5 dB. This baseline of the ambient noise level + 5 dB has been identified as the minimum ambient noise background for an approaching train to be audible for this study.

The second figure illustrates the noise level contours from the approaching train at a position closer to the receiver when the Lmax was approximately in the middle of the upward slope of the measured time history data between when the noise level first exceeded the ambient + 5 dB and when the maximum noise level occurred as the train reached the receiver location. The third figure illustrates the noise level contours when the leading locomotive of the train reached the receiver location resulting in the maximum noise level of the train passby event. Together, the sets of three figures show the increasing noise levels at the receiver locations from the approaching trains at each site for each modeled train type.

The noise modeling figures show noise level contours superimposed over aerial images at each site. The noise levels are illustrated over a gradient from dark green (noise levels less than 50 dBA) transitioning to dark red (noise levels greater than 100 dBA). The model at each site is based on ground elevation data imported from Google Earth. The train locations are shown by red lines in the figures. Amtrak trains were modeled as 460-foot-long sources, corresponding to 2 locomotives (each 60 feet long) and 4 railcars (each 85 feet long) consistent with the train consists observed in the field. Freight trains observed in the field typically consisted of up to 3 locomotives and approximately 100 railcars. Since the study is focused on approaching trains, freight trains were modeled as long as necessary to cover the focused study area at each site as necessary.

The receiver locations are shown on the figures as blue points and lines indicating the pedestrian crossing locations. These locations are the starting points where the approaching train distances and times were calculated from. Large buildings in the vicinity of each site were specifically included in the noise models and are shown in the figures as white polygons with black diagonal lines through them. Generally, only buildings taller than 15 to 20 feet were specifically included in the noise models. These tall buildings cause noise reflections off their facades, provide acoustical shielding from the train noise sources, and cause sound to diffract around them. These effects can be visually seen in the noise level contour results in each figure. Large areas of trees and foliage adjacent to the railroad tracks were also included in the noise models where appropriate. These areas provide some additional noise attenuation where the sound path travels through the attenuation areas.

Each noise modeling figure includes information identifying the site location and the modeled train conditions including the train type, direction of travel, and speed. Additional information specifying the distance from the leading locomotive to the receiver location and corresponding amount of time before the train reached the receiver location are included in the figure captions.

Accompanying each noise modeling result figure is a plot of the sample measured train passby event noise level time history used to validate each noise model. Those plots show the measured noise level of the trains passing the receiver/microphone location. The yellow lines show the ambient Leq + 5 dB. The red boxes highlight the small portion of the train passby that are of concern for this study included in the noise modeling. Each set of 3 modeled train noise figures occur within the area highlighted in the red boxes in the time history plots. The first modeling figure is when the leading train locomotive was approximately at the location where the blue line crosses the yellow line in the time history plots. The second modeling figure is when the leading locomotive was approximately midway up the ascending slope of the time history plot, and the third modeling figure is when the maximum noise level was recorded as the leading locomotive was passing the microphone location.

Table 1 provides a summary of the modeled train noise results at each site for each modeled train type and speed. The maximum noise level, distance from the receiver position, and time from the receiver position are included for the modeled trains at the ambient + 5 dB position, the position midway to the receiver, and at the receiver position.

Table 1. Train Profiles for Noise Modeling

Site #	Train Type	Train Speed (mph)	Train at Ambient + 5 dB position			Train Midway between Ambient + 5 dB Position and Receiver			Train at Receiver Position
			Lmax (dBA)	Dist. to Rec. (ft)	Time to Rec. (sec)	Lmax (dBA)	Dist. to Rec. (ft)	Time to Rec. (sec)	Lmax (dBA)
N1	Amtrak	74	52	868	8	68	217	2	88
	Freight	55	51	1,291	16	73	242	3	90
N2	Amtrak	73	64	964	9	82	642	6	91
N3	Amtrak	50	60	587	8	75	147	2	94
	Freight	50	58	293	4	69	73	1	87
N4	Amtrak	43	59	252	4	80	189	3	102
N5	Amtrak	28	57	363	9	74	81	2	90
	Freight	20	57	587	20	74	147	5	91
N6	Amtrak	74	57	543	5	74	217	2	90
	Freight	17	64	1,820	73	79	848	34	104

1.1 Site 1（China Grove）Noise Propagation Model

Figures 1 through 4 show the noise propagation model at site 1, located at the Green Lawn Cemetery in China Grove, NC. The noise propagation models show noise level contours from an approaching Amtrak train and a separate approaching freight train. The modeled Amtrak train is traveling westbound at a speed of 74 mph. The maximum noise level at the receiver location increased above the ambient Leq + 5 dB (Lmax of 52 dBA) when the approaching Amtrak train was approximately 868 feet from the receiver, which corresponds to a time of approximately 8 seconds before the leading locomotive passed the receiver.

The maximum noise level of the approaching Amtrak train approximately midway between the Ambient + 5 dB time and passing the receiver was 68 dBA. The midway location was 217 feet from the receiver, corresponding to a time of approximately 2 seconds from the receiver location. The maximum noise level of the Amtrak train as it passed the receiver location was 88 dBA.

The modeled freight train is traveling westbound at a speed of 55 mph. As documented in Figures 5 through 8, the maximum noise level at the receiver location increased above the ambient Leq + 5 dB (Lmax of 51 dBA) when the approaching freight train was approximately 1,291 feet from the receiver, which corresponds to a time of approximately 16 seconds before the leading locomotive passed the receiver.

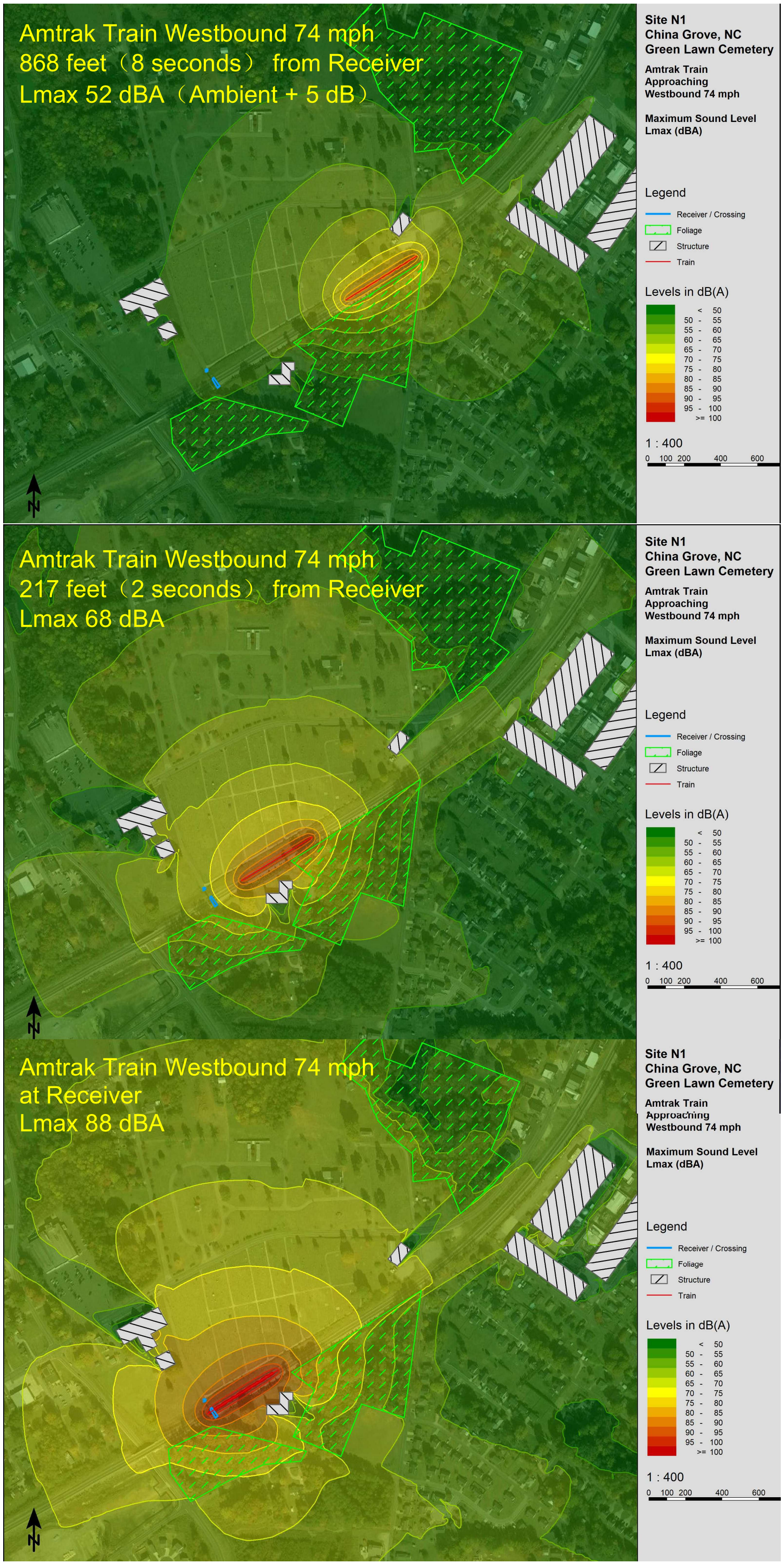


Figure 1. Amtrak Train Noise Model at China Grove

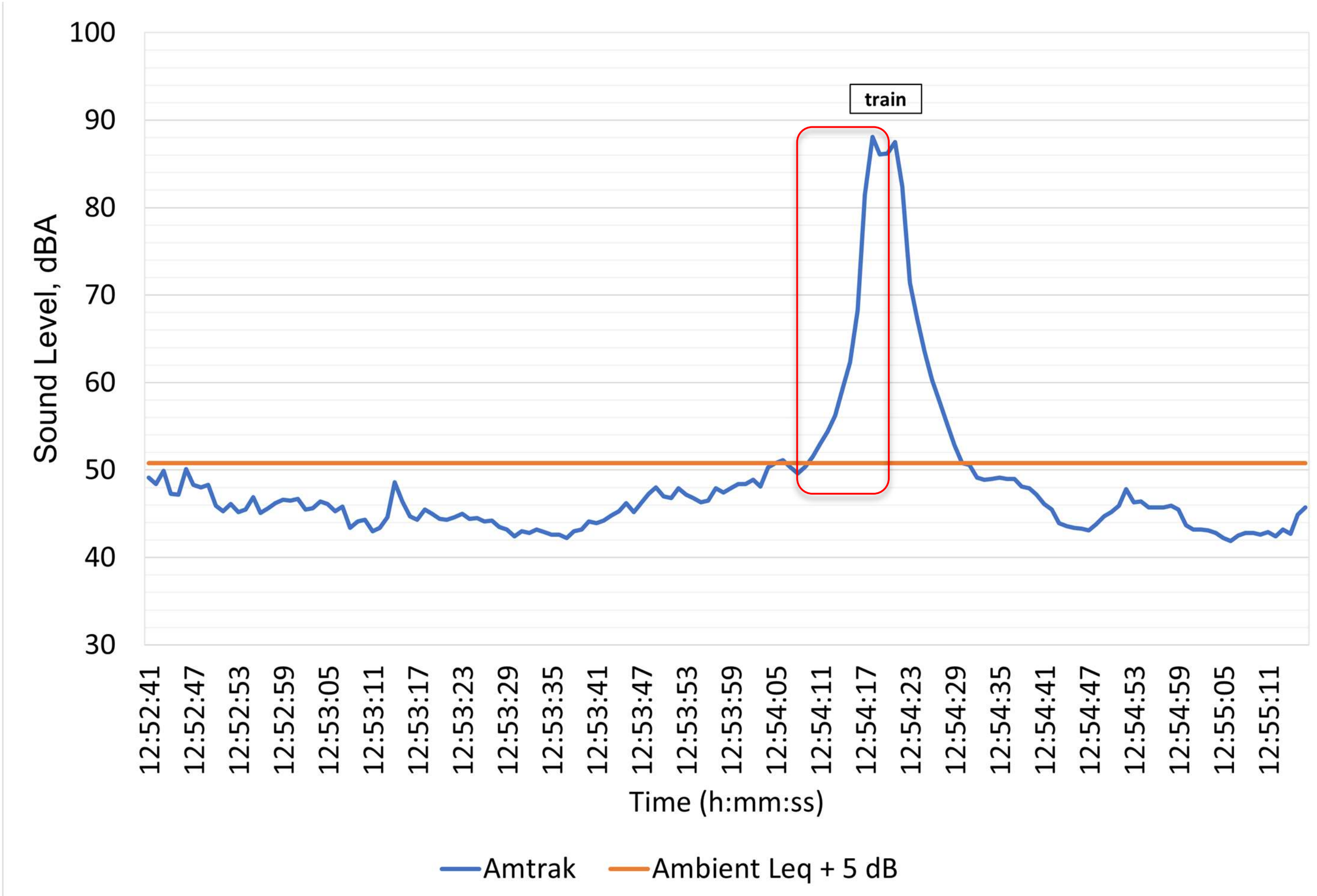


Figure 2. Amtrak Train Passby Time History at China Grove

The maximum noise level of the approaching freight train approximately midway between the Ambient + 5 dB time and passing the receiver was 73 dBA. The midway location was 242 feet from the receiver, corresponding to a time of approximately 3 seconds from the receiver location. The maximum noise level of the Amtrak train as it passed the receiver location was 90 dBA.

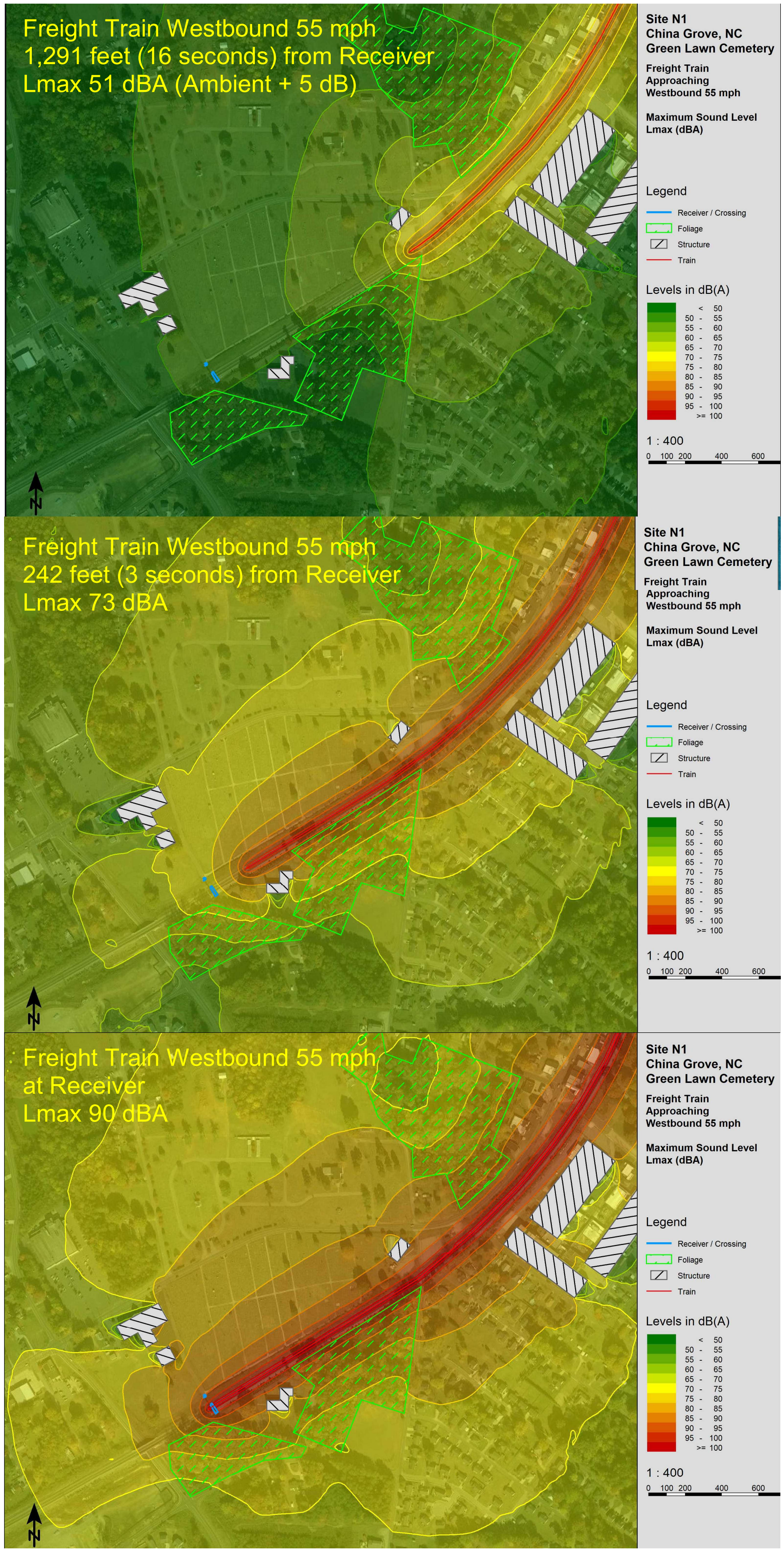


Figure 3. Freight Train Noise Model at China Grove

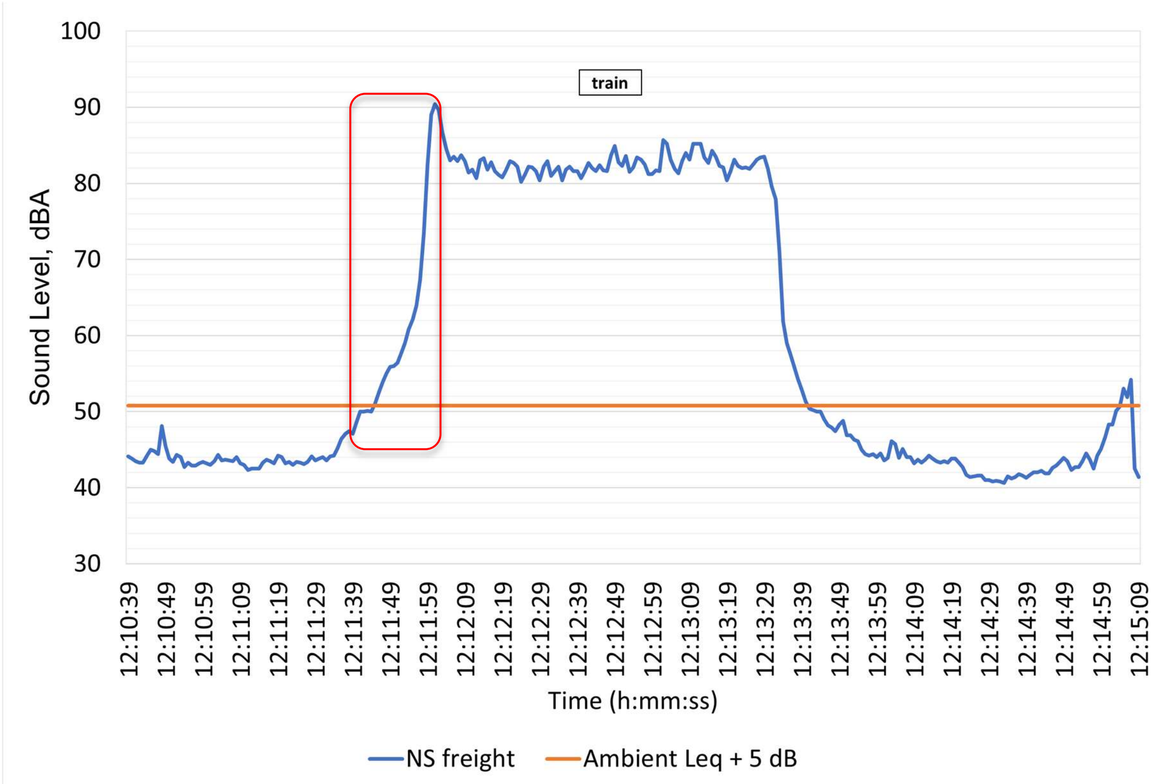


Figure 4. Freight Train Passby Time History at China Grove

1.2 Site 2 (East Centerview Drive) Noise Modeling Results

Figures 5 and 6 show the noise modeling results at site 2, located at the East Centerview Drive at-grade crossing in China Grove, NC. The modeling results show noise level contours from approaching an Amtrak train and a separate approaching freight train. The modeled Amtrak train is traveling eastbound at a speed of 73 mph. The maximum noise level at the receiver location increased above the ambient Leq + 5 dB (Lmax of 64 dBA) when the approaching Amtrak train was approximately 964 feet from the receiver, which corresponds to a time of approximately 9 seconds before the leading locomotive passed the receiver.

The maximum noise level of the approaching Amtrak train approximately midway between the Ambient + 5 dB time and passing the receiver was 82 dBA. The midway location was 642 feet from the receiver, corresponding to a time of approximately 6 seconds from the receiver location. The maximum noise level of the Amtrak train as it passed the receiver location was 91 dBA.

Freight trains were not modeled at site 2 because no freight trains were measured at the site during the field data collection.

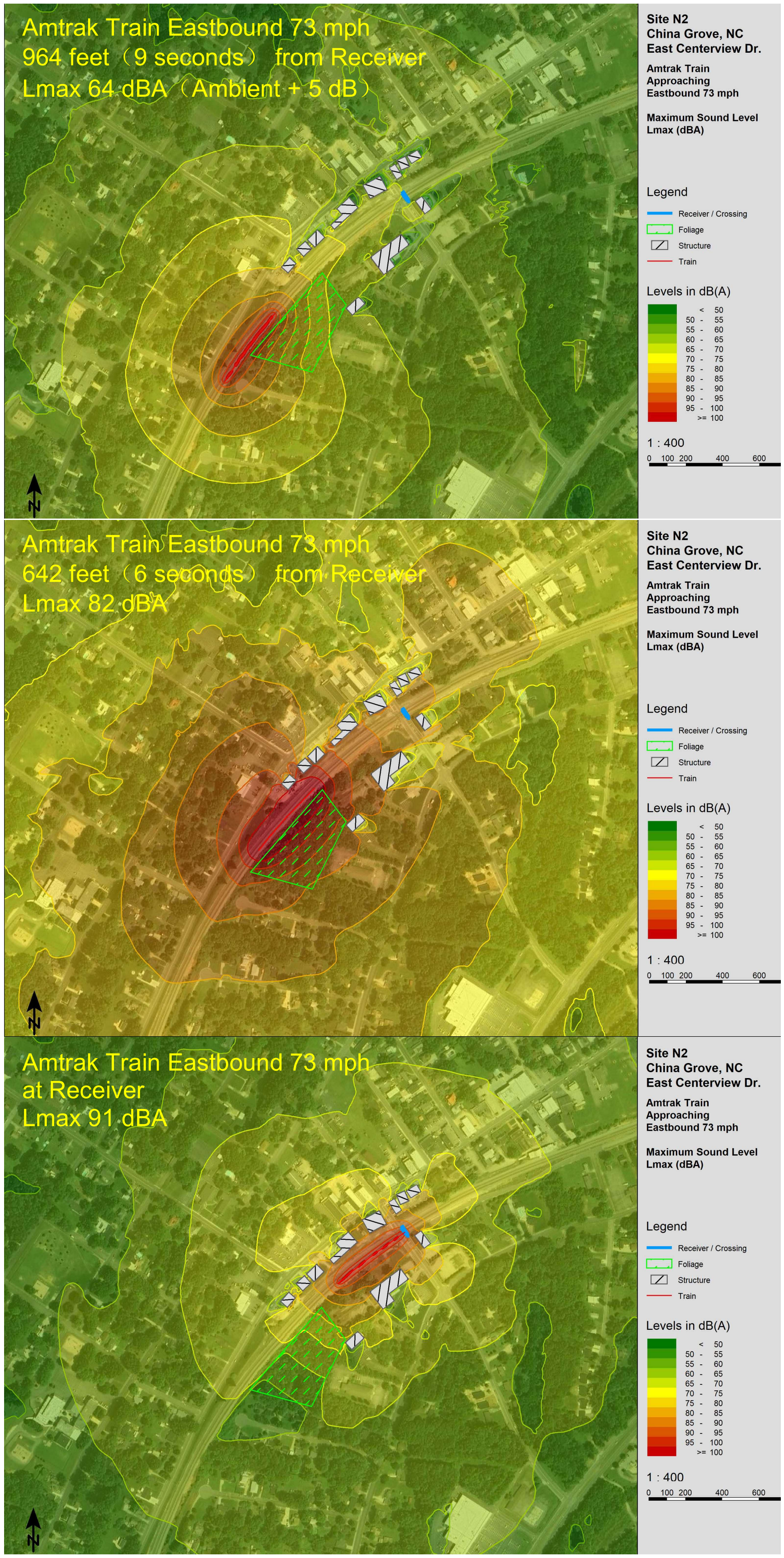


Figure 5. Amtrak Train Noise Model at China Grove

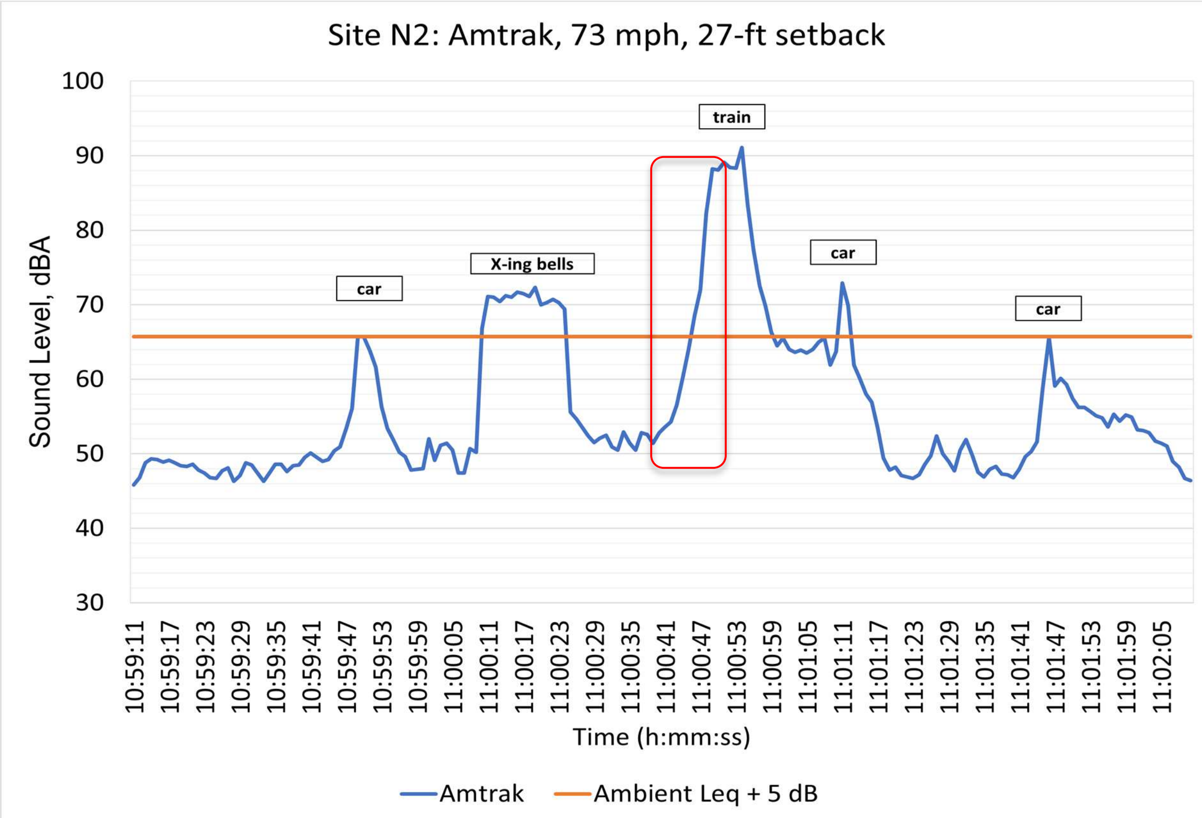


Figure 6. Amtrak Train Passby Time History at China Grove

1.3 Site 3 (East Market Street) Noise Modeling Results

Figures 7 through 10 show the noise modeling results at site 3, located behind a business on East Market Street in Greensboro, NC. The modeling results show noise level contours from approaching an Amtrak train and a separate approaching freight train. The modeled Amtrak train is traveling westbound at a speed of 50 mph. The maximum noise level at the receiver location increased above the ambient Leq + 5 dB (Lmax of 60 dBA) when the approaching Amtrak train was approximately 587 feet from the receiver, which corresponds to a time of approximately 8 seconds before the leading locomotive passed the receiver.

The maximum noise level of the approaching Amtrak train approximately midway between the Ambient + 5 dB time and passing the receiver was 75 dBA. The midway location was 147 feet from the receiver, corresponding to a time of approximately 2 seconds from the receiver location. The maximum noise level of the Amtrak train as it passed the receiver location was 94 dBA.

The modeled freight train is traveling westbound at a speed of 50 mph. The maximum noise level at the receiver location increased above the ambient Leq + 5 dB (Lmax of 58 dBA) when the approaching freight train was approximately 293 feet from the receiver, which corresponds to a time of approximately 4 seconds before the leading locomotive passed the receiver.

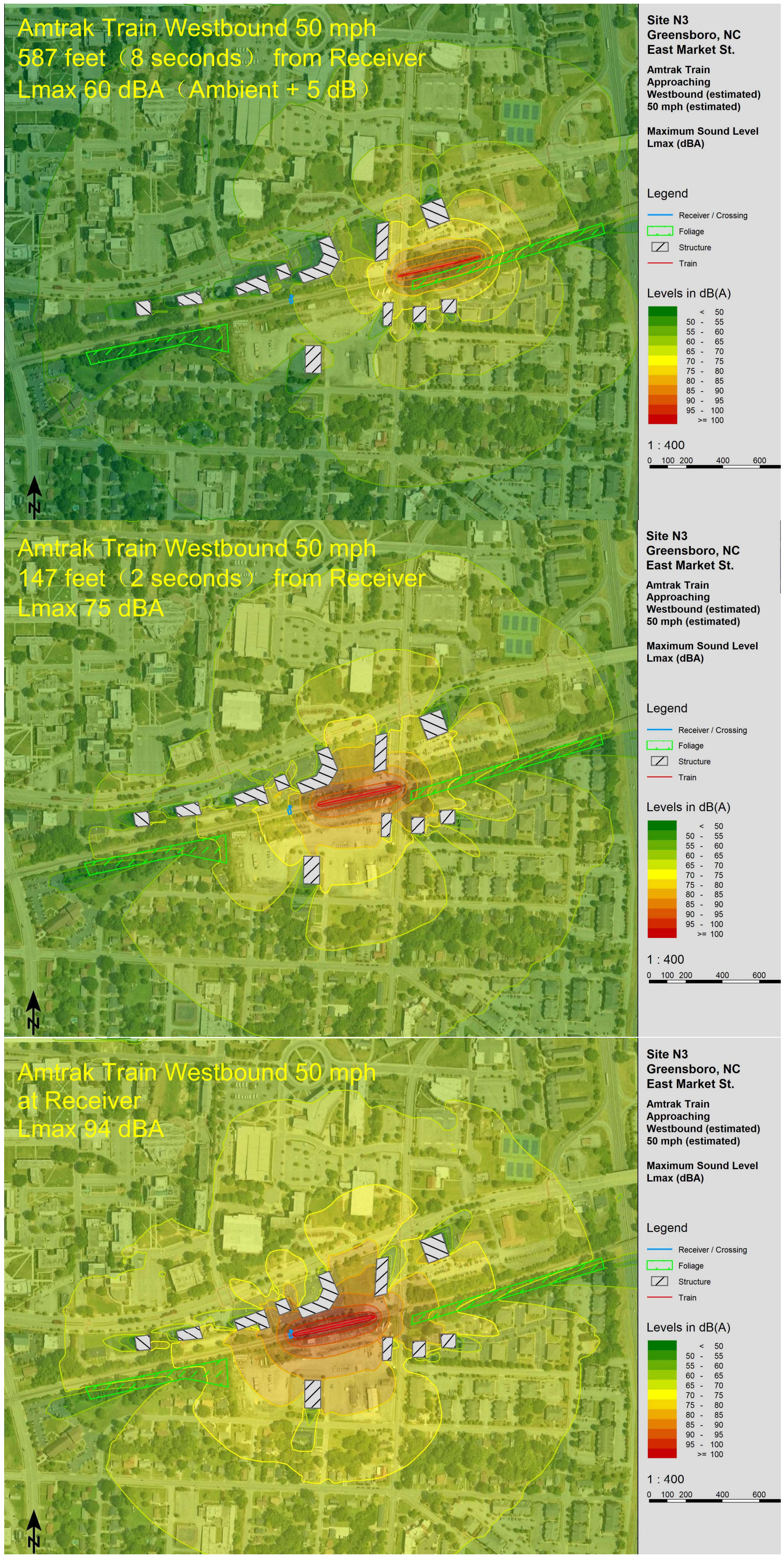


Figure 7. Amtrak Train Noise Model at East Market Street, Greensboro

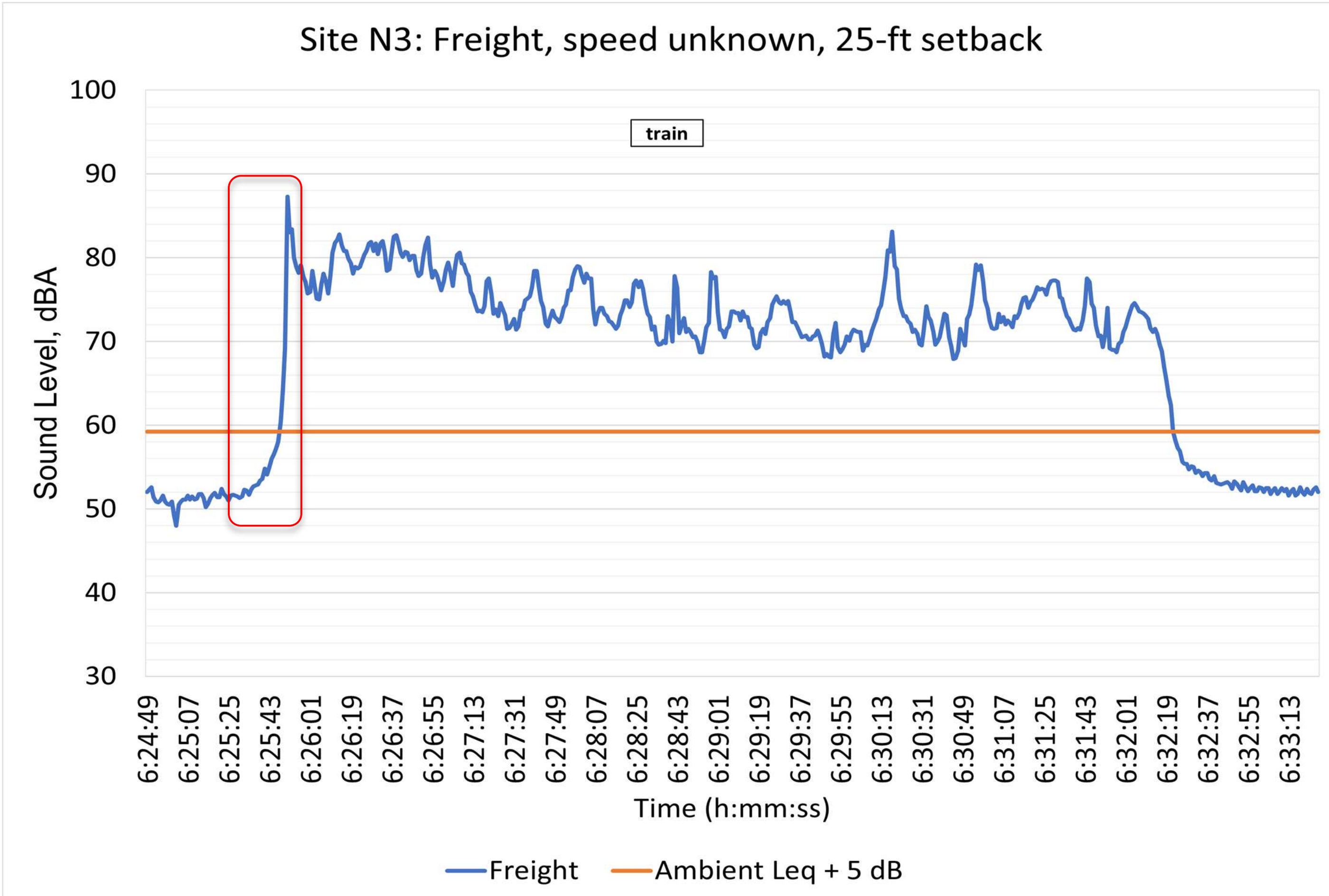


Figure 8. Amtrak Train Passby Time History at East Market Street, Greensboro

The maximum noise level of the approaching freight train approximately midway between the Ambient + 5 dB time and passing the receiver was 69 dBA. The midway location was 73 feet from the receiver, corresponding to a time of approximately 1 second from the receiver location. The maximum noise level of the freight train as it passed the receiver location was 87 dBA.

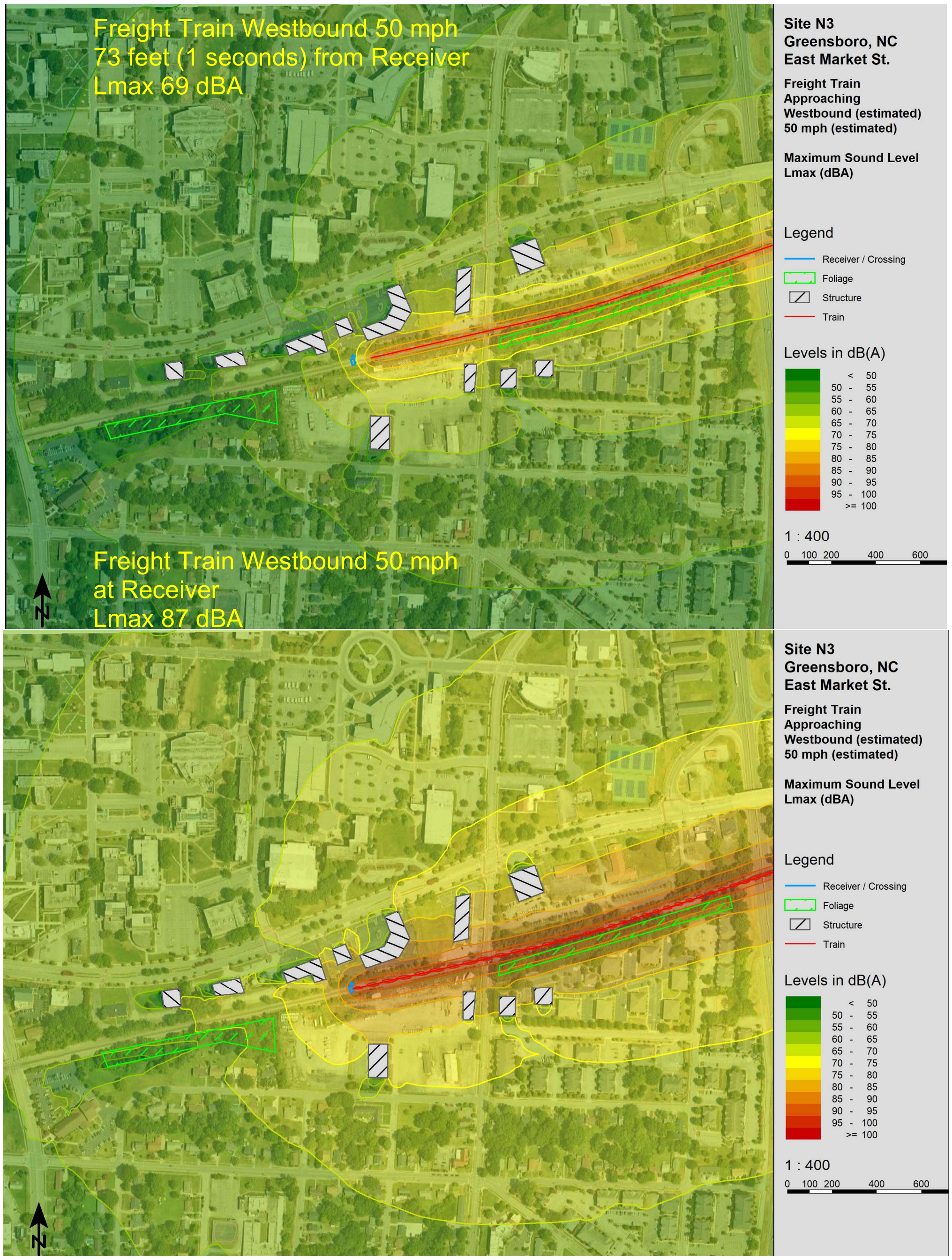


Figure 9. Freight Train Noise Model at East Market Street, Greensboro

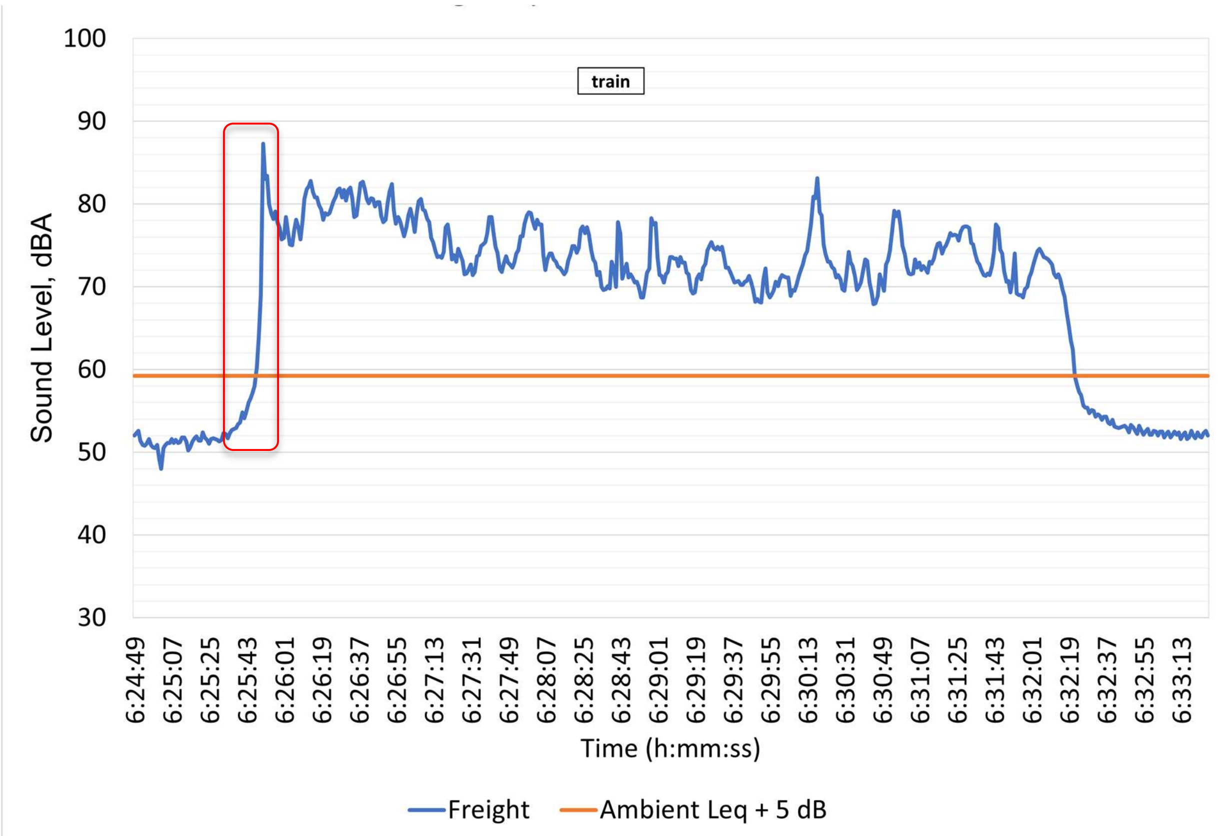


Figure 10. Freight Train Passby Time History at East Market Street, Greensboro

1.4 Site 4 (Amtrak Station) Noise Modeling Results

Figures 11 and 12 show the noise modeling results at site 4, located east of the Amtrak Station in Greensboro, NC. The modeling results show noise level contours from an approaching Amtrak train and a separate approaching freight train. The modeled Amtrak train is traveling westbound at a speed of 43 mph. The maximum noise level at the receiver location increased above the ambient Leq + 5 dB (Lmax of 59 dBA) when the approaching Amtrak train was approximately 252 feet from the receiver, which corresponds to a time of approximately 4 seconds before the leading locomotive passed the receiver.

The maximum noise level of the approaching Amtrak train approximately midway between the Ambient + 5 dB time and passing the receiver was 80 dBA. The midway location was 189 feet from the receiver, corresponding to a time of approximately 3 seconds from the receiver location. The maximum noise level of the Amtrak train as it passed the receiver location was 102 dBA.

Freight trains were not modeled at site 4 because no freight trains were observed at the site during the field data collection.

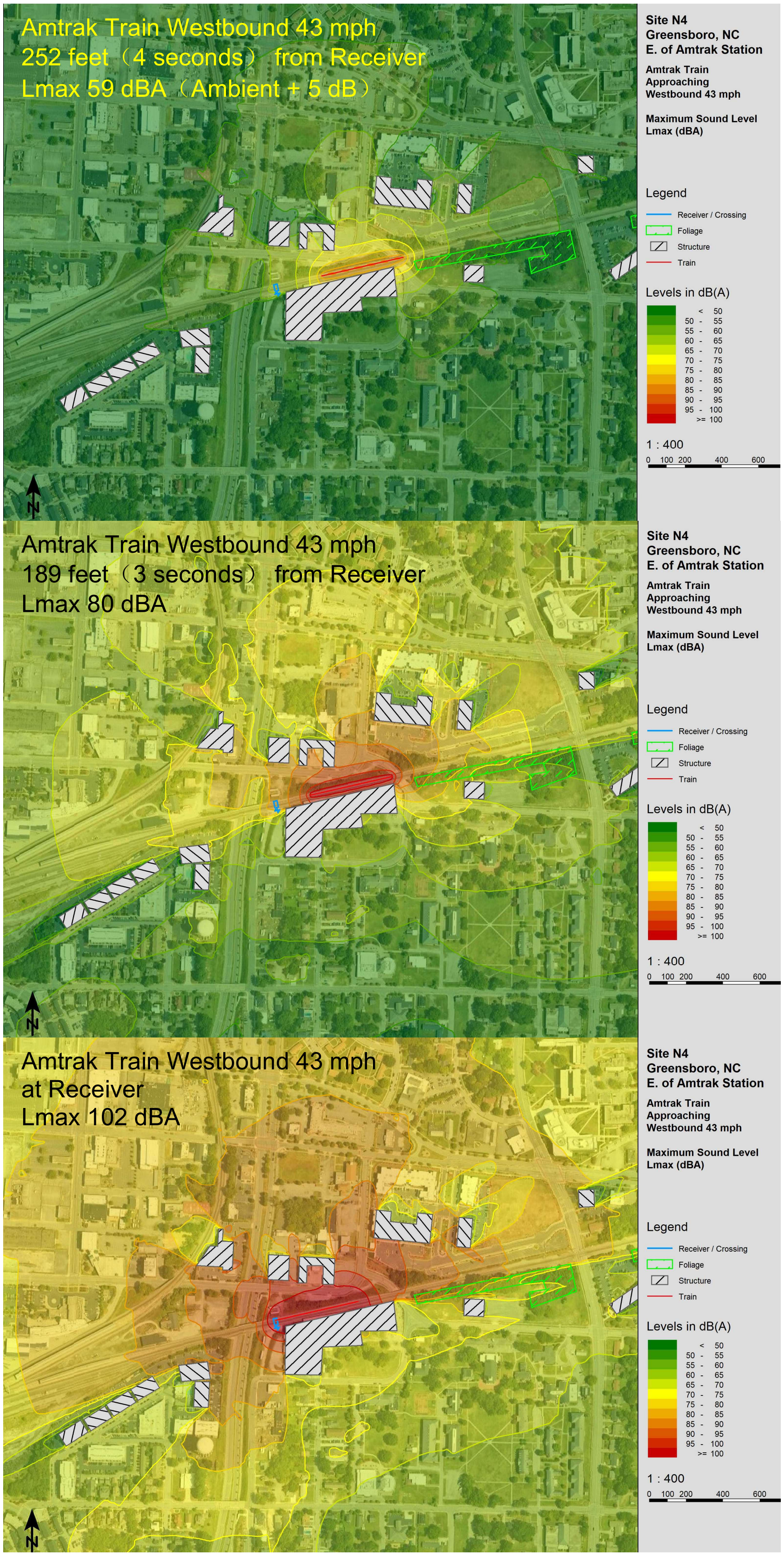


Figure 11. Amtrak Train Noise Model at Amtrak Station, Greensboro

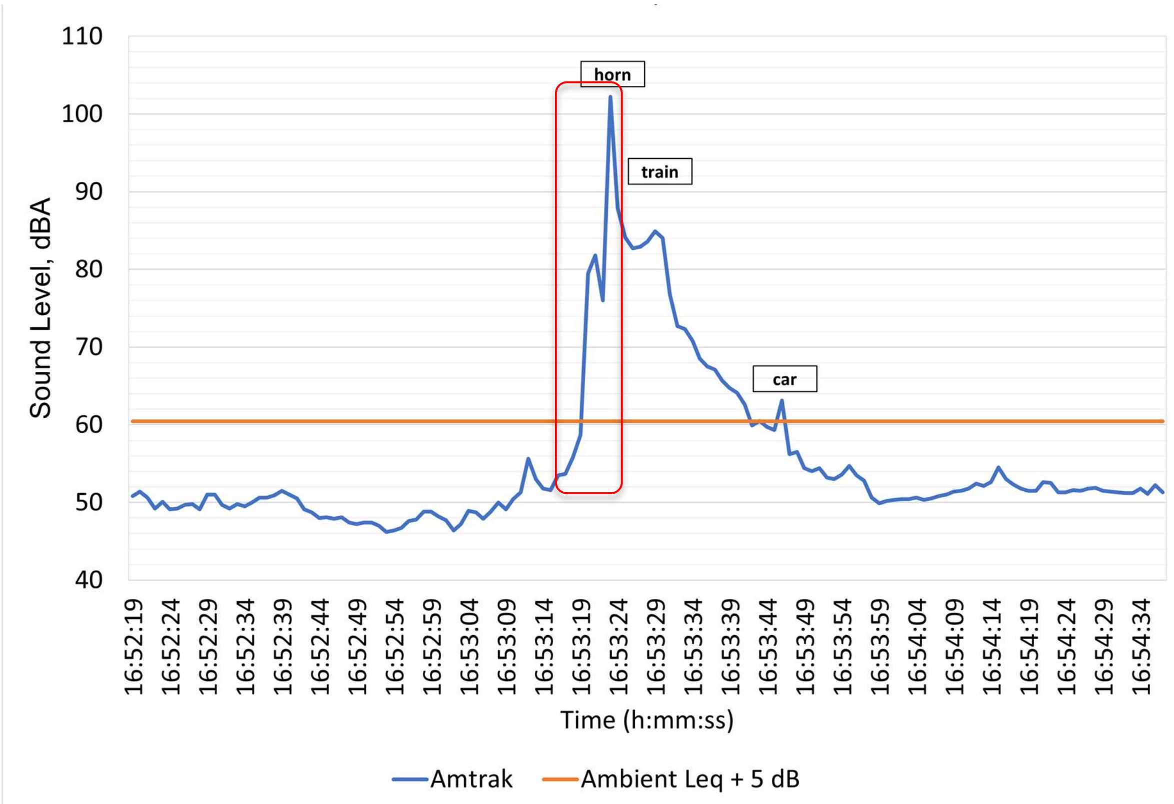


Figure 12. Amtrak Train Passby Time History at Amtrak Station, Greensboro

1.5 Site 5 (Park Avenue) Noise Modeling Results

Figures 13 through 16 show the noise modeling results at site 5, located behind a residence on Park Avenue in Raleigh, NC. The modeling results show noise level contours from an approaching Amtrak train and a separate approaching freight train. The modeled Amtrak train is traveling westbound at a speed of 28 mph. The maximum noise level at the receiver location increased above the ambient Leq + 5 dB (Lmax of 57 dBA) when the approaching Amtrak train was approximately 363 feet from the receiver, which corresponds to a time of approximately 9 seconds before the leading locomotive passed the receiver.

The maximum noise level of the approaching Amtrak train approximately midway between the Ambient + 5 dB time and passing the receiver was 74 dBA. The midway location was 81 feet from the receiver, corresponding to a time of approximately 2 seconds from the receiver location. The maximum noise level of the Amtrak train as it passed the receiver location was 90 dBA.

The modeled freight train is traveling eastbound at a speed of 20 mph. The maximum noise level at the receiver location increased above the ambient Leq + 5 dB (Lmax of 57 dBA) when the approaching freight train was approximately 587 feet from the receiver, which corresponds to a time of approximately 20 seconds before the leading locomotive passed the receiver.

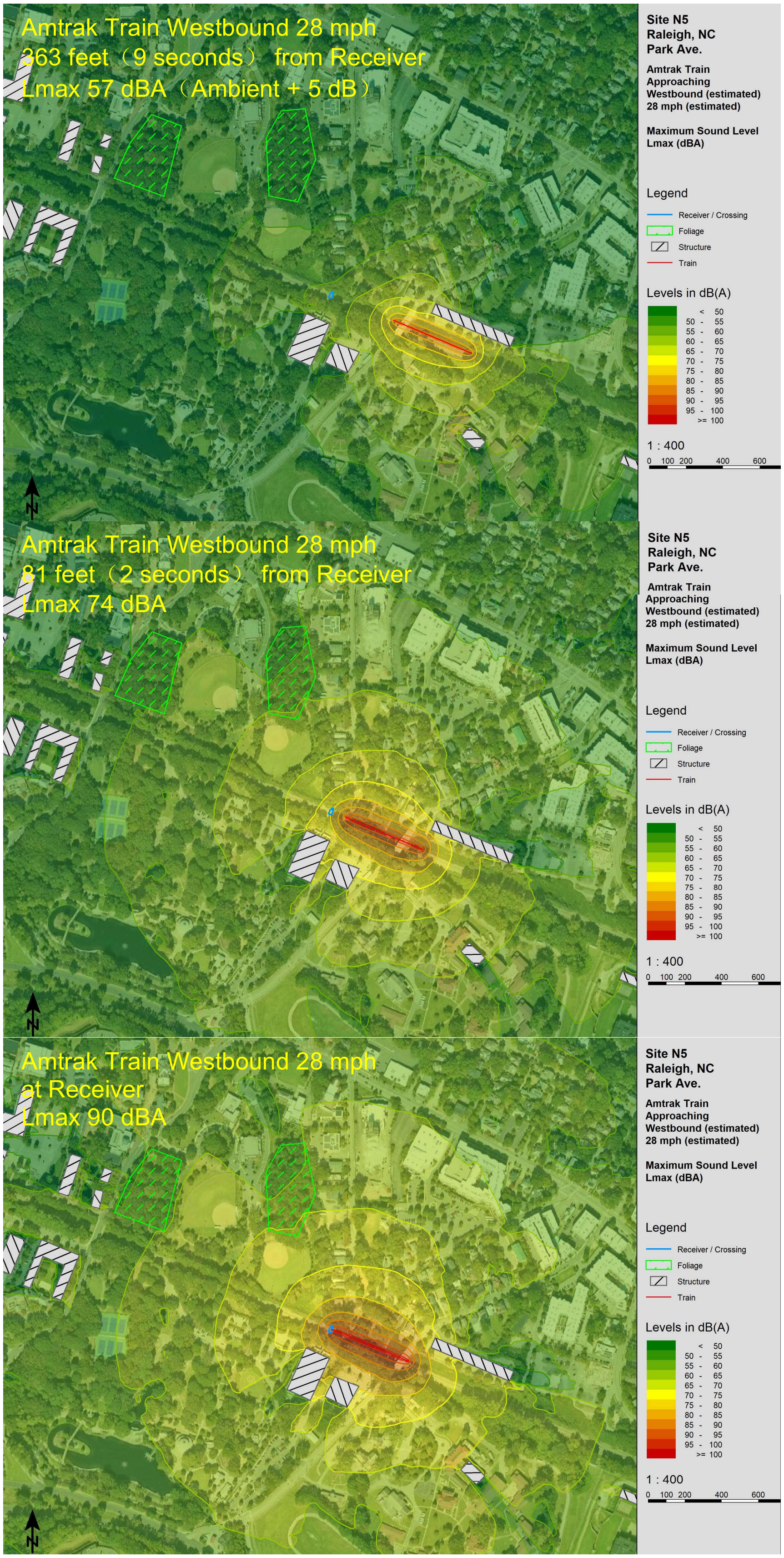


Figure 13. Amtrak Train Noise Model at Park Avenue, Raleigh

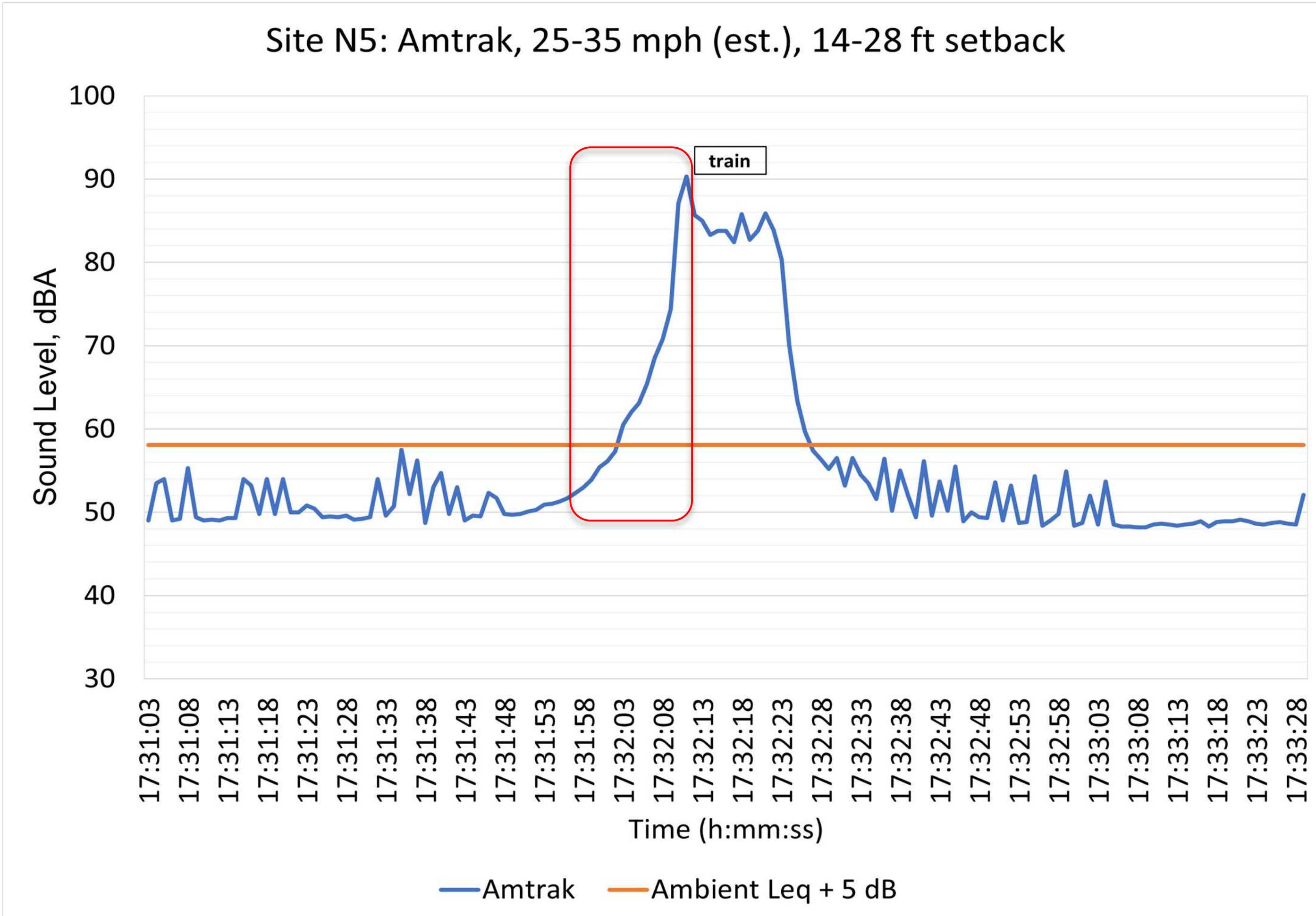


Figure 14. Amtrak Train Passby Time History at Park Avenue, Raleigh

The maximum noise level of the approaching freight train approximately midway between the Ambient + 5 dB time and passing the receiver was 74 dBA. The midway location was 147 feet from the receiver, corresponding to a time of approximately 5 seconds from the receiver location. The maximum noise level of the freight train as it passed the receiver location was 91 dBA.

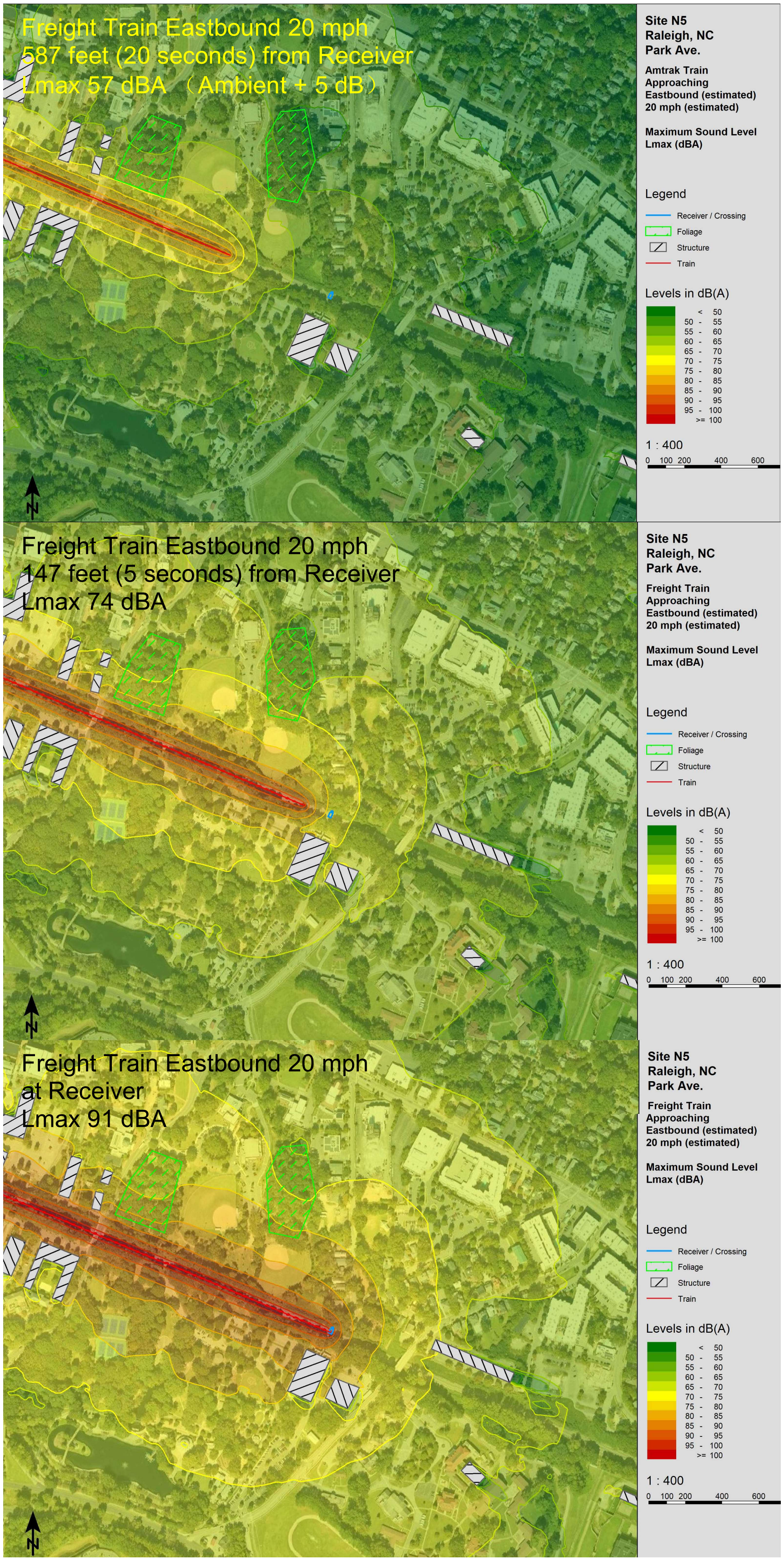


Figure 15. Freight Train Noise Model at Park Avenue, Raleigh

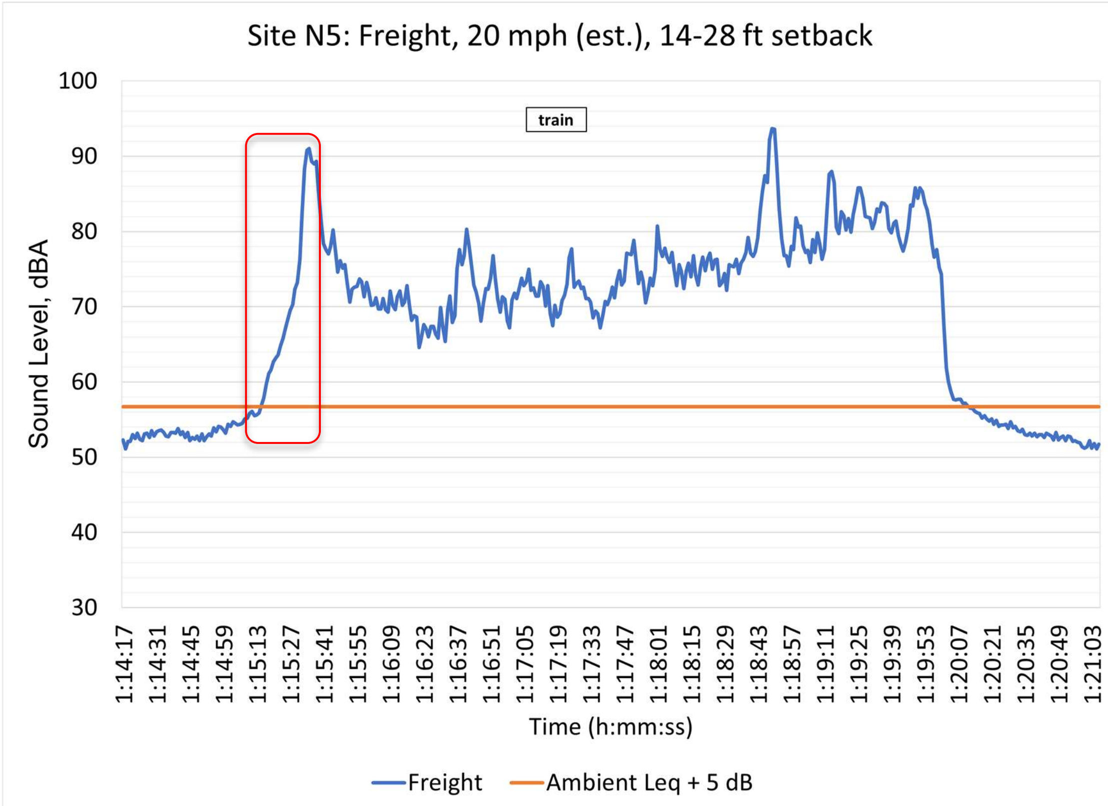


Figure 16. Freight Train Passby Time History at Park Avenue, Raleigh

1.6 Site 6（Royal Street）Noise Modeling Results

Figures 17 through 20 show the noise modeling results at site 6, located adjacent to the at-grade crossing at Royal Street in Raleigh, NC. The modeling results show noise level contours from an approaching Amtrak train and a separate approaching freight train. The modeled Amtrak train is traveling eastbound at a speed of 74 mph. The maximum noise level at the receiver location increased above the ambient Leq + 5 dB (Lmax of 57 dBA) when the approaching Amtrak train was approximately 543 feet from the receiver, which corresponds to a time of approximately 5 seconds before the leading locomotive passed the receiver.

The maximum noise level of the approaching Amtrak train approximately midway between the Ambient + 5 dB time and passing the receiver was 74 dBA. The midway location was 217 feet from the receiver, corresponding to a time of approximately 2 seconds from the receiver location. The maximum noise level of the Amtrak train as it passed the receiver location was 90 dBA.

The modeled freight train is traveling eastbound at a speed of 17 mph. The maximum noise level at the receiver location increased above the ambient Leq + 5 dB (Lmax of 64 dBA) when the approaching freight train sounding its warning horn was approximately 1,820 feet from the receiver, which corresponds to a time of approximately 73 seconds before the leading locomotive passed the receiver.

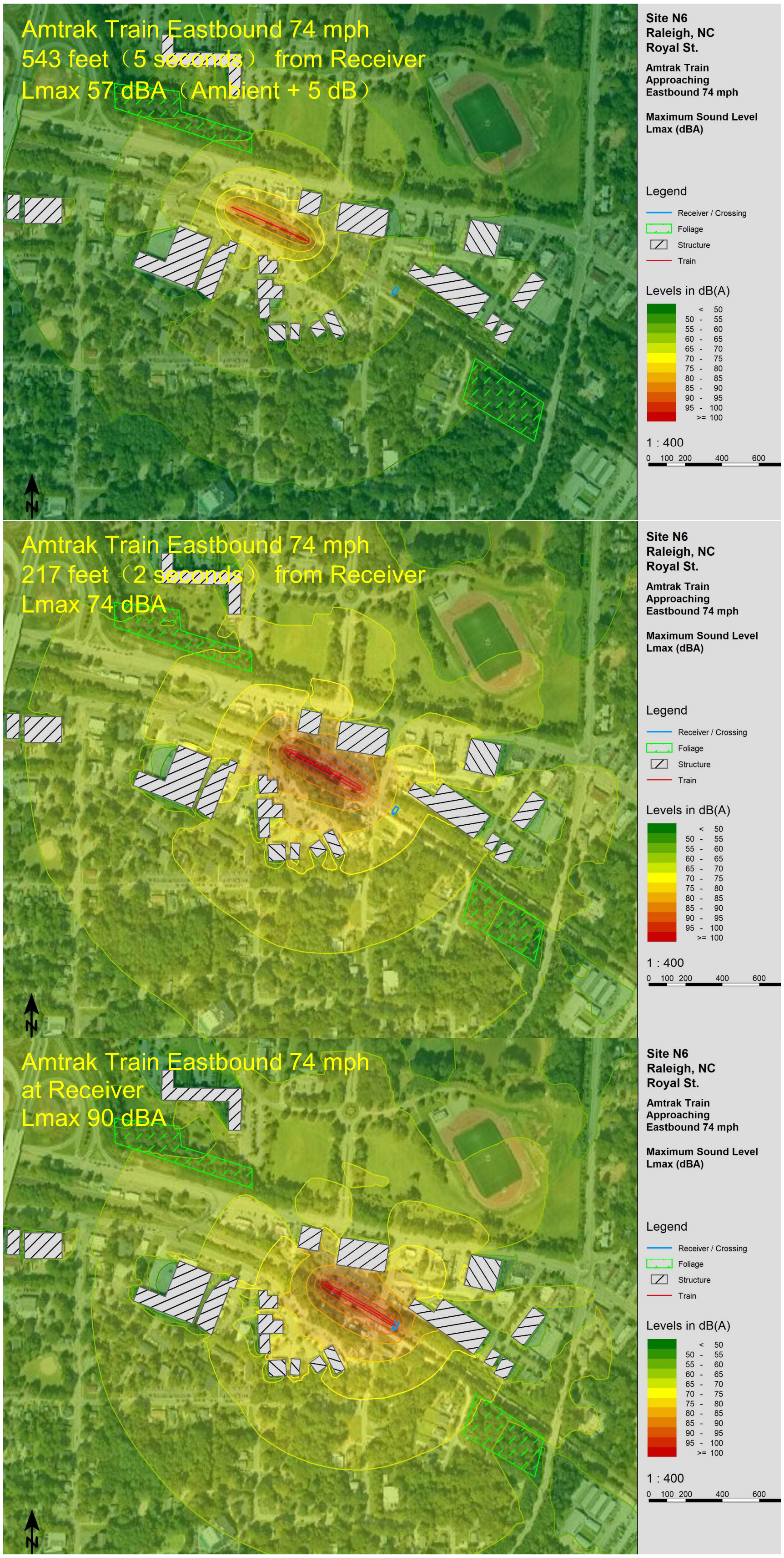


Figure 17. Amtrak Train Noise Model at Royal Street, Raleigh

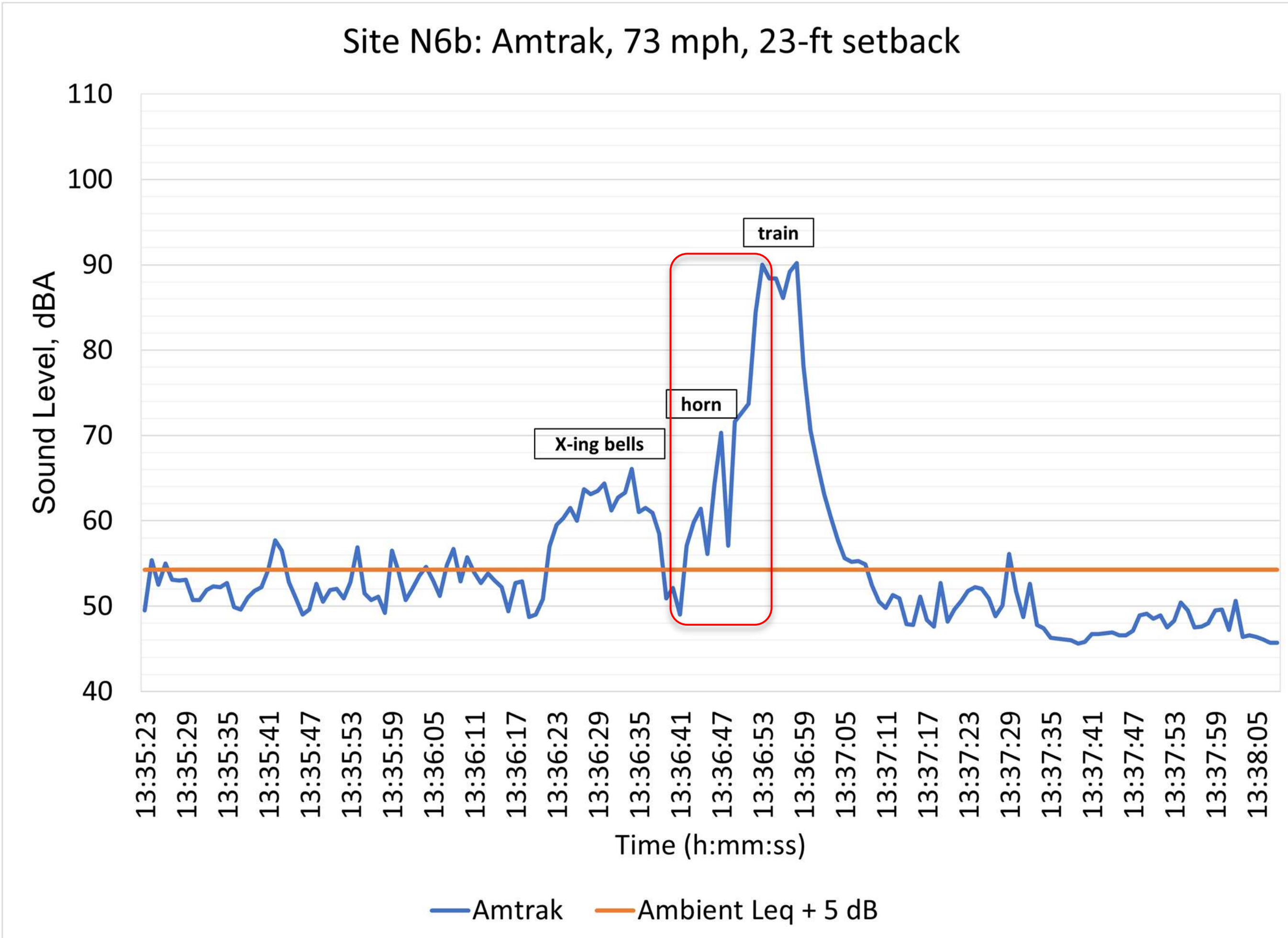


Figure 18. Amtrak Train Passby Time History at Royal Street, Raleigh

The maximum noise level of the approaching freight train approximately midway between the Ambient + 5 dB time and passing the receiver was 79 dBA. The midway location was 848 feet from the receiver, corresponding to a time of approximately 34 seconds from the receiver location. The maximum noise level of the freight train as it passed the receiver location was 104 dBA.

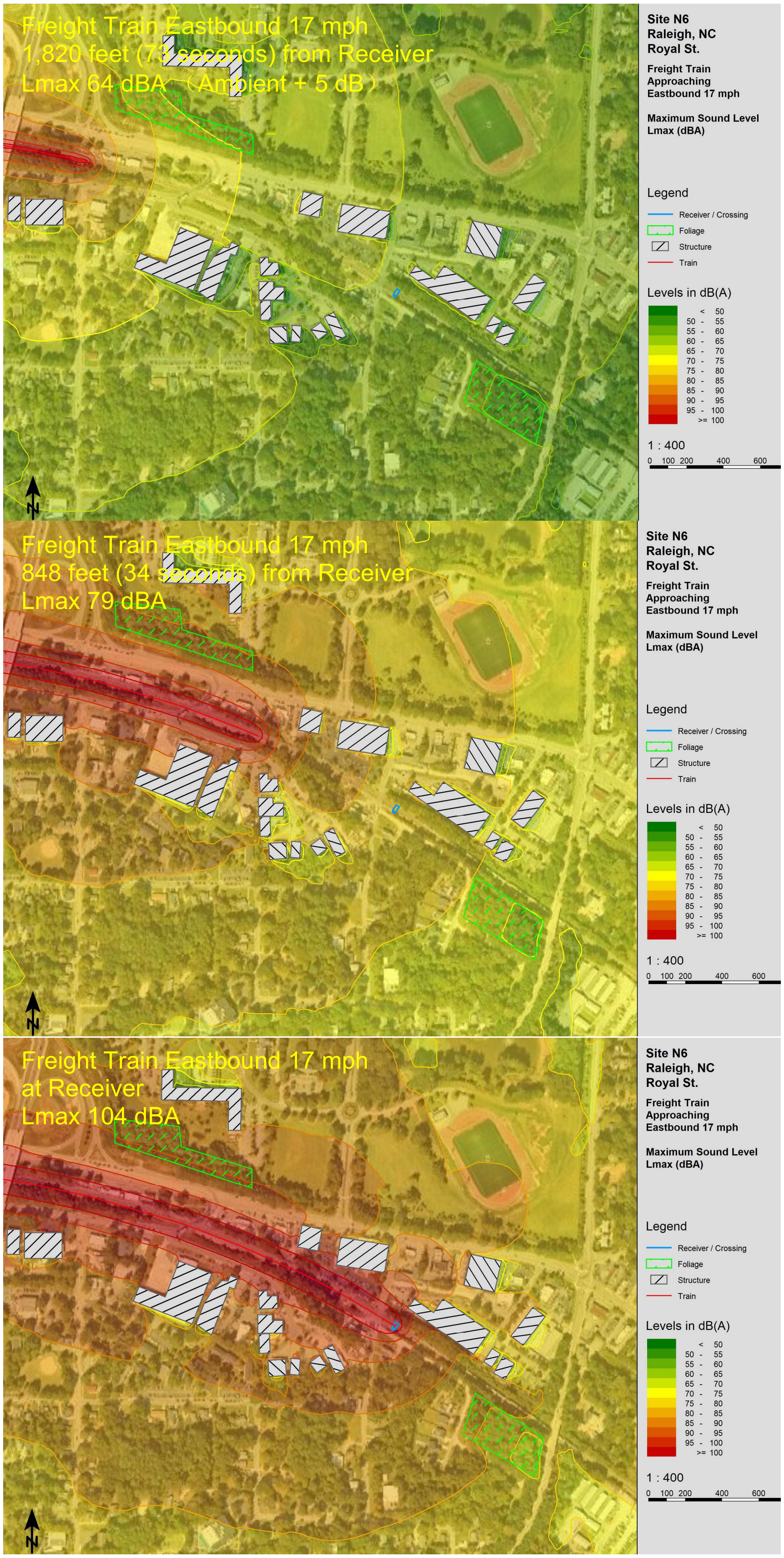


Figure 19. Freight Train Noise Model at Royal Street, Raleigh

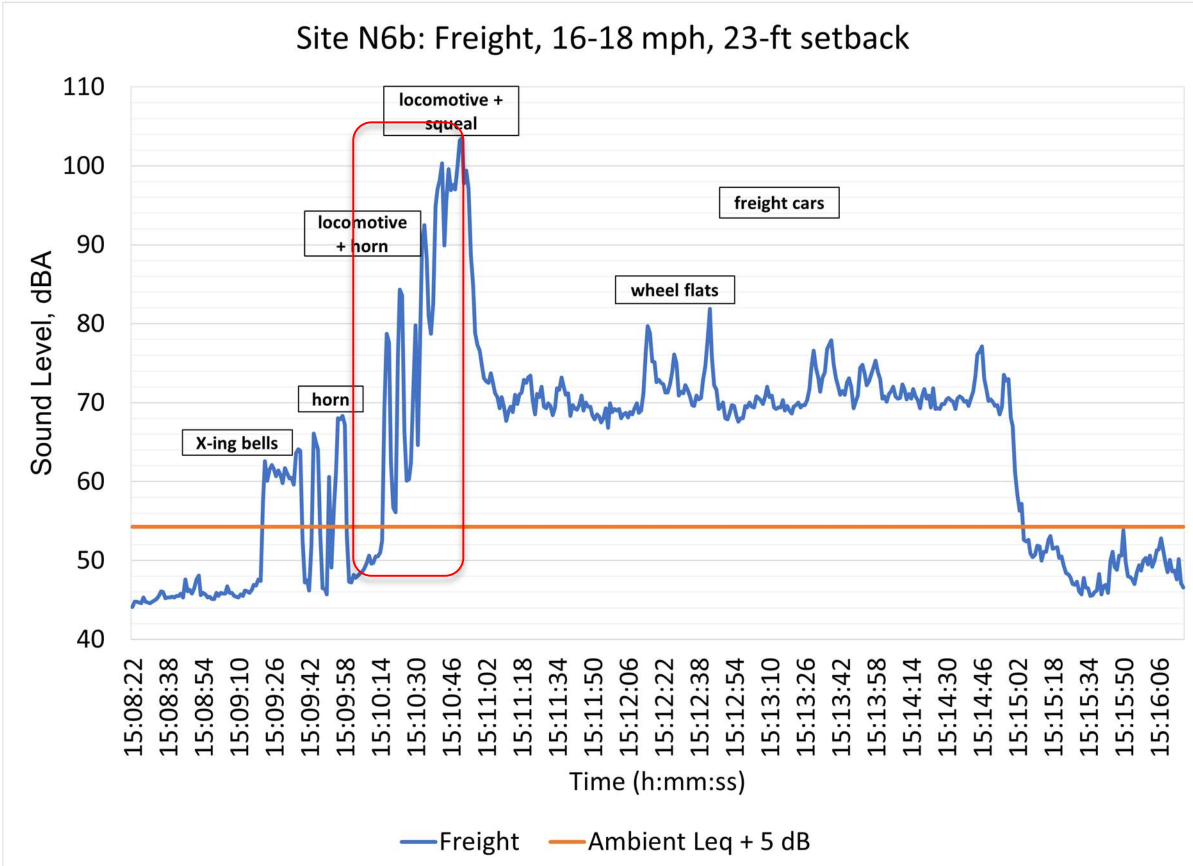


Figure 20. Freight Train Passby Time History at Royal Street, Raleigh

2 SUMMARY

The rail noise propagation models provide visual representations of the noise levels at receiver and pedestrian crossing locations from approaching Amtrak and freight trains at multiple moments in time prior to the trains passing the receiver positions. The models cover an extensive range of different railroad environment conditions affecting the perceived audibility of approaching trains in North Carolina.

The largest factors affecting these results are the ambient noise levels and the source noise levels of the approaching trains. The ambient noise levels were lowest in the rural areas far from roadway traffic and at-grade railroad crossings, such as at site N1 in China Grove where the ambient Leq + 5 dB was approximately 51 dBA. At locations closer to roadways, such as sites N2 and N6, the ambient Leq + 5 dB was up to 64 dBA. In general, the closer to urban environments the higher the ambient noise levels were, such as in Greensboro and Raleigh, ranging from approximately 57 dBA to 64 dBA. Higher ambient noise levels make it harder for pedestrians to hear approaching trains.

The largest factor, of course, affecting audibility of approaching trains are train warning horns. Some of the sites included horn noise and some did not. However, trains sounding warning horns when approaching at-grade crossings would not be a factor in all instances. For example, site N1 in China Grove is technically located within a quiet zone area, however, the site was not near a highway grade crossing, so trains do not normally sound horns there. Multiple pedestrians were observed using that location as an unauthorized place to cross the railroad tracks, however, leading to unsafe conditions.

The speed of the trains is shown to be the significant factor in the amount of time between when the noise from the approaching trains increases above the ambient noise levels and the time when the trains reach the receiver or pedestrian crossing locations. At 2 sites in China Grove, the noise from approaching Amtrak trains traveling greater than 73 mph increased above the ambient Leq + 5 dB level less than 10 seconds prior to passing the receiver location. The noise from approaching freight train traveling 55 mph in China Grove increased above the ambient Leq + 5 dB 16 seconds prior to passing the receiver.

In Greensboro, noise from approaching Amtrak and freight trains traveling greater than 43 mph increased above the ambient Leq + 5 dB from as little as 4 to 8 seconds prior to passing the receiver position.

In Raleigh, noise from approaching Amtrak trains traveling at 74 mph increased above the ambient Leq + 5 dB 5 seconds prior to passing the receiver, and at unknown slower speeds only 9 seconds prior to passing the receiver. Noise from approaching freight trains in Raleigh traveling at speeds less than 20 mph did increase above the ambient + 5 dB by 20 seconds prior to passing the receiver position and up to 73 seconds prior at a location where the train warning horn was being regularly sounded.