Project No. 25-49

DEVELOPMENT OF A HIGHWAY CONSTRUCTION NOISE PREDICTION MODEL

FINAL REPORT

Prepared For

National Cooperative Highway Research Program (NCHRP)

Transportation Research Board
of
The National Academies of Sciences, Engineering, and Medicine

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September 2018

ACKNOWLEDGMENT OF SPONSORSHIP

This work was sponsored by one or more of the following as noted:

■ American Association of State Highway and Transportation Officials, in cooperation with the Federal Highway Administration, and was conducted in the **National Cooperative Highway Research Program,**

☐ Federal Transit Administration and was conducted in the **Transit Cooperative Research Program**,

☐ Federal Aviation Administration and was conducted in the **Airport Cooperative Research Program,**

☐ The National Highway Safety Administration and was conducted in the **Behavioral Traffic Safety Cooperative Research Program,**

which is administered by the Transportation Research Board of the National Academies of Sciences, Engineering, and Medicine.

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CHAPTER 1 Background

Problem Statement and Project Objective

In reaction to growing public concern and complaints about construction noise, FHWA developed the Roadway Construction Noise Model (RCNM). The RCNM is based on the construction noise model developed and utilized at the Central Artery/Tunnel Project in Boston. It has since been available for use with FHWA, state, and municipal projects. The data used for the RCNM has since been used as a reference source for construction equipment noise emissions and predictions. The model itself has been used for planning and environmental assessment, construction noise mitigation plans, regulations development, and specification enforcement. However, RCNM has limitations. It uses simplified assumptions (e.g., equipment usage factors) that limit its flexibility and accuracy. In addition, the construction equipment noise database in RCNM provides only broadband L_{max} A-weighted levels, the calculation of time-dependent noise metrics is done by estimation, and there is no accounting for excess attenuation provided by ground effects and air absorption losses.

To ensure compliance with state, local, and project-specific noise restrictions, an improved model is needed for predicting construction noise and the effects of noise reduction efforts. The developed model will optimize noise control strategies, assist with project delivery, and help users assess public complaints.

The objective of the research is to develop and validate a noise model to calculate the acoustic environment associated with highway construction equipment and activities, to accumulate a database of noise sources, and to document the appropriate applications of the model.

The research may include, but not be limited to:

- Multiple metrics
- Interoperability with other models
- Established measurement standards
- Propagation effects
- Noise contouring
- Stochastic modeling
- Duration of construction noise
- Spectra
- Source height
- Directivity
- User-defined noise emission data

- Comparisons to limit criteria
- Operational characteristics of the equipment
- Shielding
- Temporary sites not on project corridor

Scope of Study

The Research Team was tasked with development of the Roadway Construction Noise Model Version 2.0 (RCNM2.0). This updated version of RCNM will enhance the current model capabilities and provide additional functionality. Final deliverables include completion of a Final Report that documents research procedures and a CD-ROM which contains the model (including all algorithms, source code, and software distribution package), the database as well as users' guide along with technical documentation of the model to meet the research objectives.

CHAPTER 2 Research Approach

Chapter 2 discusses the research approach detailed within the Amplified Work Plan (AWP). The AWP described the intended approach of the Research Team separated into two phases. Seven tasks were included within Phase I, including the Data Collection Program, which established the ground work for model development. Four tasks were included in Phase II including RCNM2.0 model development, model validation, submittal of deliverables as well as the Final Report.

Phase I

Work in Phase I focused on three primary work elements. Tasks 2-4 involved a literature request and review, survey, and development of the Noise Source Database (NSD) respectively. Other tasks in Phase I included project meetings, completion of the Phase II workplan, and completion of the Interim Report.

Literature Request and Review

The literature request and review entailed assessing available literature detailing construction equipment used in various phases of project construction to inform development of the NSD. This equipment list was expanded into subcategories as necessary. Each piece of equipment was researched to determine the overall range in size/horsepower commercially available by contacting major manufacturers. In addition, the Research Team requested noise emission data and corresponding model number/descriptions from manufacturers. The purpose of this step was two-fold: 1) it provided the Research Team with a goal, during field data collection, of documenting source data for equipment within the entire range of equipment size/horsepower and 2) allowed researchers (during post-processing) the opportunity to evaluate the practicality of averaging ‘similar’ noise data sets into more detailed equipment size categories than previously provided within RCNM.

Survey Request and Review

This task entailed surveying the noise representatives of each State Highway Agency or Department of Transportation. The survey instructions requested that the noise personnel who received the survey also share it with the Department’s construction engineer. The survey included the following opening statement and questions:

Introduction/Purpose & Need: As part of National Cooperative Highway Research Program (NCHRP) 25-49, our research team has been chosen to provide an enhanced construction noise prediction tool (Roadway Construction Noise Model Version 2). To ensure state transportation agency needs are met, please respond to the following questions:

1. Please review the list of equipment that the research team intends on including within the noise source database. Is there a piece of equipment not listed that you feel is important to include? [Targeted Equipment List Provided to Survey Participants]

2. For your application, what types of construction activities and resultant noise levels do you typically predict or would like to be predicted?

3. What L_{Aeq} averaging periods would be beneficial to your existing or future applications? (10-min, 1-hour, 8-hour, 24-hour, etc.)?

4. Are there any special scenarios or needs you would like RCNM2.0 to address?

5. To the best of your knowledge, are there any special construction scenarios that are unique to your agency or geographic location?

Noise Source Database Development

A detailed data collection program was developed to document quality equipment source data. Measurement equipment used included multiple Rion NL-52 octave band analyzers, Larson Davis CAL200 precision acoustic calibrators, Weather Hawk SM-19 Skymate Plus meters (on-site meteorological data: temperature, relative humidity, wind speed and direction at height of 5 feet), Nikon Forestry Pro and BOSCH GLR225 laser distance measurers, Rolatape 400 Series walking wheels, Vanguard Alta+ 233AO tripods, Shure S15A telescopic tripods, Drift HD Ghost digital video cameras with external microphones, Motorola Talkabout T465 two-way radios and earbuds with PTT microphones and an Apple iPad Air to document equipment and sound level meter perspective photos.

As summarized in Table 1, monitoring equipment was set to slow response to measure overall and 1/3 octave band maximum A-weighted levels (L_{ASmax}), sampled every second, and 1-second A-weighted noise level equivalent (L_{Aeq}) levels. All measurements were conducted in A-weighting since the scale reflects human hearing sensitivity and FHWA's Traffic Noise Model Version 3.0 (TNM3.0) as well as all predecessor models provide A-weighted results, and many noise ordinances and codes are written with A-weighted limits.

Table 1: Data Acquisition Parameter Summary

Metric	Time-weighting	Frequency Weighting	Frequency Resolution
Overall L_{ASmax}	Slow	A-weighting	Overall
1/3 OB L_{ASmax}	Slow	A-weighting	1/3 Octave Band
Overall L_{Aeq}	Unweighted	A-weighting	Overall
1/3 OB L_{Aeq}	Unweighted	A-weighting	1/3 Octave Band
Note: Although, *Measurement from Highway-Related Noise* [1] indicates a fast time weighting, the data collected, and the equations used for the original RCNM are based on a slow time weighting [2], therefore a slow time weighting was utilized for comparison purposes.			

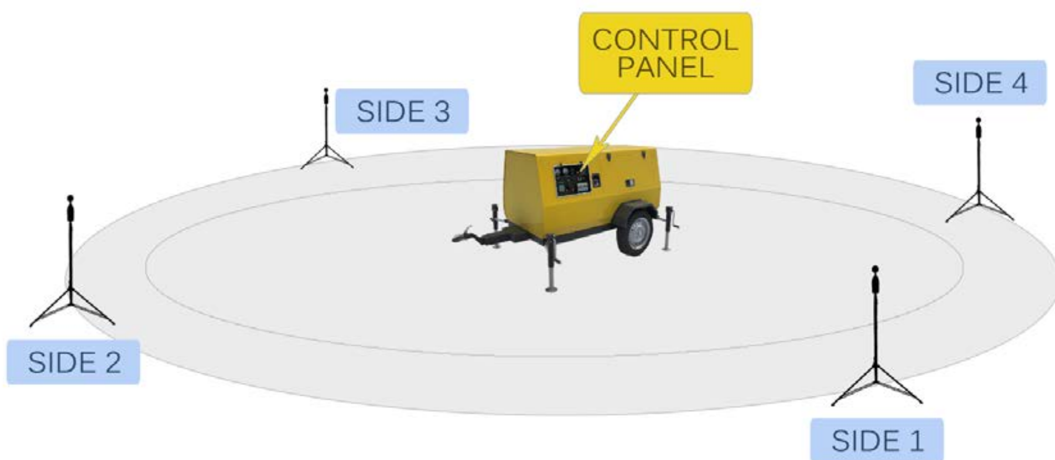
Targeted equipment was separated into three (3) categories based on work-related noise levels. Some stationary construction equipment included pieces of equipment which produce near

steady-state noise levels throughout their operation. These pieces of equipment include compressors and generators, for example. In addition, there are some ‘dependent’ pieces of equipment such as pumps, light towers, etc., which require a power source to operate, whereby the near steady-state power source is the acoustically dominant piece of equipment.

Due to several safety and site-related issues, measurements on all four (4) sides of steady-state equipment were not always achieved. Obstructions, reflective surfaces, and interfering construction activities limited available measurement locations. However, in most cases, monitoring at equipment rental yards allowed for equipment to be staged to obtain all four (4) sides of measurements.

Steady-state equipment measurements facing equipment control panels were universally assigned to Side 1. Remaining three sides were then assigned based on a clockwise rotation around the equipment. For example, a measurement conducted in front and back of a piece of equipment would be assigned Sides 1 and 3, respectively, while the ‘left’ and ‘right’ sides would be relative to front and assigned Sides 2 and 4, respectively. For further clarification, an illustration of typical four-sided measurement protocol for a steady-state piece of equipment with position labels is included in Figure 1.

Figure 1 - Four Sided Measurement Set-Up of Equipment Generating Steady-State Data



Mobile construction equipment moves forward and/or backwards, resulting in similar noise levels when traveling in both directions. This type of equipment category includes pavement scarifiers, street sweepers, graders, scrapers, etc., and associated noise levels were documented as a ‘pass-by’ event. Measurements were conducted on either side of the linear path. Side 6 measurements were assigned to the right side of the forward motion while the opposite side was assigned Side 5. For further clarification, an illustration of a typical two-sided measurement protocol for an example mobile piece of equipment with position labels is included in Figure 2.

Figure 2 - Two Sided Measurement Set-Up of Equipment Generating Pass-By Data

Cyclical construction equipment performs work in a repetitive cycle resulting in noise level variations throughout the measurement period. This equipment category includes auger drills, backhoes, rock drills, excavators, etc. Due to the nature of this construction equipment category, the dataset for each includes a full cycle of 'work'. The 'work' cycle chosen for that 'work period' was the worst-case (highest noise level), but typical, 'work' cycle.

There are several pieces of equipment within the cyclical construction equipment category that are stationary however rotate to complete a 'work' cycle. These pieces of equipment include auger drills, excavators, and backhoes. Data was evaluated for these pieces of equipment slightly different than others since the noise contribution may spread over varying distances. During each measurement period, the Research Team documented distances to the house (main equipment body) as well as to the boom and bucket (or attachment) during 'work' periods. In reviewing data sets, the Research Team determined that noise levels over a majority of the 'work' cycle resulted from the engine however the cause of the L_{ASmax} varied. Therefore, the L_{Aeq} was processed based on a distance to the house while L_{ASmax} data was processed based on the distance to the cause of the L_{ASmax}. Common sources of the L_{ASmax} over a 'work period' were an auger drill operator shaking the core barrel to release dirt, rattling of an excavator boom during a dig, or the flick of an excavator bucket while dumping material. Similarly, the shot-crete pump/spray data set was processed in the same manner since the nozzle is commonly a notable distance from the pump.

As mentioned within, dump truck and front end loader measurements were obtained and separated into 'work' and 'pass-by' data sets. Dump truck and front end loader 'work' is associated with dumping material and picking up and delivering material, respectively.

Measurements conducted facing operators were universally assigned to Side 1. Remaining three sides were then assigned based on a clockwise rotation around the equipment. For example, a measurement conducted in front and back of a piece of equipment was assigned Sides 1 and 3, respectively, while the 'left' and 'right' sides would be relative to front and assigned Sides 2 and 4, respectively. For further clarification, an illustration of a typical four-sided measurement protocol for an example cyclical piece of equipment with position labels is included in Figure 3.

Figure 3 – Four Sided Measurement Set-Up of Equipment Generating Cyclical Data

'Clean' measurements (i.e. not corrupted by background sources or other site interferences) were obtained for 'work' associated with each piece of equipment. Data was considered 'clean' when the measured source was 10 dB above the ambient noise level. Some exceptions to this rule of thumb were made when source data less than this threshold could not be obtained; as such, source data 6 dB above ambient was considered acceptable. These thresholds are in general accordance with methodology utilized to accept data when creating the reference energy mean emission levels (REMELs) for FHWA's TNM.

Data files were organized to appropriately populate a data analysis tool. Measurement information was entered to retain details regarding each individually measured piece of construction equipment. Manufacturer, model, equipment type, activity, horsepower as well as auxiliary horsepower or attachment, if applicable, were entered. On-site meteorological conditions were also entered which included temperature, relative humidity, wind speed and direction.

Additional data included within the database included the microphone distance from the equipment as well as microphone height. In addition, the database retained the predominant ground type located between the microphone and equipment. Options corresponded with

TNM2.5 ground types including dirt road, field grass, gravel, lawn, pavement soil (hard), soil (loose) and snow (granular), snow (powder), water and wood.

The data was then parsed to enable the Research Team to extract 1-second, A-weighted overall and 1/3 octave band L_{ASmax} and L_{Aeq} data samples for the entire monitoring period from the noise level meter raw data files and graph respective data. Field personnel then reviewed each data graph along with field notes and time synchronized video of the measurement period. The Research Team determined periods within the monitoring session with full work cycles or ‘pass-by’ events, without acoustic interference. Based on this exercise, field personnel created work cycles.

To normalize all data to 50 feet and a height of 5 feet above ground level, acoustically hard ground, the U.S.DOT, Volpe National Transportation Center provided the normalization code. All processed data accounted for the ground’s acoustic resistivity measured in effective flow resistivity (EFR) based on the distance from the source and height of measurement.

Once isolated work cycles and pass-by events were reviewed and entered into the data analysis tool, automatic calculations were performed to obtain a total overall A-weighted L_{Aeq} level representing the ‘work’ measurement duration, the overall L_{ASmax}, the 1-second A-weighted L_{Aeq} for the same second that the overall L_{ASmax} occurred.

Phase II

Work in Phase II focused on development of the RCNM2.0 software. The key tasks in Phase II included model development, model validation, the Preliminary Draft Final Report and responding to Project Panel comments and preparation of the Final Report and Presentation.

Developing RCNM2.0 required modification of the existing FHWA’s TNM3.0 to accommodate calculation of new types of noise sources with work divided between the acoustic code and the graphic user interface. This complex operation required that the Research Team incorporate standard software development protocols to allow multiple developers access to the code while ensuring a consistent development approach by all developers.

Development of the software focused on three areas: acoustics, graphic user interface, and geographic input (Geoinput). To maintain transparency with the Project Panel, the Research Team provided a demonstration of the draft RCNM2.0 via WebEx. This demonstration allowed the Research Team the opportunity to solicit feedback from the Project Panel.

As part of the code management strategy to save time for the developers and reduce the risk of integration problems at the end of an iteration, the Research Team configured a continuous build server. Continuous integration helped time-consuming build tasks by automating the process, detected code compatibility problems early, and enabled all Research Team members to work in the context of the latest version of the system. In addition, GeoDecisions established a control system that provided a central repository to help coordinate changes to files and provided a history of changes. The approach provided an orderly process in which, developers obtained the latest code from the server.

The Research Team used an industry-standard coding style adhered to by all developers. This created a collective work environment that was more efficient and enabled multiple developers to work together in a single style.

The FHWA's TNM3.0 acoustic code was modified, and the same GUI development tools were used to create the new construction noise prediction model (RCNM2.0). In so doing, the Research Team utilized acoustic algorithms that have been validated against extensive practical cases and repurposed them in a manner that maintained consistency between TNM and RCNM and allowed GUI development to be conducted in an efficient manner.

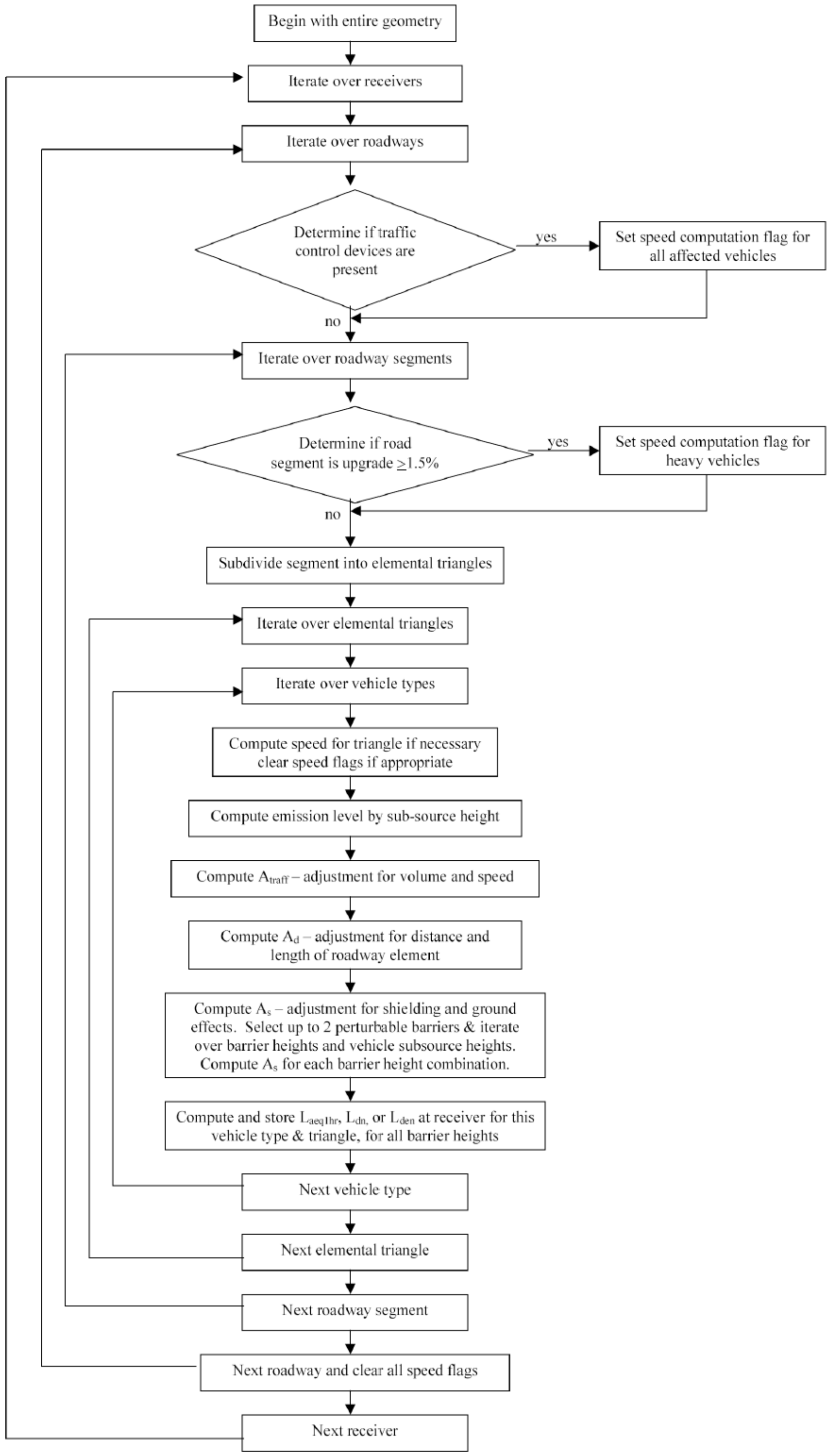
To maintain consistency with TNM's physical acoustics, the following functionality in TNM3.0's acoustic code was maintained:

1) Iteration over receivers and "roadway segments", where roadway segment was the legacy term for locations where noise sources exist
2) Iteration over one-third octave bands
3) Computation of attenuation due to free-field divergence
4) Computation of attenuation due to atmospheric absorption
5) Computation of attenuation due to diffraction over multiple wall and berm barriers [3]
6) Computation of attenuation due to housing rows
7) Computation of attenuation due to complex terrain
8) Computation of attenuation due to multiple ground reflections [4]
9) Computation of attenuation due to multiple ground types [5]
10) Computation of attenuation due to tree zones
11) Computation of effects due to single back reflections (reflections from an object behind the source relative to the receiver)
12) Aggregation of results

These algorithms were used to model the propagation of construction noise for simple scenarios such as propagation over a flat, paved surface with receivers at ground level or for more complicated scenarios such as construction noise propagating over a paved surface with a nearby noise barrier and then propagating over hilly grass fields to receivers in the second row of an apartment building. This allowed for more accurate determination of minimum lengths and heights of temporary barriers as well as other mitigation strategies such as reduced usage or relocation of sources.

The TNM acoustic code flow chart is presented in Figure 4.

Figure 4 - TNM Acoustic Code Flow Chart



The following functionality were added to TNM3.0's acoustic code to account for new source types:

1) Created a new "Stationary Source Object" (SSO) within TNM's object types.
    a. Stationary source emission levels were determined based on the data housed within the NSD.
    b. The SSO included one or more source heights that were category dependent.
    c. The SSO included a directivity pattern to represent shielding characteristics such as the shrouding around a generator. This directivity pattern included adjustments for the front, rear, and both sides of the source.
    d. The SSO included a usage factor to account for operation time of the equipment.
2) Created a new "Moving Source Object" (MSO) within TNM's object types.
    a. Moving source emission levels were determined based on the data housed within the NSD.
    b. The MSO included one or more source heights that were category dependent.
    c. The MSO included a directivity pattern to represent shielding characteristics such as the engine compartment of an earth mover.
    d. The MSO included a usage factor to account for the operation time of a piece of equipment.
3) Created a gestalt object that consisted of one or more SSOs and MSOs to model cyclic operations.
4) Created a new method in TNM to determine directivity effects.
    a. The relative orientation between SSOs, MSOs and the Receiver were determined.
    b. Attenuation due to directivity were determined by interpolating the directivity data of the source object as a function of angle between source and receiver.
5) Modified TNM to handle point sources in addition to line sources. (TNM currently expects at one or more line segments. Adding an option to compute propagation effects for just one point did not require a fundamental change in the acoustic algorithms and the two options co-exist within the same executable.)
6) Modified the adjustment for "roadway length". This was relevant for MSOs but needed to be modified to account for the point source nature of MSOs compared to TNM's traditional line source model.
7) Developed new emission methods for the new SSOs and MSOs to account for construction noise parameters such as operation and usage factor.
8) Modified TNM to read new source heights from the new objects.

The following functionality were suppressed in TNM3.0's acoustic code, as these functions are not relevant to construction noise emissions or not enough data was obtained to identify source noise levels to allow functionality of these conditions:

1) Speed computation was not invoked for construction noise sources. (This was required for highway traffic to compute emissions but was not relevant for construction noise sources.) The speed parameter is still part of the MSO, as this determines the effective length of time for the pass-by, but it was assumed to be constant and does not affect emission levels.
2) Checks for traffic control devices were also not invoked. (For the same reason as item 1.)

3) Evaluation of grade was also not invoked, as sufficient data was not obtained to accurately incorporate such functionality. Further, the research team assumed that most end-users would not have such level of detail during the time of construction noise assessment.
4) Adjustments for traffic volume and speed were not invoked. (This is relevant for continuous line sources but is not relevant for individual point sources, whether moving or stationary.)

Development of the Graphic User Interface (GUI):

1) Created a new GUI interface that shares the same "look and feel" of TNM3.0 but includes inputs relevant to construction noise sources. This includes, for example:
   a. Digitizing tools to model the construction site and surrounding areas, much like is already done in TNM.
   b. Interfaces for selecting noise sources and related parameters.
   c. Reporting tools for aggregating results.
   d. This GUI took design cues from relevant parts of TNM3.0 and RCNM
2) The GUI designs were iterated upon based on feedback from the Project Panel.

The Research Team utilized industry standard application development methodology to execute the model development task. The GeoDecisions Enterprise Methodology (GEM) has been in use for nearly a decade across hundreds of similar development projects and relies on an agile development approach. The primary emphasis of this model development activity is to adapt an existing acoustic codebase and GUI design (FHWA's TNM3.0) to meet the needs of the new construction noise prediction model (RCNM2.0). In so doing, acoustic algorithms that have been validated against extensive practical cases can be repurposed in a manner that maintains consistency between TNM and RCNM and allows GUI development to be conducted in an efficient manner, understanding best user interface technology and practitioner needs.

The Research Team began the development effort by reviewing the initial set of requirements documented by NCHRP and further defined by the Research Team. Collaborative dialogs were conducted during this period, ensuring that requirements are clarified and granular enough for the development staff to understand, and for initial design activities. Requirements, clarifications, and support materials were memorialized in Confluence, GeoDecision's dynamic document repository. Systems requirements specifications were formally recorded and considered dynamic throughout the development iterations as requirements are refined. NCHRP were provided access to Confluence as part of this project for transparency and validation of the requirements and other documentation.

The result of various development iterations was a new stand-alone noise model (RCNM2.0) leveraging existing TNM3.0 components and new components created to calculate the acoustic environment associated with highway construction equipment and activities.

The current TNM3.0 architecture consists of the following major components:

- A local, spatially enabled database that stores input and reference data as well as calculation results.

- A GUI that supports tabular data input and full map-based editing capabilities for individual acoustics objects such as receivers and barriers, in addition to 2D and 3D map display of data and results.
- GUI functions to display what-if scenarios for various barrier designs
- A full set of preconfigured reports for acoustic data
- The Acoustics Library – a set of functions developed by Volpe to take input data, carry out acoustics calculations and produce results
- An Acoustics API (Application Programming Interface) – a set of protocols to exchange data with the Acoustics Library and call its acoustics calculation functions. This API isolates the library from the GUI and the database, allowing for flexibility so changes to the GUI, the database and the Acoustics Library can be made independently without major impact on all components.
- The architecture above were modified in the following manner to incorporate the RCNM functionality described earlier:
- Modify the database schema to hold new objects such as the Stationary Noise Source and associated properties of various types of construction equipment.
- Modify the GUI to support tabular and map-based editing and display of the new objects created to support RCNM
- Modification of the Acoustics API to support function calls to RCNM acoustics for Construction Noise calculations
- Addition of new preconfigured reports for RCNM
- The architecture will utilize the following underlying platform components, like that used in TNM 3.0
- Microsoft .NET Framework based development libraries
- Spatially enabled SQLite database
- ESRI's ArcGIS Runtime technologies for 2D map editing and display
- WebGL based 3D map display

By implementing these modifications, a new tool was developed to compute construction noise in a manner that is computationally consistent with FHWA's TNM and provided a familiar user interface. The new tool does not model and compute both traffic and construction noise since this would require significant redesign of both the TNM and RCNM GUIs. However, care was taken during the development of RCNM2.0 to make changes in ways that will allow for easier merging of the two tools in the future. It should be noted that any future development of a single tool would not require any additional changes to the acoustics after the first merging, and by utilizing TNM's core acoustics, improvements to TNM's acoustics could easily be propagated into future versions of the RCNM.

Data collected was used to validate the model's accuracy and to estimate confidence intervals around the modeled levels. Comparisons were made between predicted levels based on user inputs to the model and actual measurements for:

1) Single Sources
2) Multiple Sources

For single sources, it was expected that variation was due to differences in the measured source (e.g. level, spectral shape, directivity, and source height) relative to the average source of the specified category as well as differences between the modeled and site conditions and actual geometry. For example, the ground impedance was modeled based on typical categories (e.g. water, concrete, asphalt pavement, clay, loose soil, etc.) and not on measurements of the ground present during the source measurement. Similarly, cyclic sources may deviate somewhat between the actual measured and average geometries. For example, a back hoe may swing through a different angle before dropping its load. This would not only change the duration of the operations but also the distances at which some of the operations occur.

Variations present for single sources represented the smallest amount of variation that can be expected. Additional variation is expected for multiple sources due to the more complex interaction of operations. Statistical levels (e.g. L10) were different when two sources are operated at the same time compared to when they are operated sequentially. The model utilizes statistical relationships to model these levels, and these relationships by their very nature introduce greater variation.

CHAPTER 3 Findings and Applications

This section details the results of the research and any AWP changes found to be necessary. Changes to the AWP occurred over the course of the project due to unexpected challenges faced by the Research Team as well as interaction with the Project Panel.

Literature Request and Review

The Research Team conducted an in-depth literature review of commercially available models of targeted equipment. The primary intent of the literature review was to identify the overall size range of each piece of equipment to ensure collection of noise measurement data was complete. However, during field data collection tasks, it was found that, in most cases, equipment in the upper or lower size range of commercially available equipment were not present on common roadway construction sites. In addition, performing noise level measurements for all sizes identified within the literature search was impractical due to budgetary constraints; therefore, the goal of the data collection task was to obtain a good representation of sizes commonly found on roadway construction sites of the targeted equipment list.

Survey Request and Review

The Research Team conducted an online survey, which was circulated to a total of 46 representatives comprising 42 state agency personnel, three from the FHWA, and one from the American Association of State Highway and Transportation Officials (AASHTO). Since there were states with multiple representatives, a total count of 38 unique state agencies were provided with the survey. The Research Team received a total of 22 survey responses. Based on survey responses, a few additional pieces of equipment were added to the targeted equipment list. A full list of survey responses is included within Appendix A.

Noise Source Database Development

Every attempt was made to obtain source data from the targeted list of equipment submitted within the AWP and further refined based on survey responses. The Research Team was able to obtain source measurements for fifty-five (55) pieces of equipment and seven (7) attachments. Additional equipment not originally included within the targeted list were obtained such as an air-operated post driver, directional drill rig, horizontal bore drill, joint sealer, mud recycler, shotcrete pump/spray equipment, and a jig saw included under power tools. In addition, isolated movement alarms were included within the NSD. Furthermore, measurements for dump trucks and front-end loaders were obtained and separated into ‘work’ and ‘pass-by’ data sets. Measurements were obtained from multiple New Jersey, Pennsylvania, Connecticut, New Hampshire, Florida, and Texas Departments of Transportation construction sites, as well as Port Authority of New York and New Jersey construction sites, an Amtrak construction site in Washington, D.C., several private construction sites in multiple states, equipment rental yards, and an operator training center in New Jersey. In total, 133 sites were visited, and in some cases, visited on multiple occasions. The final list, which merged equipment and corresponding attachments, where applicable, included sixty-two (62) pieces of equipment, which are provided in Table 2.

Table 2: Monitored Construction Equipment List

Equipment Type	
Air-Operated Post Driver	Pavement Scarifier (Milling Machine)
Asphalt Distributor Truck (Asphalt Sprayer)	Paving
Auger Drill	Asphalt (w/ Dump Truck)
Backhoe	Asphalt (w/ MTV & Dump Truck)
Bar Bender	Concrete (Placer + Slipform Paver)
Blasting	Concrete (Texturing/Curing Machine)
Abrasive	Concrete (Triple Roller Tube Paver)
Explosive	Power Tools
Chip Spreader	Air Hose
Compactor	Chainsaw
Plate	Chipping Gun
Roller	Circular Saw
Compressor	Grinder
Concrete Batch Plant	Hammer Drill
Concrete Mixer Truck	Impact Wrench (Air Gun, Ratchet Wrench)
Concrete Pump Truck	Jackhammer
Concrete Saw	Jig Saw
Crane	Nail Gun
Directional Drill Rig	Reciprocating Saw
Dozer	Rivet Buster
Drum Mixer	Sander
Dump Truck (Cyclical)	Power Unit (Power Pack)
Dump Truck (Passby)	Pump
Excavator	Rock Drill
Flat Bed Truck	Rumble Strip Grinding
Front End Loader (Cyclical)	Scraper
Front End Loader (Pass-by)	Shot Crete Pump/Spray
Generator	Street Sweeper
Grader	Telescopic Handler (Forklift)
Hoe Ram (Hydraulic Breaker)	Vacuum Excavator (Vac-Truck)
Horizontal Bore Drill	Ventilation Fan
Impact Pile Driver	Vibratory Concrete Consolidator
Joint Sealer	Vibratory Pile Driver
Light Tower	Warning Horn (Air Horn)
Man Lift	Water Spray Truck
Movement Alarm	Welding Machine
Mud Recycler	

Table 3 presents a list of equipment which resulted in steady-state noise levels, the corresponding size range for which noise levels were field-documented and the commercially available size range. It is important to note that the literature review identified commercially available equipment ranges however, in most cases, noise source data was not obtained for the full range of equipment sizes. Equipment sizes outside these ranges were not present at the 133 sites visited by the Research Team.

Table 3: Steady-State Data Range Summary

Steady-State Equipment	**Size Range (Monitored)**	**Size Range (Commercially Available)**
Air-Operated Post Driver	100 psi	80 – 100 psi
Bar Bender	16 - 20.5 hp	1 – 32 hp
Compressor	49 – 540 hp	49 – 580 hp
Concrete Pump Truck	300 - 400 hp	260 – 505 hp
Crane	267 - 924 hp	148 – 1360 hp
Drum Mixer	1.5 hp	0.5 – 13 hp
Generator	11 - 569 hp	2.1 – 1308 hp
Horizontal Bore Drill	174 hp	48 – 319 hp
Light Tower	12.2 – 33 hp	10 – 40.2 hp
Man Lift	48 - 74.2 hp	23.5 – 99.8 hp
Movement Alarms	NA	NA
Mud Recycler	25 hp	20 – 153 hp
Power Unit (Power Pack)	350 - 595 hp	10 – 1536 hp
Pump	9 - 139 hp	0.33 – 535 hp

Steady-State Equipment	Size Range (Monitored)	Size Range (Commercially Available)
Vacuum Excavator (Vac-Truck)	24.8 - 450 hp	24.8 – 450 hp
Ventilation Fan	0.5 hp	0.125 – 671 hp
Welding Machine	20 - 68.4 hp	5.5 – 94 hp
Note: hp – horsepower psi – pounds per square inch		

Noise levels associated with the pass-by equipment category varied greatly based on equipment type, speed, activity, work area and ground surface as well as activated movement alarms. As requested by the USDOT Volpe Center, pass-by events were defined at the L_{ASmax}, and 10 dB prior to, and after the L_{ASmax}. In most cases, 10 dB prior to and after the L_{ASmax} was obtained, however on a rare occasion, 6 dBA was considered acceptable. These thresholds are in general accordance with methodology utilized to accept data within the FHWA's TNM REMEL database.

Table 4 presents a list of equipment for which 'work' was captured as a pass-by event. In addition, Table 4 lists the corresponding equipment size range for which noise source data was documented as well as the commercially available size ranges. It is important to note that the literature review identified commercially available equipment ranges however, in most cases, noise source data was not obtained for the full range of equipment sizes. Equipment sizes outside these ranges were not present at the 133 sites visited by the Research Team.

Table 4: Pass-by Data Range Summary

Pass-by Equipment	Size Range (Monitored)	Size Range (Commercially Available)
Asphalt Distributor	270 – 300 hp	Depends on Chassis Engine
Chip Spreader	275 hp	160 – 280 hp
Compactor (Plate)	6 hp	3.5 – 32.8 hp
Compactor (Roller)	18 – 260 hp	10.7 – 405 hp
Dump Truck	Unknown	Depends on Chassis Engine
Flat Bed Truck	Unknown	Depends on Chassis Engine

Pass-by Equipment	Size Range (Monitored)	Size Range (Commercially Available)
Front End Loader	153 – 192 hp	22.5 – 1892 hp
Grader	158 - 300 hp	140 – 533 hp
Joint Sealer	33 hp	5.5 – 27 hp
Pavement Scarifier (Milling Machine)	610 – 980 hp	225 – 991 hp
Paving – Asphalt (Paver + Dump Truck)	358 – 525 hp	64 – 230 hp (paver only)
Paving – Asphalt (Paver + Material Transport Vehicle + Dump Truck)	358 - 525 hp	174 – 555 hp (paver + material transport vehicle only)
Rumble Strip Grinding	460 hp	Depends on Chassis Engine
Scraper	450 hp	210 – 620 hp
Street Sweeper	74 - 340 hp	74 – 384 hp
Telescopic Handler (Forklift)	110 hp	63 – 159.6 hp
Water Spray Truck	215 - 300 hp	Depends on Chassis Engine
Note: hp – horsepower		

Table 5 presents a list of equipment for which ‘work’ was captured as a cyclical event. In addition, Table 5 lists the corresponding equipment size range for which noise source data was documented as well as the commercially available size ranges. It is important to note that the literature review identified commercially available equipment ranges however, in most cases, noise source data was not obtained for the full range of equipment sizes. Equipment sizes outside these ranges were not present at the 133 sites visited by the Research Team.

Table 5: Cyclical Data Range Summary

Cyclical Equipment	Size Range (Monitored)	Size Range (Commercially Available)
Auger Drill	225 - 523 hp	76 – 540 hp
Backhoe	75 - 96 hp	68 - 130 hp
Blasting (Abrasive)	System	System
Blasting (Explosive)	397 lbs	Depends on Need
Concrete Batch Plant	35 lph	18 – 35 lph
Concrete Mixer Truck	Unknown	145 - 600 hp
Concrete Saw	4.4 - 66 hp	4.4 – 74.3 hp
Directional Drill Rig	160 hp	24.8 - 765 hp
Dozer	73 - 347 hp	70 - 890 hp
Dump Truck (Cyclical)	Unknown	Depends on Chassis Engine
Excavator	23.3 - 417 hp	14.5 – 672 hp
Front End Loader (Cyclical)	188 - 192 hp	22.5 – 1892 hp
Hoe Ram (Hydraulic Breaker)	58.7 - 362 hp	14.5 – 672 hp
Impact Pile Driver	28,817 – 208,300 ft-lbs	13,750 – 588,141 ft-lbs
Paving – Concrete (Placer + Slipform Paver)	600 hp	154 – 420 hp
Paving – Concrete (Texturing/Curing Machine)	60 hp	31.5 – 74.3 hp

Cyclical Equipment	Size Range (Monitored)	Size Range (Commercially Available)
Paving – Concrete (Triple Roller Tube Paver)	40 hp	26 – 44 hp
Power Tools – Air Hose	1850 cfm	Based on Compressor
Power Tools – Chainsaw	3.2 hp	1.8 – 8.6 hp
Power Tools – Chipping Gun	19.7 – 27.1 lbs	9.9 – 29 lbs
Power Tools – Circular Saw	15 amp 4.4-5.8 hp	15 amp
Power Tools - Grinder	7 - amps	6 – 15 amp
Power Tools – Hammer Drill	18 v	12 – 36 v
Power Tools – Impact Wrench	145 – 400 ft-lbs	10 – 1030 ft-lbs
Power Tools - Jackhammer	60 – 90 lbs	lbs
Power Tools – Jig Saw	5.5 amp	3.9 – 6.5 amp
Power Tools – Nail Gun	120 – Unknown psi	60 – 320 psi
Power Tools – Reciprocating Saw	12 amp	9 – 18 amp
Power Tools – Rivet Buster	30 lbs	20.5 – 34.5 lbs
Power Tools - Sander	7.8 amps	2 – 15 amp
Rock Drill	156 – 173 hp	50 – 540 hp
Shot Crete Pump/Spray	72 hp	18 – 260 hp

Cyclical Equipment	Size Range (Monitored)	Size Range (Commercially Available)
Vibratory Concrete Consolidator	Unknown	1 – 4.8 hp
Vibratory Pile Driver	396 – 595 hp	100 – 2380 hp
Warning Horn (Air Horn)	Standard	Standard
Note: hp – horsepower lph – loads per hour cfm – cubic feet per minute lbs – pounds amp – amperage v – voltage ft-lbs – foot pounds psi – pounds per square inch		

An auger drill as well as other rotating pieces of equipment were processed in a slightly different method than other equipment within this category. The Research Team documented distances to the house (main equipment body) as well as the boom and attachment due to the difference noise sources associated. The L_{Aeq} was processed based on the distance from the measurement location to the house while L_{ASmax} data was processed based on the distance from the measurement location to the attachment.

Source levels for all pieces of equipment resulting in steady-state, pass-by and cyclical noise levels were provided to the USDOT Volpe Center for processing.

Model Development

Development of RCNM2.0 followed the process outlined in the AWP.

Acoustics

This section focuses on the modifications to the TNM3.0 acoustics source code that were implemented to meet the functional requirements to compute noise levels at specified receiver locations due to specified roadway construction noise sources. Two main modifications were made to the acoustics code, the addition of Road Construction Noise Source Objects (RCNS) and a new flow that accounted removed obsolete computations and accounted for new functionality, such as stationary sources and directivity. Road Construction Noise Source Objects were derived from the TNM Roadway Object. These objects represent the fundamental source objects that are then used by the acoustics to model emission levels. RCNS Objects differ from TNM Vehicle Source Objects as follows:

1) Path Objects are used to define the geographic presence of the sources rather than Roadway Objects. Path Objects have the following characteristics that distinguish them from Roadway Objects:
    a. Paths do not have a ground type but instead depend on the underlying ground defined either by ground zones or the default ground type.
    b. Paths have no width.
    c. Paths may be composed of a point source, a single segment, or multiple segments.
    d. Paths may overlap.
2) Instead of three sub-source heights, the choice of which is determined by vehicle type, RCNM RCNS objects have a single source height that is dependent on the source being modeled.
    a. Examples of sources include: engine exhaust, drive train, impact location, motor, etc.
    b. For all sources currently defined in the database, a single source height is used to model the source. If future sources require greater fidelity, the additional sources can be modeled by creating additional entries in the database for the individual sources. These can then be modeled simultaneously to create the aggregate source.
    c. Because source heights are no longer limited to the three for road vehicles, a new set of correction factors were generated to replace those found in Table 7 of the Federal Highway Administration's Traffic Noise Model Technical Manual.
3) Source operating conditions are used rather than vehicle speeds.
    a. Examples of operating conditions include: idle, full-throttle, backing, dumping, etc.
    b. These operating conditions are selected by the user for each segment as part of the source selection process in the GUI.
    c. The operating condition is constant over a segment. (If the operating condition is expected to change over the segment, then the segment should be subdivided sufficiently that this assumption holds.)
4) Each operating condition / source pair has four associated emission level spectra.
    a. Each spectra are associated with an emission direction (front, rear, right and left sides).
    b. The emission spectra used for propagation is a derived by interpolating between the two directions that subtend the actual propagation direction between source and receiver.
5) Each operating condition / source / path segment paring has an associated usage factor.
    a. The usage factor determines the percent of the metric's duration that the given pairing is in operation.
    b. For example, a usage factor of 50% for an analysis period of one hour indicates an operation duration of 30 minutes.

Figure 5 shows the program flow for TNM3.0 acoustic computations. The program flow was modified for RCNM2.0 as shown in Figure 6 to remove obsolete computations and account for new functionality. Key changes to the program flow include:

- Speed control decision points were removed since RCNM2.0 relies on user specified operational information for each segment that will not change over the segment.
- Changes in speed caused by grade no longer occur.
- Paths and Path Segments were substituted for Roadways and Roadway Segments.
- Vehicle Types have been replaced with sources.
- Directivity is accounted for during the emission computations.
- Adjustments to emission levels due to
- Application usage factors are now also included.

Figure 5 - *TNM3.0 High-level Flowchart*

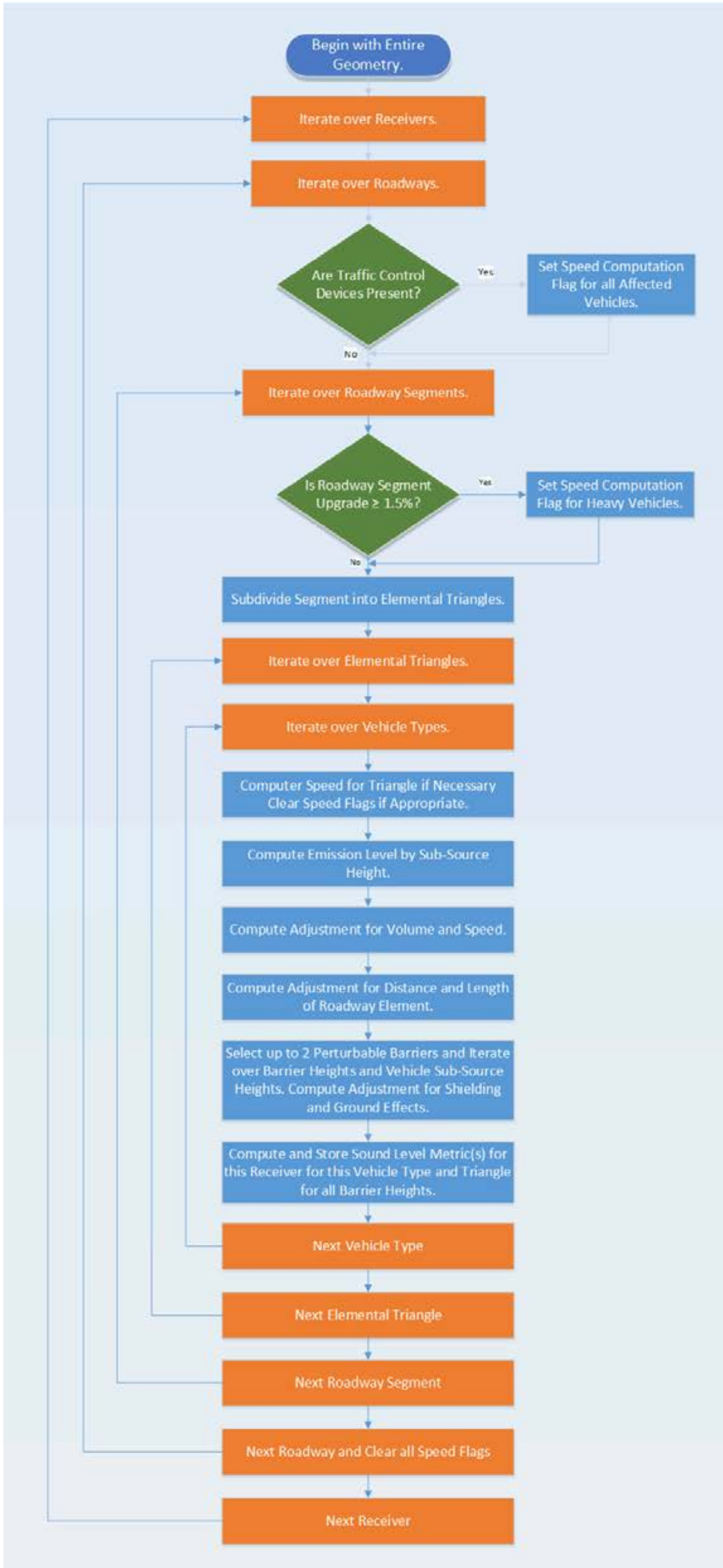
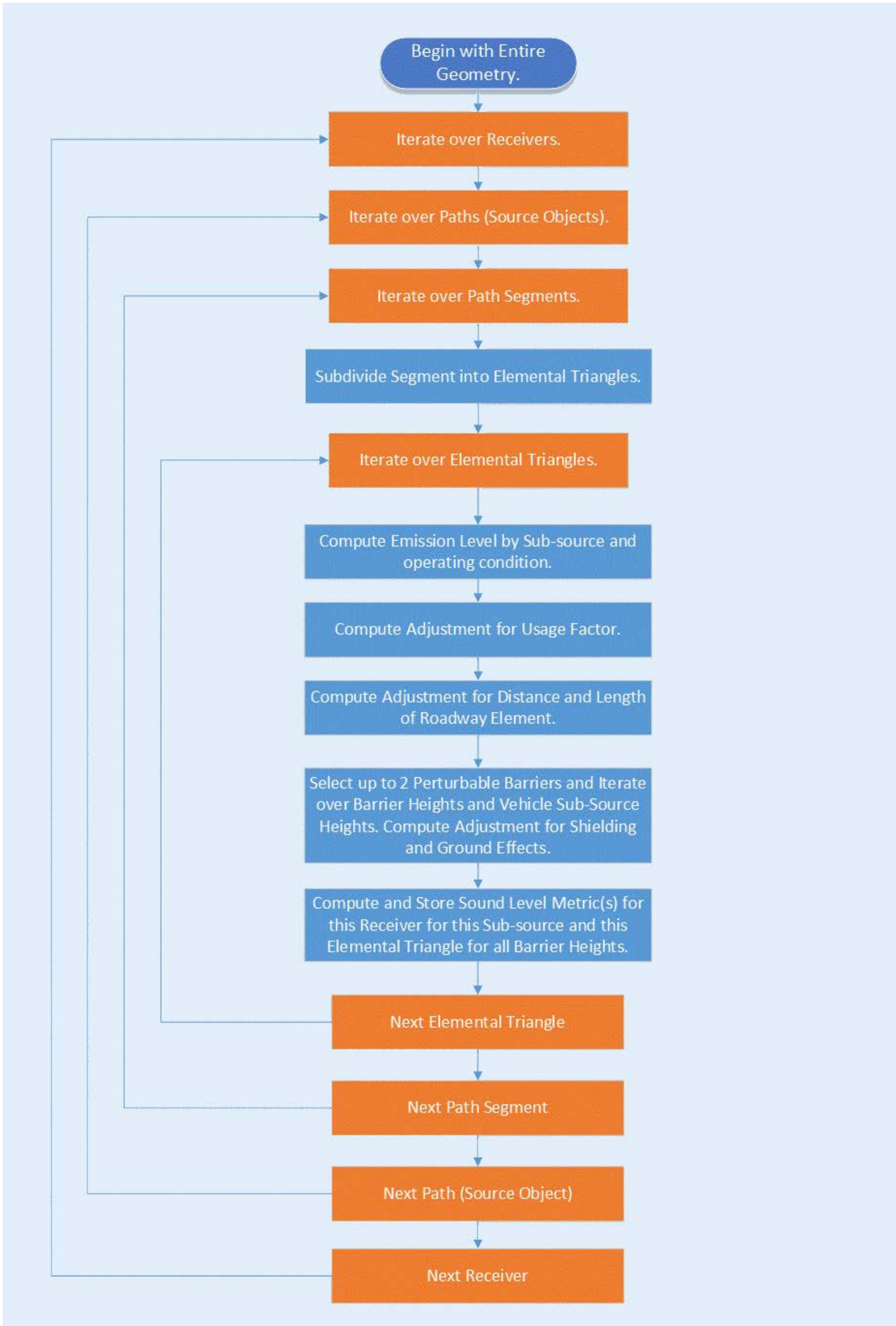


Figure 6 - *RCNM2.0 High-level Flowchart*



Application Development

Overall development tasks completed for the implementation of the Construction Noise Model are as follows:

- Prepared current user interface (UI) to model construction by removing functionality used for traffic noise model and no longer needed
- Updated UI to allow user to model construction by adding Equipment selection and related components to UI
- Allowed the user to model construction on the map by modifying geometry drawing
- Provided user with editing and mapping functionality for 2D and 3D viewer
- Updated reporting functionally to incorporate construction
- Integrated construction Acoustics library to use for calculations
- Resolved bugs as necessary

CHAPTER 4 Conclusions and Suggested Research

This section details the conclusions of the research and any suggested research recommended by the Research Team.

Conclusions

The completed RCNM2.0 improves on the functionality of RCNM by expanding the source database and providing users with the ability to analyze the project site conditions using the project design and mapping. The first generation of the Federal Highway Administration (FHWA) Roadway Construction Noise Model (RCNM) provided a simplistic tool for users to perform construction noise analyses on FHWA, state, and municipal projects. Users were faced with limited applicability due to RCNM shortcomings. A new platform was required to provide a comprehensive method of predicting construction-related noise levels

The Research Team developed RCNM2.0 utilizing an enhanced database to allow users the capability of predicting construction-related noise levels based on both stationary and mobile-source construction equipment. More importantly, the software accounts for source/receiver heights; sound propagation factors such as atmospheric absorption, divergence, intervening ground, topography, barriers, building rows, and dense vegetation; and path controls such as noise walls. The completed model sets the stage for integration with the future TNM3.0 as well as the potential to incorporate updated equipment database information throughout the life of the model.

Suggested Research

Project constraints limited research into two key areas:

- Integration with the FHWA TNM3.0
- Functionality for user defined sources
- Expansion of the Noise Source Database
- Refined equipment selection

Integration with FHWA TNM3.0

The team recognized during proposal development that interoperability and later integration with the FHWA TNM3.0 can provide substantial improvement to noise modeling. All versions of the FHWA TNM limit users to analyzing line sources of noise. Users have developed techniques to model point sources, but this is not a native function of the model. The RCNM2.0 includes line and point sources.

Users of each model are limited to predicting noise levels from the data sources included in the model. If a user needs to analyze the combined effects of highway and construction operations, they must analyze the project in each model and use post-processing techniques to combine the results.

Integration of the two models would provide functionality to analyze point and line sources within the same model and allow analysis of combined construction and highway operations.

Functionality for User Defined Sources

This feature was also recognized early in the development process as a key new component to add to the software, however, it was outside the scope of the current project. The FHWA TNM includes a function to allow users to define new vehicle types and include them in the model. The function limits users to adding new vehicles based on comparing them to the noise emission curve of one of the five vehicle categories that are already in the source database. An improved function for including user defined sources could allow users to enter pertinent information about the noise source to expand on the existing database and incorporate entirely new sources rather than use sources that area already in the database to represent new sources.

Expansion of the Noise Source Database

As detailed within Appendix A, there were a few suggested pieces of equipment that could not be included in the NSD for a variety of reasons. A future effort to include these items in the NSD will expand the capability of RCNM2.0.

Refined Equipment Selection

The approach to implementing noise sources in RCNM2.0 was to average the noise levels from classes of equipment into a single average. Users can select for example, a generator to input into the model, but this does not account for the wide range in generator sizes and source noise levels. A finer resolution of equipment classification would help users to analyze scenarios where they know what equipment contractors will use on a project or perhaps to help develop project specifications as part of construction noise mitigation plans.

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