Addressing Truck Emissions and Noise at Truck Freight Bottlenecks

Final Report

U.S. Department of Transportation
Federal Highway Administration

May 2022

Technical Report Documentation Page

1. Report No. FHWA-HEP-22-026	**2. Government Accession No.**	**3. Recipient's Catalog No.**

4. Title and Subtitle Addressing Truck Emissions and Noise at Truck Freight Bottlenecks Final Report	**5. Report Date** May 2022 **6. Performing Organization Code**
7. Author(s) Christopher Porter, Daniel Beagan, John Koupal, Roger Wayson, Elizabeth Welch	**8. Performing Organization Report No.**
9. Performing Organization Name And Address Cambridge Systematics, Inc. Eastern Research Group, Inc. AECOM Energy and Environmental Research Associates, LLC	**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** Contract or Grant No.: DTFH6117D00008L, order no. 693JJ320F000295
12. Sponsoring Agency Name and Address Federal Highway Administration Office of Planning, Environment, and Realty 1200 New Jersey Avenue, SE Washington, DC 20590	**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code** HEP

15. Supplementary Notes

FHWA Review Team: David Kall (COTR), Aileen Varela-Margolles, Victoria Martinez, Jeff Purdy

16. Abstract

This report provides information on strategies to address truck emissions and noise at truck freight bottlenecks, including significant highway bottlenecks and truck access to intermodal connectors. The report includes case studies to demonstrate the potential benefits of various mitigation strategies at three locations. The report considers the extent to which emissions reduction and noise reduction strategies may be mutually supportive or work at cross purposes. The report considers challenges to implementation of these strategies and potential solutions to overcome them. Overall, strategies that improve traffic flow and reduce congestion can have meaningful emissions benefits but are not likely to reduce noise. The same is true for strategies to replace older, more polluting trucks with newer, cleaner trucks, although electric trucks provide some noise benefits at low speeds. The potential for reducing truck volumes by improving the efficiency of drayage operations or shifting freight from truck to rail or water depends greatly on local conditions. Noise-specific mitigation strategies, such as noise barriers and quiet pavements, are generally the most effective means of mitigating noise impacts.

17. Key Words Emissions, air quality, noise, trucks, bottlenecks	**18. Distribution Statement** No restrictions.

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 118	**22. Price** N/A

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

Please view online version of SI Conversion table here.

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List of Acronyms

AADT	annual average daily traffic
ATRI	American Transportation Research Institute
BCB	Barbours Cut Boulevard
BUILD	Better Utilizing Investments to Leverage Development
CMAQ	Congestion Mitigation and Air Quality Improvement
CO	carbon monoxide
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
DANA	Database for Analysis of Noise and Air Quality
dB(A)	A-weighted decibel
DOT	Department of Transportation
EPA	U.S. Environmental Protection Agency
FAF4	Freight Analysis Framework 4
FHWA	Federal Highway Administration
FRATIS	Freight Advanced Traveler Information System
GPS	global positioning system
HDT	heavy duty truck
HPMS	Highway Performance Monitoring System
ITS	Intelligent Transportation System
Leq	equivalent continuous sound pressure level
MDT	medium duty truck
MOVES	Motor Vehicle Emissions Simulator
mph	miles per hour
MPO	Metropolitan Planning Organization
MSAT	Mobile source air toxics
NAC	Noise Abatement Criteria
NCHRP	National Cooperative Highway Research Program
NEI	National Emissions Inventory
NHS	National Highway System
NPMRDS	National Performance Management Research Data Set
NREL	National Renewable Energy Laboratory
NWSA	Northwest Seaport Alliance

PDB	project-level database
PM	particulate matter
$PM_{2.5}$	particulate matter smaller than 2.5 microns
PM_{10}	Particulate matter smaller than 10 microns
ROW	right-of-way
SH	State Highway
SR	State Route
TMAS	Travel Monitoring Analysis System
TMC	traffic message channel
TNM	Traffic Noise Model
TSMO	transportation system management and operations
TXDOT	Texas Department of Transportation
USDOT	United States Department of Transportation
USGS	United States Geological Survey
VMT	vehicle-miles of travel
VOC	Volatile organic compounds
WSDOT	Washington State Department of Transportation

Executive Summary

Study Objectives

Truck freight bottlenecks on the Nation's highway network are problematic not only due to economic impacts, wasted fuel, and delayed freight shipments, but also because they pose air quality and noise concerns due to the high emission rates and noise levels associated with medium and heavy-duty trucks. Despite making up only 10 percent of vehicle-miles of travel (VMT) nationwide, trucks are responsible for over half of fine particulate emissions from on-road sources. Congested conditions lead to trucks traveling at low speeds in stop-and-go conditions where emissions per mile are higher than at cruise speeds. Idling truck traffic is also louder than idling automobile traffic and truck noise levels are higher at full throttle, such as when trucks are entering or exiting from bottleneck locations. Air quality and noise impacts are often compounded by the fact that many of the largest truck bottlenecks are in densely populated areas.

This report provides information on hypothetical strategies that could be adopted to address truck emissions and noise at truck freight bottlenecks, including significant highway bottlenecks and truck access to intermodal connectors. The report includes case studies to demonstrate the potential benefits of various mitigation strategies at three highway freight bottleneck and intermodal connector locations. The report considers the extent to which emissions reduction and noise reduction strategies may be mutually supportive or work at cross purposes. The report also considers implementation challenges of these strategies and potential solutions to overcome them.

Case Studies and Mitigation Strategies

Three case studies are evaluated to examine the potential emissions and noise benefits of a variety of mitigation strategies at truck bottlenecks:

- Chicago, Illinois—Vicinity of the Circle (Jane Byrne) Interchange (I-90/94 and I-290) adjacent to downtown Chicago.
- Houston, Texas—Access to the Barbours Cut Terminal of the Port of Houston from State Highway (SH) 146.
- Tacoma, Washington—Interstate 5 and local streets in the vicinity of the Port of Tacoma.

The Interstate 90/94 segment running north-south through Chicago and the I-5 segment between Seattle and Tacoma are among the top 25 truck bottlenecks in the United States based on total truck hours of delay per mile. The Port of Houston and the Port of Tacoma also are major seaports generating high volumes of truck traffic.

For each case study location, a set of representative roadway segments was identified for which to model emissions and noise. For each case study location, baseline traffic speeds and volumes for these roadway segments were first developed to represent conditions without mitigation strategies Out of the 19 potential air quality and noise mitigation strategies considered, 15 were tested in at least one case study location, two were generally characterized based on the literature, one was combined with another strategy, and one was not evaluated. The strategies tested fall into four groups:

- **Capacity and operations improvements—**Strategies such as new roads, lane additions, lane management, geometric changes, or traffic operations that may affect spatial and temporal travel patterns and vehicle activity characteristics.
- **Clean vehicles and fuels—**Strategies to retrofit or replace older, more polluting or noisier trucks with newer, cleaner or quieter technology.
- **Truck operational efficiencies and mode shift—**Strategies to move the same volume of goods with less pollution, for example, by reducing empty truck trips, consolidating loads, or shifting goods from truck to rail.
- **Other noise mitigation strategies—**Strategies to mitigate the noise emitted from truck activity, such as noise barriers, quiet pavements, and building insulation.

Baseline Emissions and Noise Estimates

Emissions were modeled for the morning and afternoon peak periods, 7:00–8:00 a.m. and 4:00–5:00 p.m. respectively. These hours have the highest traffic volumes and congestion levels and therefore would be expected to have the highest emissions of any hour of the day, since emissions increase at lower speeds, especially below 30–35 miles per hour (mph). Heavy trucks were responsible for most emissions of particulates and oxides of nitrogen, with their contribution ranging from 75 to 98 percent depending upon the pollutant, location, and hour. Heavy trucks also contributed 50 to 80 percent of volatile organic compound emissions, while light-duty vehicles contributed the majority of carbon monoxide. In the Houston case study, truck idle outside and operation inside the port contributed to 60–80 percent of pollutants.

Noise was modeled for four hours—including midnight and midday hours in addition to the morning and evening peak hours. In most settings, noise levels were highest during the midday hour (12:00–1:00 p.m.), when both traffic volumes and speeds were relatively high. Because aerodynamic and road noise dominate at highway speeds, increasing traffic speeds tends to increase rather than reduce noise levels. However, noise levels generally did not differ by a perceptible amount across the three daytime hours—only at night when both truck and general traffic volumes were much lower.

Benefits of Hypothetical Mitigation Strategies

Table 1 illustrates the relative benefits of the tested mitigation strategies. While it is tempting to seek strategies that effectively reduce both emissions and noise, the findings of this study suggest that the most effective noise mitigation strategies will be different than the most effective emissions mitigation strategies:

- Strategies that reduce truck emissions by **improving traffic flow and reducing congestion** at bottlenecks are likely to have little if any noise benefit, and in fact, may increase noise as a result of higher vehicle speeds, especially during peak periods. The emissions benefits also will primarily be realized during peak periods.

- Strategies that affect the truck travel route, such as constructing a new road or restricting truck traffic in certain areas, are likely to have effects that are location specific. Rerouting trucks may decrease noise and emissions in certain areas while increasing noise and emissions in the vicinity of the new road or route.

- **Truck replacement and clean truck technology strategies** to replace older, more polluting trucks with newer, cleaner trucks can have very significant emissions benefits at all times of day if the size of the affected truck market is significant, but little if any effect on noise. The exception is for electric trucks, which reduce engine noise, particularly at lower speeds, although benefits at highway speeds are minimal.
- Strategies to reduce truck volumes by **improving the efficiency of drayage operations or shifting freight from truck to rail or water** can have on-road emissions benefits at all times of day, if a substantially sized market exists for such efficiency improvements or modal shifts. However, truck traffic reductions are unlikely to be large enough to perceptibly reduce noise. In the two port case studies, freight movement by rail was currently in use and the potential for additional mode-shift from trucks to rail or water beyond current levels was found to be relatively small.
- **Noise-specific mitigation stratgies** are generally the most effective means of reducing noise levels. Some noise measures also can have benefits for local air pollutant concentrations at near-road receptor locations. Of the measures that have air pollution benefits, noise barriers appear to be the only practical and effective strategy in most bottleneck locations. Quiet pavements on higher-speed roads show a perceptible benefit for noise reduction, but do not affect air quality.

Overall, there may not be a single “one-size-fits-all” emissions and noise reduction strategy in the vicinity of a bottleneck, but rather the best solution may be a combination of strategies tailored to local needs and opportunities on specific types of roads and locations.

Implementation Challenges and Solutions

Implementation challenges and solutions associated with emissions and noise mitigation strategies at truck bottleneck locations were also considered. The nature of the challenges and potential solutions varies somewhat depending upon whether the strategy is focused on infrastructure and operations implemented by the *transportation system owner* (e.g., State or local transportation agency, port authority, railroad), or on vehicle, fuels, or information technology adopted by the *transportation system user* (e.g., vehicle and fleet owners, operators, shippers). Still, there are many common lessons that can be identified based on a review of agencies’ experience with these strategies:

- **Listen and understand—**Hear what the needs and concerns of stakeholders are and work collaboratively on project and program designs that address these needs and concerns.

- **Educate and inform—**Help stakeholders understand and weigh the tradeoffs among the different solutions or alternatives considered.
- **Test—**Especially for innovative or unproven technologies, find controlled locations or limited-scale applications where the effectiveness of the measure can be demonstrated.
- **Leverage—**Coordinate with other public or private initiatives that may create synergies and show multiple benefits.
- **Coordinate—**Work across jurisdictions on strategies that affect interregional, interstate, or long-distance goods movement.
- **Support financing—**Especially for public or private entities with limited resources for whom up-front costs may be a barrier even if there are lifetime benefits or cost savings.
- **Increase funding—**Some challenges can be overcome by designing more expensive solutions, when the added cost is worth the benefits that are provided.
- **Mitigate other impacts—**For negative impacts that cannot be avoided, work with stakeholders, the surrounding community, and concerned parties to identify and implement appropriate measures to mitigate or offset these impacts.

Table 1. Emissions and noise benefits of mitigation strategies.

Mitigation Strategy	Air Quality Effects	Noise Effects
Additional lanes to increase capacity	++	↓↑
Truck-only lanes	+++	↓↑
New roadway	↓↑	Not evaluated
Geometric design changes	+	↓↑
Transportation systems management and operations strategies	+	↓↑
Speed limit/speed management	↓↑	↓↑
Restricting or rerouting trucks	Not evaluated	++
Accelerated retirement, retrofits, engine and powertrain, alternative fuels	+++	Not evaluated
Clean truck corridor; electric charging infrastructure	+++	+
Intermodal facility capacity and efficiency	++	Not evaluated
Truck to rail mode shift	+	+
Noise barriers	+++	+++
Low-noise pavement	○	++
Helmholtz resonators	○	++
Buffer zones	+++	++
Vegetation	+++	++
Building insulation	↓↑	+++

Legend:
- + = typically <5 percent emissions or <3 A-weighted decibels (dB(A)) noise reduction.
- ++ = typically 5–15 percent emissions or 3–5 dB(A) noise reduction.
- +++ = typically >15 percent emissions or >5 dB(A) noise reduction.
- ↓↑ = mixed effects (increase or decrease).
- ○ = no effect.

Notes:
1. The table illustrates representative ranges of benefits based on case study findings and literature. The effectiveness of a mitigation strategy can vary widely depending upon how the strategy is defined and implemented in any particular situation.
2. For noise-specific strategies (starting with noise barriers), the air quality metric is change in air pollutant concentration rather than emissions reduction.
3. A change of 1 dB(A) is considered barely perceptible to some individuals, while a change of at least 5 dB(A) is considered perceptible to most individuals.

1.0 Introduction

Objectives

This report provides information on strategies to address truck emissions and noise at truck freight bottlenecks, including significant highway bottlenecks and truck access to intermodal connectors. The report includes case studies to demonstrate the potential benefits of various mitigation strategies at three highway freight bottleneck and intermodal connector locations. The report considers the extent to which emissions reduction and noise reduction strategies may be mutually supportive or work at cross purposes. The report also considers challenges to implementation of these strategies and potential solutions to overcome them.

According to the American Transportation Research Institute (ATRI), 89 percent of the trucking industry's congestion costs are generated from just 12 percent of Interstate highway miles.[1] Truck freight bottlenecks on the Nation's highway network are problematic not only due to economic impacts, wasted fuel, and delayed freight shipments, but also because they pose air quality and noise concerns due to the high emission rates and noise levels associated with trucks, especially heavy trucks. Despite making up only 10 percent of vehicle-miles of travel (VMT) nationwide, trucks are responsible for over half of fine particulate emissions from on-road sources.[2,3] Congested conditions lead to trucks traveling at low speeds in stop-and-go conditions where emissions per mile are higher than at cruise speeds. Idling truck traffic is also louder than idling automobile traffic and truck noise levels are higher at full throttle, such as when trucks are entering or exiting from bottleneck locations. Air quality and noise impacts are often compounded by the fact that many of the largest truck bottlenecks are in densely populated areas.

A variety of potential strategies are identified to reduce emissions and noise at truck bottlenecks and in other locations with substantial truck traffic, such as roads accessing ports and intermodal facilities. The hypothetical mitigation strategies tested in this report fall into four groups, depending upon their implementation responsibility and general mechanism for affecting emissions:

- **Capacity and operations improvements—**Strategies such as new roads, lane additions, lane management, geometric changes, or traffic operations that may affect spatial and temporal travel patterns and vehicle activity characteristics. These are typically implemented by the infrastructure owner, such as a State Department of Transportation (DOT), municipality, or port authority.
- **Clean vehicles and fuels—**Strategies to retrofit or replace older, more polluting or noisier trucks with newer, cleaner or quieter technology. These may be implemented through regulatory or incentive-based measures applied by entities such as port operators or the State Government.

1 ATRI. Fixing the 12% Case Study: Atlanta, Georgia Fuel Consumption and Emissions Impacts. Available at: https://truckingresearch.org/wp-content/uploads/2019/04/ATRI-Fixing-the-12-Bottleneck-Case-Study-FINAL.pdf.

2 FHWA, Highway Statistics Series.

3 FHWA Analysis of EPA 2014 National Emissions Inventory (NEI) Data, available at: https://edap.epa.gov/public/extensions/nei_report_2014/dashboard.html#sector-db.

- **Truck operational efficiencies and mode shift—**Strategies to move the same volume of goods with less pollution, for example, by reducing empty truck trips, consolidating loads, or shifting goods from truck to rail. These may be implemented in a variety of ways, including infrastructure-based strategies such as intermodal terminal improvements, or information or incentive-based strategies such as real-time routing, load-matching applications, or price incentives.
- **Other noise mitigation strategies—**Strategies to mitigate the noise emitted from truck activity, such as noise barriers, quiet pavements, and building insulation. These are typically infrastructure-based and implemented by the DOT, municipality, or port authority.

Research Process

The research process involved the following steps:

- Assembling a list of major truck bottlenecks in the U.S. as well as major intermodal connectors.
- Flagging a subset of these locations for further investigation based on various screening criteria.
- Researching and recommending a short list of case study candidates based on a review of documents and outreach to local agency staff.
- Identifying potential mitigation strategies to test in each location.
- Finalizing the list of case study locations and mitigation strategies.
- Gathering traffic and other data to support emissions and noise modeling.
- Developing baseline estimates of emissions and noise considering existing traffic conditions.
- Estimating changes in emissions and noise as a result of various mitigation strategies.
- Comparing results across case study locations.
- Considering the extent to which each bottleneck mitigation strategy might have benefits just for emissions, just for noise, or for both effects.
- Considering challenges to implementing mitigation strategies and opportunities to overcome those challenges.

Contents of This Report

Section 2.0 of this report describes the case study locations, hypothetical mitigation strategies tested, and development of data on baseline traffic conditions as well as predicted mitigation measure effects. Section 3.0 describes the approaches used to model baseline emissions and noise conditions and mitigation measure effects. Sections 4.0–6.0 describe the specific conditions and findings for each of three case study locations, Section 7.0 discusses implementation challenges and solutions, and Section 8.0 provides overall conclusions about the estimated emissions and noise benefits of the various mitigation strategies. Appendix A includes a list of references and implementation resources. Appendix B provides additional information on the effects of traffic and other noise abatement strategies on noise levels.

2.0 Case Study Methodology

Case Study Locations

The initial list of candidate case study locations included the top 25 truck bottlenecks in the U.S., based on 2018 truck hours of delay per mile from the National Performance Management Research Data Set (NPMRDS) as calculated by the Federal Highway Administration (FHWA); as well as 18 intermodal facilities identified in a 2017 FHWA study on freight intermodal connectors.[4,5] The project team screened these locations for more in-depth evaluation considering the following criteria, based on a review of public documents and data:

- Potential data availability (e.g., existence of published studies on the location).
- Range of mitigation strategies that might be considered.
- Community size diversity.
- Geographic diversity.

The initial screening led to the selection of locations in 14 metropolitan areas for a second round of screening. The project team researched these areas more thoroughly by reviewing published documentation and by holding conversations with local agency staff to better understand the case study context, assess local interest in supporting the case study, and review screening criteria. The three final selected case study locations include:

- Chicago, Illinois—Vicinity of the Circle (Jane Byrne) Interchange (I-90/94 and I-290) adjacent to downtown Chicago.
- Houston, Texas—Access to the Barbours Cut Terminal of the Port of Houston from State Highway (SH) 146.
- Tacoma, Washington—Interstate 5 and local streets in the vicinity of the Port of Tacoma.

The Interstate 90/94 segment running north-south through Chicago and the I-5 segment between Seattle and Tacoma are among the top 25 truck bottlenecks in the United States based on annual truck hours of delay per mile. The Port of Houston and the Port of Tacoma also are major seaports generating high volumes of truck traffic.

Roadways Modeled and Baseline Traffic Data

For each case study location, the project team identified a set of roadway segments for which to model emissions and noise. These segments were identified as representative segments that are likely to be affected by the various traffic shifts resulting from mitigation strategies. The

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4 The most recently developed list is available from FHWA at https://ops.fhwa.dot.gov/freight/freight_analysis/mobility_trends/national_list_2019.htm.

5 FHWA (2017). Freight Intermodal Connectors Study. FHWA-HOP-16-057, available at: https://ops.fhwa.dot.gov/publications/fhwahop16057/sec1.htm.

representative segments also were selected based on their location near receptor areas, including residential areas, schools, and hospitals. The case studies did not attempt to quantify all emissions in the study area or all sources that would be affected by the hypothetical mitigation strategies.

For each case study location, baseline traffic speeds and volumes for these roadway segments represent conditions without mitigation strategies. To ensure consistency the FHWA [Database for Analysis of Noise and Air Quality (DANA) tool] was the primary source for speeds and volumes. DANA is a database that combines information from the NPMRDS and the Travel Monitoring Analysis System (TMAS). The project team extracted data for case study area roadways that included speeds for two vehicle types (light-duty vehicles and trucks) for every hour of the year 2019, and estimates of average annual hourly and daily traffic volumes for five vehicle types (motorcycles, light-duty autos and trucks, single-unit trucks, and combination trucks). The traffic volume data are based on 2017 reporting by States for the Highway Performance Monitoring System (HPMS). Data is included for all segments of the National Highway System (NHS). These years were the latest available at the time of data collection.

In a few cases, the project team modified or supplemented data from DANA with State or local sources such as State DOT traffic or classification counts or data from project studies. In most cases, however, State and local data were neither as consistent nor as comprehensive as the DANA tool data. Data limitations meant that the representative roadway segment analysis was for the most part limited to segments of the NHS.

The data extracted from the DANA tool included annual average daily volumes as well as speeds for four representative hours of the day. A morning peak hour of 7:00 to 8:00 a.m. and an evening peak hour of 4:00 to 5:00 p.m. were used to represent peak-period conditions when volumes, delay, and emissions are likely to be highest. These time periods were the focus of the air pollutant emissions modeling and were selected based on inspection of Motor Vehicle Emissions Simulator (MOVES) inputs provided with the DANA tool showing that these hours typically had the largest fraction of hourly volumes in the case study counties.[6] The project team also extracted additional traffic data to support the noise analysis, including the midnight to 1:00 a.m. time period to represent free flow speeds, and the noon to 1:00 p.m. time period to represent a period of high traffic volumes but higher speeds which may show higher noise levels then peak congested periods.

The project team processed the speed data from the DANA tool to develop average annual weekday speeds for each time period and vehicle type based on the speeds reported by hour and day in the DANA tool database. The speed data in DANA represents actual, observed speeds based on anonymous tracking of mobile devices such as cell phones and global positioning system (GPS) units.

6 Hourly volume fractions vary by road type and vehicle type. The peak periods were selected based on highest total vehicle volume. in some cases an adjacent time period, such as 5:00 to 6:00 p.m., showed a higher hourly fraction for some vehicle and/or road types, but in general the selected time periods were close to if not the highest hourly fractions of total volume. In some cases truck volumes peak during mid-day hours, but it was desired to keep the same analysis period for all vehicle types.

Daily volumes were assigned to the analysis hours based on an hourly distribution of volumes for each roadway segment. Segments were identified as traffic message channel (TMC) links as developed for the MOVES inputs in the DANA tool. The DANA tool uses data from TMAS to assign hourly volume percentage distributions for each vehicle type on each day measured. These hourly fractions were applied to the annual average daily traffic (AADT) to produce hourly volume estimates for each vehicle type (light-duty vehicles, single-unit trucks, and combination trucks).

Volume data in the DANA tool is taken from HPMS reporting which is based on traffic volume counts at continuous or temporary counters nearest the segment. The split of volumes by vehicle type is based on classification counts, which may represent the actual mix on the segment itself, an average mix for the same road type in the same county or State (if segment data is not available), or (if no regional mix can be identified) a national average for that roadway type.

Hypothetical Mitigation Strategies

The mitigation strategies tested for each case study, and the approach and data sources for modeling vehicle activity and emissions changes from these strategies, are described in the respective case study sections of this report. Each strategy is labeled with a strategy number (S#) that is consistent for the same strategy across all case studies. However, not every strategy was modeled in each case study. The following mitigation strategies were considered for testing in some or all case studies, numbered with their S#:[7] Strategies that were not tested have an explanatory note in parentheses. Strategies also are referred to as “scenarios” when modeled in the context of a specific case study (e.g., “Tacoma Scenario 4” refers to modeling strategy 4 for Tacoma):

- **S2:** Additional lanes to increase capacity.
- **S3:** Truck-only lanes.
- **S4:** New roadway.
- **S5:** Geometric design changes.
- **S6:** Transportation system management and operations (TSMO) strategies such as signal coordination, traveler information, incident management, and other strategies to improve traffic flow.
- **S7:** Speed limit reduction/speed management.
- **S8:** Restricting or rerouting trucks.
- **S9:** Accelerated retirement/clean truck replacement.
- **S10:** Engine and powertrain retrofits and alternative fuels (combined with S9).
- **S11:** Clean truck corridors, including electric trucks and charging infrastructure.

[7] S# starts at 2 since S1 is used to denote the base case.

- **S12:** Intermodal facility capacity and efficiency.
- **S13:** Truck to rail mode shift.
- **S14:** Truck to water mode shift (not evaluated due to lack of data).
- **S15:** Noise barriers.
- **S16:** Low-noise pavement.
- **S17:** Helmholtz resonators (characterized based on literature).
- **S18:** Buffer zones.
- **S19**: Vegetation.
- **S20:** Building insulation (characterized based on literature).

Emissions results are reported based on 2025 emission factors to represent a possible near-term year by which strategies could be implemented. The traffic data inputs may reflect conditions from different years, including baseline traffic data from 2017 and 2019 (DANA), and changes in traffic volumes and speeds based on local project studies that modeled future years as far out as 2045. For consistency, rather than attempting to reconcile different values of absolute speeds and volumes from project studies as compared to the DANA tool, the project team applied percent changes in volumes and speeds from these studies, for the project vs. no-project alternative in the study's evaluation year, to the baseline volumes and speeds from the DANA tool.

Lacking mitigation strategy data specific to medium versus heavy trucks, in most cases the same assumptions for volume or speed changes were applied to medium trucks as to heavy trucks. The exception is for electric trucks, where different market shares were used for medium and heavy trucks. Also, idle reduction strategies and strategies to increase drayage efficiency were assumed to affect only heavy truck emissions.

The traffic data (volumes and speeds by vehicle type and link) used for each scenario in each case study is contained in a set of spreadsheet files, one for each case study. These files are available upon request from the FHWA Transportation and Air Quality Conformity Team at taqc@dot.gov. The "Scenarios" tab in those files describes each strategy modeled. Strategy 1 (S1 tab) is the baseline data.

It is important to note that the mitigation strategies are hypothetical and are evaluated simply to test their potential effects on emissions and noise. The strategies tested in this report were not validated for implementation feasibility or local support in the case study locations.

3.0 Modeling Approach

Emissions Modeling

The emissions modeling approach uses the U.S. Environmental Protection Agency (EPA) MOVES model version 3.0.1, the latest version available when modeling was conducted, for baseline emissions estimation and evaluation of strategies that can be directly evaluated using MOVES. MOVES was run at the project level. The focus of the case studies was on emissions generated on the public road network. However, the mitigation strategies also included idle reduction strategies, and some of that idling may take place within the port off the public road network.

For each case study location, application of MOVES at the project scale had three elements: 1) a baseline run specification file ("runspec") which defines the basic parameters of each modeling run; 2) a baseline project-level database (PDB) that supplies vehicle fleet and traffic data specific to the case study location, in the format required for MOVES; and 3) for mitigation strategies, alternate runspec and/or PDB tables that affect the required change in traffic volume, vehicle technologies, etc. Table 2 shows MOVES run spec inputs for the case studies, for the baseline scenario.

Table 2. Motor Vehicle Emissions Simulator runspec template for case studies.

Run Spec Input	Approach	Comments
Pollutants	Volatile organic compounds (VOC) Carbon monoxide (CO) Oxides of nitrogen (NO_x) Particulate matter, smaller than 10 or 2.5 microns (PM_{10}, $PM_{2.5}$) Mobile source air toxics (MSAT) Carbon dioxide equivalent (CO_2e)	MSATs are presented as sum of five FHWA priority toxics: 1,3-butadiene, acrolein, acetaldehyde, benzene, formaldehyde.
Geographic area	County of case study location. • Chicago: Cook County, IL • Houston: Harris County, TX • Tacoma: Pierce County, WA	MOVES runspec only goes to county level, which defines default meteorology, fuel and I/M program information. Definition of specific study area will take place in project database, via definition of links.
Vehicles	Passenger cars, light-duty trucks, single unit trucks (short and long haul) and combination trucks (short and long haul).	Most mitigations only affect a subset of these classes.
Road Type	Urban restricted, urban unrestricted.	Generally urban restricted for urban bottlenecks, urban unrestricted for ports. Within this road type, individual road links were defined in the PDB.
Analysis year	2025.	–
Time periods	AM and PM peak hours (7:00–8:00 a.m., 4:00–5:00 p.m.).	–

Each case study had a custom project database created, composed of individual MySQL tables in the input format required by MOVES. Within the context of the MOVES run spec, the PDB defines the details of the case study setup (e.g., specific roadway links, lanes, or port terminals) and supplies the volume of trucks and their activity. The PDB can accommodate multiple links for a given scenario—defined as individual roadways, lanes and/or directions—with different traffic volume, vehicle mix and speeds as applicable. For each roadway segment listed, six individual links were defined, corresponding to two directions and three vehicle types (light-duty vehicle, single-unit truck, combination truck). Links were added for the Tacoma and Houston case studies to capture truck idle outside the port terminals, and operation within the terminal (Houston only). These provided the detail necessary to account for different volumes and speeds by vehicle class, and mitigation strategies aimed at specific truck types (e.g., port drayage trucks, predominantly combination trucks). The PDB also provides other attributes important for estimating emissions in a specific location such as fuel properties, meteorology, and inspection/maintenance program details. Separate PDBs were developed for the AM and PM peak hours, using the same project setup for each and differentiated only by traffic volume and speeds. Table 3 includes a list of PDB tables and data sources common to each case study.

Table 3. Motor Vehicle Emissions Simulator project-level inputs and data sources.

MOVES Project-Level Input (PDB Table)	General Sources: Baseline
Age Distribution (sourceTypeAgeDistribution)	2017 National Emissions Inventory (NEI).
Traffic Volume (Link)	6 links per road segment—2 directions x 3 vehicle types. See section 2.0 on traffic data. Additional port-related links in Tacoma and Houston for combination trucks only, using the port driving schedule referenced in National Cooperative Highway Research Program (NCHRP) Report 909.[1]
Vehicle Mix (Source Type Hour Fraction)	2017 NEI.
Operating Mode Distribution, Drive Schedule, or Average Speed	Average speeds—See section 2.0 on traffic data.
Link Length (Link)	Measurement from Google Earth based on links defined for traffic data.
Grade (Link)	Grade assumed zero for all cases.
Off-Network	This feature of MOVES was not used. Idle and port terminal links were modeled as on-network links with speed of 0 and 2.5 miles per hour (mph), respectively.
Meteorology (Zone Month Hour)	2017 NEI.
Fuels (Fuel Supply, Fuel Formulation, Alternative Vehicle and Fuel Technologies)	MOVES3 default database.
I/M Program (I/M coverage)	2017 NEI.

[1] Porter, C., et al (2019). *Guide to Truck Activity Data for Emissions Modeling*. National Cooperative Highway Research Program Report 909, Section 5.4.4, “Drive Cycle and OMD Library.”

Mitigation strategies that affect truck volume and speeds, including reduced idle at ports, were modeled by modifying average speed and traffic volume in the Link table. In the case of Tacoma, mitigation Scenario 4 (new roadway) required the addition of new links that were not present in the baseline. The same approach was required for Scenario 3 in Houston, where a new connector between a state highway and local street was modeled.

Modeling clean truck replacement programs (Scenario 9) for Houston and Tacoma required modifying the sourceTypeAgeDistribution table. The age distribution for combination trucks (short and long haul) was modified to remove trucks from model years 2007 and older, since the EPA adopted new emissions control standards that began to take effect in model year 2007 (U.S. EPA, 2001). Since the age distribution across all age bins needs to add up to 1, the fraction representing older trucks was assumed to be replaced for new trucks and added to the age bin representing the newest vehicles (age=0). An illustration of the differences between age distributions for the baseline and the mitigation scenario is shown in figure 1 for combination short-haul trucks in Pierce County.

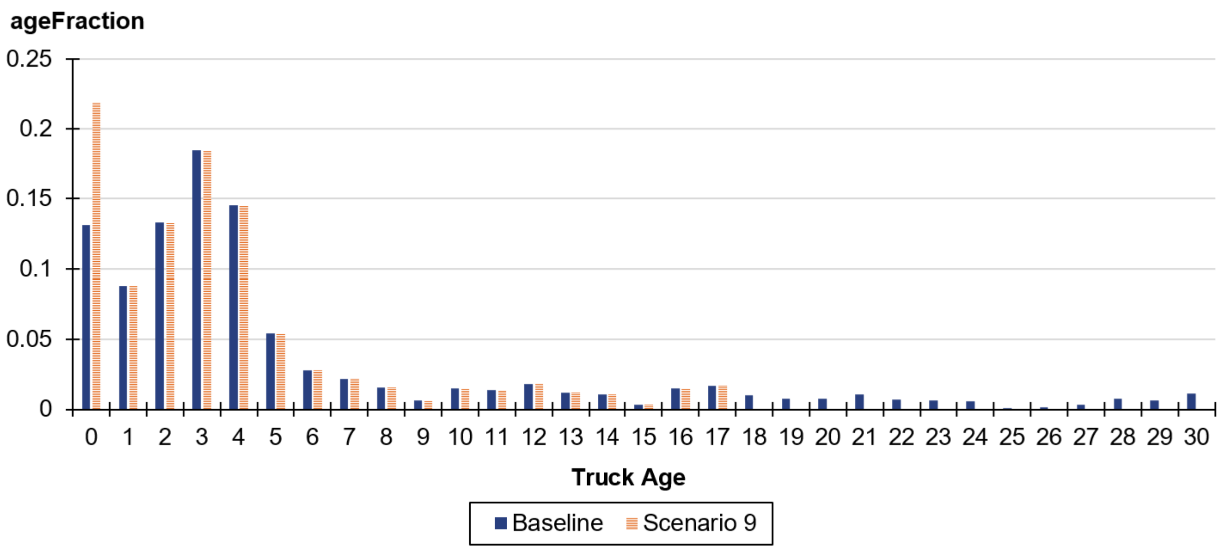

Figure 1. Chart. Age distribution for combination short-haul trucks in Pierce County in baseline and Scenario 9.

(Source: FHWA.)

For the case of Tacoma, two versions of Scenario 9 were evaluated, one in which only pre-2007 trucks serving the report were replaced, and one in which all pre-2007 trucks in the study area were replaced. For the port truck-only replacement scenario, the emissions modeled with MOVES for Scenario 9 were further postprocessed and weighted according to daily port-originating truck volumes by link estimated by the Port of Tacoma (2016) as a fraction of total truck trips. Note that the Port of Tacoma's clean truck programs (Northwest Seaport Alliance, et al, 2018) have already led to the vast majority of the fleet serving the port meeting post-2007 emissions standards, so this variation of the strategy has essentially been implemented already.[8]

[8] Correspondence with Christina Wolf and Graham VanderSchelden, Port of Tacoma, March 15, 2022.

Noise Modeling

For each case study location, the project team used the Traffic Noise Model (TNM) versions 3.0 and 3.1 to establish baseline noise levels and mitigation effectiveness (noise reduction) for strategies that could be modeled using TNM. Other information, including from literature sources and basic relationships between traffic and noise embedded in TNM, was used to generally characterize the effects of mitigation strategies that could not be directly modeled using TNM. These relationships are described in appendix B.

TNM 3.0 was initially used to model the base case for each location as well as the strategies listed in table 2 that affected traffic volumes and/or speeds. TNM 3.1 became available during the course of the study (January 2022) and was used to complete the modeling of other (nontraffic) noise mitigation strategies and additional receptor locations. Nontraffic noise mitigation strategies were modeled in TNM 3.1 using general characterizations of these strategies (e.g., noise barrier geometry and materials) rather than site-specific characterizations reflecting the constraints of each location. While TNM 3.1 included enhancements supporting ease of use, it did not contain changes to the underlying acoustics or other items that would affect modeled noise outcomes.

The following generic process was used for the TNM analysis:

- **Sources:**
  - Roadway: Representative roadway links in the bottleneck area (the same set selected for the emissions analysis) were defined using a coordinate system and endpoints for each modeled link.
  - Vehicles: Cars, medium trucks, and heavy trucks were the only vehicle types included in the analysis.
  - Other: Background noise was not included as this was a relative analysis of changes and not an absolute analysis of area noise levels.
  - Pavement: Average pavement was used in all analyses except for the quiet pavement mitigation measure.
- **Propagation Path:**
  - Diffraction: Large items were defined such as noise barriers, retaining walls, berms, terrain, vegetation, crash barriers, major buildings, smaller building rows, and other large permanent objects.
  - Ground effects: Major areas were defined including pavement, grass, soil type, water, and/or custom for any unusual surfaces. Coordinates, either endpoints or zones, were determined for each modeled object or ground surface.
  - Other: Atmospheric refraction was not considered.
- **Receivers:** Receivers were placed in three primary areas:
  - Real locations: These included sensitive receptors such as residential areas, schools, churches, historic locations, hospitals, libraries, and care facilities at key locations. In the

Chicago case study, receiver locations were taken from a previous noise analysis that was conducted in the study area.

- Other locations: Areas of interest were based on local parameters, such as near the roadways and unshielded as well as away from the roadway with diffraction objects in the path. Exact placement of other receivers varied depending on area characteristics. For example, receivers were not placed in the middle of a building or at other unreasonable locations.
- Grid location: To test the effects of buffer areas, receivers were placed in open areas at doublings of distance from the roadway, starting at 50 feet.

Table 4 indicates the sources of information used for the TNM modeling. Data was collected remotely, without field data collection.

Table 4. Information sources for noise analysis.

Information Category	Information Detail	Comments
Traffic	Hourly volume by vehicle type, vehicle speeds, expected free flow or interrupted flow.	Vehicle types in this analysis include passenger cars, medium trucks, and heavy trucks. Traffic data sources are described in section 2.0.
Cross section and plan view of roadway	Cross section and plan view of roadway at a minimum. Other mapping or details include large objects nearby (e.g., buildings), terrain profiles, land use characteristics, pavement type, and ground cover.	Information was taken from United States Geological Survey (USGS) maps, project plans if available, Google Street View, satellite imagery, other data available through State and local contacts, and literature. Needed roadway details included number of lanes, shoulder width, and grade.
General area mapping	Google Earth was used as the primary mapping tool.	Google provided the basis for much of the modeling. However, in some cases detail was dated or lacking. Other measures were used in this case, including the use of street view.
Detail mapping	USGS mapping.	In some cases, USGS maps were obtained and used for local topography needs.
TNM 2.5	Previous TNM modeling files.	The TNM 2.5 files from the Chicago project noise analysis were obtained and converted into a TNM 3.0 run.

Table 4. Information sources for noise analysis (continuation).

Information Category	Information Detail	Comments
AutoCAD	Geometric detail.	In some cases, AutoCAD files were generated and used for precision when digitizing data from maps did not provide the detail needed.
Time scales	Hourly data on volumes and speeds.	Equivalent continuous sound pressure level (Leq) was estimated based on hourly traffic data. The analysis year was the same as the air quality analysis (2025).
Noise mitigation strategies	Locations and characteristics of other mitigation strategies.	General characteristics were used, rather than developing site-specific characteristics for strategies such as noise barriers and vegetated zones.
Other inputs	Meteorology, TNM setup, etc.	Default values were used.

Summary of Emissions and Noise Analysis Methods

Table 5 identifies the basic methodology used to model or otherwise evaluate emissions and noise effects for the base case and for each mitigation strategy.

Table 5. Emissions and noise mitigation strategy evaluation methods.

S#	Mitigation Strategy	Emissions	Noise
1	Base case	MOVES model.	TNM 3.0.
2	Additional lanes to increase capacity	MOVES model, with changes in volumes and speeds based on source studies for project.	TNM 3.0, with changes in volumes and speeds based on source studies for project.
3	Truck-only lanes	MOVES model, with changes in truck speeds to represent free flow conditions.	TNM 3.0; evaluated by placing lanes on inside of roadway and changing truck speeds to represent free flow conditions.
4	New roadway	MOVES model, with changes in volumes and speeds based on source studies for project.	Not evaluated.
5	Geometric design changes	MOVES model, with changes in volumes and speeds based on source studies for project.	TNM 3.0; evaluated by changing volumes and speeds based on source studies for project(s) in the case study areas.
6	TSMO strategies	MOVES model, with changes in speeds based on estimates of strategy effects.	TNM 3.0; evaluated using speed and volume changes.

Table 5. Emissions and noise mitigation strategy evaluation methods (continuation).

S#	Mitigation Strategy	Emissions	Noise
7	Speed limit/speed management	MOVES model, with changes in speeds.	TNM 3.0; evaluated by changing free flow speed inputs.
8	Restricting or rerouting trucks	Not evaluated for emissions.	TNM 3.0/3.1; evaluated with volume changes only on the bottleneck roadway.
9	Accelerated retirement/clean truck replacement	MOVES model, with changes in truck age distributions.	Not evaluated.
10	Retrofits, engine and powertrain, alternative fuels for combustion engines	MOVES model, with changes in truck age distributions (note—the same approach was used to model both Strategies 9 and 10 so only one set of results is reported.)	Not evaluated.
11	Clean truck corridor; electric charging infrastructure	MOVES model, with reductions in truck traffic volumes corresponding to electric truck share.	TNM 3.0; electric trucks were removed from the traffic stream as a “best-case” assessment of reduced noise levels.
12	Intermodal facility capacity and efficiency	MOVES model, with changes in truck volumes.	TNM 3.0; evaluated by reducing truck volumes on study area roads to account for reduced truck drayage traffic, keeping other parameters constant.
13	Truck to rail mode shift	MOVES model, with changes in truck volumes.	TNM 3.0; evaluated by reducing truck volumes on study area roads to account for diverted truck to rail traffic, keeping other parameters constant.
14	Truck to water mode shift	Not evaluated in any case study.	Not evaluated.
15	Noise barriers	Emissions effects generally characterized based on literature.	TNM 3.1; evaluated by introducing a barrier with varying characteristics.
16	Low-noise pavement	Not evaluated for emissions.	TNM 3.1; evaluated via literature review and by comparing average to open-grade pavement.
17	Helmholtz resonators	Not evaluated for emissions.	Effects were generally characterized based on the literature.

Table 5. Emissions and noise mitigation strategy evaluation methods (continuation).

S#	Mitigation Strategy	Emissions	Noise
18	Buffer zones	Emissions effects generally characterized based on literature.	TNM 3.1; evaluated by examining noise levels and varying distances from the roadway in an unshielded location. Effects also reviewed based on literature.
19	Vegetation	Emissions effects generally characterized based on literature.	TNM 3.1; evaluated by introducing a tree zone. Effects also reviewed based on literature.
20	Noise insulation	Emissions effects generally characterized based on literature.	Effects were generally characterized based on the literature.

Presentation and Interpretation of Emissions and Noise Results

The project team modeled baseline emissions at each location for the 7:00–8:00 a.m. and 4:00–5:00 p.m. time periods. Emissions are expressed as total mass of pollutant (in kilograms) by hour emitted on the selected study area roadways. Total emissions include all vehicles in the case study: light-duty vehicles as well as medium and heavy trucks. Particulate emissions include brake and tire wear as well as exhaust emissions.

The baseline emission results are primarily useful as context for understanding the relative benefit of different mitigation strategies, which are influenced by the relative contributions of single-unit and combination trucks to total emissions, differences in AM and PM peak-hour traffic, and the relative contribution of each link to the total case study. The inclusion of port-related activity in Tacoma and Houston also sheds light on the importance of “off-network” truck activity (such as idling at gates and on port property) on emissions near goods movement hubs.

Emissions for mitigation scenarios are shown as the percent change in total emissions for the modeled facilities in each case study relative to the baseline. Although most mitigations only affect trucks, presenting emissions from all on-road vehicles illustrates the degree to which a specific mitigation could affect overall air quality in the case study area.

Noise effects were modeled at a variety of locations near the selected roadway segments. These positions include residential areas, schools, and hospitals. Baseline sound levels were modeled for the 12:00–1:00 a.m., 7:00–8:00 a.m.,12:00–1:00 p.m., and 4:00–5:00 p.m. time periods. Sound levels for mitigation strategies were modeled for one or more selected time periods where baseline noise levels were highest. Relatively modest changes in speeds and/or volumes led to very small noise effects, so only strategies with larger traffic impacts were modeled for noise effects. Summary results are presented, including average, median, minimum, and maximum noise values across receivers as well as changes in these statistics for the mitigation strategies. Cumulative distributions of noise levels across all receivers are also shown. Detailed results by receiver are available upon request from the FHWA Transportation and Air Quality Conformity Team at taqc@dot.gov.

4.0 Chicago Case Study

The Chicago case study focused on Interstate 90/94 at its interchange with Interstate 290, adjacent to downtown Chicago. The I-90/94 segment running north-south through Chicago is among the top 25 truck bottlenecks in the United States based on total truck hours of delay per mile.

Roadways and Traffic Data

Table 6 lists the roadway segments modeled for the Chicago case study. "TMC" is the traffic message channel link identification that can be used to identify the link in the DANA tool.

Table 6. Chicago case study roadway segments.

Map Key	Description	TMC 1	Direction 1	TMC 2	Direction 2
1	I-90/I-94—Through Byrne Interchange	107P04244	NB	107N04244	SB
2	I-290—Through Byrne Interchange	107N04184	EB	107P04184	WB
3	I-290—West of Interchange	107N04185	EB	107+04185	WB
4	I-290—East of Interchange	107N04183	EB	107P04183	WB
5	I-90/I-94—North of Interchange	107+05323	NB	107-04244	SB
6	I-90/I-94—South of Interchange/Taylor St	107P04243	NB	107N04243	SB

Figure 2 shows the location of these segments (dashed lines) as well as nearby receptor areas (solid polygons). In general, the study area is densely developed with multiple uses. The northwest quadrant of the study area includes dense residential, commercial, and mixed-use development while the southwest quadrant area mainly includes a postsecondary educational institution, the campus of the University of Illinois at Chicago.

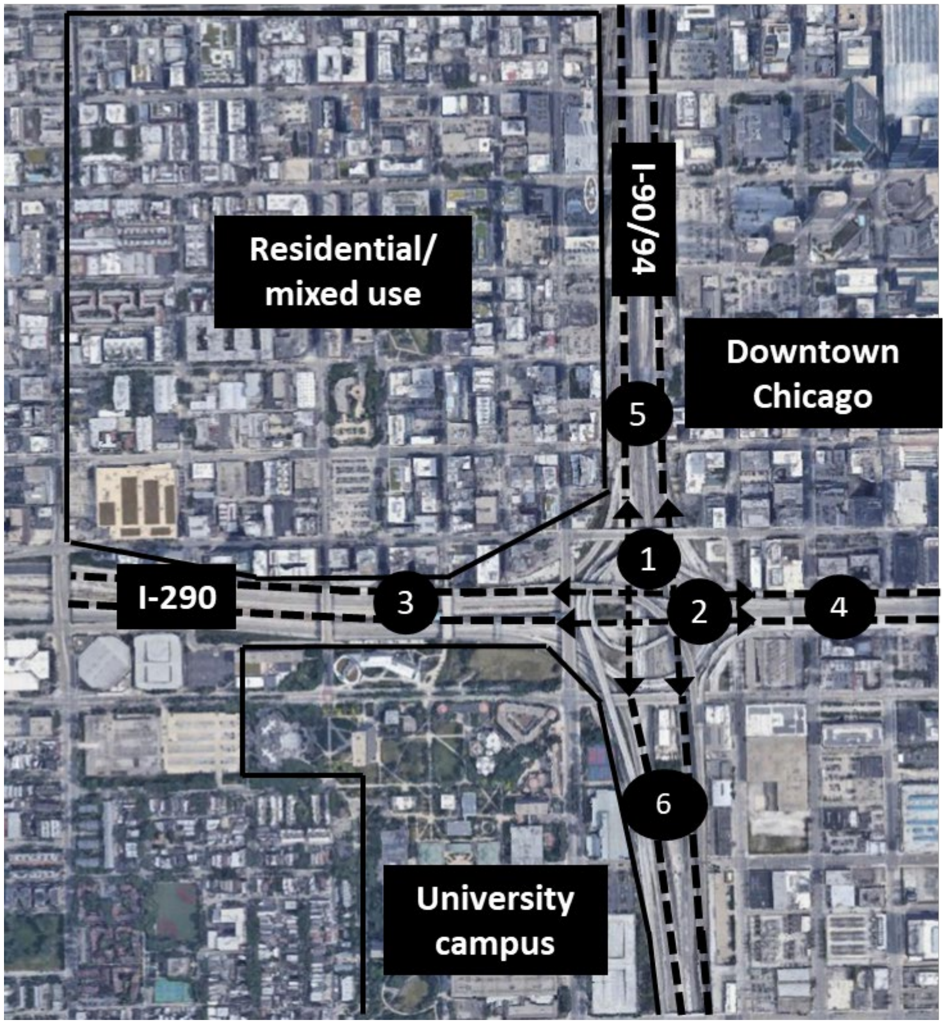

Figure 2. Map. Chicago case study roadway segments and receptor areas.

(Source: FHWA, Aerial image source: Google Earth.)

Baseline speed and volume data for the Chicago case study were taken straight from the DANA tool with no adjustments.

Mitigation Strategies

Table 7 shows the mitigation strategies considered and key data sources and assumptions used in the Chicago case study. Shaded rows labeled “N/A” are strategies that were considered but not modeled, for reasons explained in the table.

Table 7. Mitigation strategies and evaluation approaches: Chicago case study.

S#	Mitigation Strategy	Specific Project Concept	Data Sources and Assumptions
2	Additional lanes to increase capacity	Circle Interchange study (I-90/94 at I-290): the Preferred Alternative will include four lanes per direction along I-90/94, widening (to 2 lanes) and geometric realignment of north-west and east-north ramps; and new northbound and southbound collector/ distributor roads.	Traffic simulation output speeds by segment taken from Circle Interchange Combined Design Report. To the DANA speed baseline, the percent change in speeds was applied based on modeling 2040 no-build versus 2040 build conditions from table C (page 229) of the Circle Interchange Combined Design Report Vol. 1. To the DANA volume baseline, percent changes in annual average daily traffic (AADT) were applied based on 2040 no-build versus 2040 build from Circle Interchange Noise Analysis Study figure B.1.
3	Truck-only lanes	One truck-only lane in each direction on I-90/94 and I-290 (outside lanes), in addition to existing general-purpose lanes.	Increase truck speeds on I-90 and I-290 segments to 45 mph (DANA data from 12:00–1:00 a.m. shows speeds of 36–44 mph through the interchange area; speed limit is 45 mph). In selected subscenarios, move trucks close to centerline of highway (inside lanes).
4	New roadway	No viable new roadway concepts were identified for this heavily built-up area.	N/A
5	Geometric design changes	Modeled as part of Strategy #2 (Circle Interchange improvements), which include both capacity and geometry changes.	N/A
6	TSMO strategies	Managed lanes, pricing, and connected vehicle operations to achieve free flow conditions within existing geometry.[1]	Increase all vehicle speeds on I-90 and I-290 segments to 45 mph (noted by the Circle Interchange study as the speed limit within the project limits).
7	Speed limit/ speed management	The speed limit within the project limits already is a low maximum of 45 mph, and DANA data shows that maximum speeds even during off-peak hours are typically no greater than that. Therefore, further speed management is not expected to be effective at reducing emissions and was not modeled.	N/A

Table 7. Mitigation strategies and evaluation approaches: Chicago case study (continuation).

S#	Mitigation Strategy	Specific Project Concept	Data Sources and Assumptions
8	Restricting or rerouting trucks	Priority truck routes have been generally proposed as a strategy in the region, with the objective of directing trucks to certain arterials. However, local agency staff did not expect that any significant changes to truck volumes on the study area segments would be expected as a result of truck route designation. The analyzed segments are Interstates and while congested, are still higher speeds (and more removed from emission/noise receptors) than local streets. Rerouting trucks would simply shift emissions and noise elsewhere.	N/A
9 and 10	Accelerated retirement/ clean truck replacement; engine and powertrain retrofits, alternative fuels	Require trucks serving local origins/destinations to meet post-2007 emissions standards.	Freight Analysis Framework 4 (FAF4) shows 57 percent of trucks on I-90/94 and 85 percent of trucks on I-290 to have at least one trip end within the Chicago region. Age distribution adjustments to simulate a post-2007 fleet were applied to these percentages of combination truck volume. Pre-2007 "local" trucks represented 6% of study area trucks on I-90/94 and 9% on I-290.
11	Clean truck corridor; electric charging infrastructure	Regional and multistate corridor policies and investments (including truck charging infrastructure) to encourage the use of electric trucks. I-90/94 is a Federally designated Alternative Fuels Corridor.	Based on National Renewable Energy Laboratory (NREL) Electrification Futures Study[2] "medium" case projections of truck electrification, exclude 5.2% of medium duty trucks (MDT) (type 50) and 3.0% of heavy duty trucks (HDT) (type 60) for 2030 case (S11.1) from emissions and noise calculations (including for idle links), and exclude 45.4% of MDTs (type 50) and 20.1% of HDTs (type 60) for 2045 case (S11.2).

Table 7. Mitigation strategies and evaluation approaches: Chicago case study (continuation).

S#	Mitigation Strategy	Specific Project Concept	Data Sources and Assumptions
12	Intermodal facility capacity and efficiency	No major intermodal facilities were located in the study corridor, so improvements to local intermodal facility operations were not evaluated.	N/A
13	Truck to rail mode shift	Freight rail and intermodal facility improvements, such as those proposed as part of the Chicago Region Environmental and Transportation Efficiency study, to support movement of goods through the region directly on rail rather than truck or truck-rail combinations.	FAF4 freight flow data were evaluated to consider truck and rail freight flows in the Detroit—Milwaukee market as an example of where truck trips might be converted to rail. It is assumed that 50% of the tonnage between these market areas currently moving by truck could be moved by rail and the associated truck traffic (93 trucks per day) removed from I-90/94.
14	Truck to water mode shift	No market was identified to shift truck traffic from this corridor to water.	N/A
15	Noise barriers	Not modeled—tested in the Tacoma case study.	N/A
16	Quiet pavement	Not modeled—tested in the Tacoma case study.	N/A
17	Helmholtz resonators	Not modeled—no methodology in TNM.	N/A
18	Buffer zones	Hypothetical undeveloped buffer zone adjacent to highway.	Receivers at regular distances from the roadway were evaluated in an unobstructed location.
19	Vegetation	Not modeled—tested in the Houston case study.	N/A
20	Noise insulation	Not modeled—no methodology in TNM.	N/A

[1] The timeframe to achieve market penetration of a large enough share of connected and/or automated vehicles to make it possible to achieve free flow speeds with existing volumes within the existing roadway footprint is highly uncertain and may be many years in the future. However, this scenario serves to illustrate the potential benefits of such conditions should they be achieved.

[2] Mai, T., et al (2018). NREL describes the “medium” scenario as: a future with widespread electrification among the “low-hanging fruit” opportunities in electric vehicles … but one that does not result in transformational change.

Emissions

Baseline Emissions

The Chicago case study shows that modeled emissions for all pollutants are higher during the PM hour than the AM hour (table 8). Emissions for VOC and $PM_{2.5}$ double during the afternoon while the increase in other pollutants ranges from 31 percent (CO_2e) to 67 percent (NO_x). The increase in emissions is consistent with the overall lower average speed observed during the afternoon hour. While the total traffic volume is slightly lower during the afternoon (8 percent reduction relative to morning traffic volume), the volume of trucks increases slightly (7 percent) and the overall average speed is reduced from 32 mph to 23 mph, which represents a decrease of almost 30 percent relative to the overall average speed observed during the morning.

Table 8. Total emissions for Chicago baseline case.

Pollutant	Emissions in AM peak hour (kg)	Emissions in PM peak hour (kg)
CO	59	92
NO_x	18	29
VOC	1.3	2.1
Total $PM_{2.5}$	1.2	2.4
CO_2e	12,659	16,639
MSATs[1]	0.1	0.2

[1] Sum of 1,3-butadiene, acrolein, acetaldehyde, benzene, formaldehyde.

The baseline emissions modeled for the Chicago case study indicate that heavy-duty trucks dominate most pollutant emissions, contributing over 60 percent of VOC and 85 to 93 percent of NO_x and PM, while CO is contributed mainly by light-duty vehicles. There are no significant changes in the light- versus heavy-duty share between morning and afternoon rush hours, only a small increase (~5–6 percent) in the contribution of heavy-duty to $PM_{2.5}$ and VOC emissions during the afternoon peak hour.

In terms of the contribution from specific roadway segments modeled, the major contributor to the Chicago case study is the I-90/I-94 section, particularly the north link (segment 5). For all criteria pollutants, I-90/I-94 contributes close to 70–80 percent of the emissions depending on pollutant and hour of the day, with the north link consistently contributing 35–39 percent of the emissions. No significant changes are observed in the link contribution to emissions of criteria pollutants between morning and afternoon peak hours.

Emissions Effects of Mitigation Strategies

Percent reductions in total emissions for specific mitigations are shown in table 9 for the AM and PM peak hours. On a relative basis, $PM_{2.5}$ and NO_x reductions are largest since heavy trucks contribute the majority of these emissions. The Circle Interchange capacity and geometry improvements (S2) showed benefits of 7 to 21 percent in the PM peak depending on the pollutant, and up to 7 percent in the AM peak. Truck-only lanes and TSMO (in this case study, managing traffic through automated vehicle strategies to maintain free flow speeds on highways while accommodating the same volume) show the largest overall reductions—in the range of 25 to 50 percent for NO_x and up to 64 to 70 percent lower $PM_{2.5}$—as they directly address the high emissions from severe freeway congestion observed in baseline traffic data, especially for the afternoon peak. Replacement of pre-2007 trucks with post-2007 trucks (or engines) also provides significant benefits for NO_x, VOC, $PM_{2.5}$, and MSATs (12 to 18 percent for replacement of local trucks, or 15 to 30 percent for all trucks), although it has little benefit for CO or carbon dioxide (CO_2). Truck electrification benefits depend on the penetration rates of advanced technologies, which are limited in 2030 but more significant by 2045, with benefits of 11 to 22 percent (for all pollutants except CO) at the projected 2045 market share levels. For truck electrification, though exhaust $PM_{2.5}$ is reduced, brake and tire $PM_{2.5}$ were assumed unchanged from the baseline, resulting in a lower overall $PM_{2.5}$ benefit compared to NO_x and VOC. Of all strategies, shifting to rail was estimated to have less than 1 percent benefit due to the relatively low volume of truck traffic that could be shifted.

Table 9. Percent change in emissions from Chicago baseline case.

Peak Hour	Pollutant	S2—Add New Lanes	S3—Truck-Only Lane	S6—TSMO	S9a—All Post-2007 Trucks	S9b—Post-2007 Local Trucks	S11.1—Clean Trucks (2030 Share)	S11.2—Clean Trucks (2045 Share)	S13—Rail Shift
AM	CO	1	-5	-16	-1	-0.7	-1	-6	-0.1
	NO_x	-2	-25	-25	-19	-12	-3	-22	-0.6
	VOC	-2	-15	-23	-18	-12	-2	-18	-0.3
	Total $PM_{2.5}$	-7	-37	-42	-26	-17	-1	-11	-0.5
	CO_2e	3	-6	-9	-1	-0.7	-2	-11	-0.3
	MSATs	-2	-18	-24	-25	-16	-3	-21	-0.4
PM	CO	-8	-11	-33	-1	-0.6	-1	-6	-0.1
	NO_x	-15	-49	-51	-15	-10	-3	-21	-0.7
	VOC	-14	-37	-51	-23	-14	-2	-18	-0.4
	Total $PM_{2.5}$	-21	-64	-70	-21	-13	-1	-7	-0.7
	CO_2e	-7	-13	-29	-1	-0.7	-2	-11	-0.3
	MSATs	-15	-44	-54	-30	-18	-3	-21	-0.5

Noise

Baseline Noise

For the Chicago location, considerable detail was available from project team staff that completed the original analysis in TNM version 2.5 (Illinois DOT, 2013). Figure 3 shows the modeled TNM receivers as blue squares. Receivers were selected for sensitive areas, typical areas, and to determine falloff rates near the Interstate highways.

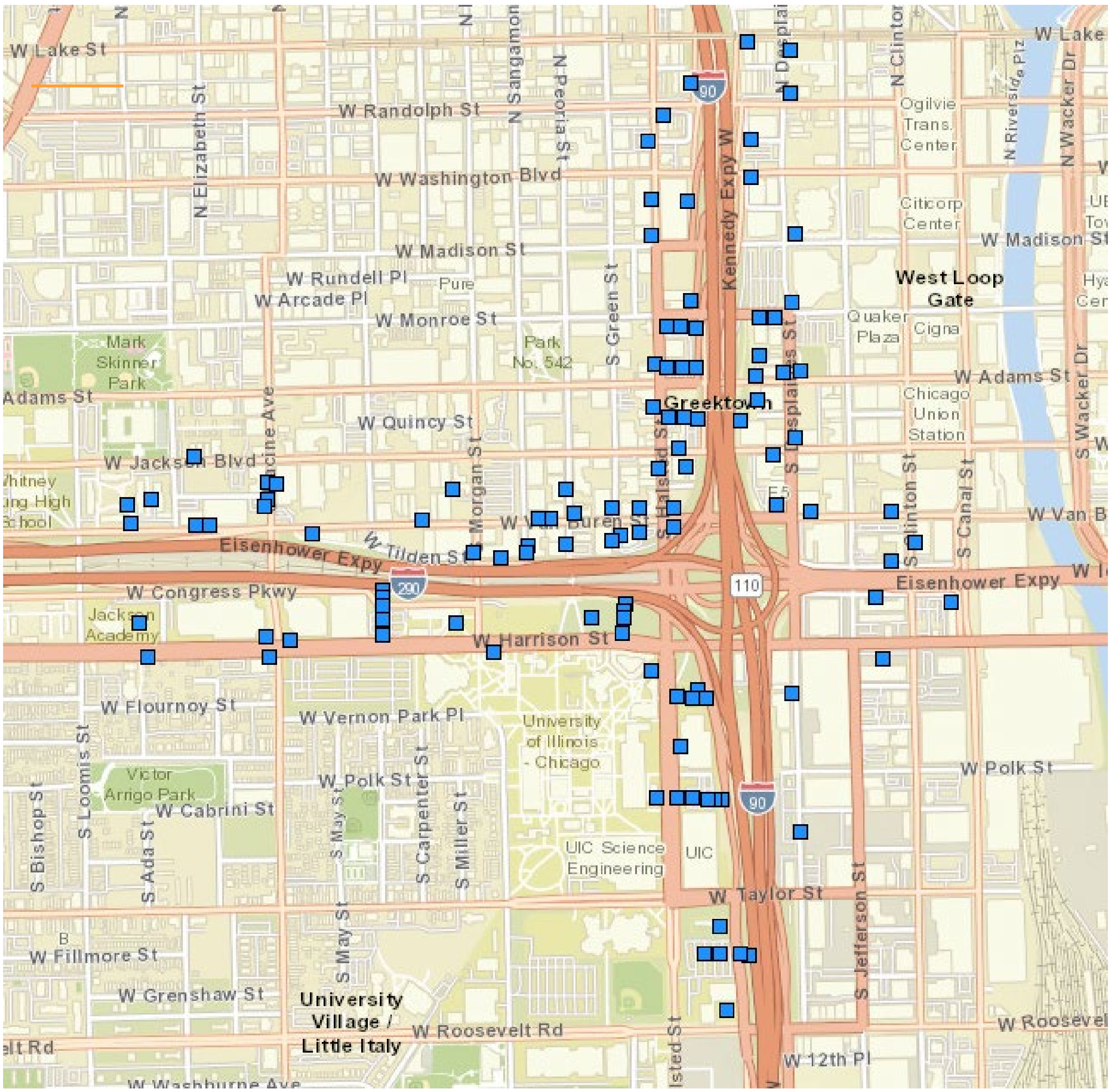

Figure 3. Map. Chicago noise modeling receiver locations.

(Source: FHWA.)

Table 10 shows summary statistics for baseline sound levels in Chicago for each evaluated hour. Figure 4 shows a cumulative plot of the number of receivers exceeding a given noise level for each hour. The hour with the highest noise level at the most receivers and the highest average level was 4:00–5:00 p.m., with 12:00–1:00 p.m. being second. However, 12:00–1:00 p.m. included the location with the highest noise level for any time period. The FHWA Noise Abatement Criteria (NAC) of 67 dB(A) for residential and recreational receptors also is shown as a reference.[9] Based on this reference, noise levels near the roadway can be quite high, with noise levels at many locations exceeding the NAC at any hour evaluated.

The greatest sound level was 77.7 dB(A) which is at a parking lot near the Interstate highway at noon. The lowest sound level, 39.2 dB(A), occurs at midnight in a heavily shielded area of the UIC Pavilion. Considering all locations, the three daytime time periods are only separated by 0.9 dB(A) for average and maximum levels, showing the small effects of the changing traffic conditions. At night, even when the traffic volumes are significantly lower than daytime volumes, only a 3 to 4 dB(A) average reduction occurs compared to the daytime hours. Speeds tended to be close to free flow at night, compared to congested daytime speeds; and heavy truck volumes were still one-third to one-half of peak-period volumes even while overall traffic volumes were reduced by over 80 percent. Volume fractions by hour and vehicle type were based on regional averages by road type, per data in the DANA tool, rather than facility-specific counts. The comparison of noise levels by hour suggests that any traffic-only mitigation strategies that are implemented to help reduce the extent and intensity of the bottleneck in Chicago are unlikely to significantly change the noise levels in this case study location.

Table 10. Baseline sound levels, Chicago.

Statistic	12:00–1:00 a.m.	7:00–8:00 a.m.	12:00–1:00 p.m.	4:00–5:00 p.m.
Average sound level	59.7	63.3	63.9	64.2
Median sound level	59.7	63.3	63.8	64.4
Minimum sound level	39.2	42.9	44.2	45.0
Maximum sound level	73.3	76.9	77.7	77.2

Note: Sound levels and changes expressed in dB(A). N = 112 receivers.

9 FHWA has seven defined activity categories in the NAC as listed in 23CR772 ranging from 57 Leq(h) to 72 Leq(h). Very sensitive areas are included Activity Category A with the 57 Leq(h) while less sensitive areas such as hotels are at 72 Leq(h). Areas such as airports have no activity criteria level. In urban areas, Activity Category B and C are most likely to be the sensitive receivers of concern as they include residences, day care centers, hospitals, etc.

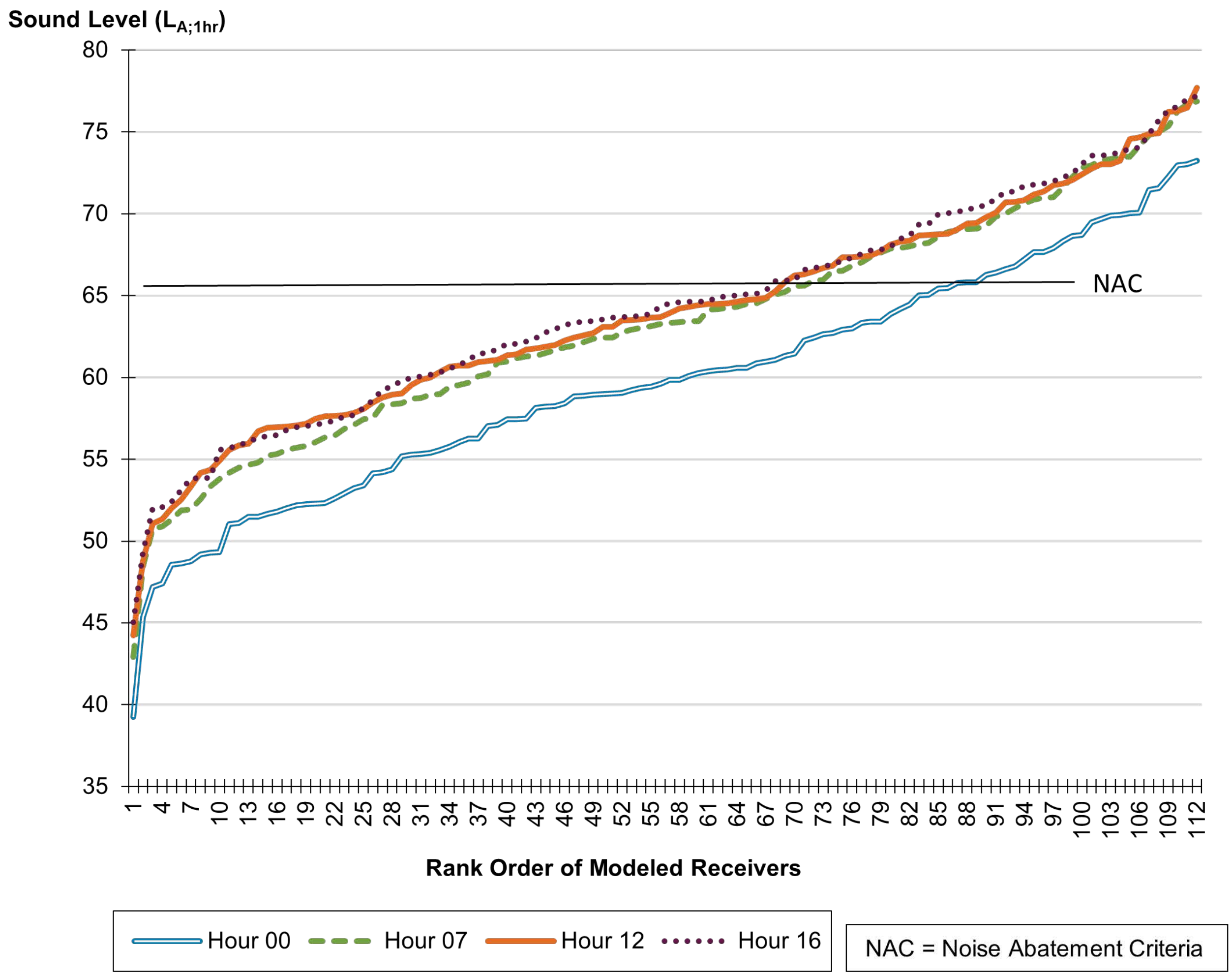

Figure 4. Chart. Baseline sound levels for Chicago.

(Source: FHWA.)

Noise Mitigation Strategies

In Chicago, noise mitigation strategies were evaluated for the 4:00–5:00 p.m. hour, since that hour saw the greatest number of maximum noise levels across the modeled receivers. For the traffic evaluations using TNM 3.0, Strategies 2 (additional lanes), 3 (truck-only lanes), and 11.2 (electric trucks) were modeled, to show the effects of representative scenarios with the largest speed and/or volume changes.

Additional Lanes and Electric Trucks

The results of the TNM noise modeling for Scenarios 2 and 11.2 are shown in table 11. Scenario 3 was modeled using a more limited set of unshielded receptors and is therefore discussed separately below since the absolute noise values from the different sets of receivers will not be directly comparable. In the first column, the previous noise level results from the baseline modeling for 4:00–5:00 p.m. are shown. In the next two columns, the results of the modeling done with the altered traffic for each scenario are shown. The last two columns show the difference (alternate scenario—baseline) comparing the values for all receiver locations. A positive value indicates the measure increased noise levels compared to the baseline, while a negative value indicates a decrease in noise levels compared to the baseline.

The changes in sound levels from the scenarios with some of the greatest traffic impacts are minimal. For Scenario 2, additional lanes to increase capacity, the average noise level increased by 0.4 dB(A), primarily due to speed increases. In the worst case a 5.4 dB(A) increase occurred, although a few receivers saw noise decreases of up to 0.9 dB(A).

Scenario 11.2, clean truck corridor/electric charging infrastructure with the 2045 market share, showed an average decrease of 0.9 dB(A), a best decrease at any receiver of 1.0 dB(A), and no receivers showing an increase in noise levels. This also shows a "best case" analysis of electric truck benefits, as it was assumed that all noise from electric trucks was eliminated. Accounting for pavement/tire noise would reduce the benefits.

Overall, traffic changes of the magnitude considered for the mitigation strategies did not offer any perceivable noise benefits, and in some cases they cause a small disbenefit as higher speeds lead to increased noise.

Table 11. Traffic change abatement scenarios, Chicago, 4:00–5:00 p.m.

Indicator	S1	S2	S11.2	S2 versus S1	S11.2 versus S1
Average sound level	64.2	64.6	63.4	0.4	-0.9
Median sound level	64.4	64.4	63.5	-0.1	-0.9
Minimum sound level	45.0	45.2	44.1	0.2	-0.9
Maximum sound level	77.0	79.7	76.1	2.7	-0.9
Largest increase	–	–	–	5.4	N/A
Largest decrease	–	–	–	-0.9	-1.0

Note: Sound levels and changes expressed in dB(A). N = 112 receivers. For the scenario versus base case comparisons, "average," "median," "minimum," and "maximum" refer to the change in the indicated statistic across all receivers. "Largest increase" and "largest decrease" show the largest changes at any individual receiver. An "N/A" value for "largest increase" means that no individual receivers saw an increase in noise levels for the mitigation versus base case scenario.

Truck-Only Lanes

The scenario of truck-only lanes (S3) was evaluated using TNM 3.1. Truck-only lanes change two key noise parameters. If heavy trucks are moved into a separate lane, the trucks are farther from receiver locations, which reduces noise due to distance. Truck-only lanes could also change truck speeds and/or general traffic speeds. In this case study, new truck-only lanes would operate at free flow speeds, but general traffic speeds would stay the same.

Two separate TNM 3.1 runs were performed to capture the effects of speed versus lane position. In the first ("S3"), truck speeds were increased but their position remained the same. In the second ("S3 moved"), truck speeds were increased, and all heavy trucks were moved to the centermost lanes (one in each direction). This was done for the northbound and southbound lanes in the northern segment of Interstate 90, away from the interchange. Select receivers that were unshielded were used for the evaluation since these would most fully capture the effects of the change. Results are shown in table 12 for both absolute levels and differences from the base. As expected, the increased speeds resulted in a general increase in noise levels. For the change in speeds only, noise levels increased by 0.4 dB(A) on average and as much as 1.5 dB(A) at one receiver. Moving the trucks towards the centerline mitigated the increase slightly, with an average increase of 0.3 dB(A) and a maximum of 1.2 dB(A).

To further test the effects of lane position, two scenarios were combined and evaluated using TNM 3.1. In this evaluation, the clean truck corridor scenario (S11.2) was combined with moving all heavy trucks to the inner lanes as before (S3). The effect of S11.2 alone was an average reduction of 0.9 dB(A) as was shown for all receivers previously. Again, a very small additional benefit occurred from the change in lane position, as the average decrease was 1.0 dB(A) with electric trucks plus moving the truck lanes towards the centerline. Repositioning the truck lanes therefore appears to result in slightly beneficial, but not perceptible, changes in noise levels.

Table 12. Evaluation of truck-only lanes in Chicago, 4:00–5:00 p.m.

Indicator	S1	S3	S3 moved	S11.2	S11.2 moved	S3 versus S1	S3 moved versus S1	S11.2 versus S1	S11.2 moved versus S1
Avg. sound level, dB(A)	69.5	70.0	69.8	68.7	68.5	0.4	0.3	-0.9	-1.0
Med. sound level, dB(A)	71.0	71.3	71.2	70.1	70.0	0.4	0.2	-0.8	-1.0
Min. sound level, dB(A)	60.5	60.7	60.6	59.6	59.6	0.2	0.1	-0.9	-0.9
Max. sound level, dB(A)	75.7	76.4	76.1	74.9	74.8	0.7	0.4	-0.8	-0.9
Largest increase, dB(A)	–	–	–	–	–	1.5	1.2	N/A	N/A
Largest decrease, dB(A)	–	–	–	–	–	-0.4	-0.5	-1.0	-1.4

Note: Sound levels and changes expressed in dB(A). N = 14 receivers.

Figure 5 shows the distribution of the change in sound level at every modeled receiver for the various scenarios 02 (capacity), 03 (truck-only lanes), 03 moved (truck-only lanes moved), and 11.2 (electric trucks). The figure shows that the majority of receivers experienced an increase in sound level for S2 and S3 (both variations), with an increase of at least 3 dB(A) at 9 locations for S2. Sound levels for S11.2 showed a consistent but small decrease. The decrease in sound level was never greater than 1 dB(A) for any receiver location or mitigation strategy.

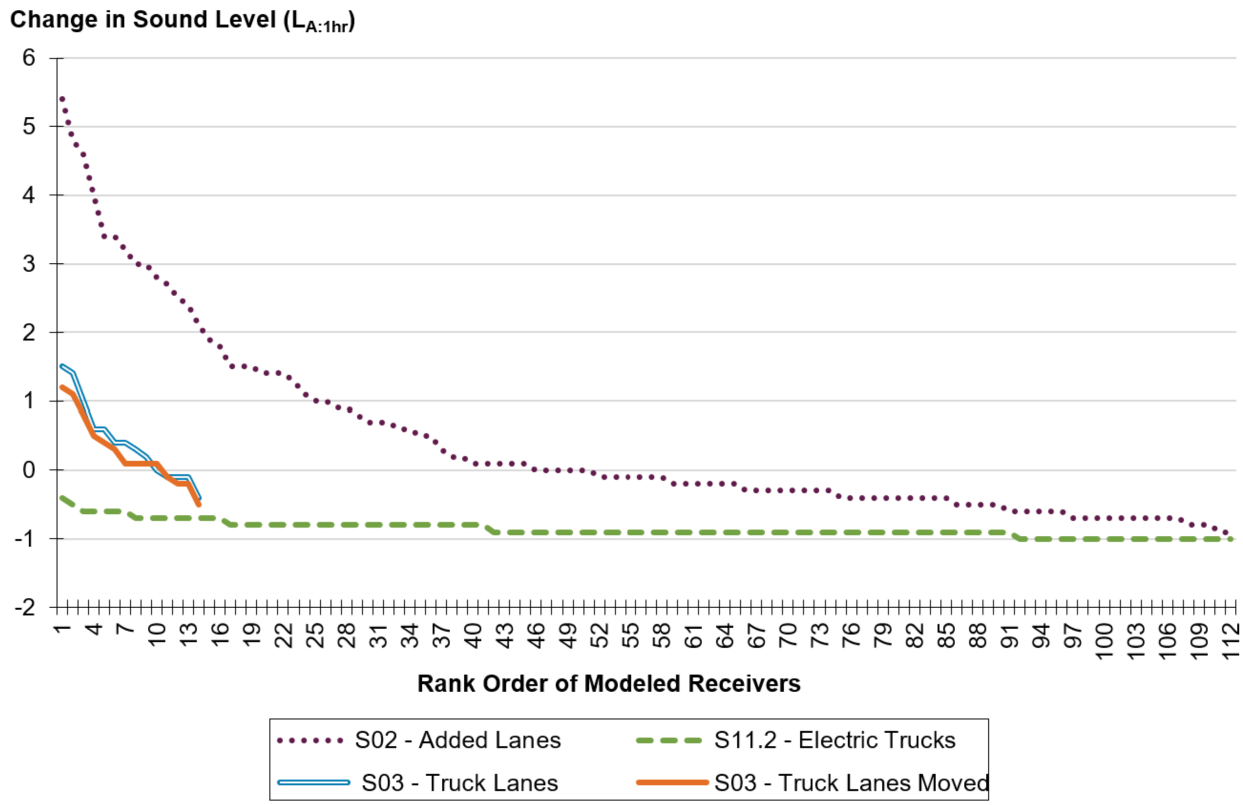

Figure 5. Chart. Change in sound level for strategy versus base condition, Chicago.

(Source: FHWA.)

Buffer Zones

Buffer zones were evaluated by placing receivers at known distances from the edge of the main lanes to multiple positions along I-290 and I-90 to evaluate what the front row receiver would be if a buffer zone was used.[10] These receivers are shown as squares in figure 6. Two cases are shown in table 13 to illustrate results both with and without a noise barrier. If buffer zones of the indicated distance from centerline was used, a corresponding noise decrease would be expected. Near Adams Street, west of I-90 with no obstructions to the roadway, a buffer zone of 100 feet would reduce the noise by 4.8 dB(A) as distance from the roadway is doubled. This is very much in agreement with the general equation presented in appendix B. If the buffer zone is increased to 200 feet, only 3.3 dB(A) more reduction is achieved since this is less than a doubling of the distance. At the Harrison Field location south of I-290, very different results occur due to the barrier. In this case, a barrier changes the impact of the roadway since there is no direct path, and the creation of a shadow zone results in reductions from a 100-foot buffer zone of only 1.1 dB(A).

10 This is intended to be a hypothetical evaluation illustrating what benefits might be possible from buffer zones if they were feasible. Given the densely built up nature of this particular case study environment, buffer zones are most likely not feasible to implement in this location.

These scenarios from Chicago show that 1) noise abatements from traffic changes in bottleneck locations are unlikely to be substantial; 2) multiple abatement strategies may increase abatement effectiveness; and that 3) buffer zones, if affordable, could be effective for unshielded receiver locations.

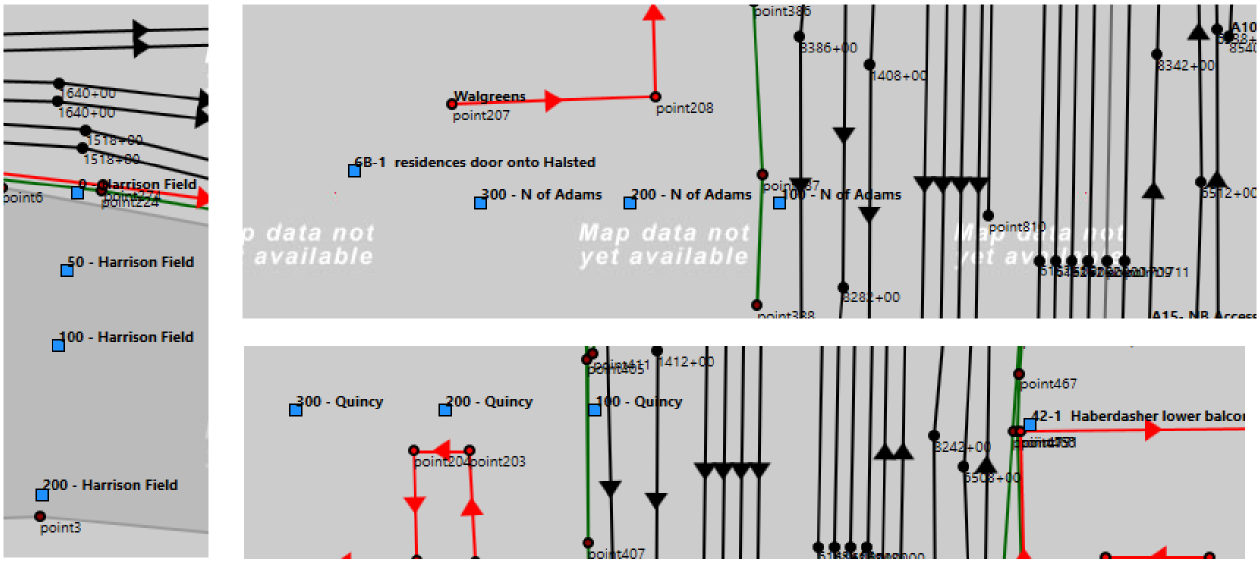

Figure 6. Diagram. Evaluation of buffer zones in Chicago.

(Source: FHWA.)

Table 13. Buffer zone benefits without and with noise barrier (4:00–5:00 p.m.)

Receiver Location	Distance from Centerline (feet)	LAeq, dB(A)
Harrison Field (barrier)	50	64.9
	100	64.7
	200	63.6
N of Adams (no barrier)	100	70.1
	200	65.3
	300	62.0

5.0 Houston Case Study

The Houston case study focused on access to the Barbours Cut Terminal of the Port of Houston from SH 146. The Port of Houston is a major seaport generating high volumes of truck traffic.

Roadways and Traffic Data

Table 14 lists the roadway segments modeled for the Houston case study. The roads include SH 146—the freeway providing access to the Barbours Cut Terminal; Barbours Cut Boulevard, which provides access from 146; and the frontage roads along SH 146 south of Barbours Cut Boulevard. The frontage roads were not included in the DANA tool data but were included for the purpose of modeling additional mitigation strategies.

Table 14. Houston case study roadway segments.

Map Key	Description	TMC 1	Direction 1	TMC 2	Direction 2
1	SH 146 South of Barbours Cut	112+04429	NB	112-04428	SB
2	SH 146, North of Barbours Cut—SH 225	112P04429	NB	112N04429	SB
3	9th St./10th St. (SH 146 Frontage Road) S of Barbours Cut	N/A	–	N/A	–
4	Barbours Cut Boulevard, N. 9th to N. Broadway	112-51047	WB	112+51048	EB
5	Barbours Cut Boulevard, N. Broadway to Lobit	112-51048	WB	112+51049	EB
6	Barbours Cut Boulevard, Lobit to Vinsonia	112-51051	WB	112+51052	EB
7	Truck idle outside of port terminal	–	–	–	–
8	Operation within Barbour's Cut terminal (1 hour per truck @ 2.5 mph average speed)	–	–	–	–

Figure 7 shows the location of these segments on a map (dashed lines) as well as receptor areas (solid polygons).

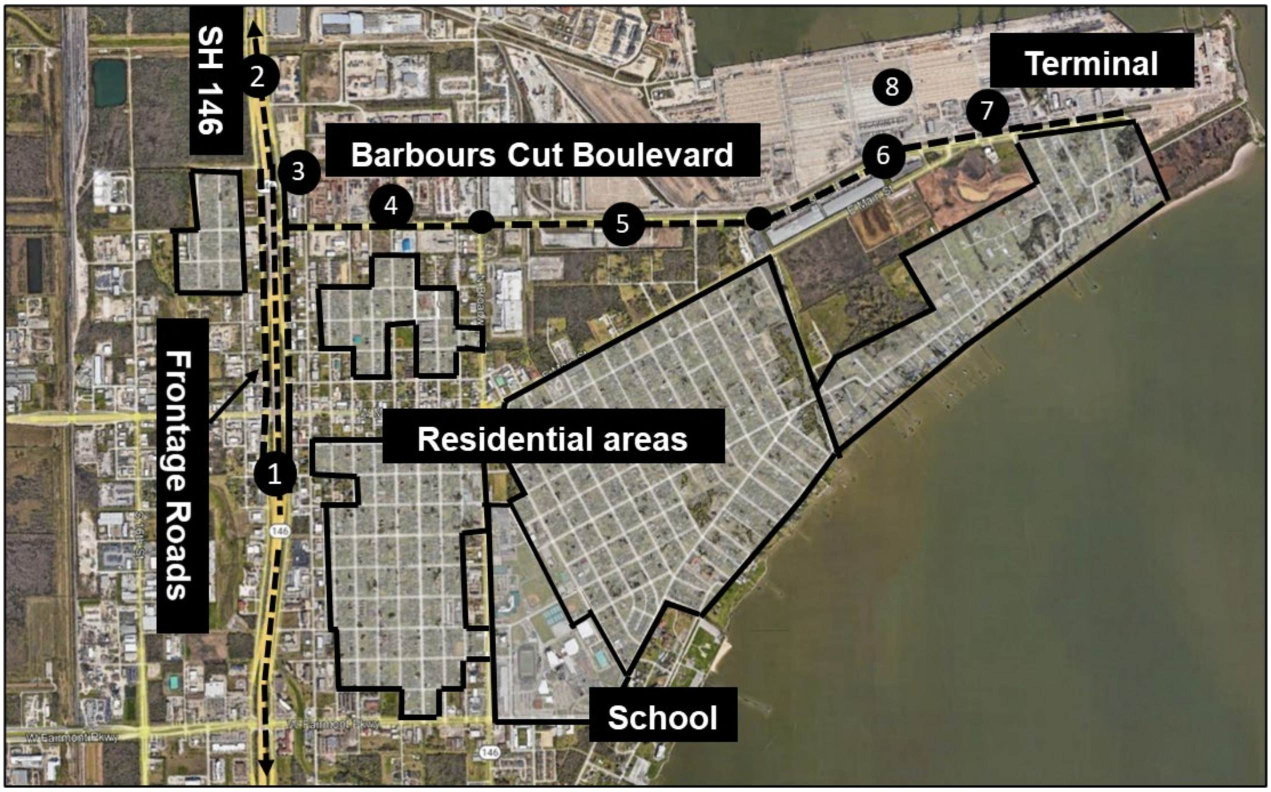

Figure 7. Map. Houston case study roadway segments and receptor areas.

(Source: FHWA, Base map source: Google Earth.)

For the Houston case study, baseline speed and volume data from the DANA tool were supplemented with 2018 traffic count data from the Texas DOT (TXDOT). The TXDOT data was used to provide volumes on the frontage roads and also to split the volumes on Barbours Cut Boulevard by vehicle type. The default vehicle type splits in the DANA tool did not appear to reflect the high numbers of trucks using this road as a port access, and the TXDOT data included classification counts at one location. The same percentage of trucks was applied to total volumes on other segments on the street.

Mitigation Strategies

Table 15 shows the mitigation strategies considered and key data sources and assumptions used in the Houston case study. Shaded rows labeled “N/A” are strategies that were considered but not modeled, for reasons explained in the table.

Table 15. Mitigation strategies and evaluation approaches: Houston case study.

S#	Mitigation Strategy	Specific Project Concept	Data Sources and Assumptions
2	Additional lanes to increase capacity	Roadway capacity does not appear to be a limiting factor on truck movement in the study area. Speed data suggests that there is very little congestion on 146 even during peak periods.	N/A
3	Truck-only lanes	New truck-only direct connector between Barbours Cut Boulevard (BCB) and SH 146.	Shift trucks on frontage roads south of BCB onto SH 146. Based on truck volumes on BCB (average of 3 segments from TXDOT counts), assume 40% are headed SB on 146, and subtract from frontage road truck volume from TXDOT counts. The shifted trucks are assumed to operate at mainline speeds rather than frontage road speeds.
4	New roadway	None—New roadways would not help to mitigate emissions or noise in this area.	N/A
5	Geometric design changes	Evaluated as part of Strategy 3 (new truck-only direct connector).	N/A
6	TSMO strategies	None—There is only one signalized intersection on BCB between 146 and the terminal. Speed data suggests that there is very little congestion on 146 even during peak periods. Therefore, it does not appear that TSMO strategies hold much promise for reducing emissions or noise in this location.	N/A
7	Speed limit/ speed management	Lowering speed limit on SH 146 to 55 mph with enforcement.	Reduce speeds greater than 55 mph on SH 146 to 55 mph.
8	Restricting or rerouting trucks	None. No feasible alternate routes in area.	N/A
9 and 10	Accelerated retirement/ clean truck replacement; engine and powertrain retrofits, alternative fuels	Assume the Port of Houston and/or other regional agencies implement effective incentives or requirements for migration to post-2007 trucks for all trucks serving local/regional destinations (assumed to be all trucks in study area).[1]	Run MOVES separately for default (county) age distribution and 2007+ age distribution. Apply post-2007 emissions results to truck volumes on study area links. Pre-2007 trucks represented 17% of study area trucks.

Table 15. Mitigation strategies and evaluation approaches: Houston case study (continuation).

S#	Mitigation Strategy	Specific Project Concept	Data Sources and Assumptions
11	Clean truck corridor; electric charging infrastructure	Port, regional and multistate corridor policies and investments (including truck charging infrastructure) to encourage the use of electric trucks.	Based on NREL Electrification Futures Study "medium" case projections of truck electrification,[2] exclude 5.2% of MDTs (type 50) and 3.0% of HDTs (type 60) for 2030 case (S11.1) from emissions calculations (including for idle links), and exclude 45.4% of MDTs (type 50) and 20.1% of HDTs (type 60) for 2045 case (S11.2).
12	Intermodal facility capacity and efficiency	12.1: Process improvements from switching to electronic forms; gate expansion and security improvements.	12.1: Reduce idling time by 10% based on data from Port of Houston on benefits of process improvements.
		12.2: Optimize drayage trips through improved and coordinated dispatch algorithms.	12.2: Remove 13% of combination truck trips from BCB, based on trip reduction estimated from modeling of prototype Freight Advanced Traveler Information System (FRATIS) implementation in Memphis.[3] Remove 40% of these trucks (based on maximum BCB volume segment) from frontage roads (south of BCB) and 40% from SH146 north of BCB.[4]
13	Truck to rail mode shift	Implement container rail drayage service between Bayport and Barbours Cut.	Remove 400 combination truck trips per day from SH 146 frontage roads and BCB.[5] Apply daily % change in combo truck volume to each hour. Apply same % change for Vinsonia-Lobit section as for Lobit-9th (fewer than 400 trucks, since some entrances to port are west of that segment).
14	Truck to water mode shift	No market was identified to shift truck traffic from this corridor to water.	N/A
15	Noise barriers	Not modeled—tested in the Tacoma case study.	N/A
16	Quiet pavement	Not modeled—tested in the Tacoma case study.	N/A

Table 15. Mitigation strategies and evaluation approaches: Houston case study (continuation).

S#	Mitigation Strategy	Specific Project Concept	Data Sources and Assumptions
17	Helmholtz resonators	Not modeled—no methodology in TNM.	N/A
18	Buffer zones	Hypothetical undeveloped buffer zone to SH 146.	Receivers at regular distances from the roadway were evaluated in an unobstructed location.
19	Vegetation	Hypothetical tree zone adjacent to SH 146.	Receivers were placed in and behind a tree zone in TNM 3.1.
19	Vegetation	Hypothetical tree zone adjacent to SH 146.	Receivers were placed in and behind a tree zone in TNM 3.1.

1 Nearly all of the trucks using SH 146 that do not stop at Barbours Cut should also have at least one destination within the region, since 146 leads to Galveston Island and is not on the shortest path for any through traffic. Data from the FHWA Freight Analysis Framework 4 (FAF4) database confirms this, showing an estimated 91 percent of truck traffic north of Barbours Cut Boulevard and 98 percent of truck traffic south of Barbours Cut Boulevard is not in the FAF4 database and can therefore be considered local.

2 NREL describes the “medium” scenario as: a future with widespread electrification among the “low-hanging fruit” opportunities in electric vehicles … but one that does not result in transformational change (Mai et al, 2018).

3 FHWA (2018).

4 Assumes split of traffic accessing terminal to be 40 percent northbound—highway, 40 percent southbound—highway, and 20 percent local. Actual origin/destination data was not available.

5 In July 2021, 297,610 loaded and empty containers moved through the Port of Houston’s container terminals, or an average of around 6,860 loaded plus 2,740 empty containers per day. In the absence of available data, and broadly assuming throughput is distributed by terminal capacity, daily throughput at Barbours Cut and Bayport terminals is potentially around 4,800 ton-equivalent units. Commodity Waybill Public Use Sample data from the Bureau of Transportation Statistics (https://prod.stb.gov/reports-data/waybill/#Public-Use) show that trains are generally around 40 carloads in the Houston region. The rail connections around Bayport have a total capacity of 850 cars and so we compare 10 trains moving 40 carloads (approximately 47 percent of nearby rail capacity and 8.3 percent of daily throughput) to 400 combination trucks moving one container.

Emissions

Baseline Emissions

Total study area emissions for the Houston baseline case are shown in table 16. Baseline results show that modeled emissions for all pollutants are higher during the PM peak hour than the AM peak hour. The largest difference in emissions is observed for CO, which is 33 percent higher during the afternoon. The other pollutants show modest differences between the 2 periods, ranging from of 8–13 percent. Traffic data shows an overall increase of 19 percent during the afternoon hour, a reduction in average speed from 41 mph to 38 mph and an increase of 20 percent in the truck traffic volume.

Table 16. Total emissions for Houston baseline case.

Pollutant	Emissions in AM peak hour (kg)	Emissions in PM peak hour (kg)
CO	18	21
NO_x	23	25
VOC	1.6	1.7
Total $PM_{2.5}$	1.2	1.3
CO_2e	5,651	6,335
MSATs	0.20	0.22

Emissions on the study links are dominated by heavy trucks coming to and from the port, especially for NO_x, $PM_{2.5}$, and VOC, with heavy trucks generating over 90 percent of VOCs and about 98 percent of NO_x and PM emissions. The inclusion of truck idle outside the port and operation within the Barbours Cut terminal was very consequential, contributing 60–80 percent of case study NO_x, VOC and $PM_{2.5}$ depending on the hour and pollutant. In-terminal operation for this analysis was estimated based on a prior study of Port of Houston turn times, indicating that trucks spend roughly 1 hour on average within Barbours Cut terminal, mostly idling.[11]

Emissions Effects of Mitigation Strategies

Percent changes in emissions for all study links in the Houston case study are shown in table 17. In this case study, Scenario 3 (adding a truck-only exit) showed very little benefit due to a small difference between emissions at speeds on frontage roads versus the mainline (table 17). For speed management the shift from 55 mph was relatively small, and actually resulted in an increase in light-duty vehicle emissions due to the speed effects estimated by MOVES in that speed range. Replacement of old trucks (or engines) serving the port showed the largest reduction in emissions, cutting total VOC and $PM_{2.5}$ roughly in half and NO_x by 20 percent, though greenhouse gas benefits are much smaller. Similar to Chicago, reductions from truck electrification scenarios depend on the penetration rate of clean trucks. For this port-

[11] Stanard et al, "Measurement and Analysis of the Operations of Drayage Trucks in the Houston Area in Terms of Activities and Exhaust Emissions," SAE Int J Commer Veh. 2018; 11(2): 77–92.

focused scenario, shifting local drayage to rail and reducing bobtail trips reduced emissions of all pollutants 13–19 percent, and 8–13 percent respectively. Although the idle reduction scenario was modest (assuming a 10 percent reduction in idle as proxy for efficiency improvements at port gates and in-terminal), the subsequent impact on total emissions was meaningful, in the range of 6 to 9 percent.

Table 17. Percent change in emissions from Houston baseline case.

Peak Hour	Pollutant	S3—Truck-Only Lane	S7—Speed Mgmt.	S9—Replace Old Trucks	S11.1—Clean Trucks 2030 Share	S11.2—Clean Trucks 2045 Share	S12—Idle Reduc-tion	S12.2—Drayage Optimi-zation	S13—Rail Shift
AM	CO	-0.1	0	-8	-2	-14	-6	-9	-13
	NO_x	-0.1	0	-21	-3	-20	-8	-13	-19
	VOC	-0.1	1	-56	-3	-20	-9	-13	-19
	Total $PM_{2.5}$	-0.2	0	-47	-2	-11	-8	-13	-19
	CO_2e	-0.1	0	-4	-3	-18	-7	-10	-15
	MSATs	-0.1	0	-60	-3	-20	-9	-13	-19
PM	CO	-0.1	0	-7	-2	-13	-5	-8	-11
	NO_x	-0.1	0	-21	-3	-20	-8	-13	-19
	VOC	-0.1	0	-55	-3	-20	-8	-12	-18
	Total $PM_{2.5}$	-0.2	0	-46	-2	-11	-7	-13	-19
	CO_2e	-0.1	0	-4	-3	-18	-6	-10	-15
	MSATs	-0.1	0	-59	-3	-20	-8	-13	-19

Noise

Baseline Noise

Figure 8 shows the TNM 3.0 receivers set up to be modeled for the Houston location. Receivers are shown as blue squares. Receiver locations were selected along the freeway and Barbours Cut Boulevard for sensitive receptors, typical areas, and for determining fall-off rates where objects were not present.

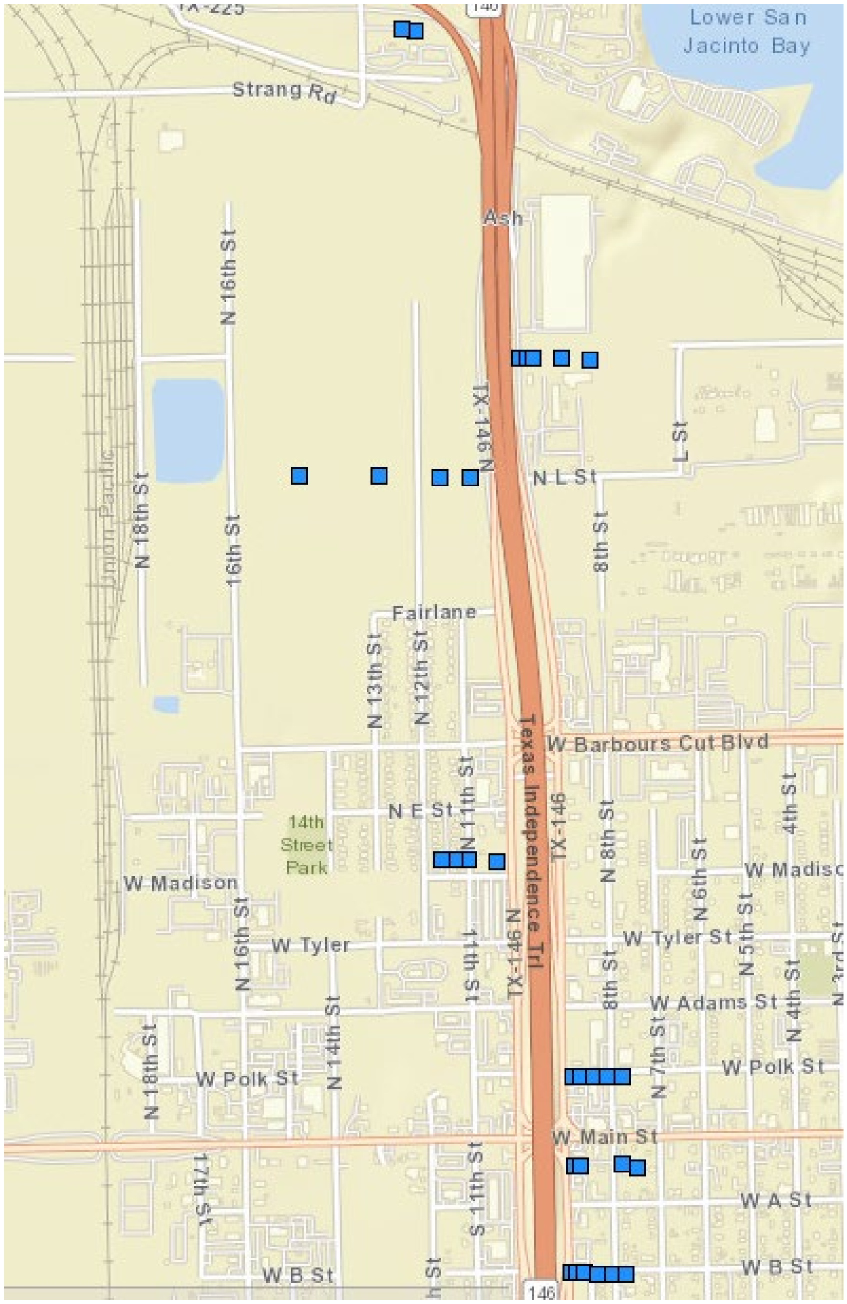

Figure 8. Map. Houston noise modeling receiver locations.

(Source: FHWA.)

Summary statistics for the baseline noise levels are shown in table 18, and a cumulative plot of receivers by noise level is shown in figure 9. The midday hour, 12:00–1:00 p.m., was the hour with the greatest number of receivers with the loudest noise level, with 7:00–8:00 a.m. being very close. The noon time period also included the greatest noise level predicted. Many near-road receiver locations are experiencing high noise levels, as indicated by a comparison to the FHWA NAC for residential and other sensitive receptors.

A total of 29 receiver locations were successfully modeled for baseline conditions to provide a representative range of the changes expected from various mitigation strategies. The greatest sound level was 73.1 dB(A) near SH 146 during the noon time period. This receptor is near residential housing. The lowest sound level, 50.6 dB(A), occurred at midnight at a local area shopping area, 500 feet away from the roadway and shielded by other buildings. Location is the most important parameter. Traffic volumes, speeds, and vehicle mix only have measurable effects for very large changes.

Considering all locations, the daytime time periods are only separated by about 1 dB(A) for both average and maximum noise levels, showing the small effects of the changing daytime traffic conditions. At night, however, when the traffic volumes are much lower, noise levels are on average 8 dB(A) lower than in the daytime. This shows that very large reductions in relative traffic volumes can have a noticeable noise benefit in some circumstances.

Heavy truck volumes in the 12:00–1:00 a.m. hour were less than one-quarter of daytime volumes on SH 146 and zero or near zero on Barbours Cut Boulevard; volumes of all traffic were 80–90 percent lower at night than during the day at most locations. Speeds were generally similar across time periods, except for some reductions during the afternoon peak (from 60 to 45–50 mph) on SH 146 and some variations in the 15–30 mph range along Barbours Cut Boulevard. The residential NAC are exceeded at over 40 percent of locations during the daytime, but are not exceeded in the midnight hour.

Table 18. Baseline sound levels, Houston.

Statistic	12:00–1:00 a.m.	7:00–8:00 a.m.	12:00–1:00 p.m.	4:00–5:00 p.m.
Average sound level	58.2	66.2	66.4	65.4
Median sound level	58.1	65.9	66.3	65.0
Minimum sound level	50.6	58.4	59.2	58.1
Maximum sound level	65.2	72.9	73.1	72.2

Note: Sound levels and changes expressed in dB(A). N = 29 receivers.

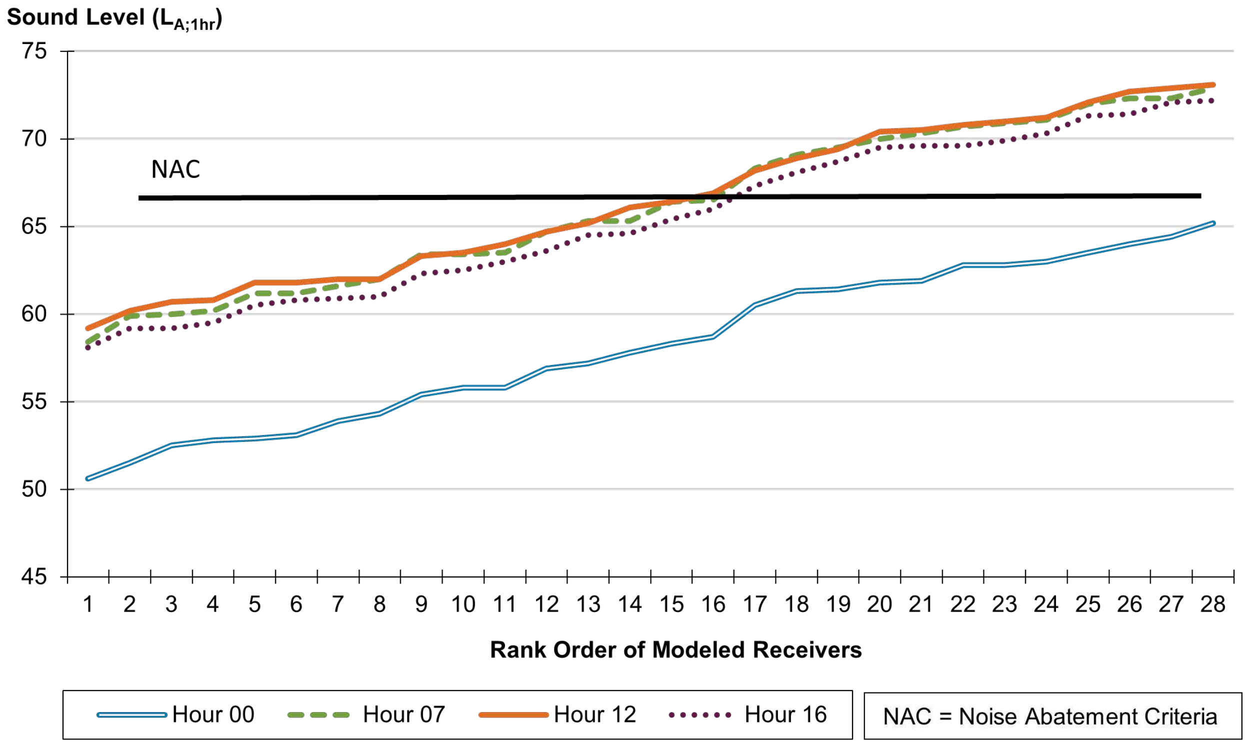

Figure 9. Chart. Cumulative baseline sound levels for Houston.

(Source: FHWA.)

Noise Mitigation Strategies

For noise mitigation, Scenarios 3 (truck-only lanes) and 7 (speed management) were modeled to illustrate changes in noise levels that might occur from changes in traffic conditions. Buffer zones (Scenario 18) and vegetation (Scenario 19) also were modeled. The 12:00–1:00 p.m. hour was modeled for this case study since that hour showed the highest overall noise levels in the base case.

Summary statistics for the traffic strategies are shown in table 19. The greatest reduction is 0.8 dB(A) in both scenarios. The average reductions were 0.3 and 0.6 dB(A) for S3 and S7, respectively. Overall, the traffic changes produce modest reductions in noise levels but the changes are not perceptible.

Table 19. Traffic change abatement scenarios, Houston, 12:00–1:00 p.m.

Indicator	S1	S3	S7	S3 versus S1	S7 versus S1
Average sound level	66.4	66.1	65.9	-0.3	-0.6
Median sound level	66.3	65.8	65.8	-0.5	-0.5
Minimum sound level	59.2	58.8	58.9	-0.4	-0.3
Maximum sound level	73.1	73.3	72.8	0.2	0.3
Largest increase	–	–	–	0.2	N/A
Largest decrease	–	–	–	-0.8	-0.8

Note: Sound levels and changes expressed in dB(A). N = 29 receivers. For the scenario versus base case comparisons, “average,” “median,” “minimum,” and “maximum” refer to the change in the indicated statistic across all receivers. “Largest increase” and “largest decrease” show the largest changes at any individual receiver. A “N/A” value for “largest increase” means that no individual receivers saw an increase in noise levels for the mitigation versus base case scenario.

Buffer zones (Scenario 18) were evaluated using the same approach used in the Chicago example. In table 20, the numbers for the receiver names indicate distance from the edge of roadway. Compared to a location 50 feet from the roadway, an additional 50-foot buffer (100-foot position) provided a 2.5 dB(A) reduction, and an additional 350 foot-buffer (400-foot position) provided nearly 10 dB(A) reduction. This is in somewhat general agreement with the general equation presented in the literature review.

Table 20. Results of buffer zone and vegetation scenarios, Houston.

Receiver Name	Distance from Roadway (feet)	Base Case—12:00 p.m., dB(A)	With Tree Zone dB(A)	Noise Change from Tree Zone, dB(A)
50’ TZ	50	72.5	71.2	-1.3
100’ TZ	100	70.0	66.6	-3.4
400’ TZ	400	62.7	53.5	-9.2
800’ TZ	800	57.9	50.3	-7.6

Note: The 200-foot location results did not compute and therefore results are not shown.

Vegetation (Scenario 19) also was evaluated for the Houston example by modeling a tree zone near the roadway, within TNM 3.1. The tree zone modeled is substantial in area (see figure 10) and uses an average height of 15 feet on loose soil (flow resistivity of 500 cgs Rayls[12]). A comparison was made using the base case S1 for the worst hour modeled, 12:00–1:00 p.m. Receivers (shown in the figure as labeled squares) were added at doublings of distance from

[12] This is a unit of measure for specific acoustic impedance (energy of sound wave entering the surface. 1 Rayl equals 1 barye-second per centimeter or 1 dyne-second per cubic centimeter; the cgs indicates the metric system (centimeter-gram-second) is used.

the roadway (50, 100, 200, 400 and 800 feet from the edge of roadway). The last receiver was behind the tree zone to show overall benefit. Table 20 shows the results. Example figures in FHWA guidance show that a 61-meter (200 feet) width of dense vegetation can reduce noise by 10 decibels. In this analysis, TNM 3.1 showed about one-half of this benefit, with a reduction of 3.4 decibels for a 100-foot tree zone or 9.2 decibels for a 400-foot tree zone, compared to receivers at the same distance with no trees.

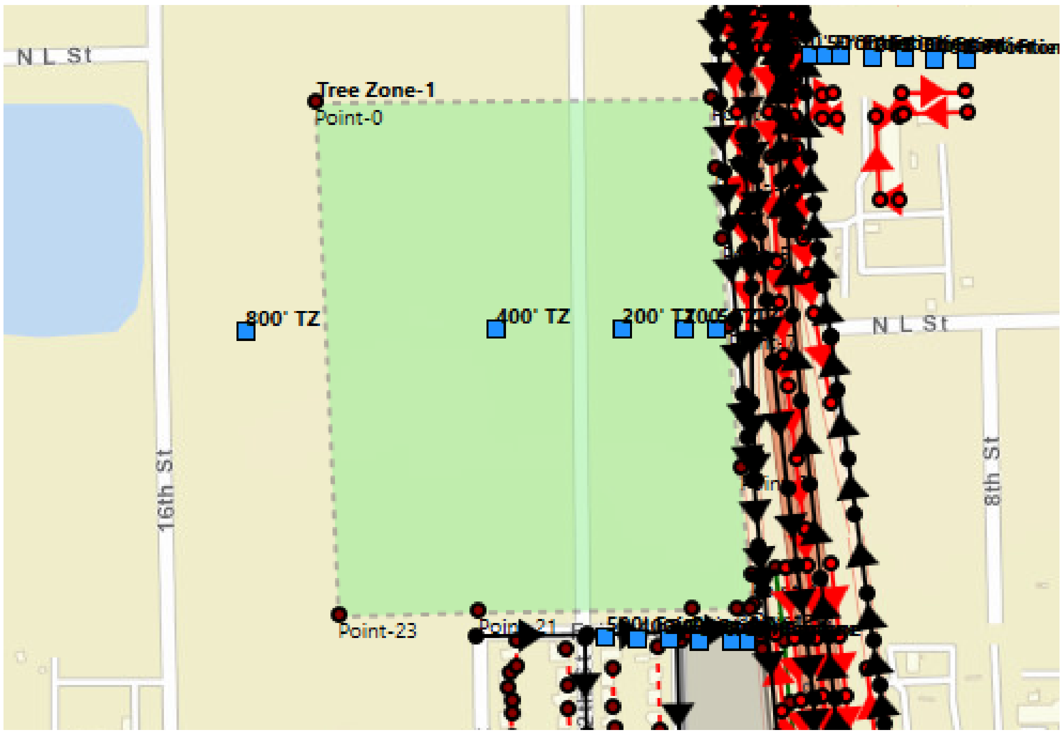

Figure 10. Map. Receivers and tree zone added for vegetation analysis.

(Source: FHWA.)

Results from Houston show that again the traffic changes are not sufficient to produce perceivable changes in the traffic noise. The use of buffer zones and tree zones (vegetation) did prove to be effective, but would require substantial area which may be cost prohibitive in bottleneck locations.

6.0 Tacoma Case Study

The Tacoma case study focused on Interstate 5 and local streets in the vicinity of the Port of Tacoma. The I-5 segment between Seattle and Tacoma is among the top 25 truck bottlenecks in the United States based on annual truck hours of delay per mile. The Port of Tacoma also is a major seaport generating high volumes of truck traffic.

Roadways and Traffic Data

Table 21 lists the roadway segments modeled for the Tacoma case study. Segments 3 and 4 are future planned roadways that have not yet been built. They were included to test an alternative that included a new roadway segment, specifically, extension of a new limited-access State Route (SR) 167 northwest from its current intersection with SR 161 to I-5, continuing to a new limited-access extension of SR 509 that would connect with existing SR 509 just east of the Port of Tacoma. Traffic volumes and speeds for the baseline analysis for these unbuilt segments were set to zero.

Table 21. Tacoma case study roadway segments.

Map Key	Description	TMC 1	Direction 1	TMC 2	Direction 2
1	I-5 East of 54th Avenue E	114P04176	EB [NB]	114N04176	WB [SB]
2	I-5 54th Avenue E to Port of Tacoma Road	114P04175	EB [NB]	114-04175	WB [SB]
3	SR 509 ext SR 509 to I-5 (future roadway)	N/A	EB	N/A	WB
4	SR 167 ext SR 512 to SR 161 (future roadway)	N/A	EB	N/A	WB
5	54th Avenue E I-5 to E 4th St.	114P08032	NB	114N08032	SB
7	Valley Avenue E 54th Avenue E to 70th Avenue	114-11520	EB	114+11521	WB
8	Port of Tacoma Gate Queue Idling (aggregate reflecting multiple gates)	N/A	N/A	N/A	N/A

Figure 11 shows the location of these segments on a map (dashed lines). Receptor areas also are outlined in the figure (solid polygons). Pockets of residential development are found scattered throughout the study area, as well as a high school adjacent to 20th Street and 54th Ave E. Roadway segments in addition to I-5 were selected for being proximate to these receptor areas and also being on the NHS and therefore having data in the DANA tool.

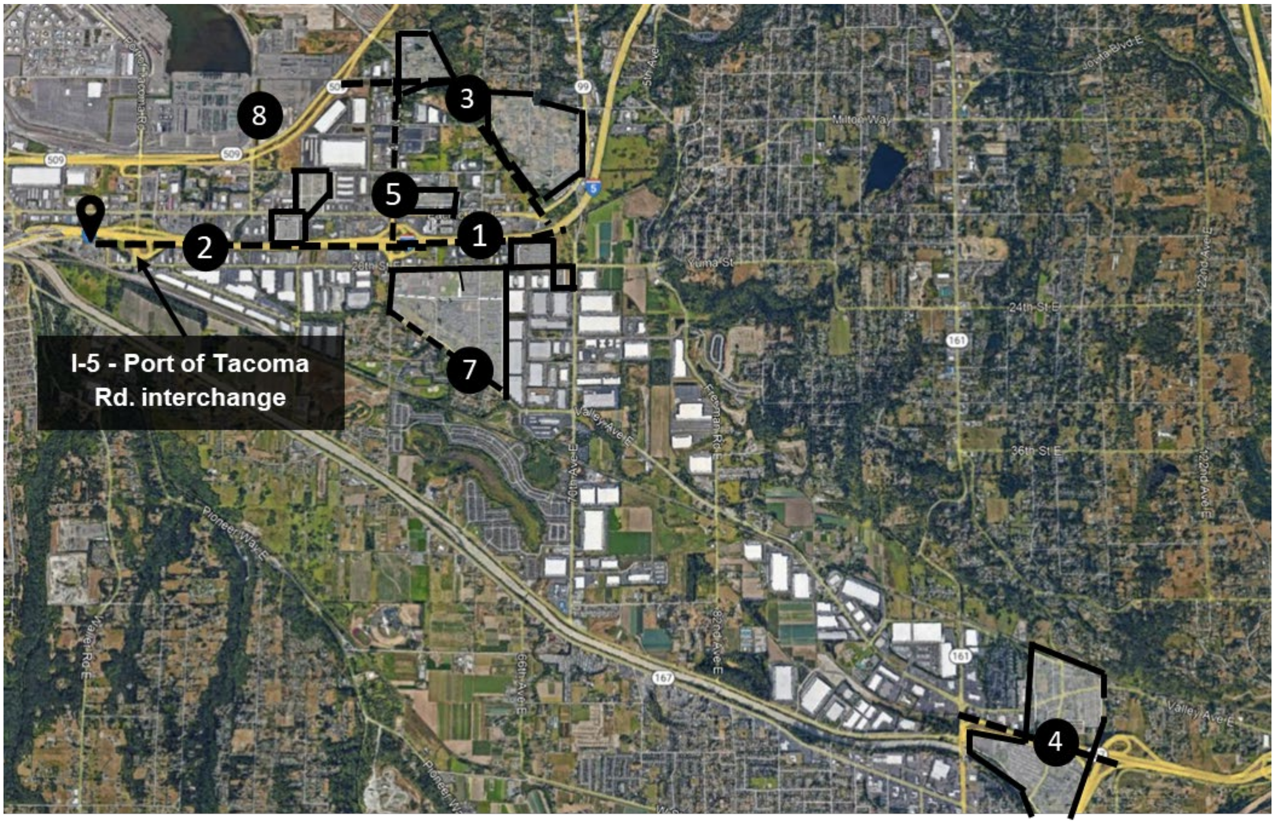

Figure 11. Map. Tacoma case study roadway segments and receptor areas.

(Source: FHWA, Base map source: Google Earth.)

For the Tacoma case study, baseline speed and volume data were taken directly from the DANA tool with one exception. For the I-5 segment east of 54th Avenue E, the hourly volume fractions for Pierce County seemed highly unusual and inconsistent with the fractions for the adjacent I-5 segment. Upon closer inspection the data associated with the month of November appeared reasonable, but all of the other months did not appear reasonable. Therefore, the hourly distribution associated with November was used.

Mitigation Strategies

Table 22 shows the mitigation strategies considered and key data sources and assumptions used in the Tacoma case study. Shaded rows labeled “N/A” are strategies that were considered but not modeled, for reasons explained in the table.

Table 22. Mitigation strategies and evaluation approaches: Tacoma case study.

S#	Mitigation Strategy	Specific Project Concept	Data Sources and Assumptions
2	Additional lanes to increase capacity	None—lane addition has not been evaluated in this corridor.	N/A
3	Truck-only lanes	One truck-only lane in each direction on I-5, in addition to existing general-purpose lanes.	Increase truck speeds on I-5 links to 60 mph (approximate free flow speed based on 12:00–1:00 a.m. DANA tool data) and place truck lanes on inside of highway. This scenario also was combined with electric trucks for the noise analysis in the Tacoma case study.
4	New roadway	New proposed extension of SR 167 and SR 509, providing direct highway access from existing SR 167 highway to the Port of Tacoma.	Modeling for SR 167 completion project. Use projected 2045 AM and PM peak hour volumes for SR 167 extension and SR 509 spur from SR 167 Reevaluation Transportation Discipline Report (Washington State DOT [WSDOT], 2018), at a speed of 55 mph. Estimate truck volumes based on county truck percentages by road type.
5	Geometric design changes	I-5/Port of Tacoma interchange redesign and C/D roads.	Based on modeling for this proposed project. Increase midday and PM peak-period speeds on I-5 SB by 15% based on project analysis that improvements will increase PM peak-period area speeds by 15–20%. Reduce traffic volumes on I-5 SB (54th Avenue to Port of Tacoma Road) by 2% based on project estimate of overall 2% VMT reduction from geometric changes.[1]
6	TSMO strategies	Signal retiming and coordination on 54th Avenue, as proposed in the Tideflats and Port of Tacoma Intelligent Transportation System (ITS) Strategic Plan (2015).	Increase speeds on 54th Avenue between I-5 and E. 4th Street by 20%, representing a proposed project to retime and coordinate five signals on 54th Avenue Effectiveness based on references in the ITS Strategic Plan that (in general) signal retiming may reduce total corridor travel time between 7 and 25% and coordinated signal timing reduces delay between 5 and 20%.
7	Speed limit/ speed management	Lowering speed limit on I-5 to 55 mph with enforcement.	Reduce speeds greater than 55 mph to 55 mph.
8	Restricting or rerouting trucks	Evaluated for noise only—restricting trucks on 20th Avenue.	Evaluated using hypothetical volume changes on a local street.

Table 22. Mitigation strategies and evaluation approaches: Tacoma case study (continuation).

S#	Mitigation Strategy	Specific Project Concept	Data Sources and Assumptions
9 and 10	Accelerated retirement/ clean truck replacement; engine and powertrain retrofits, alternative fuels	Port of Tacoma Drayage Truck Emission Reduction Program—requires 2007 or newer engine; offers scrappage bonuses.	Assume 100% compliance with program.[2] Run MOVES separately for default (county) age distribution and 2007+ age distribution. Do this for all trucks as sensitivity case (S9a), and then for port trucks only (S9b, 39% of all combination trucks) by weighting emissions totals for each link by daily port-originating truck volumes by link estimated by Port of Tacoma (2016) as a fraction of total truck trips on the link (DANA tool). Pre-2007 trucks represent 13% of all trucks in S9a and 5% in S9b.
11.1 11.2	Clean truck corridor; electric charging infrastructure	Regional and multistate corridor policies and investments (including truck charging infrastructure) to encourage the use of electric trucks. I-5 is a Federally designated Alternative Fuels Corridor as well as the multistate designated I-5 Clean Energy Corridor.	Based on NREL Electrification Futures Study "medium" case projections of truck electrification,[3] exclude 5.2% of MDTs (type 50) and 3.0% of HDTs (type 60) for 2030 case (S11.1) from emissions calculations (including for idle links), and exclude 45.4% of MDTs (type 50) and 20.1% of HDTs (type 60) for 2045 case (S11.2).
12	Intermodal facility capacity and efficiency	12.1 The Port of Tacoma's vehicle wait time awareness program (posting turn times) is intended to reduce emissions. 12.2 Optimize drayage trips through improved and coordinated dispatch algorithms.	12.1 Assume 10% of arriving trucks shift their arrival times to avoid 30 minutes of idling (one-half of average turn time), applied to 1,740 daily trips at the Pierce County Terminal per 2016 cordon study.[4] 12.2 Assume 13% reduction in combination truck bobtail/deadhead trips, based on trip reduction estimated from modeling of prototype FRATIS implementation in Memphis.[5] Apply this to 49% "dual transaction" trips.[6] Further apply to trips with local destinations on 54th Avenue and Valley Avenue, as estimated from Port of Tacoma (2016).
13	Truck to rail mode shift	The Washington Grain Train serves over 2,500 cooperative members carrying grain from regions along the Columbia River to the deepwater ports on the Puget Sound with a goal of using rail cars to remove trucks from the local roads and highways.	Estimate based on trucks displaced by the Grain Train. The Washington State Grain Train Program Strategic Plan 2017–2027 (WSDOT, 2017) notes 1,350 carloads per year carried in 2016. This is estimated to correspond to 4,875 trucks per year or about 19 trucks per day removed from I-5.[7]

Table 22. Mitigation strategies and evaluation approaches: Tacoma case study (continuation).

S#	Mitigation Strategy	Specific Project Concept	Data Sources and Assumptions
14	Truck to water mode shift	None. While there is a small short-sea-shipping operation for Boeing cargo at the port, no data was identified to do a quantitative analysis of this strategy.	N/A
15	Noise barriers	Noise barrier along I-5.	Varying heights modeled using TNM.
16	Quiet pavement	Use of open-graded instead of average pavement.	Modeled using TNM.
17	Helmholtz resonators	Not modeled—no methodology in TNM.	N/A
18	Buffer zones	Not modeled—tested in the Chicago and Houston case studies.	N/A
19	Vegetation	Not modeled—tested in the Houston case study.	N/A
20	Noise insulation	Not modeled—no methodology in TNM.	N/A

1 See: Fife BUILD grant 2020 CBA.xlsb.

2 As of early 2022, the Port of Tacoma reports that this strategy has effectively been implemented, with nearly 100 percent of trucks in compliance (email from Graham VanderSchelden, Environmental Project Manager Port of Tacoma, March 15, 2022).

3 NREL describes the "medium" scenario as: a future with widespread electrification among the "low-hanging fruit" opportunities in electric vehicles … but one that does not result in transformational change (Mai et al, 2018).

4 Pierce County Terminal selected as the analysis terminal because it is closest to residential areas. Queuing areas at other terminals are not located near residential areas. Average turn time of about 60 minutes is for the Pierce County Terminal for last 30 days posted as of July 1, 2021—see: https://www.nwseaportalliance.com/cargo-operations/cameras-truck-turn-times/historical-terminal-data.

5 FHWA (2018).

6 Email from Zachary Thomas, Director, Operations Service Center, Port of Tacoma, September 16th, 2021.

7 Based on the density of wheat and capacity of a standard grain semitruck, one train with 72 cars is estimated to carry as much grain as 260 trucks. Therefore, one rail car is ~3.6 trucks, for around 4,875 annual displaced truck trips.

Emissions

Baseline Emissions

The Tacoma case study shows that modeled emissions for all criteria pollutants are higher during the PM hour than the AM peak hour (table 23). The largest difference in emissions is observed for CO and $PM_{2.5}$, which are 66 percent and 48 percent higher during the afternoon, while other pollutants are 18 to 37 percent higher in the afternoon than in the morning. The increase in emissions is consistent with the increase in congestion levels. During the PM peak hour, traffic data shows an increase in total traffic volume of 20 percent, particularly due to light-duty vehicles. The overall average speed is reduced from 34 mph to 28 mph, representing a reduction of 19 percent from the mean average speed observed during the morning.

Table 23. Emissions of criteria pollutants for Tacoma baseline case.

Pollutant	Emissions in AM peak hour (kg)	Emissions in PM peak hour (kg)
CO	88	146
NO_x	26	31
VOC	2.2	3.0
Total $PM_{2.5}$	0.9	1.3
CO_2e	14,579	18,959
MSATs	0.22	0.29

The baseline emissions modeled for the Tacoma case study indicate that heavy-duty trucks dominate emissions of NO_x and $PM_{2.5}$. CO is dominated by light-duty vehicles and VOC emissions are shared more evenly between the light-duty and heavy-duty fleet, with the major contribution shifting from heavy-duty in the morning to light-duty in the afternoon, consistent with the volume increase of the light-duty fleet. For NO_x and $PM_{2.5}$, the share from heavy-duty trucks ranges between 74–78 percent, for VOC ranges between 43–52 percent and for CO is only 10–14 percent. Other than the VOC changes mentioned, there are no other significant shifts between morning and afternoon hours.

In terms of the contribution from specific roadway segments modeled, the distribution of emissions between links changes depending on the pollutant because of the existence of an idle link. For CO, VOC and $PM_{2.5}$ emissions, the major contributor is I-5 between 54th Ave and Port of Tacoma Road. In the case of NO_x, the idle link is the major contributor to emissions during the AM hour (38 percent) while during the afternoon its contribution is slightly lower (32 percent) compared to that of the I-5 segment (34 percent).

Emissions Effects of Mitigation Strategies

Results from mitigation scenarios modeled in Tacoma are shown in table 24 and table 25, and reflect some features of the scenarios unique to Tacoma. Similar to Chicago, truck-only lanes show a significant benefit, as they address the congestion on the highest volume and emissions roadway link in the study, I-5; and clean truck strategies show similar relative reductions to Chicago and Houston. Unlike Chicago, however, TSMO strategies show little impact because they were limited to one surface street, 54th Avenue, which contributed relatively little to overall case study emissions. When emissions changes were examined only for the street with the improvements, they were more significant, in the range of 4 to 10 percent of total emissions generated on that link. Another anomaly in Tacoma's case study results is Scenario 4 (new roadway)—while the additional road capacity is meant to spread truck traffic and alleviate congestion over the broader geographic area, the effect on the smaller case study area is a significant increase in emissions from the additional truck volume diverted to the new study area roadway, which is not offset by decreases in volumes on other study area roads. When the new roadways are excluded, total emissions generally decreased by a small amount (0.1 to 4 percent), although there were modest increases in NO_x (0.3 percent) and $PM_{2.5}$ (4 percent) in the morning peak.[13] Results from Scenario 5, geometric roadway changes, mirror modest changes in speed and VMT for the scenario. Similar to Houston, speed management has minimal impact, and in fact shows an increase in $PM_{2.5}$ due to the effect of speed changes on light vehicles.

Port truck idle reduction and drayage optimization (Scenarios 12.1 and 12.2) both show small overall improvements, since port trucks are a smaller contributor to the Tacoma case study total emissions compared to Houston. Localized benefits may be larger, as the drayage optimization was estimated to reduce truck traffic on 54th Avenue by about 7 percent, reducing both link and idle emissions in the vicinity of the port entrance. Scenario 9, removing pre-2007 trucks, is presented for the case where the strategy is applied to all trucks (9a), and port trucks only (9b), to show the sensitivity of emissions to this strategy at different levels. On I-5 the estimated port truck fraction ranged from 14–24 percent depending on direction, while for the surface streets near the port the fraction was much higher, ranging from 47–77 percent. With port idle emissions attributed 100 percent to port trucks, the overall reductions for Scenario 9b are still significant, showing how targeted strategies at goods movement hubs can be an effective means for reducing hot spot emissions near those hubs.

[13] The proposed new roadway does result in a significant decrease in truck volume and emissions on some local streets, including Valley Avenue and 54th Avenue modeled in this case study, as well as other streets not modeled here. A comprehensive assessment of the net change in emissions would require modeling all of the roadways in a broad geographic area affected by traffic volume changes, which was beyond the scope of this analysis.

Table 24. Percent change in emissions from Tacoma baseline case (S3–S6).

Time	Pollutant	S3—Truck-Only Lane	S4—Add New Roads (All Links)	S4—Add New Roads (Existing Links Only)	S5—Geometric Changes	S6—TSMO strategies (All Links)	S6—TSMO strategies (54th Avenue Only)
AM	CO	-1	59	-1	-1	-1	-4
	NO_x	-5	36	0.3	0	-1	-7
	VOC	-3	42	-0.1	0	-1	-7
	Total $PM_{2.5}$	-15	37	4	0	-2	-10
	CO_2e	-1	56	-1	-1	-1	-6
	MSATs	-4	38	-0.1	0	-1	-8
PM	CO	-2	40	-2	-3	-1	-4
	NO_x	-15	26	-2	-3	0	-6
	VOC	-8	25	-4	-5	-1	-6
	Total $PM_{2.5}$	-33	15	-4	-7	-1	-9
	CO_2e	-4	40	-2	-3	-1	-7
	MSATs	-10	23	-0.1	-5	-1	-7

Table 25. Percent change in emissions from Tacoma baseline case (S7–S12.2).

Time	Pollutant	S7—Speed manage-ment	9a—Replace All Pre-2007 Trucks	9b—Replace Pre-2007 Port Trucks	S11.1—Clean Trucks 2030 Share	S11.2—Clean Trucks 2045 Share	S12.1—Idle Reduc-tion	S12.2—Drayage Optimi-zation
AM	CO	0	-1	-0.6	-1	-4	0	-0.3
	NO_x	0	-16	-8	-3	-19	-4	-3
	VOC	0	-21	-16	-2	-14	-3	-2
	Total $PM_{2.5}$	0	-37	-23	-2	-14	-2	-2
	CO_2e	0	-1	0	-1	-10	-1	-0.8
	MSATs	0	-28	-21	-2	-17	-3	-0.8
PM	CO	0	-0.6	-0.3	0	-3	0	-0.2
	NO_x	0	-14	-6	-3	-18	-3	-2
	VOC	1	-17	-11	-2	-12	-2	-1
	Total $PM_{2.5}$	1	-29	-16	-2	-11	-2	-1
	CO_2e	0	-1	0	-1	-8	-1	-0.5
	MSATs	1	-23	-15	-2	-15	-2	-0.5

Noise

Baseline Noise

Figure 12 shows the modeled links, nodes, and noise receptor locations (blue squares) as seen in the plan view of TNM 3.0. Receiver locations were selected with sensitive receptors in mind. A total of 73 receivers were evaluated for baseline conditions near both I-5 and the local roads in the study area, with additional receivers modeled to test specific noise mitigation strategies.

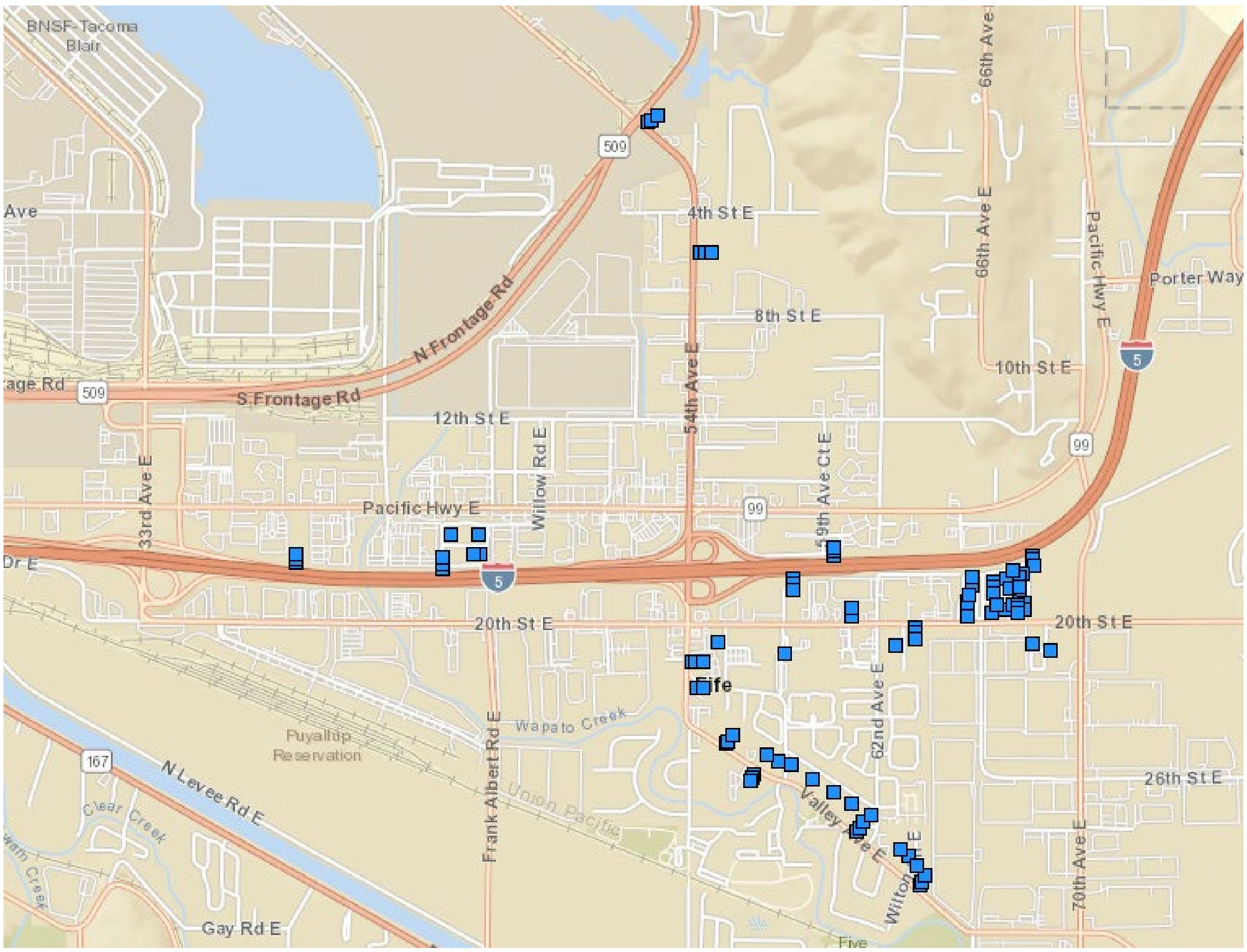

Figure 12. Map. Noise modeling links and receptors, Tacoma.

(Source: FHWA.)

Statistics for the modeled values for the baseline case are reported in table 26 and a plot of receivers rank-ordered by noise level is shown in figure 13. The solid horizontal line shows the FHWA NAC as a reference. In the Tacoma case study, the 12:00–1:00 p.m. hour had the greatest number receivers with higher noise levels. However, the 4:00–5:00 p.m. hour had the greatest noise level modeled at 77.2 dB(A). The loudest value was very close to the bottleneck roadway (Interstate 5) while the quieter value was away from the main roadway and shielded. The difference in the overall averages at the receiver locations for the daylight hours was only 0.5 dB(A) on average and for the maximum values.

However, at night a much larger reduction of over 7 dB(A) occurs compared to daytime levels. On I-5, overall traffic volumes were reduced by 85–90 percent in the 12:00–1:00 a.m. hour compared to the peak hours, although truck traffic was only reduced by just over half. On local streets, both truck traffic and total traffic were around 90–95 percent lower in the 12:00–1:00 a.m. hour compared to the peak hours. The differences in truck traffic changes for I-5 versus local streets are reflected in the figure which shows that the receptors with the highest noise levels—generally those closest to I-5—also showed the least reduction for the nighttime versus daytime hours.

Average truck speeds on I-5 varied from 16 to 55 mph during the peak hours, depending on the segment and time period, compared to 12:00–1:00 a.m. speeds of 48 to 61 mph. The limited variation in noise levels, compared to the high variation in speeds, across the daytime hours suggests that traffic and truck volumes, not speeds, are the main factor driving changes in noise levels in the observed ranges. The results also suggest that very large relative changes in truck traffic volumes must occur to create meaningful noise reductions.

Table 26. Baseline sound levels, Tacoma.

Statistic	12:00–1:00 a.m.	7:00–8:00 a.m.	12:00–1:00 p.m.	4:00–5:00 p.m.
Average sound level	54.9	62.2	62.6	62.1
Median sound level	52.0	61.7	62.2	61.1
Minimum sound level	39.1	44.7	44.6	44.5
Maximum sound level	71.4	77.1	76.7	77.2

Note: Sound levels and changes expressed in dB(A). N = 72 receivers.

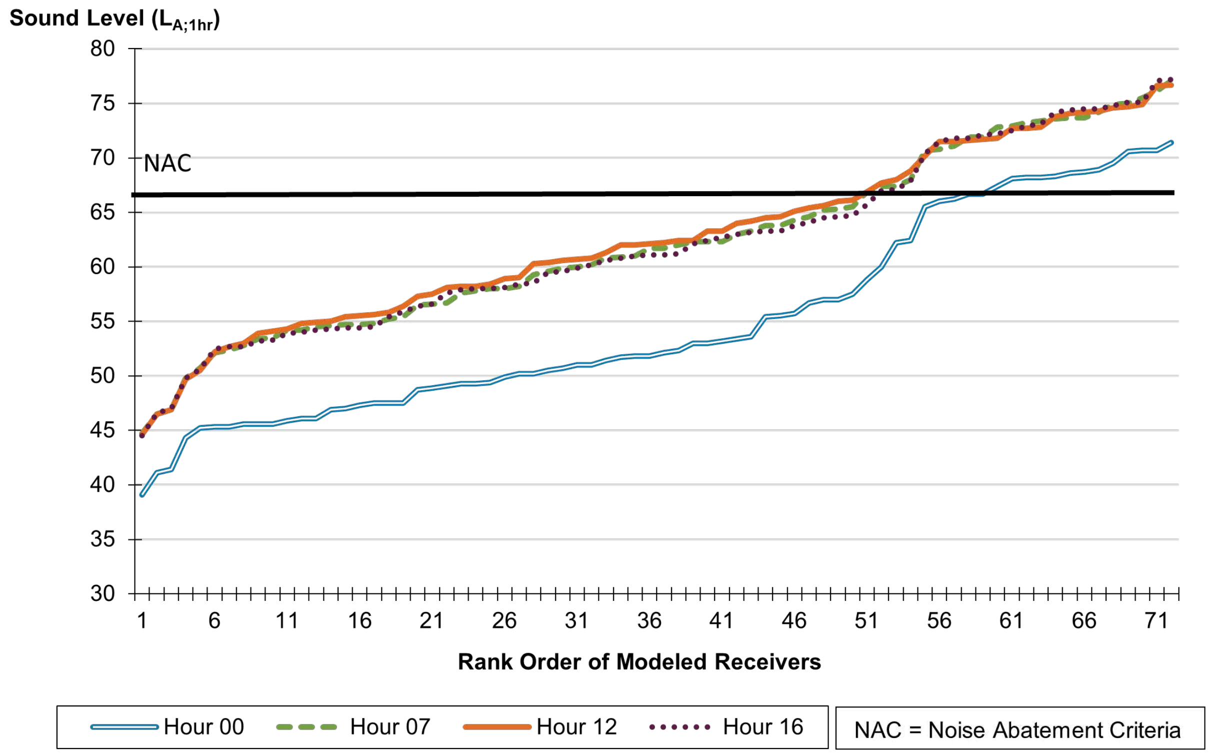

Figure 13. Chart. Cumulative baseline sound levels for Tacoma.

(Source: FHWA.)

Noise Mitigation Strategies

Nine strategies were modeled for noise abatement effects using TNM in Tacoma, including two electric truck market penetration scenarios and a scenario in which electric trucks and truck lanes were combined. Since the Tacoma case study included the broadest set of potential air and noise mitigation strategies, more noise strategies were modeled in Tacoma than for other case studies in order to show the range of results that might be expected from the various strategies and to show the extent to which results might vary by hour of the day.

Traffic and Clean Vehicle Strategies

Traffic strategies included Scenario 3 + 11.2 (truck-only lanes on I-5 with high market penetration of electric trucks), 5 (geometric design at an interchange), 6 (TSMO, specifically signal timing and coordination on one arterial street), 7 (speed limit management on I-5), 8 (restricting trucks from a local street), and 13 (truck to rail mode shift). The electric truck strategies (11.1 and 11.2) also are shown here since they are modeled by removing trucks. The results of the noise modeling using TNM 3.0 are shown in table 27 and table 28, with the rank order of receivers by decibel change shown in figure 14. Table 27 shows the relevant TNM 3.0 modeled values for the relevant baseline case and the evaluated scenarios as described in table 26. Table 28 shows the comparative difference between the baseline value and the abatement scenario value (baseline—abatement scenario) for the 12:00–1:00 p.m. hour. Figure 15 shows the change in sound levels for the 7:00–8:00 a.m., 12:00–1:00 p.m., and 4:00–5:00 p.m. hours for Scenario 3 + 11.2. This is the only scenario for which changes differed appreciably by hour of the day.

Overall, the changes in noise from the modeled traffic scenarios are minimal (never more than 1.5 dB(A), with the exception of Scenario 3 in the AM peak hour), and in many cases there is an increase in noise levels, often due to increased speed. The best scenario, with the greatest average decrease in sound levels, is Scenario 11.2 (clean truck corridor/electric changing infrastructure).This scenario is represented by significant volume reductions for medium and heavy-duty trucks (45.4 and 20.1 percent, respectively), with speeds remaining the same. For this case an average noise reduction of 0.8 dB(A) and a maximum noise reduction of 1.3 dB(A) occur. This is not a perceptible change. The scenario offering the greatest reduction for any receiver [2.8 dB(A)] is Scenario 3+11.2, truck-only lanes with electric trucks. However, some noise increases also occur. Scenario 6, TSMO strategies, provided a reduction of up to 2.6 dB(A) at a receiver but had increases elsewhere. These scenarios had changes at the edge of perception for the best-case receivers.

Table 27. Traffic and clean vehicle abatement scenarios, Tacoma, 12:00–1:00 p.m.

Statistic	S1	S3+11.2	S5	S6	S11.1	S11.2	S13
Average sound level	62.5	62.3	62.6	62.4	62.3	61.6	62.5
Median sound level	62.1	61.6	62.2	62.0	62.0	61.3	62.1
Minimum sound level	44.6	44.5	44.7	44.6	44.2	43.8	44.6
Maximum sound level	76.7	76.6	76.8	76.7	75.9	76.2	76.7

Note: Sound levels and changes expressed in dB(A). N = 71 receivers.

Table 28. Differences between baseline and mitigation scenarios, Tacoma, 12:00–1:00 p.m.

Statistic	S3+11.2 7–8 a.m.	S3+11.2 12–1 p.m.	S3+11.2 4–5 p.m.	S5 12–1 p.m.	S6 12–1 p.m.	S11.1 12–1 p.m.	S11.2 12–1 p.m.	S13 12–1 p.m.
Average sound level	-0.4	-0.2	-0.4	0.1	-0.1	-0.2	-0.8	0.0
Median sound level	-0.5	-0.1	-0.3	0.1	0.0	-0.1	-0.8	0.0
Minimum sound level	-0.6	-0.1	-0.4	0.1	0.0	-0.4	-0.8	0.0
Maximum sound level	0.1	-0.1	0.0	0.1	0.0	-0.8	-0.5	0.0
Largest increase	2.2	1.5	1.1	0.4	0.1	0.0	N/A	0.0
Largest decrease	-2.8	-1.3	-1.5	0.0	-0.8	-0.8	-1.3	0.0

Note: Sound levels and changes expressed in dB(A), all differences compared to S1 (baseline). N = 71 receivers. For the scenario versus base case comparisons, "average," "median," "minimum," and "maximum" refer to the change in the indicated statistic across all receivers. "Largest increase" and "largest decrease" show the largest changes at any individual receiver. A "N/A" value for "largest increase" means that no individual receivers saw an increase in noise levels for the mitigation versus base case scenario.

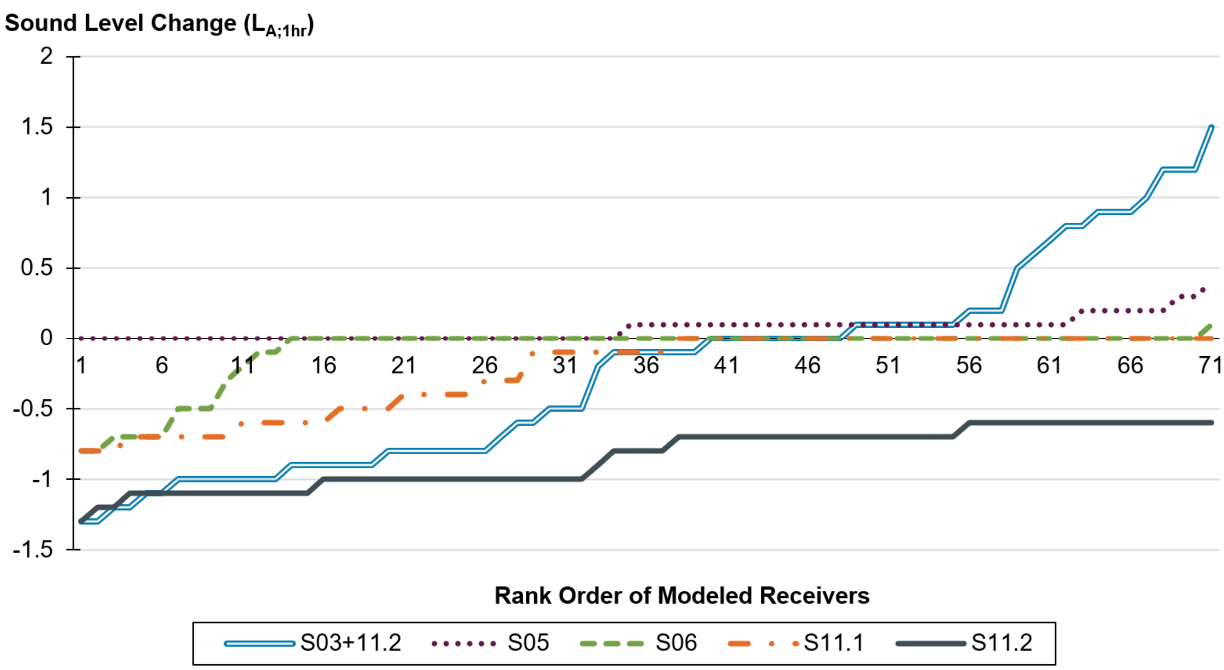

Figure 14. Chart. Change in sound levels for traffic mitigation strategies, Tacoma, 12:00–1:00 p.m.

(Source: FHWA.)

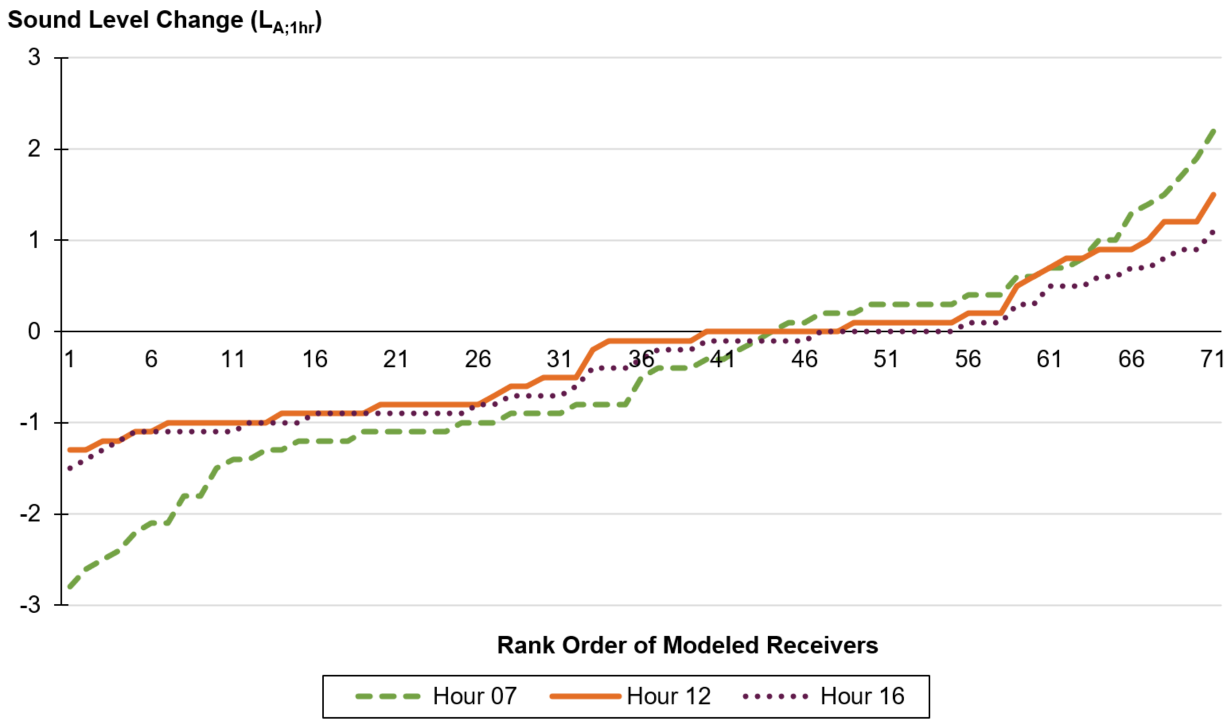

Figure 15. Chart. Change in sound levels by hour for truck lanes and electric trucks, Tacoma.

(Source: FHWA.)

If the same volume changes were applied to local streets as were applied to main roads, there could be perceptible noise abatement since the lower total volumes on these roadways would make the relative volume changes much more significant. Local roadways also are likely to be closer to sensitive noise receivers. A simple example is shown for the Tacoma case study. Most of the side roads are in industrial areas where noise reductions may not be necessary. However, one scenario was evaluated for Valley Avenue East where it passes multifamily housing. The heavy truck volume change from Scenario 11.2, high market penetration electric trucks, was applied to total truck volumes on this street. In this case the noise was reduced by about 1 dB(A) at the nearby receivers, 7, 8 and 9. Next, a hypothetical situation was reviewed where 80 percent of heavy trucks were either converted to electric drive or rerouted or rescheduled away from the evaluation hour. In this case, a meaningful noise reduction of approximately 6 dB(A) occurred as shown in table 29.

Table 29. Local road analysis traffic, Valley Avenue East (7:00–8:00 a.m.)

Vehicle Type	S1 Volume	S12.2 Volume	Heavy Truck Reroute Volume	Speed (mph)
Cars	501	501	501	15.1
Medium Truck	75	41	41	16.4
Heavy Truck	22	17	3	16.4

Table 30. Local road analysis sound levels [dB(A)], Valley Avenue East (7:00–8:00 a.m.)

Receiver	S1	S12.2	Heavy Truck Reroute
7	63.8	62.7	56.7
8	60.9	59.8	53.8
9	58.0	57.1	51.1

Noise Barriers

A simple noise barrier scenario was modeled along a section of Interstate 5 (see figure 16) by evaluating barriers of two heights (10 and 20 feet) along the edge of the right-of-way (the center median barrier shown in the figure is an existing, short Jersey-type barrier). Receivers along the Interstate were compared for 12:00 p.m. traffic with and without the noise barriers of different heights. Table 31 shows the results for the receivers in the immediate area.

For receivers 13, 14, 15, 65 and 72, which are in the front row of receivers but not located close to large buildings, a 10-foot barrier reduces noise by 4 to 11 dB(A), while a 20-foot barrier reduces noise by 11 to 13 dB(A). In some cases, the presence of large buildings magnifies the benefits of the noise barrier. For the 10-foot barrier, attenuations of up to 17 dB(A) occur in some locations where large buildings are present. A 20-foot barrier provides a noise abatement of up to 21 dB(A) at receiver 67, which is also shielded by large buildings. The results are in the range of the expected benefits of noise barriers. The results also suggest that additional attenuation could be obtained during project and site planning by jointly considering the placement of buildings and noise barriers.

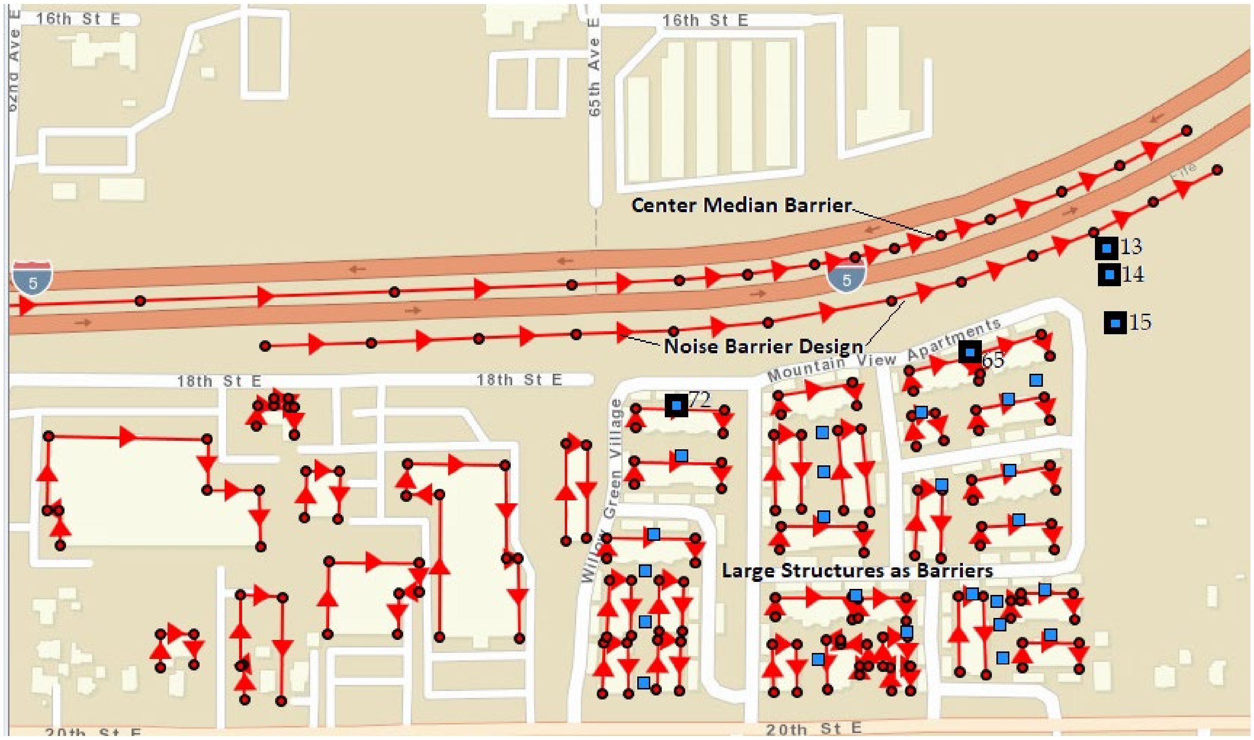

Figure 16. Map. Noise barrier inserted along I-5 right-of-way.

(Source: FHWA.)

Table 31. Noise reduction due to barrier on Interstate 5.

Statistic	No Barrier, LAeq	With 20' Barrier, LAeq	Noise Change from 20' Barrier	With 10' Barrier, LAeq	Noise Change from 10' Barrier
Average sound level	68.6	55.1	-13.5	58.2	-10.4
Median sound level	68.1	54.4	-13.7	56.1	-12.0
Minimum sound level	60.7	47.3	-13.4	49.5	-11.2
Maximum sound level	76.9	64.4	-12.5	69.6	-7.3
Largest increase	–	–	N/A	–	N/A
Largest decrease	–	–	-21.2	–	-17.4

Note: Sound levels and changes expressed in dB(A), all differences compared to S1 (baseline). N = 35 receivers, which are in the immediate vicinity of the mitigation measure and are therefore most affected; the average change across all study area receivers will be smaller. For the scenario versus base case comparisons, “average,” “median,” “minimum,” and “maximum” refer to the change in the indicated statistic across all receivers in the modeled subset. “Largest increase” and “largest decrease” show the largest changes at any individual receiver. A “N/A” value for “largest increase” means that no individual receivers saw an increase in noise levels for the mitigation versus base case scenario.

Low-Noise Pavement

Using TNM 3.1, quieter pavement in the form of open graded asphalt was compared to the base case which used average pavement, with summary results shown in table 32. Looking at results by receiver, receivers near the higher speed roadways typically had 0.5 dB(A) or greater of reduction and those near lower speed roadways had reductions of less than 0.5 dB(A). These results show smaller differences than reported in the literature for low-noise pavements. This is likely at least in part because the comparison being made is to an “average” pavement value rather than to higher-noise pavements, and because of limitations on the range of pavement types modeled in TNM.

Table 32. Comparison of average and open graded pavement.

Statistic	S1, Base Case, Hour 12	S1, Open Graded, Hour 12	Difference Open Graded—Base
Average sound level	63.2	62.6	-0.6
Median sound level	62.3	61.9	-0.4
Minimum sound level	49.7	49.6	-0.1
Maximum sound level	76.7	75.7	-1.0
Largest increase	–	–	1.6
Largest decrease	–	–	-1.3

Note: Sound levels and changes expressed in dB(A). N = 68 receivers. For the scenario versus base case comparisons, “average,” “median,” “minimum,” and “maximum” refer to the change in the indicated statistic across all receivers. “Largest increase” and “largest decrease” show the largest changes at any individual receiver.

Combination of Strategies

In some cases it may be possible to combine abatement strategies, including both traffic and nontraffic strategies. Figure 17 shows an analysis area located between Interstate 5 and 20th Street East. A noise barrier could be used to abate the Interstate highway noise since the bottleneck traffic solution scenarios do not appear to provide sufficient noise reductions. On 20th Street, however, a truck traffic change could have more effect.

To review this type of combination, a barrier was placed along I-5 and two scenarios were tested on the local street (20th Street) using TNM 3.0. Passenger car volumes of 250 per hour were left unchanged. However, in a separate run this road was assumed to be a secondary port road and medium trucks were reduced from 50 to 25 and heavy trucks from 25 to 3 per hour.

As shown in table 33, noise levels were reduced by approximately 2 to 5 dB(A) for the first-row receivers. Note that some receivers with building shielding (e.g., receiver 81) show less of an effect but the unshielded receivers (e.g., receiver 84) show reductions that would be readily noticeable to residents. These reductions were not possible without first mitigating the noise from Interstate 5.

Table 33. Comparison of removing truck traffic from a local road.

Receiver Name	With Truck Traffic	With Reduced Truck Traffic	Change From Reduced Truck Traffic
Receiver-76	56.0	52.2	-3.8
Receiver-77	54.4	50.7	-3.7
Receiver-81	48.1	46.2	-1.9
Receiver-82	53.0	50.4	-2.6
Receiver-83	54.7	50.8	-3.9
Receiver-84	59.7	54.7	-5.0

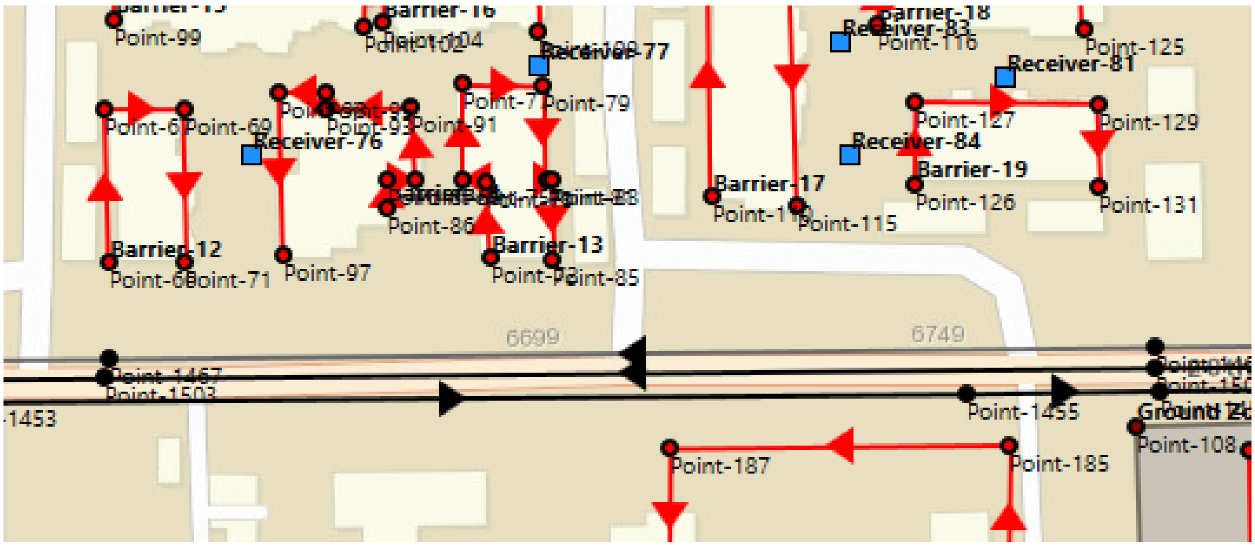

Figure 17. Map. Front row of noise receivers near 20th Street.

(Source: FHWA.)

7.0 Implementation Challenges and Solutions

This section provides information on the implementation challenges associated with emissions and noise mitigation strategies at truck bottleneck locations, as well as potential solutions to those challenges.

To identify implementation challenges and solutions, the project team:

- Consulted internal experts who have worked with State, regional, and local agencies to consider and evaluate these strategies, to identify their lessons learned.
- Reviewed existing U.S. and (to the extent relevant) international literature.
- Conducted interviews with staff at five State and metropolitan transportation planning agencies to identify additional, general lessons learned with respect to implementation of truck emissions and noise mitigation strategies. Agencies represented in the interviews included the New Mexico and Wisconsin DOTs; the Greater Nashville Regional Commission and the Capital Region Planning Commission of Louisiana, the Metropolitan Planning Organizations (MPO) for Nashville, TN and Baton Rouge, LA, respectively; and the Port of Los Angeles.

Some challenges will affect whether the strategy can be implemented in a specific location (e.g., can the roadway be widened or not); while others will affect the degree to which the strategy can be implemented (e.g., how much truck-rail mode shifting will occur?) Some challenges are highly context/situation specific, while others are universal.

Assessment of Implementation Challenges

To begin this assessment, table 34 identifies for each strategy, two indicators of how challenging and feasible the mitigation strategy appears to be:

- The degree of implementation in practice—how much has the strategy been attempted?
- How effective have these implementation efforts been at achieving their objectives, including effects (such as improved traffic flow) that may reduce truck noise and emissions?

Table 34. Mitigation strategy implementation and effectiveness.

S#	Mitigation Strategy	Degree of Implementation in Practice/Examples	How Effective Have Implementation Efforts Been?
2	Additional lanes to increase capacity	Done in many locations; feasibility varies by context.	Effective at short-term traffic flow improvements; long-term effects less certain due to induced demand.
3	Truck-only lanes	A number of proposals but very few examples in practice—two existing and one proposed location in Southern California, one being evaluated in Georgia.	Modeling studies have shown proposed lanes to be effective at improving flow and reducing emissions (Kim et al, 2018).
4	New roadway	Done in many locations; feasibility varies by context.	Effective at improving traffic flow or redirecting traffic, but often only shifts location of emissions or noise impact rather than overall impact. May provide benefit where traffic can be diverted away from more sensitive receptors.
5	Geometric design changes	Done in many locations; feasibility varies by context.	Effective at improving traffic flow.
6	TSMO strategies	Done in many locations.	Effective at improving traffic flow.
7	Speed limit/speed management	Implemented in a few locations for traffic management purposes (and broadly in the case of the National 55-mph speed limit).	Has generally been very difficult to enforce, with observed speed reductions much less than change in speed limit.
8	Restricting or rerouting trucks	A number of cities have designated truck routes with restrictions on other roads.	Effective at redirecting traffic and may improve traffic flow, but often only shifts location of emissions or noise away from more sensitive receptors.
9	Accelerated retirement/clean truck replacement	Implemented mainly at a few major port facilities.	Effective at turning over older truck engine technology.
10	Engine and powertrain retrofits, alternative fuels	Implemented in many areas through funding/ incentive programs.	Effective on a per-vehicle basis but market penetration/fleet size is generally limited.
11	Clean truck corridor; electric charging infrastructure	Increasing number of corridors designated and serviced in many States.	Emerging strategy—currently effects are small but likely to increase significantly in the future as technology is developed.

Table 34. Mitigation strategy implementation and effectiveness (continuation).

S#	Mitigation Strategy	Degree of Implementation in Practice/Examples	How Effective Have Implementation Efforts Been?
12	Intermodal facility capacity and efficiency	Improvements (capacity and/or operational) implemented in a number of port and intermodal facility locations.	There have been some demonstrated reductions in wait times and idling, although for other specific strategies, benefits have not been documented.
13	Truck to rail mode shift	A substantial volume of freight already moves by rail. Many States and regions have considered mode shift strategies as part of freight plans.	There have been some successes in achieving additional mode shift, but generally small fractions of additional tonnage have been shifted compared to the overall scale of freight movement.
14	Truck to water mode shift	A substantial volume of freight already moves by water. Some States and regions have considered mode shift strategies as part of freight plans.	There have been some successes in achieving additional mode shift, but generally very small fractions of additional tonnage have been shifted compared to the overall scale of freight movement.
15	Noise barriers	Widely implemented.	Generally effective across all time periods although in some cases barriers may have unintended consequences (e.g., reflected noise elsewhere).
16	Low-noise pavement	Implemented in a few cases, primarily on higher speed roadways.	Proven initial effectiveness, but long-term effectiveness (~7 years) may degrade and be affected by maintenance practices.
17	Helmholtz resonators	Very limited implementation.	Proven effectiveness but limited use due to other considerations such as maintenance.
18	Buffer zones	Implemented in limited cases where sufficient right-of-way (ROW) is available.	Effectiveness in proportion to buffer distance but is not linear and rate reduces with distance requiring large buffers that may be impractical from a land use or cost perspective.
19	Vegetation	Implemented in limited cases where sufficient ROW is available.	Only effective with a wide and dense belt of vegetation but thinner stands can still provide psychological benefit.
20	Building insulation	Implemented in a few cases.	Effective for indoor noise exposure in targeted buildings.

Table 35 continues by listing implementation challenges for each strategy. The table identifies how much the challenge might be a barrier (high, medium, low); the extent to which the challenge is universal versus context specific; factors that influence the degree of challenge; and potential solutions.

Implementation costs to the public sector are a universal implementation challenge and are considered separately in table 36, which discusses the relative cost of the strategy and potential funding sources.

Table 35. Mitigation strategy challenges and potential solutions.

S#	Mitigation Strategy	Challenge	Degree of Barrier	Influencing Factors	Potential Solutions
2	Additional lanes to increase capacity	ROW constraint; need for takings.[1]	Varies, low to high.	Number of lanes added; extent of property takings required; degree of community support for the project; extent to which project encroaches on environmentally sensitive areas.	Early public involvement to build understanding of project need and support for project. Offering fair and appropriate compensation or mitigation. Project design/alignment to minimize takings.
	Additional lanes to increase capacity	Opposition to highway capacity expansion due to environmental or community impact concerns.	Varies, low to high.	Local politics/public opinion may have a strong effect in addition to physical context of the expansion project.	Careful evaluation of all benefits and impacts of project, including modeling induced demand, economic benefits, emissions effects, etc. Environmental mitigation measures (e.g., emissions offsets, wetlands mitigation, community benefits).
3	Truck-only lanes	ROW constraint, especially if lanes are added; need for ROW acquisition.	Usually moderate to high.	Number of lanes added (if any), directionality, and type of separation; other factors per Strategy 2. (Often a larger ROW requirement than for lane addition since additional space required for lane separation and transition areas.)	See Strategy #2.
	Truck-only lanes	Opposition from truck drivers if lanes are tolled.	Varies.	Whether use of lanes is required, whether use is tolled, and travel time benefits relative to toll paid.	If lanes are tolled, price in proportion to congestion on main lines and associated travel time savings for trucks, so that truck drivers always receive a net benefit.
4	New roadway	See Strategy #2—similar challenges and solutions.	See Strategy #2—similar challenges and solutions.	See Strategy #2—similar challenges and solutions.	See Strategy #2—similar challenges and solutions.

Table 35. Mitigation strategy challenges and potential solutions (continuation).

S#	Mitigation Strategy	Challenge	Degree of Barrier	Influencing Factors	Potential Solutions
5	Geometric design changes	ROW constraint; need for ROW acquisition.	Usually low to moderate.	Depends on nature of changes, but generally smaller footprint than additional lanes.	See Strategy #2.
6	TSMO strategies	Institutional coordination for traffic controls operated by different agencies/ jurisdictions.	Low to moderate.	Not a problem for traffic operations on roads under a single jurisdiction, but coordination may be a challenge when multiple facility operators, law enforcement, etc. are involved.	Regional or multi-jurisdictional initiatives to coordinate TSMO implementation. Funding for under-resourced agencies to implement strategies/technologies (e.g., signal coordination support for smaller municipalities).
	TSMO strategies	For information-based strategies, the degree to which the information is accessed and used by drivers to change behavior in a way that reduces emissions or noise.	Moderate to high.	Depends on the specific strategy. In many cases there may be other reasons why a driver is not able to make use of the information (e.g., shift arrival to a less congested time).	Outreach to information recipients to understand opportunities and barriers for behavior change. Outreach to information recipients to understand the best methods for communicating relevant information.
7	Speed limit/ speed management	Enforcement to ensure driver compliance with speed limits.	High	This challenge is universally observed, especially for locations where the proposed speed limit is atypically low for the facility type or appears to drivers to be lower than the roadway would safely support.	Information campaigns to raise awareness of lowered speeds and penalties for noncompliance. Automated enforcement methods to reduce personnel costs and increase enforcement coverage.

Table 35. Mitigation strategy challenges and potential solutions (continuation).

S#	Mitigation Strategy	Challenge	Degree of Barrier	Influencing Factors	Potential Solutions
8	Restricting or rerouting trucks	Finding suitable routes that allow truck drivers to access their destinations without undue inconvenience while rerouting from sensitive areas.	Moderate to high.	Local/regional street network and existing land use affect viability of alternative routing.	Analysis to identify lowest-impact routes considering both user costs and impacts on receptor populations.
	Restricting or rerouting trucks	Providing information regarding designated and restricted routes to truck drivers.	Low to moderate.	Less of an issue where most trucks are repeating the same routes and learn the best routes over time.	Provide clear signage and online maps/information identifying designated and restricted routes. Make information available through open-source interfaces and traffic information providers.
	Restricting or rerouting trucks	Enforcing compliance with truck route restrictions.	Low to moderate.	Most truck drivers will comply if they are aware of requirements and have reasonable alternatives.	State or municipal leadership needs to set the expectation that law enforcement agencies will understand and enforce requirements.
9	Accelerated retirement/clean truck replacement	Limited regulatory authority to implement or enforce a requirement on truck age or turnover.	Moderate to high.	Port authorities have been able to require post-2007 engines for trucks operating on port property, but no municipality or State has yet implemented a broader mandate. A State might be able to do so through registration requirements, but a municipality would be less likely to have any legal authority.	If regulatory authority cannot be obtained or is politically not feasible, use a voluntary or incentive-based approach such as cash incentives or loans for new vehicle purchase, or graduated vehicle registration or facility access fees.

Table 35. Mitigation strategy challenges and potential solutions (continuation).

S#	Mitigation Strategy	Challenge	Degree of Barrier	Influencing Factors	Potential Solutions
9	Accelerated retirement/clean truck replacement	Opposition or lack of interest from truck owners/operators due to concerns regarding costs, downtime, and/or performance.	High (requirements). Moderate (voluntary programs).	Generally universal concerns.	Provide information about available technology options and their performance and cost impacts, including any benefits of the technology to the vehicle owner or operator. Make vehicle or engine replacement as easy as possible (minimal downtime). Provide financing or fully subsidize cost differential. When designing the program make sure truck owners and operators are included in discussions so that provisions do not create an undue burden. Focus on large fleets that have the most vehicles and that are likely to have more capacity for absorbing costs and/or vehicle downtime as well as interests in demonstrating sustainability.
	Accelerated retirement/clean truck replacement	Lack of any ability to influence "through" traffic that does not serve local destinations.	High.	Depends on degree to which traffic in bottleneck area is local versus through trips.	Partner with neighboring jurisdictions on multiregion/multistate policies and programs.
10	Engine and powertrain retrofits, alternative fuels	See Strategy #9—similar challenges and solutions.	See Strategy #9—similar challenges and solutions.	See Strategy #9—similar challenges and solutions.	See Strategy #9—similar challenges and solutions.

Table 35. Mitigation strategy challenges and potential solutions (continuation).

S#	Mitigation Strategy	Challenge	Degree of Barrier	Influencing Factors	Potential Solutions
11	Clean truck corridor; electric charging infrastructure	Finding suitable locations and operators for refueling/charging infrastructure.	Low.	Generally, should be able to integrate with extensive network of existing gas/diesel refueling stations.	Partner with private infrastructure and service providers to build out infrastructure. Look for opportunities to use public property and piggyback on public fleet clean fuels (e.g., maintenance yards). Provide funding guarantees/gap finance if short-term market is too uncertain to support private investment.
	Clean truck corridor; electric charging infrastructure	Availability of vehicle technology that meets cost and performance requirements for the specific application.	Moderate to high.	Depends on specific technology—compressed natural gas technology is proven, but hydrogen and electric truck technologies are nascent.	Initiate demonstration projects using public-sector applications to test technology. Work with larger locally based fleets that have the capacity to absorb risks and finance technology development/ testing. Conduct outreach to vehicle and fleet owners/operators to understand performance requirements and educate on available technologies and incentives.
12	Intermodal facility capacity and efficiency	Physical land constraints on terminal or gate area capacity expansion.	Varies.	Context-specific depending upon available property and adjacent land use.	Design/engineering to minimize footprint or repurpose underutilized areas.

Table 35. Mitigation strategy challenges and potential solutions (continuation).

S#	Mitigation Strategy	Challenge	Degree of Barrier	Influencing Factors	Potential Solutions
12	Intermodal facility capacity and efficiency	Ability to adjust arrival to off-peak times may be limited by delivery schedule requirements for shippers and receivers.	High.	Scheduling, and hours of operation.	Conduct outreach to shippers/ operators to understand opportunities and challenges for time shifting. Implement pricing strategies (e.g., time-dependent fees) to provide an incentive to shift to off-peak times.
	Intermodal facility capacity and efficiency	Ability to reduce bobtails or empty backhauls may be limited by balance of flows or requirements for matching loads to vehicles.	Moderate to high.	Nature and origins of local haul movements.	Conduct outreach to shippers and operators to understand opportunities and challenges for reducing empty trips. Encourage use of drayage optimization tools.
	Intermodal facility capacity and efficiency	Hours of operations requirements.	Low to moderate.	Local labor requirements. Increased truck operations during evening hours may increase impact on residential receptors.	Financial incentives negotiated with union contracts.
13	Truck to rail mode shift	Requirements for timeliness of product delivery.	Varies.	Product- and route-specific. Often a barrier for goods that are time sensitive, especially for markets with limited rail service.	Conduct outreach to shippers and third-party logistics providers to understand potential for mode shift in particular markets.
	Truck to rail mode shift	Additional handling costs by shippers.	Varies.	Product- and route-specific. Modal transfers incur additional costs even if per-mile cost is lower by truck than rail.	Develop marketing material for Short Line railroads and work with American Association of Railroads to identify and market to potential customers.

Table 35. Mitigation strategy challenges and potential solutions (continuation).

S#	Mitigation Strategy	Challenge	Degree of Barrier	Influencing Factors	Potential Solutions
13	Truck to rail mode shift	Complexity, funding, and time requirements for a comprehensive set of rail infrastructure improvements.	High.	Depends on the needs for improved service in a particular corridor/market, but typically long-distance routes served by rail will require capital improvements across multiple locations managed by multiple entities.	Multistate/corridor-wide freight plans. Partnerships with railways, ports, and terminal owners/operators to prioritize improvements and identify funding sources.
14	Truck to water mode shift	Requirements for timeliness of product delivery and additional handling costs by shippers.	High.	Similar to #13; water-specific factors may include seasonal closures (e.g., freezing) and congestion at locks.	See Strategy #13.
15	Noise barriers	ROW requirements.	Low to moderate.	May be a problem (or require higher costs) in constrained locations.	See Strategy #2 re: ROW constraint.
	Noise barriers	Visual/aesthetic and access concerns.	Low to moderate.	May depend on how visible the barrier is to nearby residents and businesses.	Context-sensitive barrier designs. Barrier aesthetic design, vegetation as screening or green barrier.
16	Low-noise pavement	Safety issues (e.g., reduction in surface friction).	Moderate to high.	Depends on material/surface type.	Use pavement materials/surface treatments demonstrated to have good surface friction performance.
	Low-noise pavement	Maintenance needs; loss of noise reduction over time.	Low to moderate.	Depends on material/surface type and amount of noise reduction needed.	Use pavement materials/surface treatments selected for acoustic durability. Build maintenance requirements and/or shorter resurfacing times into lifecycle cost assessment of strategy.

Table 35. Mitigation strategy challenges and potential solutions (continuation).

S#	Mitigation Strategy	Challenge	Degree of Barrier	Influencing Factors	Potential Solutions
16	Low-noise pavement	Lack of familiarity among contractors or inclusion in standard specifications.	Low to high.	Depends on contractor familiarity with method, local area characteristics, and agency endorsement/specification.	Research and seek approval for appropriate treatments meeting safety and maintenance criteria, develop standard specifications, and educate contractors.
17	Helmholtz resonators	Unfamiliar technique with limited data on effectiveness and appropriate uses, and potential maintenance concerns.	Moderate to High.	Depending on application, may require periodic cleaning or soil removal.	Build maintenance requirements into lifecycle cost assessment strategy.
18	Buffer zones	Right-of-way cost and availability.	High.	Density of development, property values.	Obtaining and reserving the necessary ROW is likely to be impractical in most if not all major bottleneck locations.
19	Vegetation	Right-of-way cost and availability.	High.	Density of development, property values, local climate.	Obtaining and reserving the necessary ROW is likely to be impractical in most major bottleneck locations.
20	Building insulation	Need to coordinate with numerous private property owners.	Moderate to High.	Number and type of properties, tenancy status, any language or cultural barriers.	Favorable and easy-to-use incentives; one-stop contracting.
	Building insulation	Ownership turnover (future purchase of uninsulated property by someone more sensitive to noise impacts).	Moderate.	Rate of turnover of property ownership.	Program maintenance/continuity (make incentives/assistance available to future buyers).
	Building insulation	Decision of which locations will receive the benefit.	Moderate.	Type of receiver location, lack of other mitigation strategies.	Use of criteria for determination.

[1] This is partly a cost issue but can also delay the project due to legal challenges or restrictions (e.g., wetlands takings).

Table 36. Mitigation strategy costs and funding sources.

S#	Mitigation Strategy	Relative Cost[1]	Potential Funding Sources
2	Additional lanes to increase capacity	High.	Federal-Aid Highway Program funds, State highway program funds, tolling.
3	Truck-only lanes	High.	Federal-Aid Highway Program funds, State highway program funds, tolling.
4	New roadway	High.	Federal-Aid Highway Program funds, State highway program funds, tolling.
5	Geometric design changes	Moderate.	Federal-Aid Highway Program funds, State highway program funds, tolling.
6	TSMO strategies	Low to Moderate.	Federal-Aid Highway Program funds, State highway program funds, tolling.
7	Speed limit/speed management	Low—mainly for enforcement.	Federal and State highway funding programs for signage and information, potentially for law enforcement costs.
8	Restricting or rerouting trucks	Low.	Federal and State highway funding programs for signage and information, potentially for law enforcement costs.
9	Accelerated retirement/ clean truck replacement	High.	FHWA Congestion Mitigation and Air Quality Improvement (CMAQ) Program, EPA emission reduction programs, State emission reduction programs (some States).
10	Retrofits, engine and powertrain, alternative fuels	High.	FHWA CMAQ Program, EPA emission reduction programs, State emission reduction programs (some States).
11	Clean truck corridor; electric charging infrastructure	Moderate (infrastructure). High (including vehicle costs—potentially offset by fuel savings).	FHWA CMAQ program (nonattainment areas), other Federal grant programs, State electrification/alternative fuel programs (some States), public-private partnerships (finance via operating cost savings/revenue generation).
12	Intermodal facility capacity and efficiency	Low (information or operations), Moderate to High (capacity/ infrastructure).	Port fees, United States DOT (USDOT) grant programs.
13	Truck to rail mode shift	High.	USDOT grant programs, State funding, public-private partnerships.
14	Truck to water mode shift	High.	USDOT grant programs, State funding, public-private partnerships.
15	Noise barriers	Moderate.	Federal-Aid Highway Program funds, State highway program funds, port authorities, developers/property owners.

Table 36. Mitigation strategy costs and funding sources (continuation).

S#	Mitigation Strategy	Relative Cost[1]	Potential Funding Sources
16	Low-noise pavement	Low to Moderate.	Federal-Aid Highway Program funds, State highway program funds, municipal funds.
17	Helmholtz resonators	Low to Moderate.	State highway program funds.
18	Buffer zones	High.	Federal-Aid Highway Program funds, State highway program funds.
19	Vegetation	Low to Moderate.	Federal-Aid Highway Program funds, State highway program funds.
20	Building insulation	Moderate.	Federal-Aid Highway Program funds, State highway program funds, developers/ property owners.

1 Relative cost for a typical application affecting a significant fraction of truck traffic at a corridor/bottleneck: Low—<$1 million; Moderate—~$1–low $10s of millions; High—$10s to $100s of millions of dollars.

Summary of Challenges and Potential Solutions

The challenges and solutions discussed in the previous section point to multiple common themes. The nature of the challenges and potential solutions varies somewhat depending upon whether the strategy is focused on infrastructure and operations implemented by the *transportation system owner* (e.g., State or local transportation agency, port authority, railroad), or on vehicle, fuels, or information technology adopted by the *transportation system user* (e.g., vehicle and fleet owners, operators, shippers). Still, there are many commonalities:

- **Listen and understand.**
  - For infrastructure and operations projects, various stakeholders may need to play a role in implementing the solution (e.g., State and municipal transportation agencies, port authorities) or will be affected by the solution (e.g., nearby residents and business owners, landowners). Hear what their needs and concerns are and work collaboratively on project designs that address these needs and concerns.
  - For vehicle, fuels, and information technology projects, entities (e.g., vehicle owners, vehicle operators, shippers) will need to change behavior to implement the solution. Understand opportunities (how the solution would benefit them), challenges, and what it might take to implement the solution. Partner on developing and testing solutions where appropriate, making it as easy as possible for people to participate.
  - For all projects, involve the State or regional freight advisory committee or council(s) to ensure that the strategy to address the bottleneck is fully understood and supported.[14] No single agency is responsible for implementing most of the strategies analyzed, and the champion of a strategy may not have authority for implementing that strategy.

14 States are strongly encouraged to establish freight advisory committees under U.S. code (49 U.S.C. Sec. 70201), and MPOs may also establish such committees.

Freight advisory committees can be an effective vehicle for coordinating the activities of State DOTs, municipalities, port authorities, motor vehicle departments, private fleet operators, law enforcement agencies, and others to implement bottleneck solutions. Identify problems that are held in common and ways in which all responsible parties could benefit.

- **Educate and inform.**
  - For infrastructure and operations projects, affected stakeholders will need to support the project. Demonstrate the benefits and importance of the proposed project. Help stakeholders understand and weigh the tradeoffs among the different solutions or alternatives considered.
  - For vehicle, fuels, and information technology projects, vehicle owners and operators may not be aware of the solution (e.g., availability of funds for clean truck replacement) or may not understand how the program will benefit them. Some large fleets may take actions with social responsibility goals, but for the most part truck owners and operators will need to understand how the solution can benefit them directly (e.g., better fuel economy, lower maintenance cost). Outreach should target the audience, e.g., including translations to reach drivers for whom English is not the native language.
  - For all projects, involve the State or regional freight advisory committee or council(s) to ensure that the strategy to address the bottleneck is fully understood and supported. Consider social benefits, not just benefits to the implementing agency. Ensure that public communication accurately describe the project and its potential benefits and impacts from the start – there is often not a second chance to make a first impression.
- **Test.**
  - For infrastructure and operations projects using innovative or unproven technologies (such as pavements or traffic controls), find controlled locations where the improvement can be proven safe and effective.
  - For vehicle, fuels, and information technology projects, implement demonstration projects, with public and/or willing private entities, to test new technologies, refine, and demonstrate benefits.
- **Leverage.**
  - For infrastructure and operations projects, coordinate with and piggyback on other efforts that may create synergies, such as including freight information systems in a regional ITS plan or constructing buildings in such a way to create noise abatement.
  - For vehicle, fuels, and information technology projects, start with low-hanging fruit, e.g., large fleets or lower-cost applications, before trying to influence smaller operators or markets or implementing higher-cost technologies.
  - For all projects, make sure the strategy is listed in the State Freight Plan so that if funds become available those will be justified.
  - Present solutions that show multiple benefits and that benefit all parties involved.
- **Coordinate.** A large fraction of truck traffic provides interstate or long-distance goods movement services—meaning that strategies to make trucks cleaner or reduce truck traffic

volumes may require coordination across multiple jurisdictions. Multistate partnerships may be needed to implement strategies such as clean fuels corridors and rail infrastructure improvements. Rail, port, and intermodal terminal operators need to be included in developing infrastructure and operations strategies to support truck-rail or truck-water mode shift. Again, the freight advisory committee can serve as a forum for coordination.

- **Support financing.**
  - For infrastructure and operations projects, some entities (such as small municipalities having jurisdiction over port access roads) may not have the technical or financial resources to implement solutions. State or regional funding can assist with local projects creating regional benefits.
  - For vehicle, fuels, and information technology projects, some strategies will result in operating cost savings over time (e.g., to vehicle or facility owners and operators) but require higher up-front costs. Programs such as grants, loans, and public-private partnerships can help overcome initial challenges of finding initial capital, especially for undercapitalized entities such as individual owners/operators.
- **Increase funding.** Some challenges can be overcome by designing more expensive solutions. However, a determination needs to be made that the added cost is worth the benefits that are provided—and that scarce resources should be allocated from other actions that also have benefits.
- **Mitigate other impacts.** For negative impacts that cannot be avoided, work with stakeholders and concerned parties to identify and implement appropriate measures to mitigate or offset these impacts. “Do no harm”—do not create one problem by solving another.

8.0 Conclusions on Emissions and Noise Benefits

Estimates of emissions and noise associated with traffic at truck bottleneck locations in Chicago, Houston, and Tacoma illustrate how heavy-duty trucks contribute to emissions and noise at and around these bottlenecks. Analysis of potential mitigation strategies in each location shows how emissions and noise might be affected by various strategies. Findings are shown for an urban freeway setting (Chicago), a goods movement hub (Houston), and an environment combining these two elements (Tacoma).

A total of 15 potential air quality and/or noise mitigation strategies were modeled in at least one case study location. For two additional noise abatement strategies, general effects were characterized based on literature findings. While many of the strategies were implemented differently in each location, and in many cases were based on hypothetical assumptions rather than specific local proposals, some common conclusions can still be drawn from the modeling.

Summary Comparison

The results for the three case studies show that truck volumes coupled with congested conditions and/or excessive idle drive total emissions. Correspondingly, mitigation strategies that substantially reduce truck volumes, replace more polluting trucks with cleaner trucks, significantly increase peak-period speeds, or reduce idling activity were found to have the largest emissions benefit.

Most of the strategies that reduced peak-period emissions showed little or no benefit for noise reduction. This is for two reasons: 1) a very large relative (percentage) volume change is needed to noticeably reduce noise—a level unachievable by most strategies in most locations; and 2) strategies that reduced peak-period emissions by reducing congestion sometimes increase noise levels, as they increase traffic speeds. Instead, the most effective noise mitigation strategies were those specifically targeted at noise reduction, particularly noise barriers.

Noise-specific mitigation strategies do not reduce emissions. However, some noise mitigation strategies—including noise barriers, buffer zones, and vegetation—can lower air pollutant concentrations at near-road receptor locations.[15] Therefore, these measures can provide a potential air quality benefit for pollutants of local concern, such as fine particulates, NO_x, and air toxics. These benefits are not provided for pollutants that operate at a regional or global scale, including ozone precursors and greenhouse gases.

Table 37 illustrates the overall range of emissions and noise benefits achieved by each mitigation strategy and discusses how these might vary by the specific strategy application and context. Note that the effectiveness of any particular mitigation strategy can vary widely depending upon how that strategy is defined and implemented in any particular situation, as well as other details related to the context of implementation. This table generally characterizes the range of expected beneficial or negative impacts, but some applications could lead to effects outside of the range shown.

15 Dispersion modeling was outside the scope of this research; however, literature cited in section 2.2.4 supports this statement.

Table 37. Emissions and noise benefits of mitigation strategies.

Category	S#[1]	Mitigation Strategy	Air Quality Effects[2]	Noise Effects	Comments
Capacity and Operations Improvements	2	Additional lanes to increase capacity	+ +	↓↑	Reductions of most pollutants in the 5–15% range for one case study example. Very modest noise increases or decreases (<1 dB(A)) at most receptor locations.[3]
	3	Truck-only lanes	+ + +	↓↑	Emission reductions of 5–64% for a project that substantially increased speeds; <15% for a project with smaller speed effects. Very modest noise increases or decreases (<1 dB(A)) at most receptor locations.
	4	New roadway	↓↑	**Not evaluated**	Increased noise and emissions near new roadway, possible modest decreases on existing roadways.
	5	Geometric design changes	+	↓↑	Modest emissions decreases (<5%) and very modest noise increases or decreases (<1 dB(A)) in one case study example.
	6	TSMO strategies	+	↓↑	Modest emissions decreases (<5%) and very modest noise increases or decreases (<1 dB(A)) in one case study location. Some TSMO strategies such as automated vehicles could achieve significant emissions benefits.
	7	Speed limit/speed management	↓↑	↓↑	Small emissions (+/-1%) and noise (<1 dB(A)) effects within typical speed change ranges.
Capacity and Operations Improvements	8	Restricting or rerouting trucks	**Not evaluated**	+ +	Emissions effects not tested. Up to 6 dB(A) reduction identified on one local street, but highly location-specific and much less on high-volume streets.
Clean Vehicles and Fuels	9 and 10	Accelerated retirement, retrofits, engine and powertrain, alternative fuels	+ + +	**Not evaluated**	Emissions benefits proportional to market penetration, with PM reductions of 13–60% and NO_x reductions of 8–21% in case studies for replacement of pre-2007 heavy trucks with post-2007 trucks (representing 6-39% of study area trucks).

Table 37. Emissions and noise benefits of mitigation strategies (continuation).

Category	S#[1]	Mitigation Strategy	Air Quality Effects[2]	Noise Effects	Comments
Clean Vehicles and Fuels	11	Clean truck corridor; electric charging infrastructure	+++	+	Emissions benefits in the range of 10–20% for most pollutants at potential 2045 levels of market penetration. Very modest noise benefits (<1 dB(A)) in most locations.
Truck Operational Efficiencies and Mode Shift	12	Intermodal facility capacity and efficiency	++	**Not evaluated**	Emissions benefits of up to 9% for idle reduction and up to 13% for drayage optimization in one case study.
	13	Truck to rail mode shift	+	+	Small emissions (<1%) and noise (<1 dB(A)) benefits from long-distance mode shift due to limited additional mode shift in case studies, but up to 19% truck emissions reduction in Houston for local rail drayage.
	14	Truck to water mode shift	**Not evaluated**	**Not evaluated**	Not evaluated in case studies, but benefits likely similar to S13 when they can be achieved.
Other Noise Mitigation Strategies	15	Noise barriers	+++	+++	Does not reduce emissions, but can reduce pollutant concentrations behind barrier. Noise benefits of 10 dB(A) or more observed in case study locations.
	16	Low-noise pavement	O	++	Noise benefits mainly at higher speeds. Modeled effects of <1 dB(A) for average versus low-noise pavement differed from effects in literature of 4–7 dB(A) for higher versus lower-noise pavements.
	17	Helmholtz resonators	O	++	Effects of about 3 dB(A) for Helmholtz resonators based on literature.
	18	Buffer zones	+++	++	Effects of 3–5 dB(A) in case studies for 100' buffer, but adequate buffers may not be feasible in bottleneck locations.

Table 37. Emissions and noise benefits of mitigation strategies (continuation).

Category	S#[1]	Mitigation Strategy	Air Quality Effects[2]	Noise Effects	Comments
Other Noise Mitigation Strategies	19	Vegetation	+ + +	+ +	Over 3 dB(A) reduction in case studies for a 100’ zone of properly designed vegetation, but adequate width may not be feasible in bottleneck locations.
	20	Building insulation	↓↑	+ + +	Can reduce noise by about 7 dB(A) based on literature, but only inside treated structures. Filtration is needed to ensure that insulation does not trap indoor pollutants and degrade air quality.

1 S = Strategy number. Strategy (or scenario) 1 is the base case (no mitigation).

2 The air quality metric is change in emissions for strategies 2–14 and change in air pollutant concentration for strategies 15–20.

3 A change of 1dB(A) is considered barely perceptible to some individuals, while a change of at least 5 dB(A) is considered perceptible to most individuals.

Legend:

+ = typically <5 percent emissions or <3 dB(A) noise reduction.

+ + = typically 5–15 percent emissions or 3–5 dB(A) noise reduction.

+ + + = typically >15 percent emissions or >5 dB(A) noise reduction.

↓↑ = mixed effects, may reduce or increase.

○ = no effect.

Discussion of Mitigation Strategies

Capacity and Operations Improvements

- Strategies that **increase capacity** (S2) were tested in the form of a project to increase capacity and improve geometry at a major freeway interchange in Chicago. In this instance, the project (which currently is being implemented) was found to have modest emissions benefits (up to 7 percent) in the morning peak and larger benefits (up to 22 percent) in the afternoon peak. The Chicago interchange project reduced PM peak-period noise by a modest, imperceptible amount (typically no more than 1 dB(A)) in many receptor locations, but also increased noise in some locations.
- **Truck-only lanes** (S3), tested in Chicago and Tacoma as additions to the Interstate mainline, resulted in significant overall emission reductions in the project area, especially for NO_x and $PM_{2.5}$, by virtue of eliminating congestion for trucks. $PM_{2.5}$ emissions were reduced by up to 33 percent in Tacoma and 64 percent in Chicago in the most congested conditions of the afternoon peak hour. A different definition of this strategy—an exclusive on/off ramp in Houston to reduce frontage road travel—had little effect on emissions. Truck-only lanes increased noise by a very small amount for the PM peak hour at most receptor locations in Chicago as a result of speed increases. In Tacoma this strategy showed mixed noise effects (modest reductions in most locations, but modest increases in others). In the Chicago case study, placing the truck lanes at the center of the road somewhat mitigated the noise impacts of higher speeds. With increased truck speeds and revised lane placement, noise levels at all receivers showed an average decrease of 0.9 dB(A), compared with an average increase of 0.4 dB(A) when speeds are increased but the truck lanes are in the same location as the previous general travel lanes. Still, these changes are generally imperceptible.
- **Addition of new roads** (S4) was tested in only one case study, Tacoma, where existing modeling results for an extension of State Route 167 (starting construction in 2022) were used. Total emissions on study area links were found to increase since emissions from traffic on the new roadway more than outweighed any offsetting effects of traffic reductions or speed increases on other study area roads. Noise also would be generated near the new roadways, although effects were not modeled. However, the effects of this type of strategy are likely to be very localized and the limited study area evaluated here paints a very incomplete picture of the overall effects. Looking only at existing roads, total emissions generally decreased by a small amount and noise is not expected to show a meaningful change, based on the small percentage changes in traffic volumes.
- **Geometric changes** (S5) were tested as a stand-alone strategy with an interchange improvement in Tacoma, as well as being part of the capacity strategy in Chicago. The Tacoma project (based on traffic analysis of a real proposed project) showed emissions benefits at the scale of the entire study area of up to 7 percent for $PM_{2.5}$ in the afternoon peak, although minimal in the morning peak. This project showed minimal noise effects, with either no change or an increase in noise by up to 0.2 dB(A) in most receptor locations. Again, the benefits of this type of strategy are likely to be localized and project specific.
- **TSMO strategies** (S6) had a wide range of definitions with a correspondingly wide range of results. Signal coordination improvements along an arterial in Tacoma showed very modest

(1–2 percent) emissions benefits on the scale of the entire study area, although benefits on the affected arterial were greater (4–10 percent). Noise increased slightly near the affected roadway, by no more than 1 dB(A). However, implementation of a hypothetical program of connected vehicles in managed lanes to maintain free flow conditions on Chicago expressways showed substantial emissions benefits for all pollutants, up to 51 percent for NO_x and 70 percent for $PM_{2.5}$ during the afternoon peak. This case study application was not tested for noise, but noise would be expected to increase due to higher traffic speeds.

- **Speed management** (S7), specifically, reducing speed limits to 55 mph with strict enforcement in Houston and Tacoma, showed no benefits, and in fact, very small emissions increases in some cases. This is partly because observed speeds were not much higher than the target speed limit overall, but also because changing speeds in the affected ranges had very little effect on reducing emission rates. It is possible that locations with higher average speeds (e.g., 65 to 70 mph) might show more of a benefit from speed management strategies. Evaluation of speed management in Houston showed a small (less than 1 dB(A)) reduction in noise levels.
- **Restricting/rerouting trucks** (S8) was evaluated for noise impacts in one location (Tacoma) by removing a majority of heavy trucks from a local street. The noise benefit was significant (6 dB(A)) when noise from the nearby Interstate highway also was mitigated, but minimal if it was not. In general, there were no truck rerouting options identified in the case study locations that would have significantly reduced emissions and/or noise without simply shifting those impacts to a new location. However, the noise analysis does suggest that if trucks could be rerouted from a low-volume road onto a high-volume road, overall noise impacts could be reduced since noise in the vicinity of the low-volume road could be reduced significantly, whereas it would only increase minimally on the high-volume road.

Clean Vehicles and Fuels

- **Replacing older pre-2007 model-year trucks with newer, cleaner trucks** (S9 and S10)—those serving the port in Tacoma, or for all local traffic in Chicago and Houston—showed significant reductions, over 50 percent in some cases for the Houston case study area. The impact in Tacoma was less because port trucks contribute a smaller share to the study project area, but reductions in total case study NO_x and $PM_{2.5}$ were still in the range of 10–20 percent. The benefit of this strategy will depend upon the market size of trucks that can be replaced. This strategy is not expected to meaningfully affect noise.
- **Adoption of clean truck technology** and specifically, electrification (S11) showed modest to moderate benefit depending on penetration scenarios. It is difficult to achieve significant reductions in fleet emissions in the short term without addressing the oldest, dirtiest trucks. In the longer term (e.g., 2045 time horizon), the benefits will increase. $PM_{2.5}$ benefits are lower than for other pollutants because brake and tire wear is not reduced by electrification. The same market penetration was assumed across all case studies, and therefore similar results were observed. This strategy reduced noise in the PM peak hour by a modest amount, no more than 1 dB(A) in most locations. The noise benefits of electric trucks are greatest at low speeds (local streets and/or highly congested highway conditions); at higher speeds, including the most common conditions on the case study bottleneck highways, road noise dominates.

Truck Operational Efficiencies and Mode Shift

- **Port truck idle reductions** (S12.1) in Houston and Tacoma showed modest to moderate emissions benefits (up to 9 percent in Houston and up to 4 percent in Tacoma), based on a 10 percent reduction in idle time. The benefits of idle reduction strategies will depend heavily on the extent to which excess idling can be reduced. Benefits may be very significant on a localized basis, for receptors located near queuing or parking areas. The noise reduction effects of this strategy were not measured.
- **Drayage optimization** (S12.2)—optimizing drayage operations to reduce bobtail or deadhead trips—was found to have moderate benefits in the Houston case study (9 to 13 percent across all pollutants) and smaller overall benefits in Tacoma (up to 3 percent reduction) where port trucks made a smaller contribution to total study area truck traffic. While reducing truck trips will reduce emissions correspondingly, the ability to actually achieve these trip reductions may vary widely depending on local truck trip patterns; the benefits estimated here are based on very limited results from modeling of one test case in a different city. This strategy is not expected to significantly affect noise, with the possible exception of local streets where a high percentage of truck traffic can be removed (see discussion for S8).
- **Truck to rail mode shift** (S13) was found to result in very small emissions benefits in Chicago and Tacoma, where sample intercity markets were evaluated. A substantial volume of freight in the U.S. already moves by rail, avoiding the need for numerous trucks to move high-volume, lower-value goods and reducing carbon emissions up to two-thirds per ton-mile of goods moved.[16] However, the additional volume of trucks that might be removed from the study area roads through intermodal shifts was found to be very small relative to the total volume of trucks already operating in each case study area. A much more significant benefit (11 to 19 percent) was found in Houston, where local drayage movements were evaluated, but these results come with caveats. First, they are based on rough estimates of the total volume of freight that might be moving between two terminals; and second, modeling rail emissions was outside of the scope of the analysis so any offsetting emissions from additional locomotive operations were not considered. The ability to achieve localized truck-to-rail drayage mode shifts is likely to be unique to a given location. This strategy is not expected to significantly affect noise, with the possible exception of local streets where a high percentage of truck traffic might be shifted from local truck to rail drayage (see discussion for S8).
- **Truck to water mode shift** (S14) was not evaluated, as there was no data to support any assumptions about opportunities in the case study locations to divert truck traffic on the bottleneck roads to water. Similar to rail, water already moves a substantial volume of freight in the U.S., but mainly along specific corridors (large rivers and intercity waterways) where the infrastructure exists, and mainly for bulk goods that are not time sensitive.

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16 Average CO_2 emissions are about 65 g/ton-mile for truck vs. 22 g/ton-mile for rail (EPA (2019), "Intermodal for Shippers: A Glance at Clean Freight Strategies," http://www.epa.gov/smartway). Movement by rail may involve some additional emissions from handling at intermodal terminals and truck drayage between the terminal and destination.

Other Noise Mitigation Strategies

- **Noise barriers** (S15) along limited-access highways were found to be very effective, decreasing noise levels in the Tacoma case study by an average of 10 to 14 dB(A) depending on the barrier height. While barriers do not reduce emissions, they have been found to reduce pollutant concentrations behind the barrier by approximately 20 to 80 percent within the first 100 meters (330 feet) (Eisinger, et al, 2019).
- **Low-noise pavements** (S16) were found to have very small benefits, less than 1 dB(A), when open-grade pavement was compared to average pavement using TNM 3.1. The literature, in contrast, suggests that quiet pavements can reduce noise by typically 4 to 7 dB(A), depending upon the pavement types that are being compared.
- **Helmholtz resonators** (S17) were generally characterized for their effects, based on the literature, with an estimated reduction of about 3 dB(A) on the other side of the resonator.
- **Buffer zones** (S18) of 100-foot width were estimated to provide a noise benefit of between about 3 and 5 dB(A), based on modeling in two case study locations. Shifting an alignment horizontally so that the highways are about twice as far from the receiver location (or providing a corresponding buffer area) can provide approximately 3–4 dB(A) in noise reduction. However, providing a buffer of sufficient width to meaningfully attenuate noise impacts is probably impractical in most bottleneck locations, including the case study locations, which traverse built-up urban environments.

  Buffer zones do not reduce emissions, but they can reduce local pollutant concentrations. Primary pollutant concentrations fall off sharply within 100 to 150 m (330 to 480 feet) of a roadway and most reach background concentrations within 300 to 400 m (1,000–1,300 feet) (Karner, Eisinger, and Niemeier, 2011).
- **Vegetation** (S19) also was evaluated using TNM in one case study location, where a 100-foot vegetated buffer showed a noise reduction of 3.4 dB(A) compared to the same buffer area without vegetation. The noise reduction effect depends upon the type, density, height, and width of vegetation. When breaking the line-of-sight, especially for solid vegetation belt depths of more than 15 meters, the level of attenuation is comparable to that of noise walls, but in most cases it provides less. However, similar to buffer zones, wide vegetation belts are probably impractical to implement in most bottleneck locations.

  Vegetation belts also can affect air pollutant concentrations, although effects are complex and depend on the design of the vegetation; in some cases, pollutant concentrations can increase.[17] The additional buffer area needed for a vegetative buffer is likely to reduce air

[17] For example, Janhall (2015) noted that low vegetation can filter pollutants (reducing concentrations), while high vegetation such as tall trees can trap them and reduce mixing with clean air (increasing concentrations). Deshmukh et al (2018) found that vegetation can enhance mixing by reducing turbulence, with some types of densely planted vegetation resulting in decreased air pollution concentrations by as much as 50 percent, although with large gaps concentrations might not be reduced at all or might even increase. Generally, a vegetation barrier along a high-volume highway should be tall, thick, and dense to achieve greater reductions in downwind pollutant concentrations (Baldauf, 2017).

pollution levels at receptors on the far side of the buffer, for the same reasons as noted under buffer zones.

- **Building insulation** (S20) was generally characterized for its effects, based on the literature. In-practice reductions in the range of 7–10 dB(A) may be achieved with measures such as from wall insulation, upgraded windows, and upgraded ventilation systems; windows must be closed to achieve maximum noise reductions. The combination of better insulation and closed windows may trap indoor pollutants, meaning that air filtration systems also may be needed to ensure that indoor air quality is not degraded as a result of the noise mitigation strategies (Vijayan et al, 2015).

Benefits of Combining Strategies

The findings of this study suggest that if both emissions and noise are of concern at a particular bottleneck location, multiple strategies may be needed to fully address these concerns, including effective noise mitigation strategies as well as effective emission reduction strategies.

The combination of emissions and noise abatement strategies may be tailored to achieve benefits throughout the study area and to leverage specific situations in which a strategy may be most effective and/or have multiple benefits. For example, bottleneck traffic relief strategies could be combined with noise barriers to reduce air quality and noise impacts from mainline highways, but these strategies might have little if any effect on local streets. Instead, strategies targeting truck fleets serving local destinations (such as electric trucks, drayage efficiency, rerouting, and TSMO) could have relatively larger effects on traffic on local streets, leading to potentially meaningful reductions in emissions and noise near these streets.

Overall, these findings suggest that there may not be a “one-size-fits-all” strategy, but rather the best solution may be a combination of strategies tailored to local needs and opportunities.

Appendix A. References

Implementation Resources

Douglas, J.G. (2003). *Strategies for Managing Increasing Truck Traffic*. NCHRP Synthesis 314. http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_314.pdf, accessed September 2022.

> This report identifies a wide range of strategies for managing the impacts of increasing truck traffic, including emissions and noise. It provides information from a State DOT survey on expected benefits, relative costs, implementation considerations, number of projects approved or rejected, and factors leading to adoption or rejection of a strategy. Many of the strategies overlap with those considered in this report.

FHWA (2016). *Freight Advanced Traveler Information System (FRATIS) Impact Assessment*. USDOT, Federal Highway Administration—Joint Program Office, FHWA-JPO-16-225. https://rosap.ntl.bts.gov/view/dot/3587, accessed September 2022.

> This report is an independent assessment of three prototype FRATIS tests at Los Angeles, Dallas/Fort Worth, and South Florida. The FRATIS technologies deployed at one or two drayage companies in each test area included drayage truck fleet scheduling optimization, real-time information exchange with trading partners involving arrival, departure, and status information related to current or pending container movements. Considered part of USDOT's Dynamic Mobility Applications Program, FRATIS prototype systems were tested during 2014–2015. The report includes a series of findings and lessons learned to improve future prototype tests.

Graham, A.R., and D.S. Eisinger (2015). *Case Studies of Truck Replacement Mitigation Programs*. Prepared by Sonoma Technology, Inc. for Washington State Department of Transportation.

> This report identifies lessons learned from the Heim Bridge Replacement Mitigation Truck Program implemented in southern California to offset construction emissions. Common lessons learned among truck retrofit/replacement programs span the planning, recruitment, and implementation phases of the programs. Important considerations include identifying target truck types and target participants early on in the planning stage, being adaptable when challenges arise, advertising heavily and through multiple venues, streamlining administrative requirements, and providing ongoing support to program participants during the application and implementation phases. Lessons from other truck replacement programs also are summarized, including The Houston Galveston Area Council Drayage Loan/Grant Program created in 2009 to help finance the purchase of a newer heavy-duty diesel truck and bridge the gap between replacement vehicle costs after incentives.

Browning, L., et al (2017). *NCHRP Report 862, Guide to Deploying Clean Truck Freight Strategies*. NCHRP Research Report 862, Prepared by ICF and ATRI. https://www.trb.org/Publications/Blurbs/176904.aspx, accessed September 2022.

This document provides decisionmakers with a guide to assist in the potential deployment of fuel-efficient and low-emission truck freight strategies. The guide includes an analytical tool and a user manual to identify and evaluate appropriate strategies that can be deployed at the State, regional, and local levels. The guide includes case studies of deployment, lessons learned, and funding approaches.

Nadel, S. and P. Huether (2021). *Electrifying Trucks: From Delivery Vans to Buses to 18-Wheelers*. American Council for an Energy-Efficient Economy. https://www.aceee.org/research-report/t2102, accessed September 2022.

This report describes the characteristics of electric trucks and buses; challenges for their introduction and use; current status; and policy efforts in various States and countries. The report recommends a number of steps to increase electrification, including infrastructure expansion, incentives, and low-emission vehicles and fuel economy requirements.

The Tioga Group, et al (2011). *Truck Drayage Productivity Guide.* National Cooperative Freight Research Program Report 11. Washington, DC: The National Academies Press. https://www.trb.org/Publications/Blurbs/165528.aspx, accessed September 2022.

This is a practitioner's guide to measuring, analyzing, and improving port intermodal drayage. The focus of this guidebook is helping planners better understand the causes of bottlenecks, delays, and extra trips that increase the time, cost, emissions, and congestion impacts of port drayage beyond what is necessary to accomplish the underlying transportation task.

Rensselaer Polytechnic Institute and Jack Faucett Associates, Inc. (2019). *Impacts of Policy-Induced Freight Modal Shifts*. National Cooperative Freight Research Program Report 40. Washington, DC: The National Academies Press. https://www.trb.org/NCFRP/Blurbs/180033.aspx, accessed September 2022.

The main goal of this report was to develop a handbook for public practitioners that describes the factors shippers and carriers consider when choosing freight modes and provides an analytical methodology for public practitioners to quantify the probability and outcomes of policy-induced modal shifts. The report identified the top four factors influencing mode choice as: freight rates, quality of service, product type, and seasonal changes. The top three suggestions for improving factors affecting mode choice were: More consistency in rail delivery times; Dredging and preserving the land for waterways; and increasing the allowable weight limits on trucks.

Rochat, J., S. McKenna, D. Barrett, K. Cubick, S. Riffle, L. Samples, R. Rasmussen, *Breaking Barriers: Alternative Approaches to Avoiding and Reducing Highway Traffic Noise Impacts, Summary of Noise-Reducing Strategies*, NCHRP 25-57, National Cooperative Highway

Research Program. http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP25-57TechMemo.pdf, accessed September 2022.

This project examined strategies other than traditional noise barriers to reduce highway traffic noise. A literature review was conducted and investigated over 13 alternative strategies, and a survey of State DOTs was conducted to learn about implementation experience. Information was provided on noise reduction, construction costs, maintenance costs, and the context-appropriateness for highway design and management. The report also provided information on the benefits of combining strategies.

Donovan, P.R., et al (2013). *Evaluating Pavement Strategies and Barriers for Noise Mitigation*. NCHRP Report 738. Washington, DC: The National Academies Press. https://www.trb.org/Publications/Blurbs/169200.aspx, accessed September 2022.

This report presents a methodology for evaluating feasibility, reasonableness, effectiveness, acoustic longevity, and economic features of pavement strategies and barriers for noise mitigation. The methodology uses lifecycle cost analysis to examine the economic features of mitigation alternatives, the FHWA Traffic Noise Model to integrate the noise reduction performance of pavements and barriers, and onboard sound intensity measurements as an input to the prediction model. Based on the results of the evaluation, a methodology that considers acoustic and economic features of both pavements and barriers was developed and applied to several example cases.

FHWA (2012). *Freight and Land Use Handbook*. Washington, DC: USDOT. https://ops.fhwa.dot.gov/publications/fhwahop12006/, accessed September 2022.

This handbook provides transportation and land use planning practitioners in the public and private sectors with the tools and resources to properly assess the impacts of land use decisions on freight movements, as well as the impacts of freight development and growth on land use planning goals. The handbook identifies freight-related land use issues, key considerations, and available resources. Throughout the handbook, examples and case studies from a range of urban and rural areas across the country are used to demonstrate the effectiveness of these techniques.

Case Study Project Documents

Chicago

Chicago Region Environmental and Transportation Efficiency (2016). *70 Projects to CREATE Chicago's Transportation Future.*

Illinois Department of Transportation (2013). *Circle Interchange Noise Analysis Study.*

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Houston

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Appendix B. Understanding the Effects of Traffic and Other Noise Abatement Strategies on Noise Levels

This section presents a general understanding of how traffic volumes, speeds, and composition, as well as nontraffic noise mitigation strategies, affect noise levels. This understanding is based on studies from the literature and also reflected in the algorithms within the Traffic Noise Model. Each roadway and abatement measure evaluated in the case studies represents a unique case. The information provided in this section helps to inform a more general understanding of the expected effects of noise mitigation strategies, as well as to provide context for the results obtained using TNM for the individual case studies. It also provides information on strategies that cannot be directly represented in TNM.

Changes to Traffic Volumes and Speed

A large change in vehicle speed or volumes is required to have a significant effect on traffic noise levels. Figure 18 shows the noise reduction theoretically expected for a given percent reduction in traffic volume, all else remaining constant. Heavy truck volume was assumed to be 15 percent of the total volume in this example. The figure shows that to achieve barely perceptible noise reductions to some individuals of 1 dB(A), truck volume reductions of over 30 percent are needed. To get a perceptible reduction for most individuals, considered to be 5 dB(A), would require a total volume reduction of nearly 70 percent. On main roadways with large volumes of through traffic, the only way to get these types of reductions would be by rerouting traffic (e.g., construction of a bypass or setting time limits on truck traffic) or through incentives such as congestion/peak-period pricing to change the times of usage. For smaller facilities the impact would be more pronounced for the same amount of traffic change and more easily achieved through local control measures.

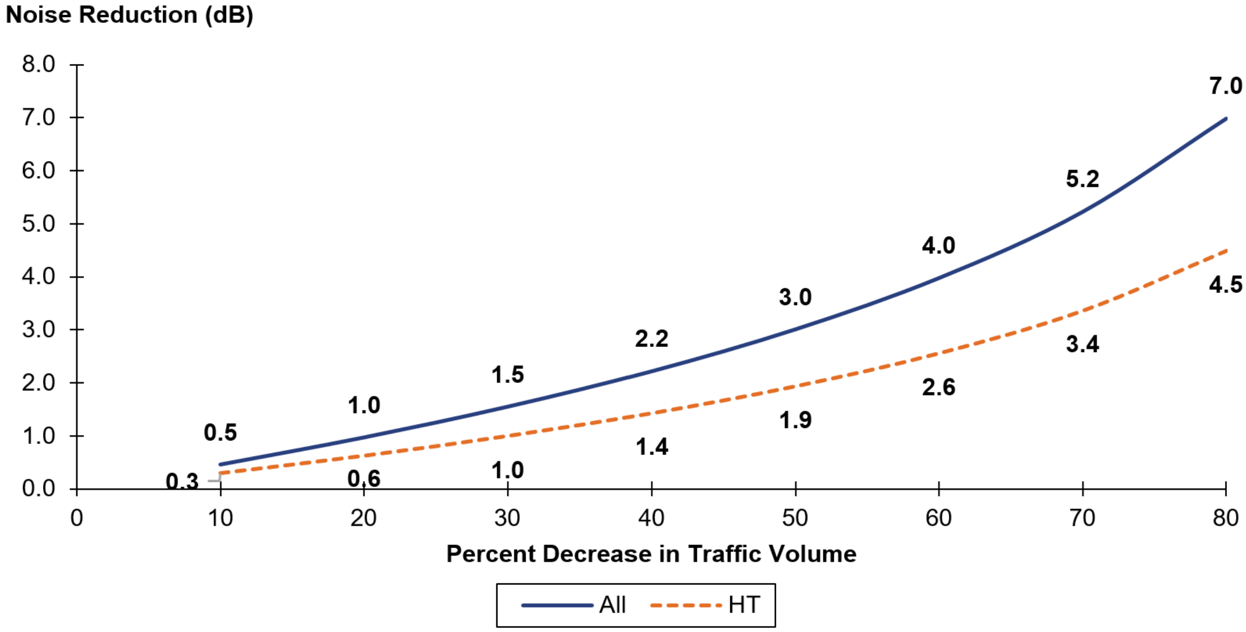

Figure 18. Chart. Noise reduction by changing volume.

(Source: FHWA.)

Figure 19 illustrates the theoretical noise benefits of reducing speeds, compared to a base speed of 60 mph, again for a traffic mix that includes 15 percent heavy trucks. Reducing speed from 60 to 55 mph shows only a minor benefit of around 1 dB(A). To achieve a perceptible change for traffic operating at highway speeds, a reduction from 60 to 45 mph or less would be needed.

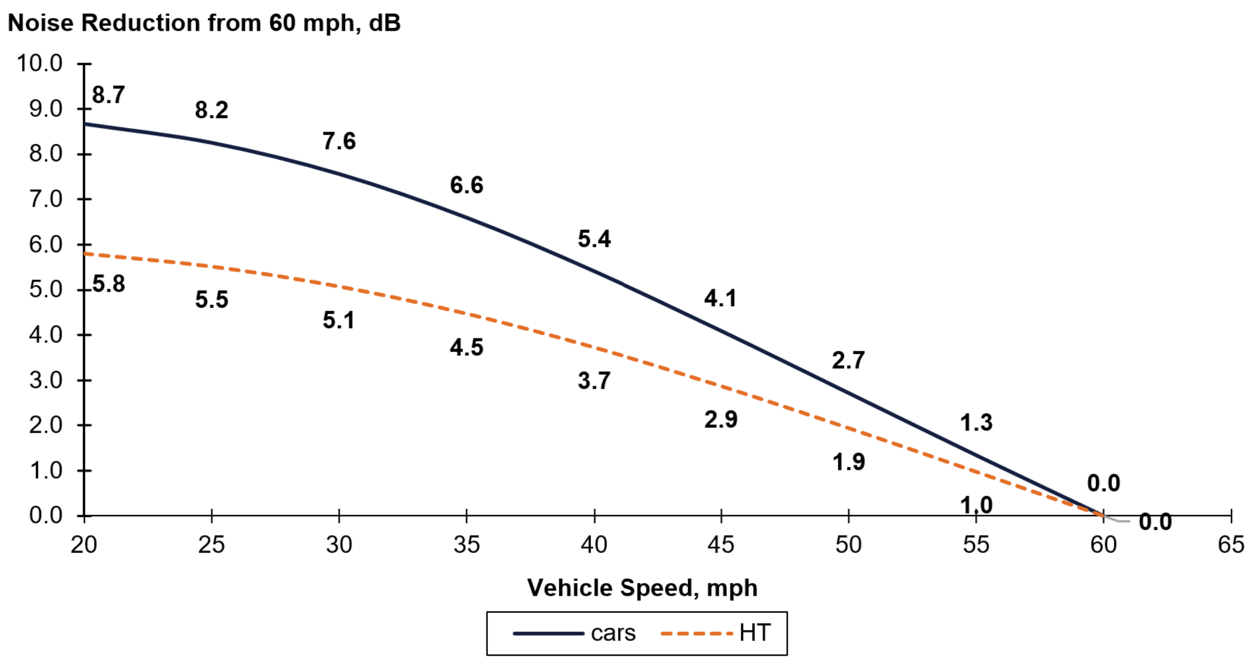

Figure 19. Chart. Noise reduction by changing speed (all values compared to 60 miles per hour).

(Source: FHWA.)

The figure also shows that reducing speeds below a base speed of 35–40 mph is unlikely to show a perceptible noise benefit. At higher speeds the tire/pavement noise dominates, but at low speeds engine noise becomes the dominant noise source. In stop-and-go conditions, speeds of less than 20 mph would occur, and the engine noise from combustion vehicles would dominate as a result of acceleration and deceleration. Note that many of the traffic mitigation strategies applied at bottleneck locations would likely have the effect of *increasing* traffic speeds, and therefore could result in increased noise levels, even if they reduce air pollutant emissions.

Stop-and-go traffic, a condition often caused by bottleneck traffic, is not a normal function in TNM. Instead, the reference energy mean emission curves within TNM 3.0 were evaluated outside of the model.[18] Noise emissions are relatively flat at speeds less than 25 mph and are not pavement specific, since there is less effect of pavement at low speeds. At higher speeds, noise emissions increase, at a rate depending on the vehicle type and pavement type. For heavy trucks at full throttle, noise emissions start at around 80 dB(A) at low speeds and increase to over 85 dB(A) at highway speeds. Passenger cars, at approximately 68 dB(A), are 12 dB(A) below heavy trucks at low-speed full throttle, and medium trucks are approximately 73 dB(A). In the traffic stream each heavy truck is equivalent to about 16 light-duty vehicles or 5 medium trucks in terms of noise energy. To put this into perspective, for a traffic scenario with 85 percent light-duty vehicles, 5 percent medium trucks, and 10 percent heavy trucks, the heavy trucks represent approximately 79 percent of the total energy while medium truck and light-duty vehicles represent 16 and 5 percent, respectively. This clearly points out that the noise levels due to stop-and-go traffic would be dominated by the heavy trucks, assuming that heavy trucks make up a significant fraction of traffic.

Relationships for the three vehicle types were compared at full throttle, which would be equivalent to acceleration in stop-and-go traffic as compared to the curves for cruise as used in free flow traffic conditions. As tire/pavement noise begins to lessen at lower speeds, the engine/ drivetrain noise takes over. The curves are all relatively flat at speeds less than 25 mph and are not pavement specific, since there is less effect of pavement at low speeds. Heavy trucks, as expected, have the greatest reference levels of approximately 80 dB(A). Passenger cars, at approximately 68 dB(A), are 12 dB(A) below heavy trucks, and medium trucks are approximately 73 dB(A).

For cruise conditions, at low speeds light-duty vehicle noise emissions drop to 50 dB(A), medium trucks to 68 dB(A), and heavy trucks to 74 dB(A). Heavy trucks dominate and light-duty vehicles can essentially be ignored, with medium trucks also having smaller effects. Using the dominant heavy truck noise, it can be predicted that the reference levels will drop by about 3 dB(A) for cruise compared to stop-and-go conditions. Replacing combustion engine trucks with electric trucks would therefore have a noise benefit under low-speed conditions by eliminating engine noise, especially the revving due to acceleration.

[18] Hastings, *Traffic Noise Model 3.0—Technical Manual*, FHWA-HEP-20-012, 2019.

Noise Barriers

Each barrier is unique and each application is different. Attenuation is determined by barrier placement, height, length, and local conditions. A common design consideration among States is that a barrier should achieve at least 5 dB(A) of attenuation in order to provide perceptible benefits. A very good barrier will provide over 10 dB(A) and in some conditions 20 dB(A) of attenuation for the first-row receivers. This general range provides the limits of what might be expected from noise barrier attenuation.

Low-Noise Pavement

Low-noise pavement has been shown to be an effective abatement measure for higher traffic speeds. There are many different pavement types with different noise effects, such as open-graded asphalt, stone-mastic, and diamond grind concrete surfaces. The benefits of low-noise pavement are very much speed dependent. While findings vary, it is generally agreed that the pavement/tire noise dominates for speeds above 25 mph for light vehicles (passenger cars) and above approximately 35 to 40 mph for heavy trucks.[19] Low-noise pavement will have minimal effect on the overall noise levels at speeds below these thresholds.

Two comprehensive sets of onboard sound intensity measurements at the tire/pavement interface were reviewed to establish an effectiveness with speed for various surfaces.[20,21] In these studies, the pavement type was found to change noise levels by approximately 8 to 14 dB(A) for a speed range of 55 to 60 mph. When comparing average pavement to low-noise pavement it would be expected that noise reductions would be about one-half the range of all pavements, or about 4 to 7 dB(A).

Vegetation

Example figures in FHWA guidance show that a 61-meter (200 feet) width of dense vegetation can reduce noise by 10 decibels.[22] In most situations where bottlenecks occur, it would be difficult to obtain sufficient land area for vegetation to achieve anywhere close to this width of a vegetative buffer. FHWA notes, “the planting of trees and shrubs provides psychological benefits by providing visual screening, privacy, or aesthetic treatment, but not highway traffic noise abatement.” Accordingly, use of vegetation is considered to be ineffective for most bottleneck cases, unless a large area is available along an extended length of roadway. It is

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[19] Tire-Pavement Noise—References—Sustainable Pavement Program—Sustainability—Pavements—Federal Highway Administration (dot.gov). https://www.fhwa.dot.gov/pavement/sustainability/articles/tire_noise.cfm.

[20] Wayson, R.L., J.M. *MacDonald, A. Martin, Onboard Sound Intensity (OBSI) Study, Phase 2*, FDOT Project #BDT06, June 23, 2014.

[21] Rasmussen, R. O., R. J. Bernhard, U. Sandberg, and E. P. Mun. 2008. *The Little Book of Quieter Pavements.* FHWA-IF-08-004. Federal Highway Administration, Washington, DC.

[22] FHWA, *Highway Traffic Noise: Analysis and Abatement Guidance*, FHWA-HEP-10-025.

possible, however, that smaller areas along roadways could provide effective noise abatement for small clusters of receivers.

Buffer Zones

The same challenges exist for buffer zones as for vegetation. Large areas are needed along the roadway to produce meaningful results. Noise decreases with distance are not linear and also are affected by diffraction objects in the path. For a highway situation, with ground cover such as lawn grass, noise decreases by about 4.5 dB(A) for each doubling of distance. A general equation for computing the effect is:

$$Change\ in\ dB(A) = 10\log\left[\frac{new\ distance}{original\ distance}\right]^{1.5}$$

Figure 20. Equation. Change in sound level as a function of distance from source.

As an example, if the receiver was 50 feet from the center of the traffic lanes, 100 additional feet would be needed to reduce the noise levels found at the right-of-way by 4.5 dB(A). To achieve another 4.5 dB(A) of reduction, 200 feet of additional right-of-way would be needed, and the trend continues. This is generally not practical in situations near bottlenecks.

Helmholtz Resonators

The use of roadside attenuation such as Helmholtz resonators has been shown to provide noise reduction. It has been reported that the effectiveness ranges from 2 to 4 dB(A).[23] As such, 3 dB(A) was selected as a representative effect for this abatement measure. Helmholtz resonators cannot be directly modeled using TNM.

Noise Insulation

Noise insulation can be applied to individual structures to reduce interior noise. Table 38 suggests that significant reduction of interior noise can be obtained from insulation. In practice, noise reduction from insulation has been reported to be about 7–10 dB(A), although more reduction is possible from total insulation of a structure which includes not only exterior surfaces but also attics and controlling of any openings such as vents or fireplaces.[24] In TNM, adjustment factors can be applied to account for the reduction when predicting interior noise, but a true analysis must include a sound transmission class evaluation based on areas of walls, windows, etc.

23 Forssén J., Van der Aa, B., Initial results for traffic noise mitigation with Helmholtz resonators in the ground surface beside a road, Internoise 2013.

24 Wayson, R.L., J. Cowans, P. Berge, C. Porter, M Marks, *State of the Practice—Evaluating and Quantifying the Benefits of Noise Abatement Measures: Literature Review and Synthesis*, FHWA Report, January, 2020.

Table 38. Noise reduction from insulation.

Building Type	Window Condition[1]	Noise Reduction Due to Exterior of the Structure
All	Open	10 dB
Light Frame	Ordinary Sash (closed)	20 dB
Light Frame	Storm Windows	25 dB
Masonry	Single Glazed	25 dB
Masonry	Double Glaze	35 dB

1. The windows shall be considered open unless there is firm knowledge that the windows are in fact kept closed almost every day of the year.

(Source: FHWA Highway Traffic Noise: *Analysis and Abatement Guidance*. August 11, 2010.)

Electric Vehicles

Electric vehicles could be an effective noise mitigation measure in low-speed conditions. If speeds are below 25 mph the tire/pavement noise no longer dominates, and the engine becomes the dominant source. In these cases, the engine noise for trucks could drop from 80 dB(A) at 50 feet to almost zero during idle. However, it has been reported from testing that reductions of only 0.6 dB(A) occurred for speeds of 12 mph for buses.[25] For cars, this reduction also may be less due to National Highway Traffic Safety Administration requirements to emit noise below 18.6 mph to warn individuals with visual impairments. The vehicle must make a continuous noise level of at least 56 dB(A) within 2 meters, which still provides some reduction from the current noise levels.

25 Laib, F., A. Braun, W. Rid, *Modeling noise reductions using electric buses in urban traffic.* A case study from Stuttgart, Germany, Transportation Research Procedia, 37, Pp. 377–384.

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May 2022

FHWA-HEP-22-026