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New York City Western Rail Yard Construction Noise Study

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ABSTRACT

This paper will describe the technical approach, regulatory environment and outcome of a construction noise study performed on behalf of a $2.5 billion private development to be built over the Western Rail Yard in Manhattan. Community noise modeling for the nine year project was performed in accordance with New York City Environmental Quality Review (CEQR) Manual requirements using the Cadna-A and FHWA TNM models. The on-site noise analysis accounted for the staggered schedule of excavation, foundation laying, erection and finishing of eight high-rise residential and commercial buildings. Construction equipment source emissions used in the Cadna-A model were taken from the FHWA Roadway Construction Noise Model (RCNM) and the NYC DEP Construction Noise Regulations (Local Law 113, Chapter 28). Project-related trucking (mobile) noise was evaluated using the TNM model. Seventeen multi-story noise receptor locations surrounding the development site were evaluated with ambient noise measurements and predictive noise modeling. A construction vibration assessment for the elevated High-Line park was also conducted. The results indicated that noise exceedance conditions were expected from pile driving, hoe ramming and jackhammering operations during daytime, nighttime and weekend periods, so noise mitigation measures were developed and incorporated into the project's construction permit.

1. INTRODUCTION

Construction of the proposed Western Rail Yard (WRY) development will potentially generate noise and vibration levels that may annoy or disturb nearby residents and businesses. Analyses were performed to determine the potential impacts of the project's construction activities on the surrounding land-uses.

Potential noise and vibration impacts associated with construction will vary dramatically based on the type of equipment working in the field, the activities being performed, the locations where the work may be occurring, and the ground conditions. Potential noise and vibration impacts for each phase of construction (i.e. on-site noise), as well as noise from delivery and dump trucks using the proposed haul routes (i.e. trucking noise), were analyzed in accordance with noise criteria contained in the *CEQR Technical Manual*. Construction noise conditions were also evaluated against the new *New York City Construction Noise Regulations* with respect to equipment noise emission levels, the use of noise mitigation barriers, and the development of and adherence to a Noise Mitigation Plan. Finally, the potential damaging effects of construction-induced vibration were evaluated for the elevated High-Line rail structure which has been converted into public park space.

2. CONSTRUCTION NOISE CRITERIA

A. NYC CEQR Manual – Construction Noise

The relevant criteria to evaluate construction noise at receptor locations from on-site equipment comes from the *New York City Environmental Quality Review (CEQR) Manual*, Chapter 3R, Sections 335, 410 and 423. The CEQR construction noise criteria allow for an increase of 3, 4 or 5 decibels above the existing noise conditions depending on the *measured* ambient hourly Leq noise levels at each receptor. CEQR construction noise guidelines state that:

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- During the daytime hours of 7:00 AM to 10:00 PM, if the existing ambient noise level is 60 dBA Leq(h) or less, a 5 dBA or greater change would be considered to be an exceedance;
- If the ambient noise level is 61 dBA Leq(h), the maximum incremental increase would be 4 dBA would be considered an exceedance;
- If the ambient noise level is 62 dBA Leq(h) or more, a 3 dBA or greater change would be considered to be an exceedance.
- During the nighttime hours of 10:00 PM to 7:00 AM the following day, a change of 3 dBA would be considered to be an exceedance regardless of the ambient level.

B. NYC CEQR Manual – Traffic (Trucking) Noise

The relevant criteria to evaluate noise at receptor locations from mobile construction vehicles (i.e. trucks) come from the *New York City Environmental Quality Review (CEQR) Manual*, Chapter 3R, Sections 332, 410 and 421. The CEQR traffic noise criteria allow for an increase of 3, 4 or 5 decibels above the existing (or in this case, future No-Build) noise conditions depending on the traffic noise hourly Leq levels at each receptor. As such, the existing (or future No-Build) traffic noise levels must be determined through *modeling* in order to isolate the traffic noise component rather than by measurements which would inherently include all ambient noise sources.

C. New York City Construction Noise Regulation

New York City Local Law 113 of 2005 established the mandate to create a new set of construction noise regulations (i.e. Rules) for inclusion in Section 24-219, Title 15, of the Rules of the City of New York (i.e. the New York City Noise Code). To this end a completely new Chapter 28 (*written by PB*) was developed to specifically address construction noise and to provide requirements for proactive avoidance and options for mitigation. The new construction noise regulations went into effect on 1 July 2007 and apply to all work occurring within New York City.

Thus, contractors must adhere to the requirements contained in the City's new Construction Noise Regulations. These requirements include, but are not necessarily limited to, the following:

- Develop and follow a Noise Mitigation Plan,
- Erect noise barriers around the perimeter of the construction site when within 200 feet of a receptor,
- Use equipment whose noise emission levels comply with those found in the FHWA Roadway Construction Noise Model (RCNM®) ~ *also developed by PB,*
- Provide worker/supervisor training for quieter work methods,
- Inform the affected public about work schedule and mitigation plans,
- Use quieter-type adjustable backup alarms on equipment post 2008, and
- Select from a menu list of additional mitigation options for particularly noisy work involving pile driving, hoe-ramming, jackhammering or blasting.

3. CONSTRUCTION DESCRIPTION

A. On-Site Construction Activities

On-site construction work will take place in and above the Western Rail Yard site. As shown in the site map in **Figure 1**, the area is bounded by 12th Avenue (Route 9A) to the west, 11th Avenue to the east, 33rd Street to the north, and 30th Street to the south. The area is currently an active rail yard above which a platform will be built to cover the rail yard allowing for the erection of eight high-rise buildings. Receptors surrounding the site include mixed residential/commercial buildings, trailer storage areas, the Javits Convention Center to the north, the Hudson River to the west, and the future Eastern Rail Yard development to the east.

The construction equipment expected for use in building the platforms over the rail yard includes typical heavy equipment such as cranes, caisson drill rigs, excavators, loaders, pneumatic tools and compressors. Erection of the eight buildings will include the use of cranes and lifts, excavators, concrete pouring, concrete saws, pneumatic tools, bar benders, tampers and rollers, and pile drivers in two locations. Of the noisier types of equipment, an impact pile driver is expected for occasional use at buildings WR-3 and WR-4, and a hoe-ram is expected for use at building WR-2. Additionally, jackhammers, pavement cutters and impact wrenches are expected to be used during construction of all eight buildings. Finally, dump trucks and delivery trucks are expected to service the site on an intermittent basis as needed. All of these noise sources were taken into account in this study in accordance with the equipment and trucking schedule provided by the contractor (Bovis).

Work is scheduled to take place in a sequential but intermittent manner from July 2011 until December 2019 (102 months). Work will progress as quickly as possible with two-eight hour work shifts expected during the weekdays and evenings ranging from 8:00 AM to 11:00 PM, and occasionally on Saturdays from 8:00 AM to 4:30 PM. Consequently, construction noise levels were evaluated in this study for weekday, evening/night and weekend periods.

B. Ambient Noise Measurements

Ambient noise levels were measured from May 28th to December 6th 2008 at seventeen receptor locations in order to document existing environmental noise conditions and to allow evaluation of construction noise in accordance with CEQR noise guidelines. Hourly Leq noise levels were measured during daytime, evening/night and weekend periods using a Brüel & Kjær (B&K) Model 2231 Precision Sound Level Meter (SLM). All the noise data were measured in A-weighted decibels using an RMS Slow time response. While several noise metrics were measured in the field, only the Leq levels are reported in this study because they are the only metric relevant to the CEQR noise guideline.

C. Receptor Locations

Seventeen receptors were selected in consultation with NYC DEP and City Planning officials for the purposes of evaluating noise from on-site construction activities at various locations in the community. The receptors were selected primarily because they either had a direct line-of-sight to the construction site or they could potentially be affected by construction-related truck traffic on designated haul routes. Based on the CEQR procedures, no distinction is made to include or exclude potential receptors based on their current land-uses. This is because the noise criteria approach used by CEQR is applied equally to any type of building, structure or property. This approach also recognizes that a given receptor's land-use may change over time. The receptor locations and land-uses for this project, along with the measured ambient noise levels and corresponding CEQR noise criteria limits, are shown in **Figure 1** and summarized in **Table 1**.

Table 1. Construction Noise Receptor Description

Site No.	Location	Land-Use	Ambient Noise Level (and CEQR Noise Limit) Leq(h) in dBA		
			Weekday	Night	Weekend
R1	12th Avenue between W.33rd St. & W.34th St.	Open Space and Outdoor Recreation (1 story tall)	78 (81)	72 (75)	72 (75)
R2	W.34th Street between 11th Ave. & 12th Ave.	Commercial and Office Buildings (3 stories tall)	72 (75)	71 (74)	71 (74)
R3	W.28th Street between 11th Ave. & 12th Ave.	Commercial and Office Buildings (5 stories tall)	69 (72)	64 (67)	66 (69)
R4	W.33rd Street between 11th Ave. & 12th Ave.	Parking Facility (1 story tall)	73 (76)	67 (70)	67 (70)
R5	W.30th Street between 11th Ave. & 12th Ave.	Transportation and Utility (4 stories tall)	68 (71)	67 (70)	71 (74)
R6	11th Avenue between W.35th St. & W.36th St.	Open Space and Outdoor Recreation (1 story tall)	74 (77)	69 (72)	72 (75)
R7	11th Avenue between W.34th St. & W.35th St.	Commercial and Office Buildings (4 stories tall)	74 (77)	70 (73)	71 (74)
R8	11th Avenue between W.33rd St. & W.34th St.	Commercial and Office Buildings (5 stories tall)	73 (76)	72 (75)	73 (76)
R9	11th Avenue between W.31st St & W.33rd St.	Transportation and Utility (1 story tall)	74 (77)	74 (77)	72 (75)

R10	11th Avenue between W.29th St. & W.30th St.	Industrial/Manufacturing (6 stories tall)	73 (76)	70 (73)	72 (75)
R11	11th Avenue between W.28th St. & W.29th St.	Transportation and Utility (4 stories tall)	72 (75)	69 (72)	68 (71)
R12	W.33rd Street between 10th Ave. & 11th Ave.	Commercial and Office Buildings (5 stories tall)	69 (72)	67 (70)	65 (68)
R13	W.30th Street between 10th Ave. & 11th Ave.	Transportation and Utility (6 stories tall)	72 (75)	69 (72)	68 (71)
R14	10th Avenue between W.31st St. & W.33rd St.	Commercial and Office Buildings (5 stories tall)	75 (78)	75 (78)	75 (78)
R15	10th Avenue between W.30th St. & W.31st St.	Building Under Construction (5 stories tall)	76 (79)	75 (78)	75 (78)
R16	10th Avenue between W.33rd St. & W.34th St.	Commercial and Office Buildings (4 stories tall)	75 (78)	75 78)	75 (78)
R17	10th Avenue between W.29th St. & W.30th St.	Commercial and Office Buildings (5 stories tall)	76 (79)	75 (78)	75 (78)

Figure 1. Western Rail Yard and Construction Noise Receptor Locations

4. NOISE MODELS

A. On-Site Construction Noise Model – Cadna-A®

Construction noise levels from on-site equipment were modeled at receptor locations using the Cadna-A noise model. The Cadna-A model implements ISO Standard 9613-2 for environmental noise sources and outdoor sound propagation. It is a comprehensive three-dimensional model in which noise sources are assembled from point, line and/or area components; each emitting sound power in octave bands or broadband A-weighted format. Distance losses, ground attenuation, wind effects, building shielding, and barrier/berm effects are computed in the Cadna-A model, and the resulting noise levels are predicted at any number of receptor locations of interest.

The Cadna-A model developed for this project was first configured by importing a Google Earth® base map of the area, as shown in **Figure 2**. In this manner the positions of various buildings, receptor locations and distances could be determined to a high degree of accuracy.

An equipment schedule was provided from the contractor (Bovis) showing the construction equipment required for each phase of work on a monthly basis. Six horizontal area sound sources were entered in the Cadna-A model to represent the work associated with building the platforms over the rail yard. Eight vertical area sound sources were configured in the model to account for the ground-based equipment necessary to build each of the eight subject buildings. A single point source was also located on the top floor of each building to account for smaller hand tools and tower cranes being used as the buildings are erected. In this manner the equipment expected for use in any given month could be entered into the Cadna-A model for each phase of work.

The equipment noise levels entered into the Cadna-A model were in the form of A-weighted sound power levels derived from the sound pressure emission levels contained in the FHWA *Roadway Construction Noise Model* (RCNM®). Noise emission levels for dozens of generic types of heavy equipment are contained in a database in the RCNM model. The equipment noise emission levels in the RCNM model - which were all measured under actual field conditions during the Big Dig in Boston - are expressed as A-weighted Lmax levels at 50 feet using an RMS Slow time response. The RCNM model also provides typical acoustical usage factors, or the percentage of time equipment may operate at full power, thus allowing for an estimate of Leq sound pressure levels and equivalent sound power levels to be computed for each piece of equipment. The new *NYC DEP Construction Noise Rules* use this same database to establish equipment noise criteria limits in the field.

The eight subject buildings were entered into the model in their designated locations, as shown in **Figure 2**. This was done because the buildings themselves provide acoustic shielding as noise propagates in various directions away from the site. It was assumed that each building required approximately 3 to 6 months to begin erection, and then the heights of the buildings were entered into the model as they grew taller month-to-month.

Finally, as shown in **Figure 3**, the Cadna-A model can generate noise contour lines (isopleths) on a base map showing how noise radiates from the sources and is attenuated by intervening structures and terrain. The noise contour lines are useful for presenting the results in a graphical format which can be easily interpreted by regulators and the public to estimate the noise level at any location of interest. In this case, in accordance with NYC DEP and City Planning guidelines, noise levels were modeled exterior to each floor, not just at the ground floor elevation, for each of the seventeen receptors.

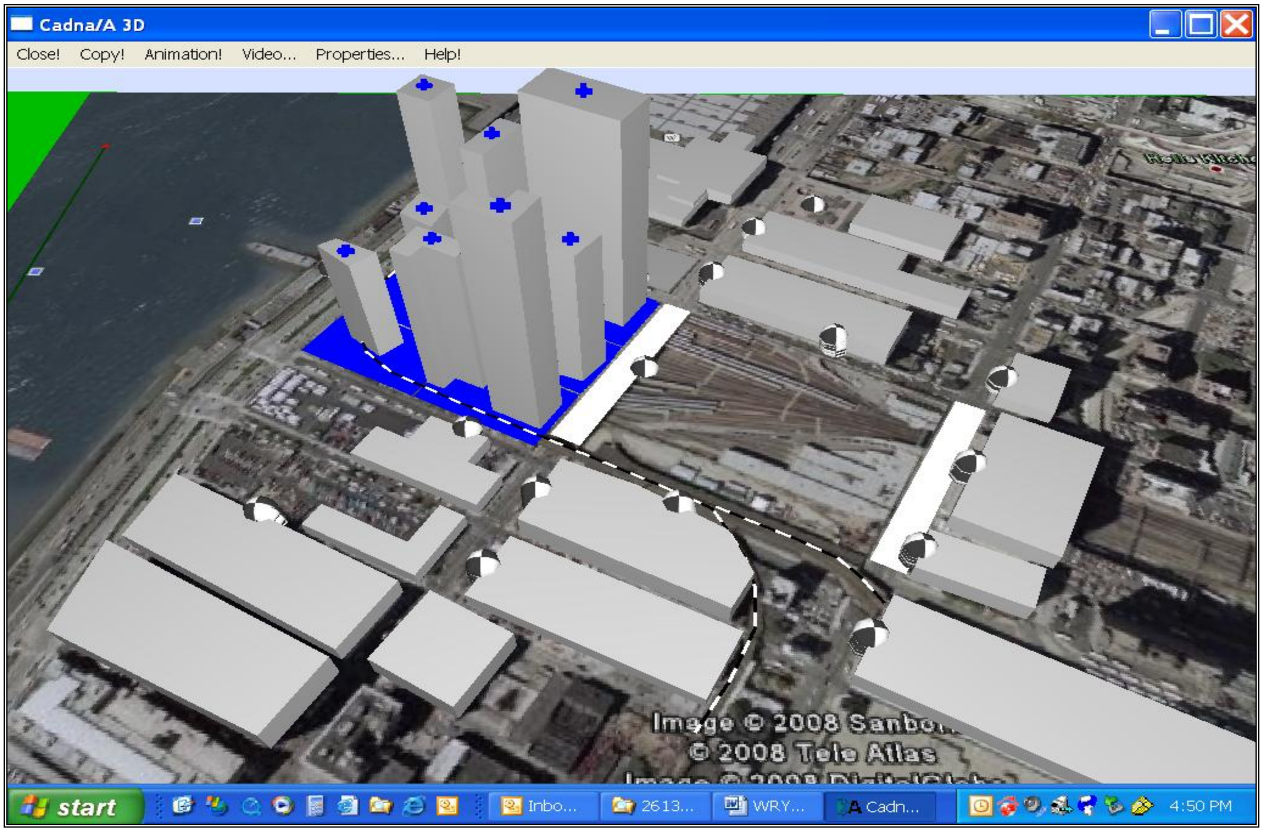

Figure 2. Cadna-A model input (typical) for the Western Rail Yard project

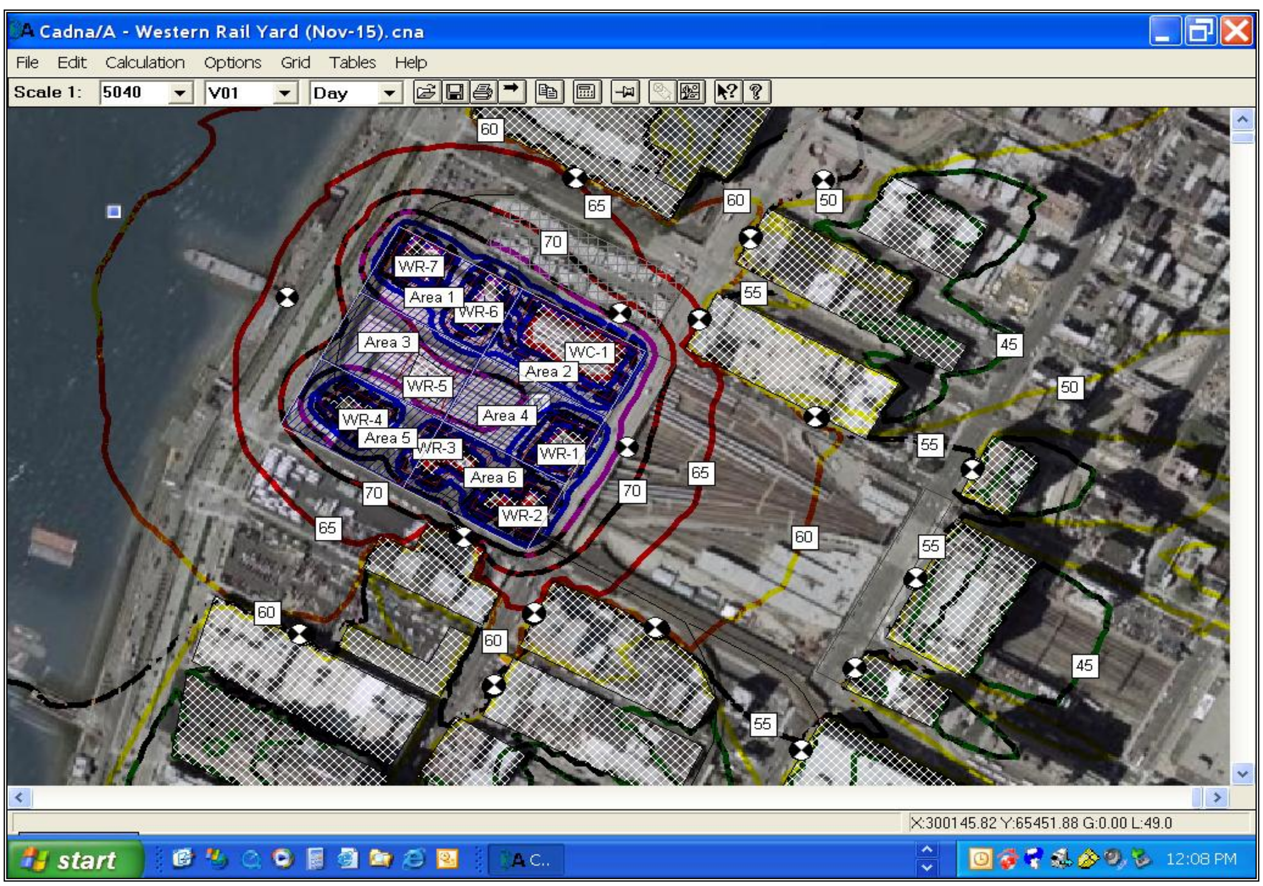

Figure 3. Cadna-A model output (typical) for the Western Rail Yard project

B. Traffic (Trucking) Noise Model – TNM®

The traffic noise model used in this study to evaluate mobile construction vehicle (i.e. trucking) noise was the FHWA-approved version of *Traffic Noise Model* (TNM) version 2.5. TNM has been in public use since the late-1990s. The TNM model configured for this particular project can be seen in **Figure 4**.

The TNM model is created by entering the spatial coordinates (X, Y and Z) of subject roadway segments, receptor locations, and intervening obstacles such as buildings, terrain and barriers. Surface conditions of the ground are also defined which might affect noise propagation.

Each modeled roadway segment is then loaded with traffic data including the number of vehicles per hour disaggregated into automobiles, medium trucks, heavy trucks and buses, as well as the vehicles' speeds in miles per hour for each direction of traffic flow. The noise levels associated with each type of vehicle are automatically retrieved from a database of reference vehicle noise emission levels. The TNM model will then compute the predicted A-weighted Leq(h) noise levels at each receptor location.

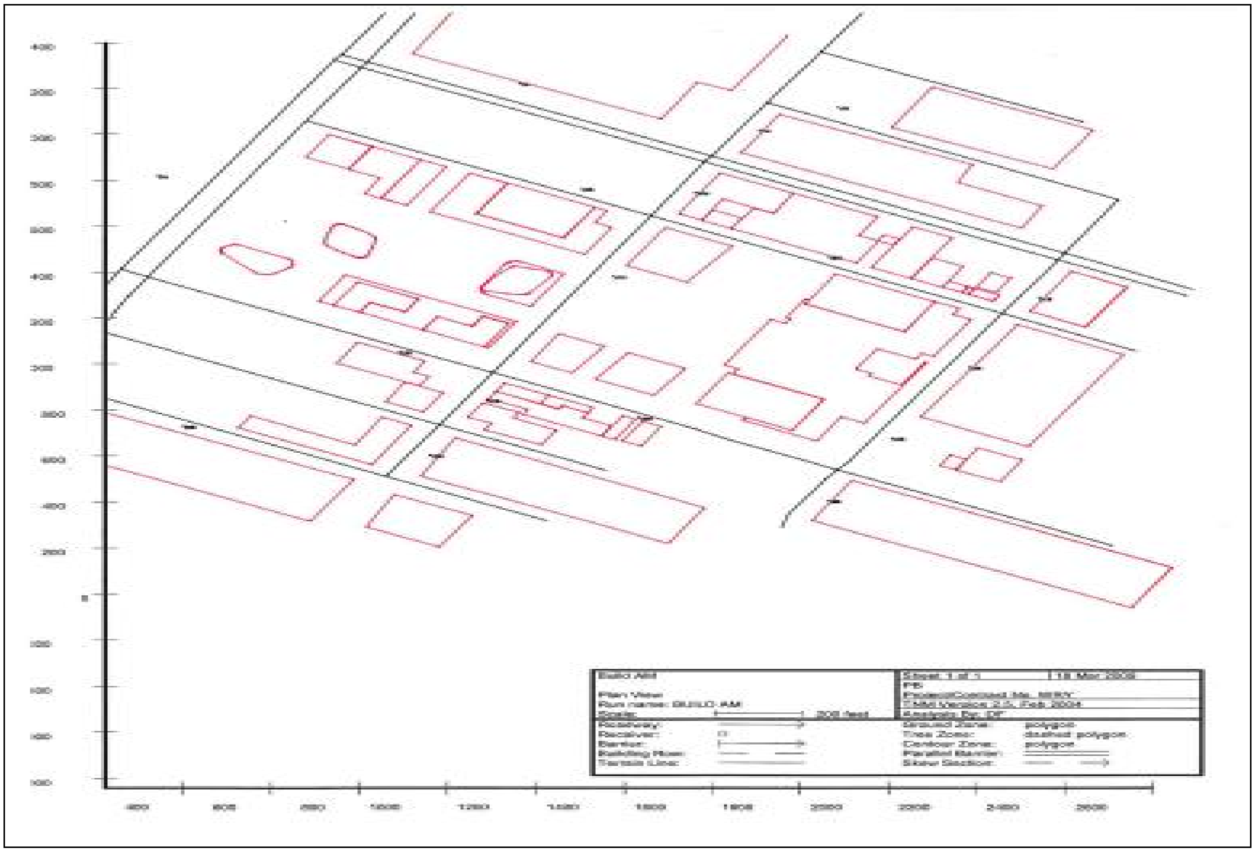

Figure 4. TNM Configuration for Mobile Construction (Trucking) Noise Analysis

5. NOISE ANALYSES RESULTS

A. Construction Noise Results

An example output result from the Cadna-A model is shown in **Figure 3** which shows the typical results for one of the more active months, namely November 2016, during which time seven of the eight buildings are under construction. In total, some 102 separate Cadna-A files were produced, covering the alternating equipment, phases of work, and building conditions for each month of the project.

A summary of the results of the construction noise analysis can be seen in **Table 2** for weekday, evening/night and weekend time periods for those receptors expected to be exposed to construction noise levels exceeding CEQR noise guidelines. The reported results show only the loudest predicted conditions and/or greatest exceedances of CEQR noise guidelines for each receptor.

It is important to note that the results in **Table 2** represent worst-case potential noise conditions which assume that all of the equipment and phases of work disclosed by the contractor (Bovis) for a given month are occurring simultaneously. Actual noise levels will vary dramatically from day-to-day and hour-to-hour, with noise levels perhaps fluctuating by 20 to 40 decibels during quieter periods of work. Even with this conservative approach, the worst-case predicted noise levels are expected to comply with CEQR noise guidelines during the vast majority of the time.

For example, during weekday periods, noise exceedances are expected at only two receptor locations, (R4 and R5) during 6 months and 55 months, respectively, of the project's 102 month duration. The worst-case weekday exceedance of 9 decibels above the CEQR noise limit is expected to occur during 1 month at receptor R5. Similarly, during evening/night periods, noise exceedances are expected at only three receptor locations, (R3, R4 and R5) during 7, 51, and 55 months, respectively, of the project's 102 month duration. The worst-case evening/night exceedance of 10 decibels above the CEQR noise limit is expected to occur during 1 month at receptor R5. And lastly, during weekend periods, noise exceedances are expected at only five receptor locations, (R3, R4, R5, R9 and R12) during 1, 62, 41, 15 months and 5 months, respectively, of the project's 102 month duration. The worst-case weekend exceedance of 5 decibels above the CEQR noise limit is expected to occur during 6 months at receptor R4 and during 3 months at receptor R5.

Finally, **Figure 5** shows the worst-case total noise (i.e. construction plus trucking plus ambient) Leq(h) levels anticipated at the most-impacted receptor, namely R5, during evening/night hours for each of the project's 102 months duration.

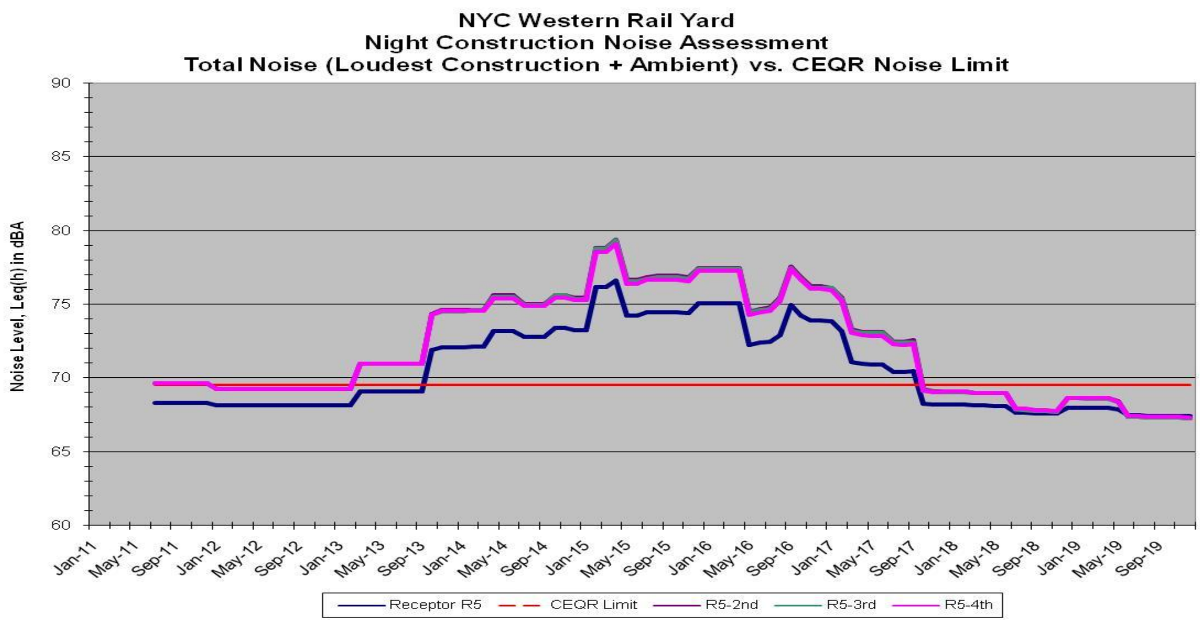

Figure 5. Evenings/Night Results for Receptor R5

B. Mobile (Trucking) Noise Results

The TNM traffic noise model results for the mobile noise analysis revealed little or no noise affects at the seventeen receptors. Future baseline traffic noise levels were computed using projected 2017 No-Build traffic volume and fleet mix data for automobiles, medium trucks, heavy trucks and buses. Future Build noise levels were then predicted using projected 2017 Build traffic volumes which included the number of delivery and dump trucks associated with the project.

Given the relatively high baseline traffic noise conditions found in the City, it is not surprising that the results indicated an increase of no more than one decibel at any of the receptor locations along the haul routes. These results easily comply with applicable CEQR traffic noise guidelines which allow for an increase of three decibels. As such, people living and working along the haul routes should not notice any increase in traffic noise levels attributable to project-related trucking. Consequently, no impact was predicted in accordance with CEQR guidelines, and therefore construction mobile noise mitigation measures were not necessary.

Table 2. Construction Noise Impacts

Receptor Site No.	Total No. of Months Exceeding CEQR	Total Months with Potential Noise Exceedances	Maximum Noise Results, Leq(h) in dBA					Total No. of Months with Max. Exceedance	Primary Equipment or Phase of Work Causing Maximum Predicted Exceedances
			Ambient Noise	Constr. Noise	Total Noise	CEQR Limit	Exceed-ances		
Weekdays (8:00 AM to 6:00 PM)									
R4	6 months	Jan-15 thru Jun-15	73	74	76	76	1	6 months	Ground-based equipment for building WC-1
R5	55 months	Mar-13 thru Sep-17	68	79	79	71	9	1 months	Ground-based equipment for building WR-2 and WR-3 (including pile driver at WR-3)
Evening/Nights (6:00 PM to 11:00 PM)									
R3	7 months	Apr-15, Aug-16 thru Oct-16, Mar-17, Mar-18, Apr-18	64	68	69	67	2	3 months	Ground-based equipment for building WR-3, WR-4 & WR-6
R4	51 months	Jul-11 thru Feb-13, Nov-13 thru Oct-15, Jul-16 thru Jan-17	67	74	75	70	4	28 months	Ground-based equipment for building WC-1
R5	55 months	Mar-13 thru Sep-17	67	79	79	70	10	1 month	Ground-based equipment for building WR-2 and WR-3 (including pile driver at WR-3)
Weekends (8:00 AM to 4:30 PM)									
R3	1 month	Oct-16	66	68	70	69	1	1 month	Ground-based equipment for building WR-4 and WR-6
R4	62 months	Jul-11 thru Feb-13, Nov-13 thru Oct-15, Jan-16 thru Jun-17	67	74	74	70	5	6 months	Ground-based equipment for building WC-1
R5	41 months	Oct-13 thru Feb-17	71	79	80	74	5	3 months	Ground-based equipment for building WR-2 and WR-3 (including pile driver at WR-3)
R9	15 months	Aug-15 thru Oct-15, Jul-16 thru Mar-17, Sep-17, Dec-17, Jan-18	72	74	76	75	1	15 months	Ground-based equipment for building WC-1, WR-1 & WR-2
R12	5 month	Apr-15, Sep-16, Oct-16, Dec-16, Jan-17	65	66	69	68	1	1 month	Ground-based equipment for building WC-1, WR-1 & WR-4

5. NOISE MITIGATION MEASURES

A. Construction Noise Mitigation

Construction noise mitigation measures are warranted for consideration and inclusion in this project because exceedances of applicable CEQR noise criteria limits were predicted at several receptor locations. However, the anticipated exceedances, of not more than 10 decibels above CEQR limits, can be subjectively described as being minor to moderate in severity.

In general, mitigation measures to reduce construction noise can be applied directly to a noise source, applied along the pathway between the source and receptor, or applied at the receptor itself. Specific construction noise mitigation recommendations for this project included the following listed actions, all of which specifically address the most problematic noise sources revealed through this study.

<u>Pile Driving:</u> Pile driving, however limited in duration, is expected to cause the greatest noise exceedance condition at receptor locations. There are cost, schedule, structural strength and efficiency consequences associated with all of these mitigation measures that the contractor must take into account. Pile driving noise mitigation options include:

- Use of a hydraulic pile pusher system should be considered (such as those offered by Ken-Jet, Giken, or equivalent) if ground and substrata conditions allow.
- Another alternative is to use vibratory pile drivers instead of diesel impact pile drivers.
- Pre-augering or pre-trenching the pile hole to loosen the ground.
- Using a pile cap cushion made of strong rubber or plastic.
- Use a completely alternative method such as slurry walls excavated using a milling machine.

<u>Hoe Rams:</u> Hoe rams are large hydraulically-powered impact chisels that are mounted on the end of a backhoe arm. They are used to break up or demolish large rock or concrete objects so that the pieces can be more easily removed and disposed. While noise mitigation options to reduce noise from hoe rams are somewhat limited in their effectiveness, every effort should be made to reduce hoe ram noise because it can be very loud and annoying. There are cost, schedule and efficiency consequences associated with all of these mitigation measures that must take into account. Hoe ram noise mitigation options include:

- Perform the hoe ram work during less sensitive times of day or night.
- Use as small a hoe ram as possible to accomplish the required work.
- Wrap and enclose the hoe ram head and chisel with a noise shroud (available from the manufacturer) or improvised a shroud in the field made of noise curtain material.
- Use a completely alternative method such as drilling holes in the objects and using hydraulic jacks or chemical agents to split the objects.

<u>Jackhammers:</u> Noise from jackhammers or pavement breakers can be mitigated by any of several very effective means. Jackhammer noise mitigation options include:

- Installing quality exhaust mufflers (such as those offered by Zo-Air, or equivalent).
- Use the jackhammer inside a noise enclosure tent made of heavy vinyl material (such as Sound Seal Model BBC-13-2, or equivalent).
- Use an alternative method for cutting pavement such as a concrete saw or backhoe bucket.

<u>Noise Barriers:</u> Noise barriers will be required around the perimeter of the job site when within 200 feet of receptors in accordance with NYC Construction Noise Regulations. The perimeter barriers must be at least 15 feet tall and provide for an acoustical Sound Transmission Class (STC) of at least 32. If properly installed without any gaps, a noise barrier that breaks the line-of-sight between the noise source and the receptor can reduce noise at the receptor’s location by 5 to 10 decibels.

6. CONSTRUCTION VIBRATION

A. High-Line Vibration Impact

A construction vibration assessment was conducted to evaluate potential structural consequences for the existing elevated High-Line rail structure. The High-Line is a decommissioned eighty year old elevated steel and concrete rail viaduct located along the southern and western sides of the project site. The High-Line structure is expected to remain in place during construction of the project and eventually be turned into an open public park area. Therefore there is concern about the potential adverse affects of construction vibration on this relatively fragile historic structure.

For this task the vibration assessment computed so-called “critical distances”, or the distances within which use of certain construction equipment may be expected to cause damage to the High-Line structure.

For this study an analytical/empirical vibration prediction model was used to estimate the vibration levels that might propagate from high-vibration-producing-equipment such as pile drivers, hoe rams and drills. The model is based on a combination of several previous works including measured equipment vibration emission data from the Federal Transit Administration and the Central Artery/Tunnel Project in Boston, and ground propagation relationships found in Charles Dowding’s reference textbook *Construction Vibrations*. In consultation and agreement with NY City Planning, site-specific vibration measurements were not performed for this project because ambient vibration levels for the non-active structure were not a concern.

B. Vibration Criteria

Several vibration criteria guidelines were considered in this case; all of which were applied as conservatively as possible in order to yield cautious results. The criteria include those published by the *Federal Transit Administration* for minor cosmetic damage of fragile structures, the *Central Artery/Tunnel Project’s Vibration Design Policy* for potential damages to extremely susceptible buildings, and the *Swiss Standard 640-312* which also addresses extremely susceptible buildings. More tolerant damage criteria were also considered, such as those from US Bureau of Mines and New York City.

Vibration levels may be quantified using several different metrics depending on the issue being evaluated. Vibration is mechanical energy in oscillatory motion and can therefore be evaluated in terms of instantaneous (Peak) or average (RMS) acceleration, velocity or displacement. For structures it is most common to evaluate the vibration velocity component. The results can be expressed in units of velocity such as inches per second. The peak particle velocity (PPV) is the preferred metric for evaluating potential damages to structures, and its results are also expressed in units of inches per second. Alternatively, vibration velocity levels can be expressed in decibel units (VdB) where the vibration RMS level is logarithmically compared to a reference velocity level of 1 micro-inch per second. The PPV represents the highest (or worst-case) instantaneous vibration level, and RMS vibration levels expressed in VdB represent a time and energy-averaged vibration level. Therefore potential damages to structures are usually evaluated in terms of PPV whereas the annoyance of vibration as perceived by human beings is usually evaluated in terms of VdB.

As mentioned above there are vibration criteria intended to prevent major structural damage to buildings. These vibration limits are much higher than those used to evaluate minor cosmetic damage or human annoyance. For reference, major structural damage criteria limits of about 1.9 to 2.0 PPV inch/sec are intended to avoid significant damage that could weaken a structure’s integrity. Minor structural damage criteria limits are set much lower and are intended to avoid cosmetic damages such as hair-line cracking of plaster or concrete. Minor structural damage vibration criteria for fragile historic structures ranges from about 0.12 PPV inch/sec for continuous or steady vibration sources, to 0.30 PPV inch/sec for transient or impulsive vibration sources.

C. Vibration Critical Distances

Based on the vibration emission levels produced by certain equipment, the critical distance, or distance (in feet) within which vibration levels might exceed relevant criteria, can be computed. **Table 3** summarizes six typical high-vibration-producing-equipment found on construction sites and provides the computed critical distances for each piece of equipment with respect to major and minor structural damage criteria.

Based on the results shown in **Table 3** it was concluded that vibration impacts to the existing elevated High-Line rail structure could be avoided providing certain high-vibration-producing equipment were not used within the critical distances stated in the table. Thus, jackhammers, drills and clam shell buckets should not be used within 1 to 4 feet of the High-Line, and hoe rams and pile drivers should not be used within 14 to 17 feet of the High-Line, in order to avoid potential major structural damages. More conservatively, jackhammers, drills and clam shell buckets should not be used within 6 to 16 feet of the High-Line, and hoe rams and pile drivers should not be used within 70 to 120 feet of the High-Line, in order to avoid potential minor structural damages.

Table 3. Construction Equipment Vibration Critical Distances for High-Line

Construction Equipment	Reference Vibration Emission Level PPV at 100 feet	Vibration Critical Distance		
		Major Structural Damages	Minor Damages From Impulsive Sources	Minor Damages From Steady Sources
Clam Shovel Drop	0.025 PPV inch/sec	4 feet	15 feet	n/a
Auger Drill Rig	0.011 PPV inch/sec	2 feet	n/a	16 feet
Jackhammer	0.003 PPV inch/sec	1 foot	n/a	6 feet
Mounted Hoe Ram	0.190 PPV inch/sec	17 feet	70 feet	n/a
Vibratory Pile Driver	0.150 PPV inch/sec	14 feet	n/a	120 feet
Impact Pile Driver	0.200 PPV inch/sec	17 feet	73 feet	n/a

D. Vibration Mitigation Measures

In the event high-vibration-producing equipment is to be used in close proximity to the High-Line structure then vibration mitigation options should be considered. Potential vibration mitigation measures for hoe rams might include the use of rock drills combined with hydraulic jack or chemical splitters, or the use of carefully controlled blasting, to demolish large rock or concrete obstacles. Pile driving mitigation options would include the use of a hydraulic pile pushing system, the use of slurry walls dug out by a hydromill, or pre-trenching the piles with a backhoe or water jet.

7. CONCLUSIONS

The assessment of potential noise and vibration levels associated with construction of the Western Rail Yard development in NYC served a valuable purpose to anticipate potentially excessive noise conditions, identify candidate mitigation measures, ensure compliance with CEQR and NYC DEP noise regulations, and allow the project to move forward through the permitting phase. Pertinent lessons learned from the study that may be helpful to other noise practitioners include:

- The Cadna-A noise model served well for prediction of construction noise and allowed for easy alterations to account for ever-changing sequencing over the project’s 102-month duration.
- When loaded with equipment emission levels from the FHWA RCNM model, the Cadna-A model results then had ties to both Federal and City-endorsed construction noise methodologies.
- The CEQR guidelines for construction noise can be somewhat confusing and ambiguous. They should be updated to clarify the approach using more appropriate construction noise criteria.
- Construction-induced vibration is rarely a problem for structures, but fragile and/or historic structures should be evaluated to ensure that damages can be avoided.