ANALYSIS AND ABATEMENT OF HIGHWAY CONSTRUCTION NOISE

October 1981

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16. ABSTRACT

This study investigated the noise associated with highway construction activities. It involved the identification and examination of: highway construction activities, noise characteristics associated with highway construction activities, availability of highway construction noise abatement measures, demonstration of construction site noise abatement measures, and development of a computer-based model for use as a tool to predict the noise impact of construction activities and to plan mitigation measures. The model was developed for use on the FHWA computer (IBM 360).

A total of seven reports were prepared in this study and have been released for public distribution.

This report (Part A) contains all of the information from the engineering study phase of the project. It gives information on highway construction procedures, highway construction site noise characteristics, available abatement measures, and results from field demonstrations of noise abatement.

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FORWARD

This study was jointly sponsored, through an Interagency Agreement (IAG), by the Office of Noise Abatement and Control (ONAC), U.S. Environmental Protection Agency (EPA), and the Federal Highway Administration (FHWA), U.S. Department of Transportation (DOT). The study was conducted by Wyle Laboratories under contract to FHWA Contract No. DOT-FH-11-9455. Wyle Research of El Segundo, California, and Wyle Research of Arlington, Virginia, performed the study.

The object of the study was to investigate and study the noise associated with highway construction activities. The study involved the identification and examination of: highway construction activities, noise characteristics associated with highway construction activities, availability of highway construction noise abatement measures, demonstration of construction site noise abatement measures, and development of a computer-based model for use as a tool to predict the noise impact of construction activities and to plan mitigation measures. The model was developed for use on the FHWA computer (IBM 360).

The principal project officers for Wyle Laboratories on this project were Mr. William Fuller of Wyle Research in El Segundo and Dr. Kenneth Plotkin of Wyle Research of Arlington, Virginia.

The government project managers for the study were Mr. Fred Romano of FHWA, and Mr. Roger Heymann of EPA/ONAC.

The various technical reports completed by Wyle under this contract and submitted to FHWA have been released for public distribution by EPA.

PREFACE

This study involved a comprehensive review of the environmental noise associated with highway construction activities. A total of seven reports have been released for public distribution. These reports are:

1. Analysis and Abatement of Highway Construction Noise, EPA 550/9-81-314-A, September 1981.
2. A Model for the Prediction of Highway Construction Noise, EPA 550/9-81-314-B, September 1981.
3. IBM 360/System Batch Version of Highway Construction Noise Model, EPA 550/9-81-314-C, September 1981.
4. Appendix A, Highway Construction Noise Field Measurements, Site 1: I-201 (California), EPA 550/9-81-314-D, September 1981.
5. Appendix B, Highway Construction Noise Field Measurements, Site 2: I-205 (Oregon), EPA 550/9-81-314-E, September 1981.
6. Appendix C, Highway Construction Noise Field Measurements, Site 3: I-95/I-395 (Maryland), EPA 550/9-81-314-F, September 1981.
7. Appendix D, Highway Construction Noise Field Measurements, Site 4: I-75 (Florida), EPA 550/9-81-314-G, September 1981.

The first two reports (Part A and Part B) might be considered the principal reports since they are relatively self-contained units on this study's efforts, the engineering studies and the computer model, respectively. In this regard, if there is to be a limited purchase of the reports, one might consider obtaining either or both of Part A and Part B, and obtaining the other reports as additional informational needs arise.

- The first report (Part A) contains all of the information from the engineering study phase of the project. It gives information on highway construction procedures, highway construction site noise characteristics, available abatement measures, and results from field demonstrations on noise abatement.

- The second report (Part B) presents a complete description of the highway noise prediction model. The report contains a description of the model's formulation and construction, a description of the program, and a user's manual.

- The third report (Part C) provides additional information to the Part B report on the highway construction noise model installed at DOT's Transportation Computer Center on an IBM 360 computer. It delineates the differences between the version of the model as installed on the IBM 360 and the two models (HINPUT and HICNOM) operating on the Wyle Computer (PDP-11). The report has additional user's manual information for use on the IBM 360, a programmer's manual describing changes in going from the PDP-11 to the IBM 360, and a maintenance manual.

- Reports 4, 5, 6, and 7 (Part D through Part G) contain field data gathered at the field demonstrations at highway construction sites in: Route I-201, California; I-205, Oregon; I-95/I-395, Maryland; and I-75, Florida. They contain noise data on single and multiple pieces of equipment, provide general description of highway site activities, and activity analyses of equipment.

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1.0 EXECUTIVE SUMMARY

This report documents the results of a program aimed at analysis and abatement of highway construction noise. Primary objectives of the study were:

1. Development of a highway construction noise model, and validation of that model using data acquired through field measurements.
2. Evaluation of all feasible construction noise abatement measures, and demonstration of a selected number of these under in-situ conditions.

A detailed description of the resulting highway construction prediction model is presented in Wyle Research Report WR 80-58. Discussion of all other pertinent technical results is presented in this report.

Examination and analysis of construction site noise characteristics is facilitated by specifically defining highway types, construction procedures and phases, and construction equipment. While four distinct types of highways can be identified, attention in this study was focused on those classified as major arterials (i.e., high-speed, high traffic density, limited access highways), as these represent the most complex of highway construction projects.

Previous studies have shown that variations in construction site noise levels are more pronounced between phases rather than types of highway construction, this due to the fact that construction equipment, the dominant source of noise on site, will vary with phase, but typically will not vary much with the type of highway construction. Therefore, construction phases represent the most feasible classification of highway construction site noise. The specific phases have been identified as:

<u>Highway Construction</u>

- Mobilization
- Cleaning and grubbing
- Demolition and removal
- Earthwork
- Paving and shoulders
- Signing, finishing, and cleanup

<u>Bridge Construction</u>

- Mobilization
- Clearing and grubbing
- Demolition and removal
- Structural excavation

- Foundation support
- Substructure construction
- Earthwork
- Superstructure construction
- Bridge details, finishing, and cleanup

Construction site noise characteristics may also be influenced directly or indirectly by such factors as geology, terrain, climate, and demography. No attempt was made, however, to assess directly the impact of these site variables on construction site noise.

As mentioned previously, construction equipment represents the primary noise source on site. Such equipment are best represented by two general categories: (1) medium to heavy equipment utilizing an internal combustion engine, and (2) impact equipment and power tools utilizing pneumatic, hydraulic, electric, or small gasoline engines as a power sources. Further, the medium/heavy equipment is best classified in terms of mobility (i.e., mobile, quasi-mobile, and stationary), as mobility is quite important in describing a construction task and the noise generated by it. Impact equipment and power tools encompass machinery which are stationary as well as tools which are hand-held and, for the most part, stationary.

A thorough review of the literature revealed that the ground clearing and earthwork phases are the noisiest periods during highway construction, while the foundation support and earthwork present the most significant noise-producing activities associated with bridge construction. While little data exists on construction site boundary noise levels, that data which was compiled suggests a wide range of noise levels within most phases of construction. This appears primarily due to variations in site terrain, machinery operating characteristics, and construction work cycles.

Extensive research has verified that medium and heavy construction equipment utilizing an internal combustion engine will exhibit seven primary noise-producing components: fan, exhaust, engine casing, air intake, transmission, hydraulic, and track. Fan and exhaust noise typically account for 85 to 100 percent of the noise produced by medium/heavy construction equipment, depending on general machinery condition and the mode of operation.

Primary noise sources on impact equipment are (1) exhaust of air to the atmosphere, (2) casing noise resulting from impact of piston-hammer impact, and (3) ringing noise from chisel impact on a rigid surface. Primary noise sources for power tools will vary with equipment size and function. Review of the literature suggests that analysis and abatement of hand-held power tool noise has been very limited.

Careful review of existing literature also resulted in compilation of noise level data for 912 individual pieces of equipment representing 19 distinct categories of construction machinery. Comparison of mean values of equipment noise levels in each category reveals impact equipment (pile drivers and rock drills) produce the highest levels, followed closely by highly mobile heavy equipment powered by internal combustion engines (scrapers and trucks). Regression analyses performed to assess the relationship between sound level and engine horsepower indicate only fair agreement.

To supplement the existing data base on construction site noise, a series of extensive field measurements were performed at four major highway construction sites:

- I-210 (California)
- I-205 (Oregon)
- I-95/I-395 (Maryland)
- I-75 (Florida)

On-site inspection of numerous candidate construction sites was performed prior to final selection of the above four sites. These sites were selected to provide representative examples of all key construction phases and procedures under varying site conditions. A discussion of the site selection criteria, and a brief description of each field site, is presented in this report.

Uniform procedures were established for measuring construction noise levels and equipment operating modes. The following types of measurements were performed:

1. Controlled single equipment noise levels
2. Single equipment task operating noise levels
3. Activity perimeter noise levels
4. Site boundary noise levels
5. Community noise levels
6. Construction noise propagation

To supplement these noise measurements, equipment duty cycles and elements of the duty cycle were timed and evaluated. Activities involving multiple pieces of equipment were filmed for later evaluation of duty cycles.

An in-depth review of the literature has revealed that while many potential construction noise abatement techniques have been previously identified, actual implementation and evaluation of these techniques has been limited, thereby limiting the amount of data on acoustical and cost effectiveness of each treatment. Still, the literature does provide sufficient information to define each potential abatement treatment and evaluate its relative effectiveness.

Five categories of abatement measures have been identified:

1. Construction Equipment Noise Control – reduction of source noise levels through modification of new equipment designs, or retrofitting of existing on-site equipments; includes equipment utilizing an internal combustion engine as well as impact and power tools.
2. Construction Site Noise Control – utilization of sound path modification methods and preferred positioning of equipment to reduce site noise emissions.
3. Construction Strategy Modifications – adoption of alternative construction processes, operational techniques, or scheduling procedures in order to minimize noise impact.
4. Noise Control Incentives – use of contractual incentives to gain contractor cooperation in reducing site noise levels.
5. Community Relations – minimization of the impact of unavoidable noise through the maintenance of good public relations.

Reduction of noise from medium/heavy equipment has received the most attention in the literature, as these represent the dominant sources on most construction sites. Considerable research in both Europe and the United States has led to numerous recommendations for control of primary noise sources on equipment using an internal combustion engine. However, little insight is provided into what currently exists in terms of new equipment design or retrofit noise reduction technology on construction equipment. Except for many of the latest models of construction machinery, off-the-shelf component noise abatement hardware is very limited at this time. Of the two major sources of noise (fan and exhaust) on medium/heavy equipment, retrofit of the exhaust is a relatively straightforward process. However, fan noise reduction is an engineering problem which generally cannot be resolved through on-site retrofitting of existing equipment. The five remaining component noise sources (engine casing, air intake, transmission, hydraulic, and track) tend to rank as secondary; reduction of these sources is not necessary until the primary noise sources (fan and exhaust) have been reduced significantly.

Considerably less attention has been paid to noise reduction techniques for impact equipment and power tools. With respect to breakers and rock drills, noise control methods are currently limited to mufflers for pneumatic tools, and damped moils for portable breakers. Their combined use has been shown to provide a 12 dB reduction in noise for a portable breaker. However, these abatement techniques can lead to reduced operator efficiency. This may help to account for their limited use at present.

Alternative designs of quieted pile drivers have been developed and evaluated, primarily in the United Kingdom. However, it appears very difficult to achieve a reduction in pile-driving noise in excess of 10 dB. Little indication is provided as to the current availability and application of quiet pile drivers in the U.S.

Construction site noise controls can be effective abatement tools in areas where noise exposure is confined to a small area. Techniques such as sound barriers, earth berms, equipment enclosures, equipment relocation, and site maintenance are cited as feasible site noise control methods. Both the benefits and restrictions associated with these abatement techniques are discussed in this report.

Construction strategy modifications essentially include equipment substitution and task rescheduling. Equipment substitution encompasses several alternative strategies, although actual implementation of these strategies may be hampered by reduced operating efficiency and increased costs. Examples demonstrating the feasibility and effectiveness of strategy modifications as a noise abatement tool were not found in the literature.

Noise control incentives include: (1) equipment and/or noise specifications included in the project bid documents; (2) extended working hours for those contractors complying with lower site noise levels; and (3) bonuses for those contractors who maintain lower site noise levels. Specific examples in the literature of their application were not identified.

Community relations represents a simple, cost-effective tool which should be employed in unison with necessary physical abatement methods to minimize construction noise impact.

Physical demonstration of four construction noise abatement methods were performed in order to better understand the benefits and limitations associated with implementing such techniques. Information on the acoustical and cost effectiveness of each abatement methods was compiled and evaluated.

Two demonstrations involving equipment substitution were performed at the I-95/I-395 site. First, a portable breaker with an exhaust muffler was substituted for the identical type of breaker having no muffler. An 11 dB reduction in noise level (measured at 50 feet) was achieved with little or no additional impedance in the operation of the tool.

A similar demonstration was performed in which a portable air compressor meeting the EPA noise emission standard was substituted for an older compressor of equivalent size. With the quiet compressor operating in its recommended configuration, a 19 dB reduction (measured at 50 feet) was achieved. There was no change in the operating efficiency as a result of introducing the quieted compressor.

To demonstrate the effectiveness of off-the-shelf retrofit techniques, new mufflers were introduced onto the exhaust systems of three pieces of heavy-duty construction equipment – two track dozers and one scraper. The noise reduction achieved ranged from 2 to 4 dB, the highest value being for a dozer originally equipped with a straight stack. The fact that the noise reduction was limited to a maximum of 4 dB indicates that the engine and/or fan is a significant contributor to the overall equipment noise level.

The final demonstration consisted of the fabrication and installation of a simple enclosure for a well point pump located near the boundary of a construction noise site. The enclosure was representative of a noise abatement device that could be installed easily and quickly by on-site personnel, and provided a reduction of 7 dB in nearby noise levels.

2.0 HIGHWAY CONSTRUCTION CHARACTERISTICS

Highway construction site noise may cause significant adverse effects to either equipment operators or the surrounding community.[19] High noise levels of both heavy machinery and power tools, together with unusual spectral and temporal characteristics, make the highway construction process a potentially annoying source of noise.[14,77]

Highway construction noise is characterized by noise levels significantly above residual levels for time periods ranging from a few hours (for minor street repair) to many months (for major new highway construction).[58] Further, the noise generated during a highway construction project can vary substantially from site to site based upon type and mix of equipment and the construction procedures employed.

Construction site noise levels are greatly influenced by the type of highway to be constructed. Highways are typically categorized according to their functional classification:*

- Major arterial (including interstates)
- Minor arterial
- Collector
- Local

Each of these classifications can be further subdivided according to whether the highway is constructed in an urban or rural environment. For the purposes of this study, attention is focused on major arterials located in urban/suburban areas where the major community exposure is likely to occur.[91] This type of highway is best typified as a high-speed, high traffic density, controlled access highway. Cross traffic is routed above or below by way of overpass or underpass grade separations, thereby signifying construction of bridges or tunnels. Observing that an urban major arterial rarely follows the lay of the land, a sizable amount of cut and fill earthmoving is typically necessary. In all, the major arterial represents the most complex of highway construction projects.

It is important to note that within the general classification of "highway construction" there exist several types of construction projects, each exhibiting its own set of characteristics. Specifically, this would include:**

1. New construction
2. Reconstruction and widening

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* DeLeuw, Cather and Co., "Definition of Typical Highway Types", Working Paper No. 1, prepared for Wyle Research under Task B, Contract No. DOT-FH-11-9455, 1978.

** DeLeuw, Cather and Co., "Definition of Highway and Bridge Construction Phases," Working Paper No. 2, prepared for Wyle Research under Task B, Contract No. DOT-FH-11-9455, 1979.

3. Rehabilitation
4. Repair and maintenance

New construction implies development of a highway along a right-of-way over which a highway previously did not exist. New highway construction represents the most complex, intense, and lengthy of all the construction types.

Reconstruction begins with demolition and removal of an existing road and concludes with the in-situ replacement by a new road – subgrade through pavement. Earthwork may be substantial depending upon the particular project details. Therefore, while the duration of a reconstruction project may be less than that for new construction, site noise levels during construction may be quite similar, except for the demolition aspect of reconstruction.[77]

Widening represents an increase in the paved width of an existing road, thereby resulting in additional traffic lanes. Sometimes in anticipation of expansion, initial construction of a highway will include extra-wide graded shoulders or extra-wide median strips, in which case little or no earthmoving is necessary when widening occurs. Many widening projects occur concurrently with reconstruction or rehabilitation of the existing road. Whatever the circumstances, traffic on the existing road will likely be disturbed by the closure of some lanes or by the establishment of detours. Note also that in most instances the highway traffic initially controls the ambient noise level at the construction site. Maintenance of construction noise levels below traffic noise levels would be highly advantageous.

Rehabilitation entails a comprehensive maintenance and repair of an existing road. Resurfacing, sealing, surface planing, recaulking of joints, and limited pavement replacement are part of the rehabilitation job. These operations are typically less noise intensive than other types of construction. Regardless, rehabilitation can generate adverse noise exposure and thus deserves some scrutiny.

Repair and maintenance represent comparatively minor construction activities of relatively short durations. Noise impact associated with such construction is considered minimal.

Construction site characteristics which can influence, directly or indirectly, highway construction activities and their associated noise levels include geology, terrain, climate, and demography. Geology affects functions of soil mechanics such as blasting, ripping, foundation, compaction, dewatering, and swell and shrinkage of bank yardage. Terrain may influence choice of highway alignment and the need for major structures (e.g., bridges and tunnels), and will determine the degree of earthwork necessary. Harsh climatic conditions seasonally constrain construction activities in many areas of the nation, thus influencing both construction procedures and construction scheduling. Demography as reflected by the extent of existing development, and possibly even by type of development and socio-economic complexion of a neighborhood, may also influence the contractor's choice of construction procedures used to perform various tasks. It should be noted that the literature provides no indication of the effect which these parameters might have on noise levels at a highway construction site.

2.1 Highway Construction Procedures

The construction process represents the final determinant of equipment needs. In general, a construction project may be divided into several distinct phases, defined and discussed in several documents.[13,14,19,29,102] It has been shown that the differences in noise levels are more pronounced between phases of construction than types of construction.[13,14] The probable reason for this lies in the fact that equipment types and operations are typically what define a phase, and these are reasonably constant regardless of project type. Therefore, while the average noise generated per phase will vary significantly from site to site, division of a construction project into phases represents the most feasible method for evaluating changes in noise over time.

A highway construction project generally consists of construction of both highway and bridge structures. Although some of the phases found in highway construction are also found in bridge construction, the two processes vary significantly enough to warrant individual definition of their specific construction phases. The specific phases are listed below:*

Highway Construction

- Mobilization
- Cleaning and grubbing
- Demolition and removal
- Earthwork
- Paving and shoulders
- Signing, finishing, and cleanup

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* DeLeuw, Cather and Co., "Definition of Highway and Bridge Construction Phases," Working Paper No. 2, prepared for Wyle Research under Task B, Contract No. DOT-FH-11-9455, 1979.

Bridge Construction

- Mobilization
- Clearing and grubbing
- Demolition and removal
- Structural Excavation
- Foundation support
- Substructure construction
- Earthwork
- Superstructure construction
- Bridge details, finishing and cleanup

A brief description of each phase is provided below.

2.1.1 Highway Construction Phases

Mobilization

The mobilization phase includes such operations as preparation of contractor's yards, setting up offices and storage sheds, hauling equipment, hauling and stockpiling materials and building shops and plants as required for proper initiation of sitework. Trucks, dozers, graders, and forklifts are typically present during this phase.

Clearing and Grubbing

The clearing and grubbing phase includes clearing away of trees, bushes, stumps, roots and boulders, shaving off of topsoil for disposal or stockpile, and relocation of minor utilities.[114] Equipment present during this phase may include bulldozers, loaders, backhoes, explosives, chain saws, and dump trucks.[89,109,119]

Demolition and Removal Phase

The demolition and removal phase includes destruction and removal of existing bridges, roadways, and buildings when necessary from the design alignment.[19] It can also include blasting and/or removal of large existing foundations and relocation of utilities. Equipment can include paving breakers, explosives, dozers, hand power tools, loaders, heavy-duty dump trucks, and crane and wrecking ball.[19,89]

Earthwork

Cut, fill, and haul characterize the earthwork phase. Loaders, dozers, scrapers, motor-graders, shovels, trenchers, backhoes, and dump trucks are some of the major pieces of machinery which excavate, transport and deposit soil. Before rock can be moved it must be ripped, hammered, or blasted into material of manageable sizes such that excavation machinery can proceed. The goal of the earthwork phase is to contour the land to the elevations called for in the construction plans. This is the most time-consuming phase. The machines perform activities in more or less spatially and temporally repetitive patterns over wide ranges of the site. This results in cyclically fluctuating noise levels at the site boundary.

Paving and Shoulders

The paving and shoulder phase includes construction of bituminous or concrete pavements and adjoining shoulders, and finishing of pavement surfaces.[114,126] Typical equipment types include pavers, concrete transport trucks, dump trucks, loaders, dozers, and compactors. Construction of bituminous pavements may also require spreaders, screed heating systems, and rollers. Batch plants, spreaders, finishing machines, vibrators, screeds, and concrete saws may be used in construction of concrete pavements.[89]

Signing, Finishing and Cleanup

Signs, pavement striping and markers, lighting, guard rails, etc., are installed during this phase. In addition, all necessary cleanup is performed and landscaping is typically completed at this time. Relatively light, low-noise machinery is utilized during this phase.

2.1.2 Bridge Construction Phases

Several of the phases associated with bridge construction are similar in description to those found in highway construction. However, a few differ significantly enough to warrant discussion here.

Structural Excavation

This-phase involves excavation of materials necessary to enable construction of footings for abutments and piers. The extent of this phase depends largely on the type of materials to be excavated. Structural excavation is not typically carried out in a continuous operation but in coordination with other operations such as construction of foundation supports, formwork erection, and concrete placement.

Foundation Support

The foundation support phase consists of the preparation of subgrade to receive the footings of the bridge structure. This may include the job of driving piles, drilling holes for piles or caissons, or simply the clearing and compaction of the subgrade in the case of spread footings. Pile drivers, crawler or truck-mounted cranes, rubber-tired compactors, tampers, and pumps are typically used during this phase.

Substructure Construction

Construction of piers and abutments occur during this phase. Piers and abutments are usually built of reinforced concrete, although steel and precast concrete are sometimes used. Small cranes and mobile hoists, as well as numerous power tools (saws, drills, etc.) are utilized during this phase.

Earthwork

Earthwork associated with bridge construction consists of the construction of approach fills when the bridge is above the existing groundline. Approach embankments may be built using material excavated from cuts near the bridge site, from commercial pits, or from borrow pits. Some subsoils experience large settlements when subjected to the weight of approach fills, thus requiring placement of the final layers of fills several months after construction of the initial embankment. Dozers, dump trucks, compactors, and graders are generally used to perform this phase.

Superstructure Construction

This phase generally consists of shoring, erection, construction and placement of formwork, placement of reinforcement, transportation and placement of concrete, removal of falsework and shoring, and erection of girders. The specific methods utilized are highly dependent upon the actual type of bridge structure under construction. Cranes, welding machines, concrete trucks, immersible vibrators, and various power tools will be in use during this phase.

Bridge Details, Finishing and Cleanup

Bridge detailing will include installation of parapets and handrails, construction of concrete approach slabs, painting of metals, and treatment of concrete surfaces. Finishing and cleanup are quite similar to those described for highway construction. Light, low noise machinery is generally used during this phase.

2.1.3 Details of the Earthwork Phase

Because of its comparatively long duration and the high concentration of heavy machinery, the earthwork phase is typically the most crucial in terms of total noise exposure from the highway construction project. For this reason, earthwork is the most thoroughly documented construction phase, with a majority of the research originating from the Transport and Road Research Laboratory.[77,78,79,80]

The earthwork phase of a highway construction project involves the transport of soil from some locations to others in order to bring the vertical alignment of the site topography into compliance with the design specifications of the highway plans.[19,79,114] Earthwork generally consists of three primary operations: cut, haul, and fill. Cut involves excavation and removal of soil from a given area. Soil sometimes is pushed but most often is loaded and carried from the cut area. The process of transporting the material is termed the haul operation. Transport occurs on a haul road which connects the cut area with a fill area. The fill operation involves unloading of the material, compaction and finish grading. Note that the haul road normally follows the alignment of the planned highway. As work progresses at the cut and fill areas, the location of the cut and fill operations will gradually shift spatially, thereby varying the length and alignment of the haul road.[93]

Earthmoving operations are most commonly performed by motorized scrapers, belly dumps, loaders, and bulldozers.[19,77,78,79,89] Soil conditions, soil composition, and the cut-to-fill distance determine the types of machinery used. There are three basic methods used to perform earthwork. Rubber-tired scrapers assisted by tracked dozers in cut and fill may be used for medium distances up to perhaps two miles.[78] The motorized scraper operates along the line of the planned highway alignment, loading with cuts of 30 to 60 meters in length. The intensity of a scraping operation is primarily dependent upon the length of the haul and the number of scrapers utilized. In cutting operations, a tracked dozer will generally assist a scraper, except in light soils. Following the scrape operation in the cut area, the load is hauled by the scraper to the fill area where the material is dumped and spread evenly over fill terrain. This soil is then compacted and eventually finish graded.[77]

For haul distances over approximately 3,500 feet, a dump truck or belly dump is preferred over scrapers. Use of a truck in cut areas requires the assistance of a front-end loader. Instead of shaving off a thin layer of soil over a large area as does a scraper, a loader-dump truck operation progresses slowly over the area, making deep cuts in concentrated areas. A bulldozer is often used to rip hard soil and deliver soil to the loader to minimize loader movement, thereby increasing the efficiency of the cut process. The truck then transports its load over a haul road to a fill area where the soil is dumped, spread by a dozer and compacted, as is scraper fill.[77]

The third method used to perform earthwork involves a scraper towed by a tracked dozer. Because a dozer moves relatively slowly, this alternative can be used efficiently for short hauls only. Sometimes this method is utilized when a plan calls for the shoving off of topsoil, followed by its storage close by for use later in the earthwork phase.

Earthwork maneuvers are repeated cyclically, during which each apparatus, i.e., scraper, truck, loader, dozer, performs a number of activities.[93]

In areas of deep excavation (as is often encountered in urban settings) cut may penetrate the water table. In these circumstances dewatering equipment such as pumps, and vertical risers and wellpoints (1¼- to 2½-inch pipe with slots for water to enter) are installed.

2.2 Highway Construction Equipment

Equipment operating on a highway construction site comprise the primary source of noise. Virtually all noise, save human sounds, PA systems, or other activities such as the movement of materials and blasting, can be attributed to the equipment. The sections which follow provide a description of equipment typically found on a highway construction site, including an analysis of their general noise characteristics.

2.2.1 Classification of Construction Equipment

Contained within the general classification of highway construction equipment are a large variety of types serving many special needs, both in function and size. Two major categories of equipment exist: (1) medium to heavy equipment utilizing an internal combustion engine, and (2) impact equipment and power tools utilizing pneumatic, hydraulic, electric, or small gasoline engines as a power source.

Medium/Heavy Equipment

Within the category of medium to heavy equipment are mobile, quasi-mobile, and stationary equipment. This consideration of equipment mobility is important when describing a construction task and the noise generated. Although other features such as function, size, and power are also important, the mobility aspect is paramount.

Each highway construction phase requires a specific mix of equipment, and while many mix variations are possible, the degree of equipment mobility is dictated by the required tasks and the site geometry. Equipment mobility requirements, for the most part, relate to extent or size of the phase site. For instance, the earthwork phase of highway construction generally requires highly mobile equipment, while construction of bridge structures utilizes mostly quasi-mobile and stationary equipment. The categories of mobility and the equipment contained within each are:

- Highly Mobile Equipment
  - Dozers and crawler tractors
  - Scrapers
  - Loaders
  - Excavators
  - Graders
  - Rollers and Compactors
  - Pavers
  - Trucks
  - Off-highway haulers
- Quasi-Mobile Equipment
  - Cranes and shovels
  - Cableways
  - Trenchers
  - Concrete Mixers
  - Pavement cutters and breakers
- Stationary Equipment
  - Pile drivers
  - Compressors
  - Welders
  - Pumps
  - Generators
  - Concrete/Asphalt Batching Plants
  - Drilling Rigs

Two types of medium/heavy construction equipment, namely, air compressors and medium- and heavy-duty trucks, are affected by federal noise emission standards. Portable air compressor noise emission standards, promulgated in 1976, stipulate the following:

a. All portable air compressors manufactured after January 1, 1978, and having a capacity of 250 cubic feet per minute (cfm) or less, must not produce an average A-weighted sound level in excess of 76 dBA, when measured at 7 meters from the compressor.

b. All portable air compressors manufactured after July 1, 1978, and having a capacity of greater than 250 cfm must not produce an average A-weighted sound level in excess of 78 dBA when measured at a distance 7 meters.

The federal noise emission standard affecting new medium and heavy duty trucks stipulates that all trucks manufactured after January 1, 1978 having a gross vehicle weight rating in excess of 10,000 pounds must exhibit noise levels below 83 dBA measured at 15.2m (50 feet) when operated under low speed, full throttle acceleration conditions.

Further insight into the background of these noise emission standards is provided in References 129, 130, and 147.

Impact Equipment and Power Tools

The second category of equipment includes impact equipment as well as other hand-held tools. Construction equipment generating noise which contains high-intensity, short-duration impacts may be identified as:[13,123]

- Pile drivers
- Pavement breakers
- Rock drills (jackhammers)

Hand-held power tools used during construction will generally include:

- Pneumatic or electric rotary equipment (drills, grinders, nut runners, etc.)
- Circular or chain saws.

Another special class of noise generation on a construction site which does not directly involve the use of equipment is blasting. In some cases, blasting can create serious problems for nearby neighbors, both from noise propagated through the air and from ground vibration.[112] In areas where heavy earthwork is required, blasting can be a common phenomena on the construction site.

3.0 HIGHWAY CONSTRUCTION SITE NOISE CHARACTERISTICS

Considerable data on construction site noise characteristics have been identified and assembled from the literature. This information is presented here in three sections. First, data describing overall construction site noise characteristics, including descriptions of individual construction phases, is presented in Section 3.1. Second, information describing the noise characteristics of medium/heavy-duty construction equipment and impact and power tools is summarized in Sections 3.2 and 3.3. Finally, key construction equipment noise levels distilled from the literature are compiled and reviewed in Section 3.4.

To supplement noise data derived from the literature, and to obtain equipment operation details, a series of extensive field measurements were performed at four major highway construction sites. A description of the test sites and test procedures, and a summary of the resulting noise data, is presented in Section 3.5.

3.1 Construction Site Noise Characteristics

Based upon information derived from the literature, it is apparent that the earthwork and ground-clearing phases represent the noisiest periods during highway construction.[13,14,66,87,88] From the above references, it is also apparent that pile-driving activities during the foundation support phase, together with earthwork, represent the most significant noise-producing activities associated with bridge construction.

Little in the way of construction site boundary noise measurements are presented in the literature. Rank, et al.,[105] present overall boundary noise level measurements for various types of construction sites, as summarized here in Table 1. Five distinct types of construction projects are included in this data. Note that the site designated as "Public Works" is the I-66 highway construction site in Falls Church, Virginia.

Data published by EPA[13] in 1971 present typical ranges of noise levels at construction sites (Table 2). This body of data appears to corroborate previous comments regarding the importance of the earthwork (excavation) and foundation (pile driving) activities with respect to noise output. It is questionable, however, whether the absolute levels indicated in Table 2 are representative of noise levels found at construction sites today.

The sound level measured at the site boundary during any construction phase is dependent upon both site characteristics and machinery characteristics. Martin and Solani[77] found that for the earthwork phase these levels were less dependent upon differences between cut and fill operations than upon the manner in which the machinery

Table 1

Boundary Noise Levels For Various Construction Sites
(Reference 105)

Site Type	Noise Level Range at Boundary (dBA)	Dominant Noise Sources
Public Works	60-94	Scrapers, Dump Trucks, Watering Truck, Grader
Non-residential	62-92	Crawler Tractor, Arc Welders, Jack Hammer, Derrick Crane, Excavator, Saws, Back-up Alarm
Non-residential	69-82	Arc Welders, Derrick & Mobile Crane, Crawler Tractors, Back-up Alarm, Hammering, General Activity
Non-residential	64-94	Pile Driver, Derrick Crane, Saws
Residential	66-78	Crawler Tractor, Excavator, Saws, Carpentry Work
Residential	64-82	Concrete Truck
Industrial/commercial	64-84	Scraper, Arc Welders
Industrial/commercial	62-83	Wheeled Loader, Crawler Tractor, Scraper, Excavator
Industrial/commercial	62-92	Vibratory Roller, Grader, Concrete Truck
Residential	60-74	Concrete truck, Cement Mixers Small pump, Saws, Crawler Tractor, Carpentry Work, General Activity
Residential	74-78	Backhoe Loader, General Activity

Table 2

Typical Ranges of Noise Levels at Construction Sites in Urban Areas
(Reference 13)

	Domestic Housing		Office Building, Hotel, Hospital School, Public Works		Industrial, Parking Garage, Religious, Amusement & Recreations, Store, Service Station		Public Works Roads & Highways, Sewers, and Trenches	
	I	II	I	II	I	II	I	II
Ground Clearing	84	83	84	84	84	87	84	84
Excavation	88	76	89	79	89	74	89	79
Foundations	81	81	78	78	78	78	88	88
Erection	82	71	85	76	85	74	79	79
Finishing	88	74	89	76	89	75	84	84

I - All pertinent equipment present at site.
II - Minimum required equipment present at site.

is used in performing its operation. For example, in the cut area, scrapers and dozers contribute equally to the average noise level exhibited during a scraper cut operation. However, in the fill area, the scraper is operated in a drive-by mode as it releases its load. Thus the average noise level in the fill area is most influenced by the compactor operating in a relatively concentrated area over long periods of time.

Martin and Solani[77] determined that, to varying degrees, the cycle rate of a given earthwork operation will influence construction noise levels. One-hour L_{eq} values were found to be a function of (1) the haul machinery flow rate, and (2) the machinery type. Empirical data revealed a correlation between the construction site L_{eq} and the scraper flow rate. This would suggest that a reduction in scraper activity represents a potential method for reducing site noise levels. However, it is important to note that the relationship is logarithmic and hence the reduction in L_{eq} is proportional to the logarithm of the fractional change in flow rate.

Noise propagation at a site changes as excavation and fill operations change the terrain. A cut even a few meters deep may be sufficient to provide a partial noise barrier between the earthwork activity and a nearby community. The deeper a cut, the greater the expected attenuation. Equipment position and bank edge shape are two additional influences on attenuation.

Duration of operation plays a role in noise contribution. Compared to the total earthwork operation period, the duration of a cut or fill activity at a single location within the cut or fill area is relatively short, while the less noisy haul road activity is continuous between those areas. As a result, the cut or fill operation may cause less of a disturbance than haul road activity.[78]

Trucks moving to and from the site on haul roads exhibit a cycle of five segments:[29]

- Entering the site:
  1. constant speed (approaching)
  2. deceleration (approaching)
- Departing to empty load:
  3. idle (loading)
  4. acceleration (departing)
  5. constant speed (departing).

The site L_{eq} depends upon the amount of time the truck operates in each mode, and the truck noise characteristics in each mode. Haul road noise can be sufficiently modeled using the similarities which exist between haul roads and highways.[78]

In summary, little effort has been expended to date in attempting to characterize highway construction site noise levels per phase. Attention has been focused upon the earthwork phase as this represents the most intense of all phases. Data relating to other phases of construction appear too old to be of much relevance today.

3.2 Noise Characteristics of Medium/Heavy Construction Equipment

Most highway construction equipment is powered by internal combustion engines, with the diesel engine being the primary source of noise.[7,31] A great deal of information on the noise characteristics of the diesel engine is presented in the literature. Most medium and heavy construction utilizing the diesel engine will exhibit seven primary noise producing components:[127]

- Fan
- Exhaust
- Engine casing
- Air intake
- Transmission
- Hydraulics
- Track (for crawler tractors and other track-mounted equipment)

Figure 1 shows the relative contribution of component noise sources to the overall exterior noise level of a typical rubber-tired front-end loader.[107] Stephenson, et al.,[122] state that the relative contribution of component sources to total vehicle noise on one stationary wheeled loader are as follows:

Fan	70%
Exhaust	25%
Other Sources	5%
	100%

When the equipment is moving, the relative contributions are:

Fan	50%
Exhaust	35%
Engine Transmission Induction Chassis	15%
	100%

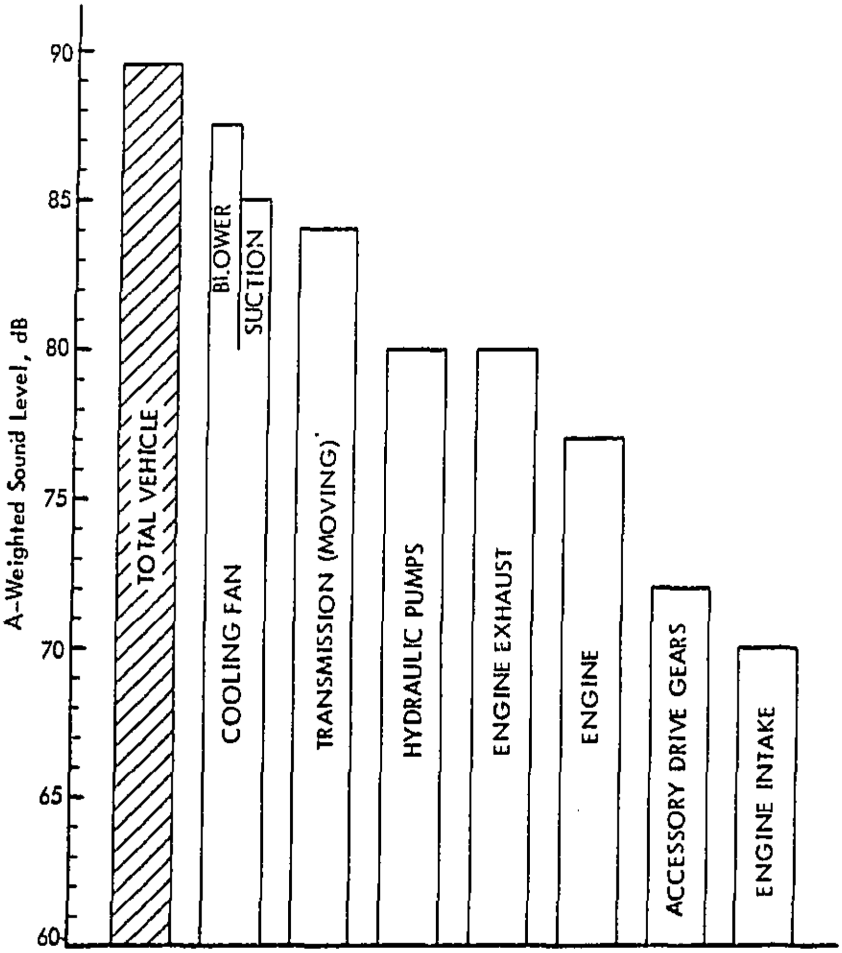


Figure 1. Relative Sound Level of Source Components
At an Exterior Position (Reference 107).

These data show that a stationary noise test accentuates the contribution of fan noise. Clearly, the fan represents the most critical noise source, with exhaust noise second in importance. Further discussion of each noise source is given below.

Fan Noise

References 6, 64, 127, and 139 provide useful insight into fan noise, which is generally classified as (1) discrete or pure-tone noise, and (2) broadband noise. Discrete frequency noise originates as a result of periodic fluctuations in air pressure each time a blade passes a fixed point. These pure-tone noise levels generally occur at integral multiples of the blade passage frequency. Further, these tones are enhanced when obstructions are located in the air stream, causing disturbances in the flow field.

Broadband noise is generated as a result of turbulent flow created by the presence of the fan blade.[6,127] The broadband spectra are related to force fluctuations that are random in time, consistent with turbulent flow.[6]

The literature further indicates that the principal factors affecting fan noise include:[6,127,139]

1. Periodic pressure field caused by the fan blades
2. Inflow distortion
3. Inflow turbulence caused by engine blockage of the air flow field
4. Boundary layer separation caused by flow separation along the blade
5. Vortex shedding along the blade edge
6. Vibration caused by aerodynamic loading

Fan noise is known to vary with the fifth power of speed and the seventh power of diameter.[6] Thus ΔL changes in A-weighted sound levels associated with changes in fan speed or diameter may be expressed as:

$$\Delta L = 50 \log_{10} (S) + 70 \log_{10} (D),$$

where S is the speed ratio change and D the diameter ratio change.

Exhaust Noise

Exhaust noise on construction equipment includes noise produced by exhaust gases, radiation from the muffler shell, and flanking from the exhaust system components.[127,139] The exhaust noise is a function of both engine RPM and engine load.

The exhaust system may contain the following components:

- Mufflers
- Exhaust stacks

- Exhaust pipes
- Splitter tees
- Resonators
- Resonator tees

Earlier exhaust systems typically consisted of a straight exhaust pipe, as noise was not a major consideration. Increased awareness of construction noise, and tougher OSHA standards dictated the development of the basic single-plug muffler. Today, muffler designs have advanced to the point where significant reductions can be achieved in related exhaust noise on most construction machinery.[19,24]

There is a strong acoustical interdependence between the three main elements of an exhaust system: exhaust pipe, muffler, and tailpipe.[139] Pressure waves in the exhaust pipe are reflected by the muffler and combine with the follow-on exhaust pulses. The resultant standing wave frequencies determined by the exhaust pipe length, gas temperature, and engine fundamental firing frequency. If the muffler is located where the pressure fluctuations are largest in the pipe, it will result in the highest noise reduction and the lowest back pressure.

Engine Casing Noise

The EPA Background Document for the Proposed Wheel and Crawler Noise Emission Regulation[127] provides a concise summary of engine casing noise. Specifically, the noise radiated from engine surfaces is caused by the periodic cylinder pressure fluctuations and mechanical impacts generated by the piston slapping against the cylinder liner walls, and by mechanical impacts occurring within the whole power train system, the timing gear, and the auxiliary drives. The structural vibrations excited by such components within the engine are transmitted through the inner structure of the engine to its outer surfaces and the attached covers where they radiate acoustically. The noise power radiated from the surfaces of an engine can be highly significant since many pieces of construction equipment do not benefit from enclosures around the engine.[107,122,127]

Air Intake Noise

Air intake noise includes sound produced at the air inlet and sound radiated from the air cleaner shell and related system ducting. Intake noise is not normally a major noise source on construction equipment with the exception of some two-cycle diesel engines.[127,139]

Transmission Noise

The mechanisms associated with transmission noise are highly complex. Transmission noise characteristics are highly dependent upon such parameters as gear type, diameters, tooth loading, tooth misalignment, tolerances on pitch and profile error, tooth contact frequency, and casing vibration.[127] Data presented by Rudny[107] (shown in Figure 1) for a front-end loader indicate that transmission noise can contribute significantly to overall exterior vehicle noise levels on moving equipment. However, the problem of construction equipment transmission noise is addressed only minimally in the literature.

Hydraulic Noise

The literature on hydraulic noise as it pertains to construction equipment is limited probably because hydraulic noise is typically not a significant contributor to overall noise. Hydraulic pump noise is the result of abrupt changes in fluid pressure.[127] That is, changes in pressure result in excitation of fittings, valve stems, and other components which are in the fluid system. Additionally, fluid borne noise may be radiated from hoses, valves, and reservoirs.

Track Noise

Tracked construction vehicles emit noise as the result of track segment impact with the ground and against drive sprockets, idlers, and guide rollers.[127] On-site evaluation indicates that track noise can be highly annoying, and can be easily detectable at great distances from the construction site.[149] The EPA Background Document indicates that track noise can vary significantly with soil conditions.[127] Additional information in the literature on track noise is very limited.

3.3 Noise Characteristics of Impact Equipment and Power Tools

Impact noise is generated by sound radiation associated with the collision of two or more bodies.[1] Impact noise typically exhibits some form of rapid and substantial variation in the envelope of the time history of the instantaneous peak pressures.[123] Construction equipment which generate impact noise were previously identified in Section 2.2.1. For this equipment, Sutherland, et al.,[123] note that under any given operating condition, the repetition rate will be fairly constant so that the envelope will exhibit a definite periodicity. Further, the repetition rates of the impacts fall below the auditory range (i.e., about 20 Hz).

The primary sources of noise on impact equipment are identified as follows:[13,38,140]

1. Exhaust of air to the atmosphere
2. Casing noise from the impact of the piston on the anvil and hammer body
3. Ringing noise from the moil (chiesel) as a result of tip impact on a rigid surface

Noise generated by power tools and other stationary equipment may come from a variety of sources depending on the equipment type. Hallman[38] provides a summary of the primary noise sources on the major types of equipment:

- Exhaust noise is the primary component on pneumatic rotary equipment such as air motors, hand grinders, hoists, drills, and nut runners.
- The tool bit is the primary radiator of noise on an electric wrench.
- For poker vibrators, maximum noise occurs when the tool is not actually engaged in work, i.e., when it is out of the wet concrete.
- Exhaust noise is generally the primary noise component on small gasoline engine generators.
- Noise from a circular saw blade results from the high-frequency vibration of the saw blade itself.

Information compiled here on power tool noise has been derived from a limited set of references. It appears that only minimal attention has been given to date to the assessment of this source of noise.

No literature was found which dealt with the characteristics of blast noise as it pertains to a construction site. However, studies of blast noise as it pertains to mining[63,65,116] and military operations (i.e., sonic booms, artillery fire)[111,112] can be cited. Schomer[112] notes that little is known regarding the effects of below-ground blasts (such as generally used at a construction site). According to Schomer, the general relation for determining the overpressure, P_c, at distance x is:

$$P_c = T\,(d/W_c^{1/3})\,P_g$$

where T = transmissivity factor (a function of the depth d and charge weight W_c),

P_g = pressure W_c lbs of TNT would produce at distance x when exploded at ground level

The process is further complicated by the fact that acoustic radiation beamed upward from an underground blast can be focused back onto the ground anywhere from 2 to 40 miles from the source.[112] Tests performed by Kamperman[63] revealed that the factor that startled residents inside a dwelling due to a quarry blast was the groundborne vibration rather than the airborne noise.

In general, evaluation of blast noise characteristics from a construction site has not been effectively addressed in the literature. However, useful conclusions may be drawn from that literature pertaining to quarry blasts and military operations.

3.4 Construction Equipment Noise Emission Levels

The equipment noise level data has been derived from noise studies performed at construction sites as well as measurements made by various manufacturers. In reviewing the literature, care was taken to extract only data obtained under similar measurement conditions. All data points compiled here represent single equipment maximum sound levels measured at a distance of 15m (50 feet) from one side of the machine (not necessarily the noisiest). Equipment was operating under either (a) controlled conditions as specified by SAE J88a,[118] (b) stationary with the engine operating at high-idle (governed RPM), or (c) normal working conditions.

The references from which data were obtained and a brief description of the data follow:

- Power Plant Construction Noise Guide[7] – From this report, a total of 76 values of noise level for various pieces of equipment were derived. All data were measured at a distance of 15m (50 feet) with the equipment operating at maximum power or full speed during typical operations.
- Construction Noise in California[14] – Data on 29 pieces of new Caterpillar equipment measured in 1973 were derived from this report. Both stationary and drive-by SAE J88a test data were included.
- Construction Site and Equipment Noise in New York City[35] – Data from 29 pieces of equipment, some of which were measured at a distance of 7.5m (25 feet), were derived from this report. A distance correction factor (6 dB attenuation per doubling of distance) was applied to obtain levels expected at 15m under typical operating conditions.
- Construction Site Noise Control Cost-Benefit Estimation[67] – Data on 53 pieces of equipment measured at Fort Hood, Texas, and Fort Carson, Colorado, construction sites were derived. In addition, data from 92 vehicles measured by Donaldson Company were taken from this report. All data were obtained at 15m under typical operating conditions and at maximum power.

- Proposed Wheel and Crawler Tractor Noise Emission Regulation – Background Document[127] – Noise level data for 84 pieces of equipment, wheel and crawler tractors only, were derived from this report. Data were obtained at Fort Belvoir, Virginia, and consist primarily of measurements performed using the SAE J88a test procedure.
- ARTBA Noise Survey - 1973 – Data on 429 pieces of equipment measured at distances up to 15m from the machine during normal operations were obtained from this listing. These data were provided to Wyle by the American Road and Transportation Builders Association (ARTBA). Additionally, data from measurements of 120 pavement breakers and rock drills were obtained from ARTBA and included here.

Data for various types of equipment have been classified and grouped according to the equipment categories shown in Table 3. The terminology utilized by the construction industry, equipment manufacturers, and industry analysts is not entirely free of differences. This problem cannot easily be eliminated, but the reader may benefit from an examination of Table 3, which contains many of the commonly used names and their assignment to the selected equipment classes. An attempt has been made to group similar types of equipment together to minimize the number of essentially repetitive categories. The categories shown in Table 3 will be utilized to the greatest extent possible throughout this study.

The sound level data for all major categories derived from the literature are shown in Table 4. The level associated with each piece of equipment is displayed in a histogram format in order that the distribution of levels for each category may be clearly visualized. In most cases, especially where a reasonably large number of data points are shown for a given category, the approximate average vehicle noise level becomes obvious. However, for some, where only a small number of data are available and the spread in levels is great, the average is not so apparent. These data have been analyzed to determine the mean level and standard deviation of each distribution. These data are presented in Table 5. Also included in this listing are other miscellaneous types of equipment for which only limited data were available. Note that the mean values represent a potential method for prediction of levels created by various construction activities involving these types of equipment.

The relationship between equipment sound levels and other physical descriptors of the vehicles has been examined by various investigators.[67,7,127,14,61] One of the most recent studies, Proposed Wheel and Crawler Tractor Noise Emission Regulation - Background Document,[127] presents data on each of five separate equipment types: crawler

Table 3

Equipment Type Categorization

The following additional equipment is included within the types shown:

Equipment Category	Equipment Types
Batching Plant	Asphalt and Concrete Plants
Compactors	Rollers (Sheepsfoot, Steel Drum, Steel Wheel, Pneumatic Tired, Vibrating)
Compressors	Stationary and Portable Compressors, Air Compressors
Cranes	All Types (Derrick, Mobile, etc.)
Dozers	Bulldozer, Crawler Dozer, Crawler Tractor, Track Type Tractor, Pusher, Ripper, Ripper Scarifier
Excavators	Backhoe, Clamshell, Shovel, Front Shovel, Dragline, Trenchers
Generators	All Types
Graders	Motor Grader, Gradall
Loaders	Wheel Loader, Track Type Loader, Front End Loader, Skid Steer Loader
Mixers	Portable, Truck Mounted, Stationary
Pavement Breakers	Portable and Mounted, Chipping Hammer, Jackhammer
Pavers	Concrete Paver, Bituminous Paver
Pile Drivers	All Types
Rock-Drills	Portable and Mounted
Saws	Chain Saw
Scrapers	Wheel Tractor Scraper, Hauler, Elevating Scraper
Tractors	Wheel Tractor, Utility Tractor
Trucks	Rear Dump
Welders	All Types

Table 4

Maximum A-Weighted Sound Levels of Construction Equipment
Operating or Stationary at 15m (50 Feet)

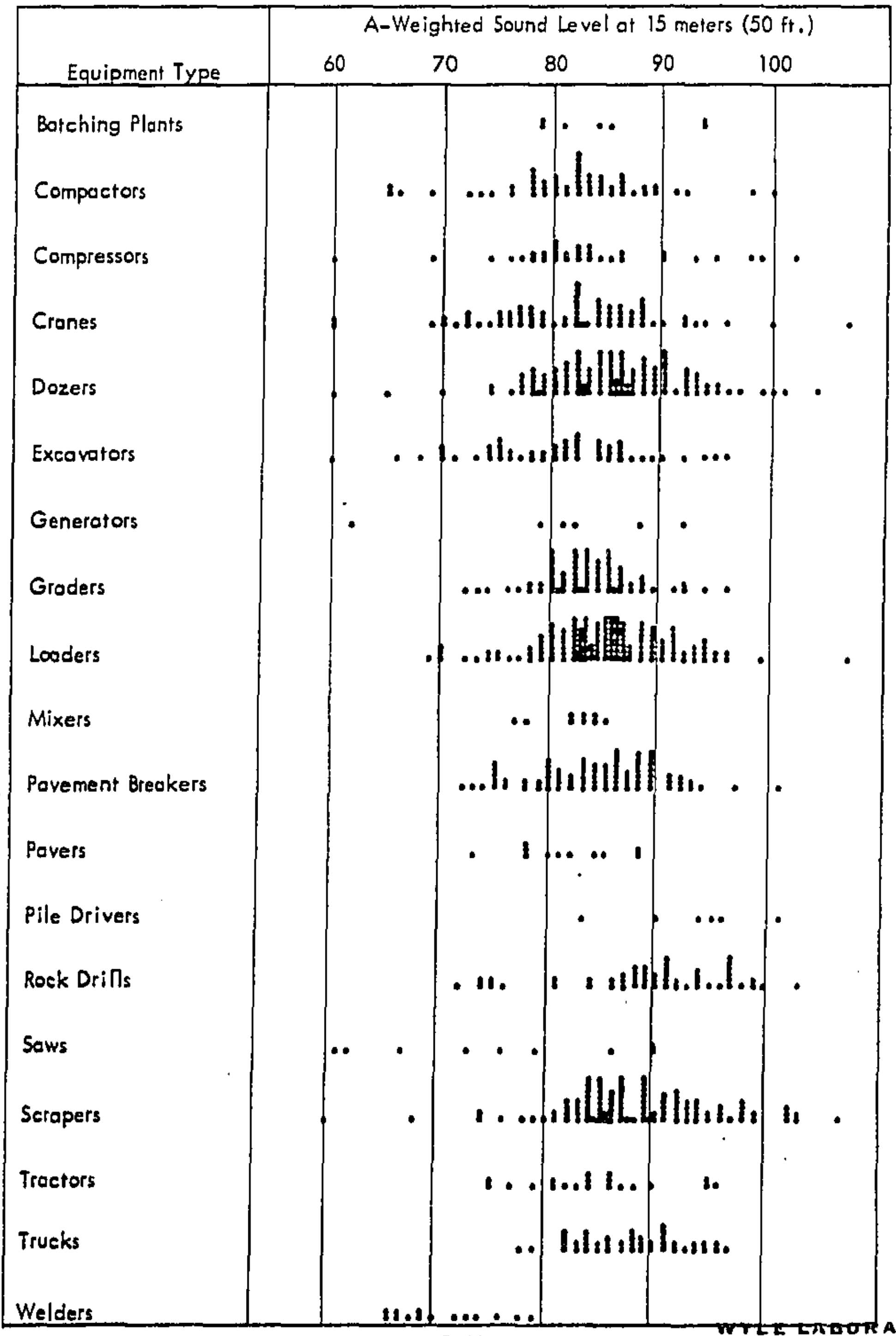


Table 5

Maximum A-Weighted Sound Levels of Construction Equipment

Equipment Type	Number Measured	Mean Level (dB)	Standard Deviation (dB)
Batching Plants	7	85.1	6.5
Compactors	54	81.6	6.9
Compressors	32	83.0	8.5
Cranes	71	81.6	8.0
Dozers	120	85.1	6.6
Excavators	53	80.2	7.4
Generators	6	80.7	10.3
Graders	70	83.2	4.4
Loaders	137	84.6	6.0
Mixers	9	82.0	2.7
Pavement Breakers	80	84.4	5.7
Pavers	11	81.4	4.6
Pile Drivers	6	93.2	6.1
Rock Drills	52	89.6	7.3
Saws	9	76.0	11.2
Scrapers	102	88.5	7.4
Tractors	20	84.7	6.1
Trucks	43	88.1	4.8
Welders	14	71.0	4.4
Others:			
Pumps	2	68,78	
Concrete Pumps	2	80,87	
Broom	4	66,71,75,102	
Asphalt Burner	2	88,92	
Crushing Plant	2	85,96	
Finisher	2	83,86	
Grinder	2	84,92	

dozers, crawler loaders, wheel loaders, wheel tractors, and skid steer loaders. Analyses of these data were performed to determine the relationship between sound level and engine horsepower. Only minor differences were exhibited between equations defining the relationship for each category of equipment; thus the analyses indicate that individual attention to each separate category is not warranted.

Based on the similarity among many types of construction equipment, and assuming the engine and accessories are the predominant noise sources, then it is feasible to lump several categories of equipment together in an attempt to determine if a close relationship exists between noise level and engine horsepower. All data from the previously cited reports were examined and extracted for those cases where sound level was identified with an equipment horsepower rating. These data are shown plotted in Figure 2 with horsepower as the linear dependent variable.

The data plotted in Figure 2 have been analyzed through a least-squares linear regression procedure to determine the equation which best fits the data. Both linear and logarithmic functions were tested and the resultant equations were found to yield similar accuracy. These equations follow:

Linear Equation $\quad SPL = 77.6 + 0.025\ (HP)$

Logarithmic Equation $\quad SPL = 58.9 + 10.77\ (\text{Log}_{10}\ HP)$

For the linear equation the correlation coefficient has a value of 0.62 and for the logarithmic equation the value is 0.66. These values indicate fair agreement between the data and the equations, with only a slight advantage occurring from the use of the logarithmic equation. It should be noted, however, that the above regression analysis is presented merely to provide an idea of the correlation between engine horsepower and equipment noise emission level. It is not suggested at this time that the resulting equations be utilized in a noise prediction model.

Some types of equipment are specified in terms of bucket size rather than horsepower. The EPA Background Document[127] states that there is a strong correlation between these two parameters for wheel loaders. These data are shown in Figure 3. Where bucket size is used to specify equipment size, the equation shown will provide an estimate of horsepower which, in turn, can be utilized to yield an estimate of the equipment sound level using the equation shown in Figure 2.

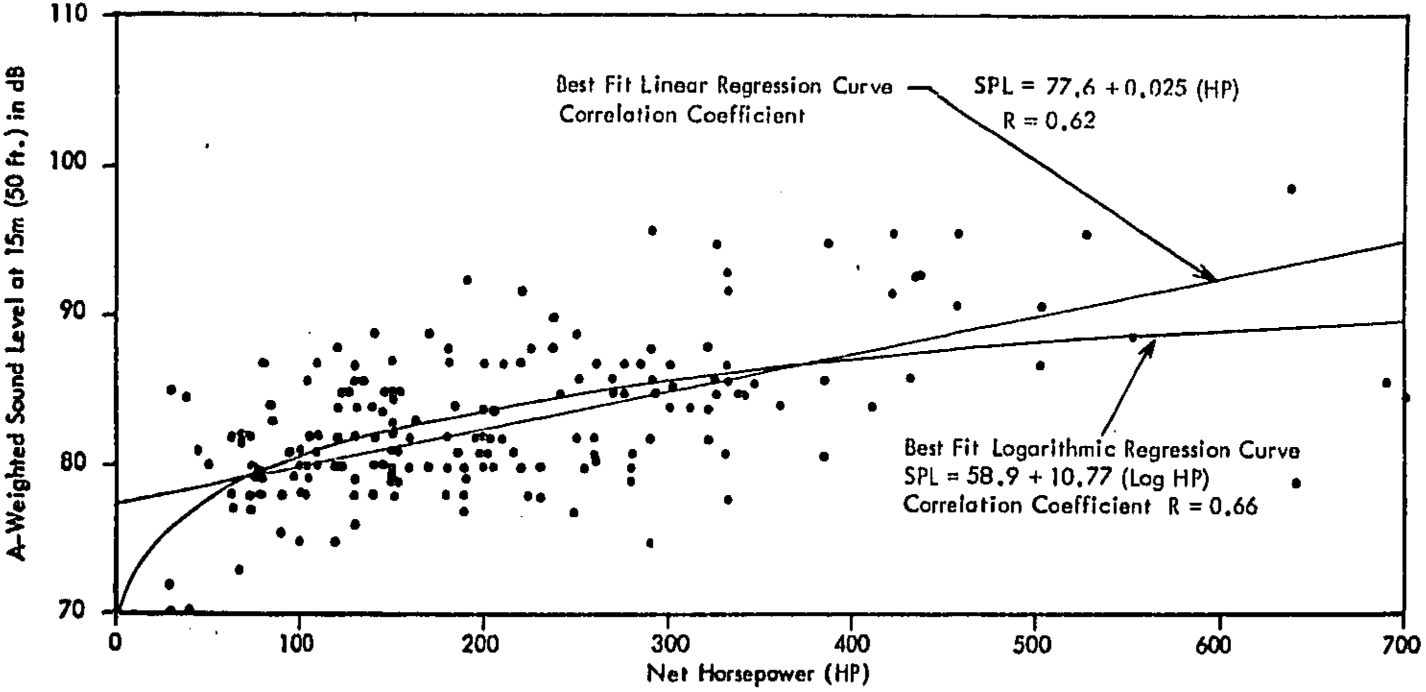


Figure 2. Maximum A-Weighted Sound Level of Diesel-Powered Equipment Versus Horsepower.

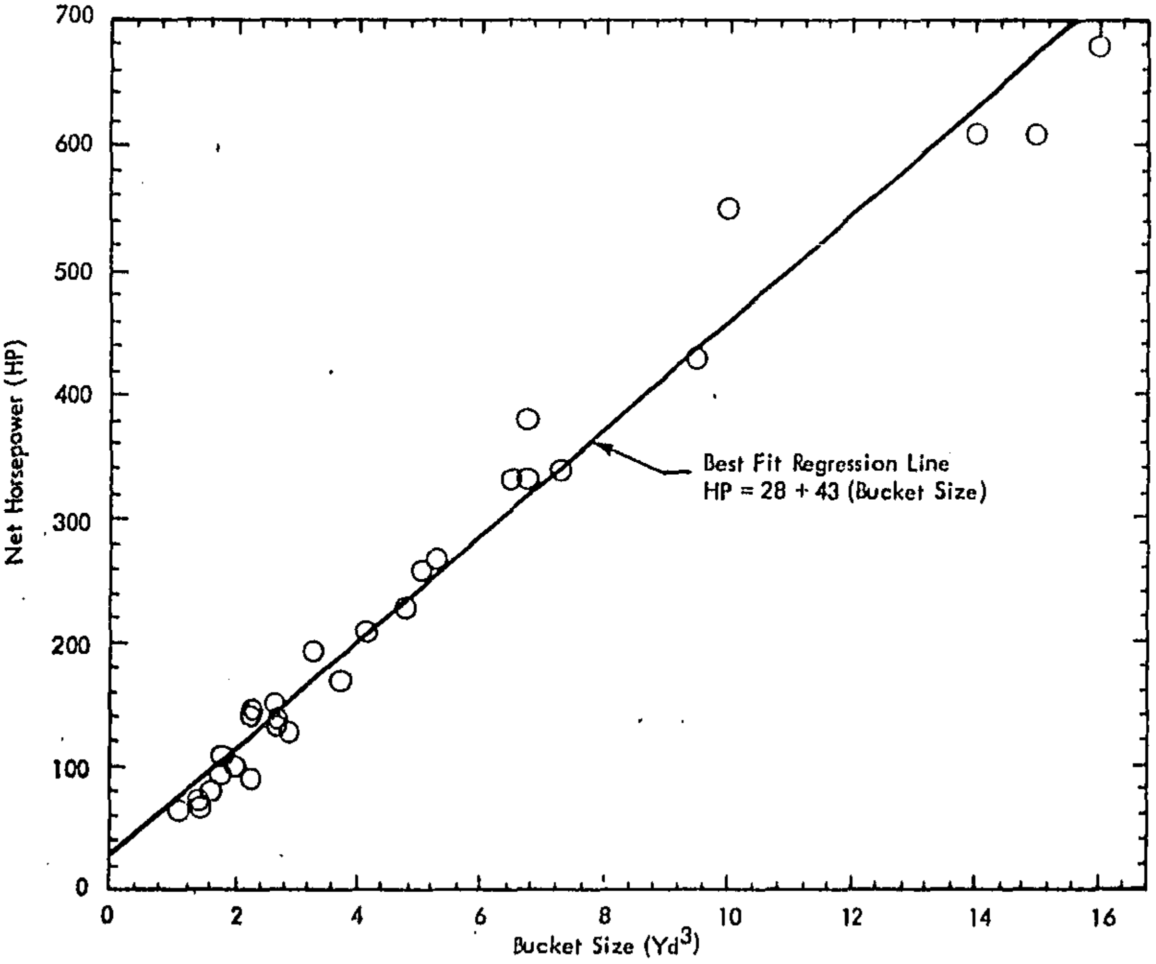


Figure 3. Net Horsepower Versus Bucket Size for Wheel Loaders (From Reference 31).

3.5 Highway Construction Site Noise Measurements

3.5.1 Description of Construction Test Sites

Careful examination of the operational and scheduling characteristics of numerous major ongoing highway construction projects has led to selection of four sites for inclusion in the field measurement program designed to expand the existing noise and operational data base. This section provides a detailed description of each of these sites.

The four construction sites were distilled from a list of approximately 75 preliminary sites identified through discussions with 13 State Departments of Transportation. Final selection of the test sites was based upon the following factors:

- The sites selected were representative of major arterial highway and bridge construction projects.
- The sites provided examples of highway construction in both urban and rural areas.
- The sites provided examples of both new and reconstruction projects.
- The sites were representative of the various types of geographical regions found in the U.S.

A brief summary of each selected test site is provided on the pages which follow.

Construction Test Site No. 1

STATE: California

HIGHWAY: I-210; 15 miles northwest of downtown Los Angeles.

DESCRIPTION: The project encompassed 6 miles of 8-lane divided interstate highway which completes construction on I-210 (see Figure 4). The highway at this location runs through a suburban area characterized by low-density housing and small farms. Approximately two-thirds of the highway alignment is flat. However, at the southern end of the site, major earthwork activities were in progress through hilly terrain. Common soil is typical at this site, with little or no rock excavation anticipated. The soil in this area is dry..

This site provided numerous examples of major earthwork activities involving heavy equipment. Particular attention focused on a large cut operation at the southern section of the site, belly dump truck operations on the haul road, and subbase compaction work in the central section of the site. Batch plant and crushing plant operations were also located on the highway construction site.

Some bridge construction existed during the measurement timeframe. Two concrete box girder bridges were under construction at the site, thus assuring that examples of activities associated with the structural excavation, foundation support, substructure, and superstructure construction phases will be available.

Construction Test Site No. 2

STATE: Oregon

HIGHWAY: I-205; City of Portland

DESCRIPTION: This site consists of 9 miles of 6-lane divided highway being constructed on new alignment (see Figure 5). The site topography is generally flat to gently rolling with some hilly canyon terrain. The highway cuts through an urban area characterized by single-family dwellings, schools, small stores, etc.

Common soil was most typical at this site. However, in one section where construction has yet to begin, rock excavation (including blasting) was encountered. Wet soil conditions were also encountered throughout.

The project was in varying stages of construction during the measurement period. With respect to highway construction, activities representing each of the primary phases of construction, were ongoing including mobilization and clearing and grubbing of trees. Haul routes used for transporting subbase aggregates and concrete were also active.

Six bridge construction projects were underway during the measurement timeframe, and thus were available for observation. Both steel and concrete bridges were being erected on this highway project.

Construction Test Site No. 3

STATE: Maryland

HIGHWAY: I-95/I-395

DESCRIPTION: Located in the City of Baltimore (see Figure 6), this test site was highly typical of highway construction projects in urban, high-density housing areas. While this site will be identified throughout the report as I-95/I-395, the test site actually encompasses four distinct projects in close proximity to each other:

- I-95
- I-395
- I-170
- "Boulevard" project

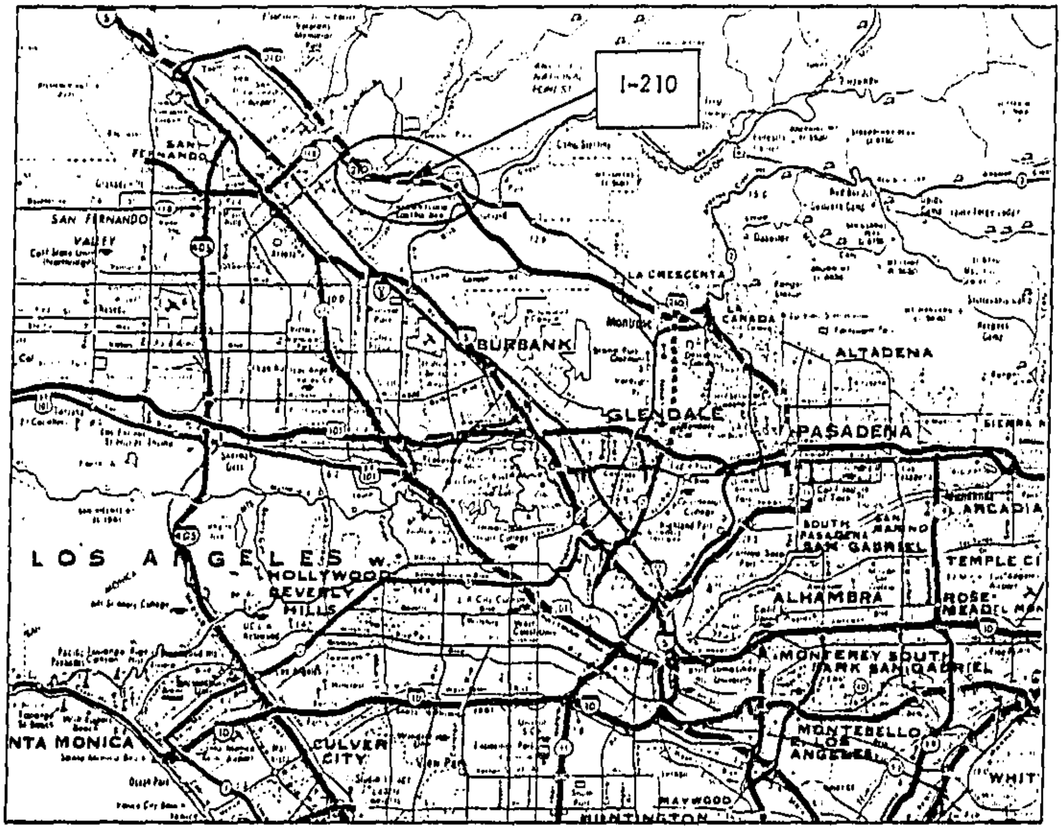


Figure 4. Location of Construction Test Site No. 1.

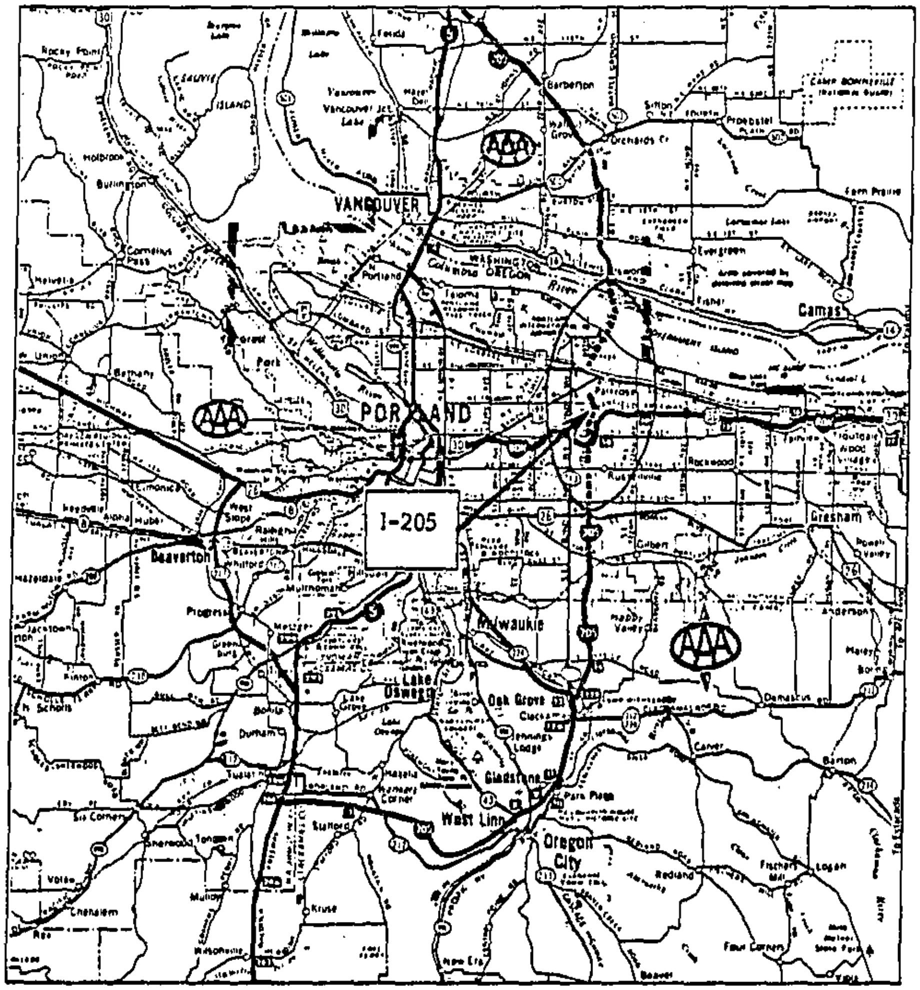


Figure 5. Location of Construction Test Site No. 2.

I-95 is an elevated interstate upon which major new construction was planned. At the time of the measurements, mobilization and clearing activities were ongoing. I-395 is also an elevated structure. A substantial amount of demolition was scheduled during the measurement timeframe, including asphalt pavement removal and structural demolition. Earthwork and pile driving were also ongoing during this period. I-170 is an urban interstate which was in the cleanup, signing, and landscaping stages. It provided an opportunity to study activities which occur late in a construction operation. The Boulevard project is a major 6-lane arterial which encompassed both new and reconstruction. Much of the project was in the earthwork phase. This site provided good examples of asphalt pavement removal, grading and subbase compaction, trenching, and stockpiling.

Construction Test Site No. 4

STATE: Florida

HIGHWAY: St. Petersburg Section of I-75; south of the City of St. Petersburg.

DESCRIPTION: In total, the I-75 construction site encompasses 120 miles of divided 4-lane highway being built on new alignment running from St. Petersburg to Ft. Myers (see Figure 7). Because most of the construction activities along the 120-mile stretch were highly repetitious from one contract section to another, it would have been inefficient to perform measurements along the entire construction project. Therefore attention was focused upon the St. Petersburg section, consisting of 25 miles of the I-75 project and located just south of the City of St. Petersburg.

The highway alignment passes through flat, rural landscape, many times encountering large stands of trees. Sparse residential areas exist at various locations, but are some distance from the right-of-way. The water table in this area is very high, such that during wet periods the soil is quickly saturated and turns to mud. Examples of dewatering operations that are unique to the southern states were observed at this site.

During the measurement timeframe each phase of highway construction, with the exception of demolition, was ongoing. This included tree removal during clearing and grubbing, use of dragline cranes during excavation, and cut/fill operations involving borrow pits located adjacent to the site and spaced at about 1/2-mile intervals. Examples of concrete slipform paving, signing, and finishing operations were also available for operation.

Seven concrete bridges were under construction in the St. Petersburg section during the measurement period. Numerous activities associated with structural excavation, foundation support, substructure, and superstructure construction were also evident at that time.

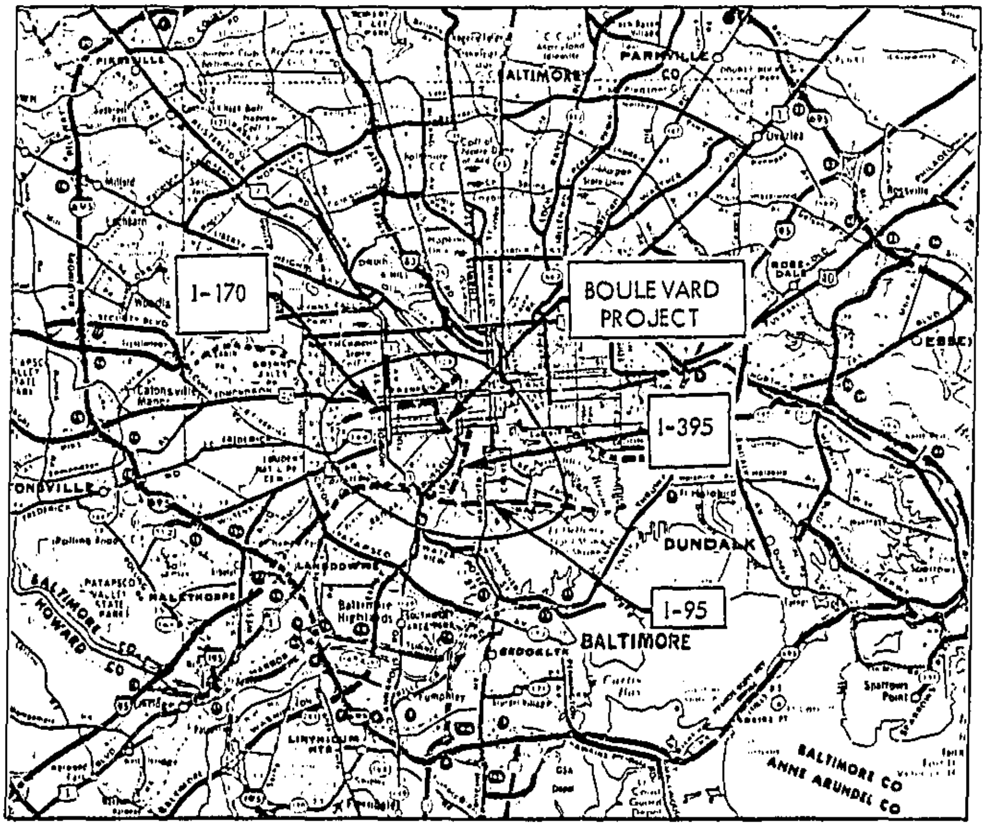


Figure 6. Location of Construction Test Site No. 3.

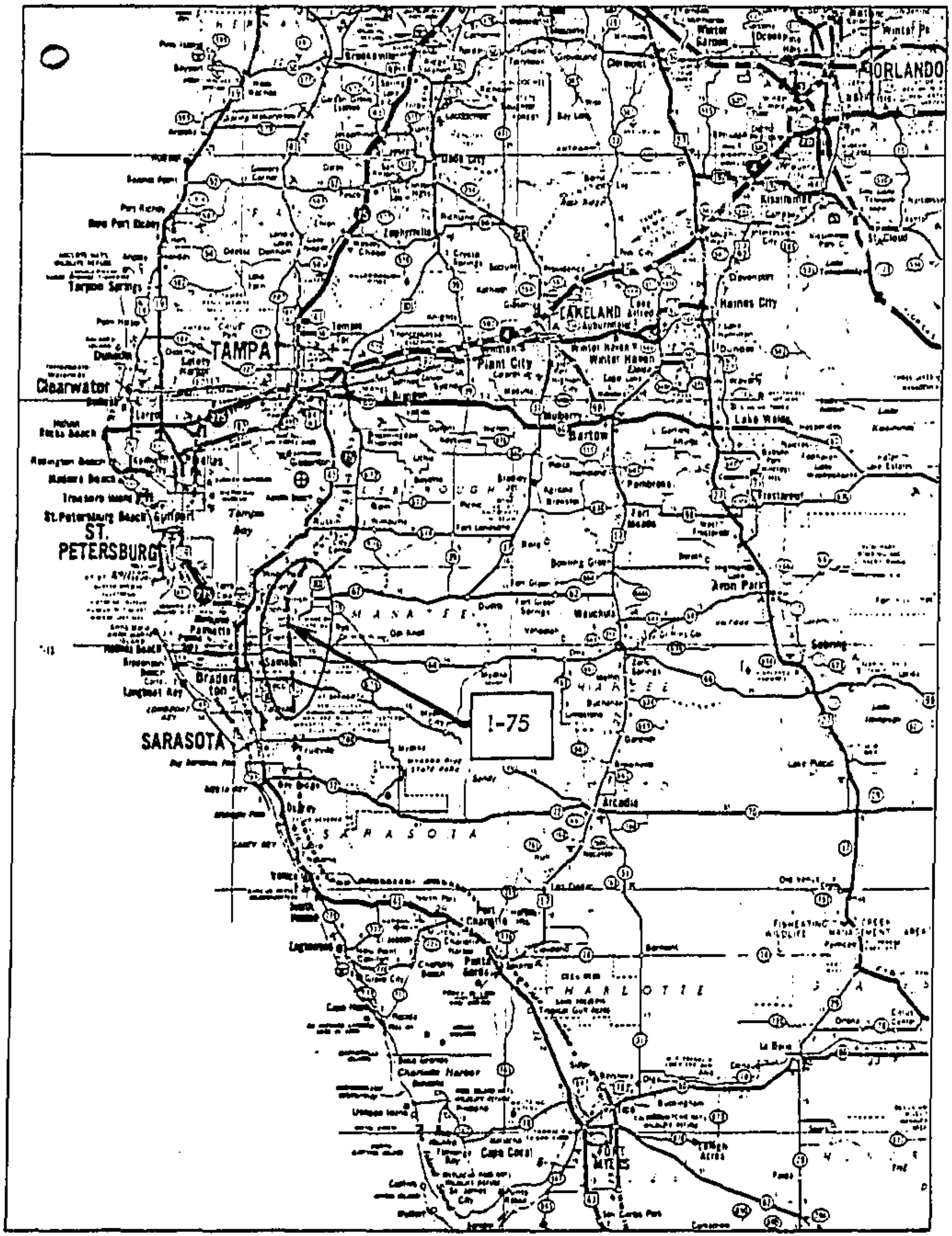


Figure 7. Location of Construction Test Site No. 4.

3.5.2 Description of Noise and Equipment Operational Measurement Procedures

The purpose of the field measurements was to obtain data for model development, calibration, and validation. Data compiled at the sites included the following:

- Equipment and activity emission levels;
- Equipment duty cycles and operation;
- Sound propagation at measurement sites;
- Site boundary and community noise levels.

Section 3.5.2.1 describes the types of measurements performed at each site. Specific instrumentation packages which were used are described in Section 3.5.2.2. Field measurement procedures and data reduction methods are described in Sections 3.5.2.3 and 3.5.2.4, respectively.

3.5.2.1 Measurements

The following types of measurements were performed:

1. Instantaneous measurement of A-weighted sound level, read manually from a sound level meter. This was appropriate for equipment which exhibited constant noise levels with time.
2. Analog tape recording, providing a continuous record of the sound pressure level. A multiple-channel recorder was used, thus enabling detailed voice annotation on the channel not used for data. Non-acoustic observations were recorded synchronously. An analog system was used where such annotation was required, and/or where subsequent analysis required frequency weighting or spectral analysis.
3. Digital tape recording. Sound was detected, A-weighted, and the sound level L_A was recorded digitally. This was analyzed to give the time history of A-weighted levels and statistical noise metrics such as L_{eq}, L_{10}, etc.
4. Equipment duty cycle and operational data. For simple tasks, observations were made manually, using a stopwatch for time data. Where several pieces of equipment were operating such that one observer could not document everything at once, movies were taken. The movies were replayed several times, allowing repeated manual observations of individual pieces of equipment.

A full description of each of the measurement systems and associated data reduction methods is presented in Section 3.5.2.2.

The application of each of these systems to particular types of measurements were as follows:

- Individual equipment sound levels of stationary, constant noise equipment were made using a sound level meter.
- Controlled single equipment tests (e.g., SAE procedures) which simulate single operating modes were made on analog tape.
- Measurements of impulsive noise sources, which will require a faster time constant for analysis, were recorded on analog tape.
- Noise measurements of tasks involving single pieces of equipment were made on analog tape. This permitted simultaneous voice annotation of the activity, so that levels identified with different modes could be identified during data reduction.
- Noise measurements of activities involving several pieces of equipment were recorded digitally. Synchronized voice annotation (feasible with analog recordings) was not required because complex activities were not directly analyzed to relate instantaneous levels to equipment operating mode.
- Equipment operating mode, consisting of paths of mobile equipment and time spent in each mode, were observed manually using a stopwatch and dimensional measurements of the work area. Movies were made where several pieces of equipment were involved and a single observer could not record all in real time.
- Site boundary and community noise measurements were made digitally.
- Noise propagation measurements were recorded on analog tape.

Specific procedures followed in the field are given in Section 3.5.2.4.

3.5.2.2 Instrumentation

The array of instrumentation utilized during the measurement program parallelled the variety of data required to satisfy several different requirements. For the most part, the variety of instruments required matched the complexity of the construction task being monitored. Acoustic data were recorded in the following manner:

1. Digital recordings were utilized where the equivalent level (L_{eq}) or statistical levels (L_x) were needed.
2. Analog recordings were made where greater definition of equipment noise levels was required; recordings were annotated for later detailed analysis.

3. Equipment generating constant noise levels (e.g., a generator) were measured using a standard Type I sound level meter.

4. Other equipment were required to obtain supplementary information and support and acoustic measurements: microphone calibrators, headphones, a movie camera, stopwatch, and weather measuring instruments.

The array of instrumentation used is illustrated in Figure 8. The following paragraphs discuss these instruments and their required functions.

Digital Recordings

At locations where only L_{eq} and statistical levels were needed, long-term samples of the A-weighted level were recorded on digital tape (see Figure 8a). The acoustic signal was first A-weighted and then detected with a "slow" time constant applied. This level was then sampled once per second, converted to a digital format, and recorded on magnetic tape. The battery-operated recorder had the capability of unattended operation for over 42 hours. Recorded data were subsequently analyzed in the laboratory to obtain the desired descriptors of the construction activity noise levels.

Analog Recordings

In situations where construction activities are simple, that is, where operations were performed by only one or two pieces of equipment and their operational patterns were well-defined, annotated analog recordings were made (see Figure 8b). Response characteristics allow recording frequencies from 20 Hz to 10 kHz at a recording speed of 3-3/4 inches per second. At this speed, over 1 hour of data could be recorded on a 5-inch reel of tape.

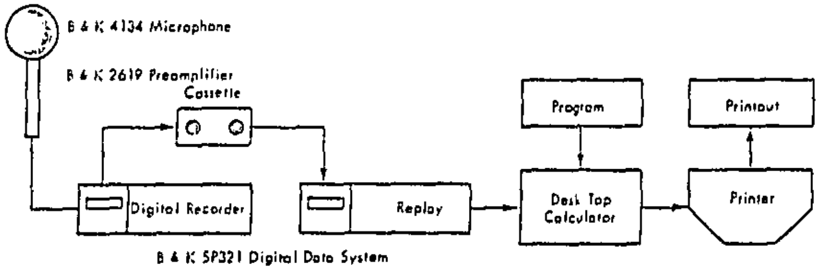
A third channel on the recorder was used for annotation. This annotation channel contained a great deal of detail regarding equipment operational characteristics during each cycle of its activity.

Analog recordings were also allowed for detailed analyses of impulsive noise, as maximum levels using a very fast response were available.

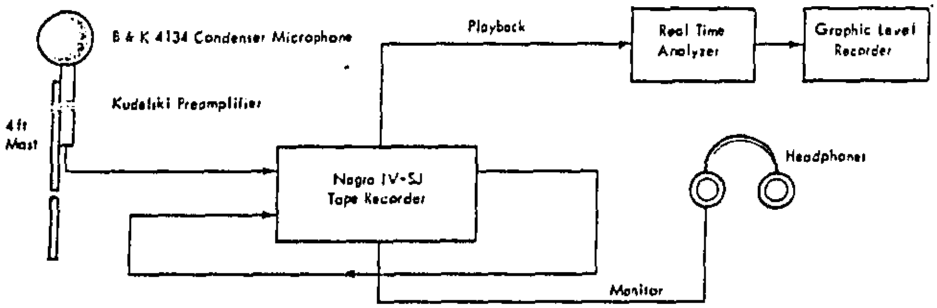
Spectral analyses were also used to obtain frequency content of particular construction equipment or processes. These were especially useful in predicting propagation effects into surrounding communities.

Steady-State Levels Measurement

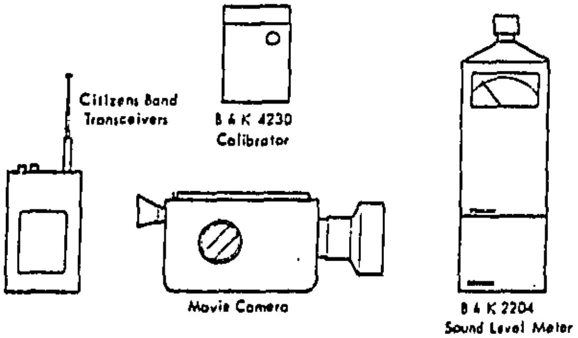
Certain operations were performed with stationary equipment producing nearly constant noise levels. When necessary, short analog samples were recorded to allow



a. Long-Term Recording and Analysis



b. Broadband Recording and Frequency Analysis



c. Single Equipment Samples and Activity Operational

Figure 8. Data Acquisition and Analysis Systems.

spectral analyses. Otherwise, a Type I sound level meter was used to measure the level at specific locations (see Figure 8c). The sound level meter enabled rapid determination of the maximum A-weighted level produced by the equipment being examined.

Supplementary Instrumentation

During periods when acoustic data were being gathered, a variety of supplementary information was obtained. Among the most important are the following:

1. Detailed sketches of each activity were produced to accompany the noise data. Equipment types, areas of activity, and site terrain features were accurately portrayed relative to each measurement location.
2. Movies of complex activities involving several pieces of equipment were taken to allow more detailed analyses in the laboratory. A camera with the capability of operating at a low frame rate was used such that an activity could be recorded for long durations.
3. Time/motion logs of individual equipment activities were generated in conjunction with the analog recordings to enable detailed analyses of activity cycles. A stopwatch was the main requirement for this task.
4. Weather parameters (especially wind speed, temperature, and relative humidity) were logged to allow for acoustic propagation corrections if needed. A hand-held wind meter, a thermometer, and a sling psychrometer were used to obtain these data.

3.5.2.3 Field Procedures

General Practice

- All instrumentation was tested prior to field use. Formal calibration procedures were performed within the time period recommended by the manufacturer.
- Field calibration was performed before and after each data set, using a coupler-type calibrator.
- Ambient conditions of wind, temperature, and humidity were measured and logged. Except for site boundary and community measurements, data was not collected if wind speed exceeded 12 mph. If wind speed exceeds 12 mph during site boundary or community measurements, wind conditions were documented.
- Noise data collected during periods of precipitation were discarded.

- Sites were documented with maps (where available), sketches, and descriptive notes. Photographs were taken of the activity site, microphone position(s), and intervening terrain.

Controlled Single Equipment Noise Tests

Equipment noise levels were measured using procedures based on SAE Recommended Practices J88a, J1077, and J1096, and the EPA test for compressors. Ideally, these procedures would have been followed exactly. However, under field conditions, the following modifications were necessary:

- Site surfaces were typically not paved, and generally did not satisfy normal flatness criteria. Propagation data collected at the sites were used to correct measurements to equivalent standard condition noise levels. Sites were used only if a surface correction of less than ±3 dB was expected.
- Moving tests were not always possible due to site restrictions. In such cases, only stationary tests were performed.

The following extensions were also made:

- Noise levels were measured under modes other than maximum noise conditions if these modes appeared to be significant.
- Tape recordings were made of all impulsive sounds. These were analyzed to give A-weighted levels.
- The procedures were extended as needed to include equipment not specifically covered under existing standard test procedures, but for which these tests were considered adequate.

Single Equipment Task Operating Noise Levels and Operation

In-use sound levels of single pieces of equipment performing a task were measured and operating cycles were documented. The following procedures were used:

- The microphone was placed 50 feet from the center of equipment which was either fixed or whose position did not vary by more than ±15 feet from its center of activity.
- Microphone placement for mobile equipment which moved on a fixed path (e.g., trucks, scrapers on one lane, etc.) was 50 feet from the point of nearest approach.

- For equipment which moved over an area larger than the above (compactors, bulldozers working an area on one lane, etc.), two microphones were placed along a radial line from the centroid of the activity. Specific placement depended on site conditions. Typically, for a task over an area of diameter, D, microphones were placed at distances of D and 2D from the center.
- Microphone height was 4 feet.
- Data were recorded on magnetic tape. A detailed voice annotation was made so that levels at different points of the cycle could be obtained in addition to L_{eq} over a cycle.
- Equipment producing constant noise levels were measured using a sound level meter.
- Recording typically covered at least 10 cycles of the task. Total recording time was in the 10- to 30-minute range.
- Duty cycle and elements of the cycle were timed, using a stopwatch, simultaneously with the recording. Times not obtained under field conditions were measured from the annotated tape. Appropriate reference marks were placed on the voice track.

Activity Perimeter Noise Levels and Operations

Noise levels of an activity (i.e., an operation involving simultaneous use of several pieces of equipment) were recorded in a manner similar to that described above for single equipment task operations, with the exception of the following noticeable differences:

- The microphone was placed at a greater distance, such that it was in the acoustic far field of the activity. If this required placement more than 100 to 200 feet from an activity center, two microphones were used in a manner similar to that described above for covering a large area.
- Data were recorded on a digital tape recorder.
- Equipment operation and duty cycles were documented by field notes and timing. If the activity was too complex to be documented by a single observer, movies were made simultaneously with the noise measurements. Operational characteristics and times were obtained subsequently during data reduction.
- Movies were taken only when there was a suitable elevated vantage point. Field calibration of frame rates were accomplished by placing an accurate timer in the field of view at the beginning and end of each filmed record.

Site Boundary Noise Measurements

Digital recorders were placed at the site boundary. Locations were chosen based on the following criteria:

- Boundary location, i.e., position of boundary relative to right-of-way and community, was representative of typical site geometries.
- Location was near major construction activities, preferably ones for which activity and/or task noise measurements were made.
- Noise at the location was dominated by construction activity. Anomalous locations, adjacent to a local source such as a compressor, were avoided.
- Location was secure against vandalism and/or theft. This sometimes required placing recorders somewhat inside the project fence line.

Recordings of A-weighted levels were made for the full construction workday, typically 8 to 12 hours.

Community Noise Measurements

Digital recorders were placed in the community adjacent to the construction site. Locations were chosen where construction noise dominates. Twenty-four-hour recordings of A-weighted noise levels were made.

The greatest concern with community measurements was security of unattended monitors. The usual approach (if a nominal 4-foot microphone height is desired) was to put the recorder in the back yard of a private home. Community noise measurement were contingent on ground level locations being available.

Propagation Measurements

Measurements were made at various microphone positions from fixed noise sources to obtain excess attenuation values for local ground and terrain. The following types of measurement were made:

- Ground surface effects. Microphones nominally 4 feet high were placed on a single radius at geometrically increasing distances. Nominal distances were 25 feet, 50 feet, 100 feet, 200 feet, and 400 feet. The shorter distances were not used if they were in the acoustic near field; the longer distances were not used if they exceeded the space available. These data were used to obtain the local value of excess attenuation.

All propagation measurements were made on a two-channel analog tape recorder. The procedure was to record noise simultaneously with one microphone at a fixed reference location (either 25 feet or 50 feet, 4 feet high) and the second at one of the other locations. The second microphone was then moved from point to point radially. Attenuation was based on differences between the two. This procedure provides automatic compensation for variations in source level.

Where practical, propagation measurements were combined with stationary task measurements for a fixed piece of equipment. Where not feasible, then the measurements were done when construction activity was stopped, using a readily available noise source.

3.5.3 Construction Site Noise Data

The full details of the measurement conditions existing at each site, and the construction equipment for which noise and operational data were obtained, are given in Appendices A, B, C, and D of this report. A summary of the equipment noise data obtained is given in Tables 6 through 15 in this section.

Prior to visiting each of the four construction sites to obtain the necessary data, the construction phases in progress were known. However, the specific types of equipment utilized at each site were not completely known. Accordingly, the noise data presented in the following tables is for equipment taken as targets of opportunity. As noted in previous sections, some of the data was recorded for subsequent analysis in the laboratory, and some was measured on-site by hand-held sound level meters. For this reason, the data is more comprehensive for some equipment than for others.

The information presented in the following tables is as follows:

- Sample Number – the identification given to the measurement, providing a means of relating the data to the site conditions specified in Appendices A, B, C, and D.
- Equipment – a description (where available) of the equipment manufacturer and model number.
- Test Condition – the operation of the equipment during the noise measurements. The term "IMI" refers to the "idle-max-idle" test where the throttle is rapidly opened to achieve maximum rated engine speed, held at that position, and then rapidly closed.
- Number of Samples – the number of samples used to obtain the average noise levels.

- Noise Descriptors – L_{eq}, L_{max}, and SEL (Single Event Level) meaured at 50 feet unless otherwise noted.
- Duration of Measurement t – the duration of the pass-by or activity for which the L_{eq} was measured.

Table 6

Measured Noise Data For Scrapers

Sample No.	Equipment	Test Condition	N*	Lmax, dB (at 50 Feet)
2-17	Fiat-Allis 460			
	• Empty	Pass-by	9	85.8
	• Loaded	Pass-by	6	76.8
2-19	Caterpiller 623	Pass-by	1	90.4
3-39	Caterpiller			
	• Empty	Pass-by	1	88.2
	• Loaded	Pass-by	1	85.2
3-40	Unknown Scraper	Pass-by	2	86.6
4-3	Caterpiller 631 B&C			
	• Empty	Pass-by	8	95.2
	• Loaded	Pass-by	9	94.6
4-9	Caterpiller 631 B (no muffler)	IMI	1	96.0
4-12	Caterpiller 631 B	Pass-by	2	81.0
4-25	Caterpiller 637			
	• Empty	Pass-by	3	83.2
	• Loaded	Pass-by	3	77.8
4-25	Caterpiller 631 B			
	• Empty	Pass-by	1	94.0
	• Loaded	Pass-by	1	85.7
4-26	Caterpiller 631 B – Empty	Pass-by	1	95.5
4-29	Caterpiller 637	IMI	1	82.0
4-44	Caterpiller 631 B	Pass-by	1	95.0
	Caterpiller 631 D	Pass-by	1	84.0
4-45	Caterpiller 631 B	IMI	1	92.0
	Caterpiller 631 C	IMI	1	84.0
	Caterpiller 631 D	IMI	1	84.0
4-91	Caterpiller 631 B&C – Loaded	Pass-by	5	83.9

* Number of Samples

Table 7

Measured Noise Data For Trucks

Sample No.	Equipment	Test Condition	N*	Noise Descriptors, dB		Δt** (secs)
				L_{max}	SEL	
3-26	Water Truck	Pass-by (10 mph)	1	72.7	78.4	10.0
	Truck (Loaded)	Pass-by	1	87.1	92.3	17.5
	Truck (Loaded)	Pass-by	1	78.1	86.6	20.0
	Truck (Loaded)	Pass-by	1	76.4	81.9	15.0
	Truck (Empty)	Pass-by	1	83.0	88.7	24.9
	Truck (Empty)	Pass-by	1	81.9	87.6	22.5
	Truck (Empty)	Pass-by	1	76.2	81.2	12.5
	Truck (Empty)	Pass-by	1	85.7	89.4	21.4
3.47	Mack Water Truck	Pass-by	3	85.7	--	--
4-18	Ford 9000 Concrete Truck	Pass-by	4	75.5	--	--
4-43	Caterpiller 613 Water Truck	IMI	1	81.0	--	--
4-57	Mack Dump Trucks					
	• Empty	Pass-by	3	76.0	--	--
	• Loaded	Pass-by	4	74.8	--	--
4-67	Mack Dump Trucks					
	• Semi (Empty)	Pass-by	1	74.1		
	• Semi (Loaded)	Pass-by	2	78.7		
	• Single (Empty)	Pass-by	2	73.0		
	• Single (Loaded)	Pass-by	1	70.5		

* Number of Samples

** Duration of Measurement

Table 8

Measured Noise Data For Loaders

Sample No.	Equipment	Test Condition	N*	Noise Descriptors dB			Δt** (secs)
				L_{eq}	L_{max}	SEL	
3-7 3-9	Caterpiller 988	Loading/ Unloading	8	76.9	83.3	92.9	39.6
3-11 3-12	Komatsu D755	Loading/ Unloading	7	75.6	80.8	89.6	25.3
3-21	Michigan 175B	Loading/ Unloading	1	79.8	83.8	95.4	36.0
3-36	Caterpiller 950	Loading/ Unloading	1	76.2	81.0	89.6	22.0
3-46	Caterpiller 983	Loading/ Unloading	7	81.6	86.2	96.6	32.3
4-5	Caterpiller 950	Pass-by	1	--	80.0	--	--
4-6	Caterpiller 966C	IMI	1	--	88.0	--	--
4-8	Caterpiller 950 (with muffler)	IMI	1	--	79.0	--	--
4-14	Tenex 72-31B	Activity (80-90 Ft)	1	78.6	--	--	--
4-15	Tenex 72-31B	Activity (60-100 Ft)	1	73.6	--	--	--
4-55	Caterpiller 950	IMI	1	--	77.0	--	--
4-60	Tenex 72-31B	Activity (20-50 Ft)	1	77.1	--	--	--
4-61 4-82	Tenex 72-31B	IMI	3	--	79.7	--	--
4-77	Caterpiller 955	IMI	1	--	79.0	--	--
	Caterpiller 966C	IMI	1	--	77.0	--	--
4-78	Tenex 72-31B	Pass-by	1	--	81.0	--	--

* Number of Samples
** Duration of Measurement

Table 9

Measured Noise Data For Graders

Sample No.	Equipment	Test Condition	L_{max}
4-5	Caterpiller 12F (or 12G)	Pass-by	84
4-10	Caterpiller 12G	IMI	82
4-64	Autograde	Pass-by	83.5

Table 10

Measured Noise Data For Backhoes

Sample No.	Equipment	Test Condition	N*	Noise Descriptors dB			Δt** (secs)
				L_{eq}	L_{max}	SEL	
3-9	Gradall G660	Activity	1	78.4	80.2	89.2	12.0
3-10	Koehring 666	Activity	6	84.0	86.5	98.9	30.7
3-18 3-19	P&H Backhoe	Activity	8	88.7	91.4	103.8	32.4
3-30 3-38	Caterpiller 225	Activity	12	85.5	87.1	99.5	25.0
3-36	Koehring 466	Activity	7	84.5	88.5	99.1	28.9

* Number of Samples
** Duration of Measurement

Table 11

Measured Noise Data For Dozers

Sample No.	Equipment	Test Condition	N*	Noise Descriptors dB	
				L_{eq}	L_{max}
3-7 3-40	Caterpiller D6	Activity	5	--	83.6
4-2A	Caterpiller D8H	IMI	1	--	82.0
4-2	Caterpiller D7G & D8H	Activity	1	77.6	--
4-28	Caterpiller D7F	IMI	1	--	79.0
4-30	Caterpiller D9 (No Muffler)	Activity	1	--	96.0
4-38	Caterpiller D7G (With Partial Engine Enclosure)	IMI	1	--	78.0
4-48	Caterpiller D6D	Activity	1	71.3	77.0
4-49	Caterpiller D6D	IMI	1	--	80.0
4-51	Caterpiller D7F	IMI	1	--	78.0
4-58	Caterpiller D7G	Activity	1	73.8	--
4-59	Caterpiller D7G	IMI	1	--	76.0
4-63	Caterpiller D8H	IMI	1	--	77.0

* Number of Samples

Table 12

Measured Noise Data For Cranes

Sample No.	Equipment	Test Condition	N*	Noise Descriptors dB			Δt (secs)
				L_{eq}	L_{max}	SEL	
3-33	Koehring 665C	Concrete Bucket Pour	1**	72.0	75.0	--	120***
3-37	Heavy-Duty Crane	Loading	1**	74.6	81.5	--	45***
4-23	Link Belt LS78	Dredging	1**	77.3	85.0	--	--
4-65	American 797	Lifting	1**	65.1	73.0	--	--

* Number of Samples

** Several Cycles

*** Time Per Cycle

Table 13

Measured Noise Data For Compactors

Sample No.	Equipment	Test Condition	N*	Noise Descriptors dB			Δt** (secs)
				L_{eq}	L_{max}	SEL	
3-3	Čaterpiller 470 (With Modified Scraper)	Activity	-	73.2	80.0	--	180
3-7	Vibratory Roller	Activity		--	86.0	--	--
3-29	Buffalo Springfield K458 Roller	Pass-by		--	93.0	--	--

* Number of Samples

** Duration of Measurements

Table 14

Measured Noise Data For Pile Drivers

Sample No.	Equipment	Test Condition	Noise Descriptors, dB	
			L_{eq}	L_{max}
3-20	Pile Driver	49 Impacts Per Minute	99	106
3-39	Pile Driver	Operation	96	105
3-40	Pile Driver	Operation	95	101
4-35	Pile Driver	80 Impacts	98	---

Table 15

Measured Noise Data For Miscellaneous Equipment

Sample No.	Equipment	Test Condition	Noise Descriptors, dB		Δt* (secs)
			L_{eq}	L_{max}	
3-48	Barber Greene Asphalt Spreader, Dynopac Vib. Roller, Mack Dump Truck, Ford Water Truck	Asphalt Paving	80	82.5	--
3-48	Roller	Pass-by	--	87	--
3-M2	Homelite 3-5 Kw Gas Generator	Operation	74	76	--
3-45	Homelite 3-5 Kw Gas Generator	Operation	72.5	73.9	--
3-45	Hand Grinder on Concrete	Operation	70	71	--
3-M1	Jaeger 600 cfm compressor	Operation	--	84	--
4-8	Well Point Pump	Operation	--	63	--
4-66	Concrete Saw	Cutting	88	--	8 min.
4-84	Jackhammer + Compressor	Operation	83.9	86	15 min.
4-19	Concrete Batch Plant	Operation			
	• Pump Off		82	--	--
	• Pump On		88	--	--
4-16	Concrete Paving Train		78.3	82.0	41
4-47	Concrete Pouring, Including Truck, Crane, Vibrator, Gas Generator	Operation	72.8	78	15

* Duration of Measurement

4.0 CONSTRUCTION NOISE ABATEMENT MEASURES

4.1 Summary of Feasible Abatement Measures

An in-depth review of the literature has revealed that while many potential abatement techniques have been identified, in situ implementation of these techniques has been limited, thereby minimizing the volume of data available for assessing the acoustical and cost-effectiveness of each treatment. Still, the literature has provided sufficient information to define each potential abatement treatment and evaluate its comparative effectiveness. This section summarizes the results of this evaluation.

At the FHWA Symposium on Highway Construction Noise,[19] construction noise impact abatement methods were identified and classified into four categories. This list of candidate methods has been modified and extended here to include five categories of abatement measures:

1. Construction Equipment Noise Control – reduction of source noise levels through modification of new equipment designs, or retrofitting of existing on-site equipment; includes equipment utilizing an internal combustion engine as well as impact and power tools.
2. Construction Site Noise Control – utilization of sound path modification methods and preferred positioning of equipment to reduce site noise emissions.
3. Construction Strategy Modifications – adoption of alternative construction processes, operational techniques, or scheduling procedures in order to minimize noise impact.
4. Noise Control Incentives – use of contractual incentives to gain contractor cooperation in reducing site noise levels.
5. Community Relations – minimization of the impact of unavoidable noise through the maintenance of good public relations.

Further insight into what has been learned through the literature regarding each type of abatement is provided below.

4.1.1 Construction Equipment Noise Control - Medium/Heavy Equipment

Mitigation of construction noise at its source, i.e., equipment noise control, is the most advantageous approach to noise abatement, as medium/heavy equipment represents the predominant sources of noise on a construction site. Basically equipment noise control may be subdivided into:

1. New equipment design;
2. In-use equipment retrofit;
3. Maintenance of equipment.

Equipment abatement measures have been delineated in this manner in order to further understand the practicality of each.

Equipment powered by the internal combustion engine generally represents the primary source of noise on a construction site. Numerous research efforts aimed at reducing one or more of the major noise-producing sources on diesel engines can be cited. In few instances, however, have the resulting equipment noise control techniques been implemented on a broad basis by the construction machinery manufacturers. It would appear that the major efforts by manufacturers to control noise on construction equipment have been in response to European noise emission regulations as well as to the need to reduce operator noise exposure in accordance with OSHA requirements.[6,75,106,107,127] It should be noted, however, that equipment design modifications aimed at increasing operating efficiency have also led to distinct ancillary benefits in the form of reduced noise emissions.

Literature summarizing manufacturers' efforts to meet European noise regulations generally emphasizes the fact that extremely short lead times were provided to meet very stringent noise standards.[6,75] This necessitated the implementation of component noise source abatement techniques which did not require major modifications associated with design cycle engineering changes.[127] A survey of manufacturers revealed that while several major pieces of heavy equipment now benefit from major noise control design modifications, a majority of the equipment sold in the U.S. utilize only a limited set of component noise reduction techniques, if any.*

In total, it may be concluded that the literature provides little insight into what currently exists in terms of new equipment design or retrofit noise reduction technology on construction equipment. The EPA Background Document[127] points out that no program aimed at demonstrating noise abatement treatments for construction equipment has been undertaken, although a great wealth of applicable information on diesel engine noise reduction techniques has been derived from the U.S. DOT Quiet Truck Program. It is apparent that further details as to the availability of noise abatement hardware must be sought through communication with the construction equipment manufacturers.

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* Based on a survey of five major construction equipment manufacturers undertaken as part of Task B of this study.

Recall from Section 3.2 that the primary sources of noise on equipment using an internal combustion engine are:[127]

- Fan
- Exhaust
- Engine Casing
- Air Intake
- Transmission
- Hydraulics
- Track

A review of applicable noise abatements as they pertain to each of the above sources is presented below.

Fan Noise

Several documents indicate that fan noise is the dominant source on most typical construction equipment.[75,107,122] The French Noise Test Procedure is such that cooling system noise rather than intake, exhaust, or mechanical noise are emphasized.[75] For these reasons, fan noise reduction methods are addressed far more extensively than any of the other component noise reduction techniques. Mann[75] points out that the cooling system must be treated as a system due to the interrelationship between noise, cooling capacity, component design, and environmental installation in the vehicle. Hence the problem of fan noise reduction is an engineering problem which cannot readily be resolved through on-site retrofitting of existing equipment.

Kamperman, et al.,[64] report that excessive fan noise can be reduced through consideration of the following design changes:

- Fan shroud improved and fan tip clearance reduced
- Aerodynamic open grill in front of the radiator
- Suction fan instead of pusher fan
- Mechanical obstructions minimized on the engine side of the fan
- Thermostatically controlled or viscous clutch

Later references provide examples of the effectiveness of the above-mentioned noise reduction techniques, as well as others.

- Fan speed reduced
- Fan redesigned
- Radiator redesigned
- Rear duct with deflector vanes

The effectiveness of several of the above techniques was demonstrated by Stephenson and Thomas[122] on a wheeled loader and a crawler excavator. A summary of the equipment noise levels achieved as a result of sequentially implementing a series of noise abatement treatments is presented in Tables 16 and 17. With the exception of the muffler and undertray modifications, each of the modifications applied to the loader or excavator relate to the cooling system. The data in Table 16 indicates that a reduction in external noise by 17 dB at the rear and 8.5 dB at the sides was achieved on one loader as a result of cumulative modifications to the cooling system. However, it should be noted that these high values of noise reduction were obtained for a machine in which 92 to 97 percent of the vehicle noise energy was contributed by the fan. It is questionable whether this example is typical of wheeled loaders. In applying each modification, careful consideration was given to its resulting effect on cooling system performance.

Reductions in excavator noise levels through cooling system modifications are not as high as for the loader, due primarily to the fact that fan noise is not as predominant on this machine. External noise levels were reduced by 6 to 10 dB with the fan clutched-out, 4 to 7 dB with the fan clutched-in. These figures include the effects of muffler and undertray modifications also. Note that this is the only reference identified where use of a fan clutch on construction equipment is proposed. It would appear that the operating characteristics of most equipment are not conducive to use of fan clutches, although this is not explicitly stated.

Rudny[107] provides insight into the effectiveness of a louvered fan silencer duct in reducing the exterior sound level of a wheeled loader. V-shaped louvers lined with absorptive material were mounted directly behind the radiator core of the rear-mounted engine. This type of installation is capable of reducing exterior A-weighted sound levels at the rear of the vehicle by about 7 dB (measured at 7m). The effects on sideline measurements are not discussed. No indication is given as to the availability of such fan silencers for adaptation to existing loaders, or whether such louvers are being utilized on current domestic designs of these machines.

Evidence as to the effect of other fan noise reduction techniques can be cited. Mann[75] presents results of a study into cooling system noise reduction on a Case 580CK Loader-Backhoe. The key results may be summarized as follows:

- A 21-percent decrease in fan speed resulted in a 7.5 dB reduction in A-weighted sound level at the second blade pass frequency (200 Hz), which represents the peak sound level in the fan noise spectrum. Reduction of the fan speed necessitated the implementation of a more efficient radiator.

Table 16

Summary of Acoustic Test Results for
Wheeled Loader (Reference 122)

Test Condition	A-Weighted Sound Level at 7m From Machine (dB)		
	Rear	Left-Hand Side	Right-Hand Side
Standard Machine	104	94.5	94
Fan and Radiator Moved 64mm, Hose Rerouted, Guard Removed	96	88.5	88.5
Grill Removed	94	88.5	88.5
Fan Speed Reduced 25%	91.5	86.5	85.5
Rear Duct, Aerofoil Fan	87	86	85.5
Total Reduction	17	8.5	8.5

Table 17

Summary of Acoustic Test Results for Crawler Excavator (Reference 122)

Test Condition	A-Weighted Sound Level at 7m From Machine (dB)		
	Rear	Left-Hand Side	Right-Hand Side
Standard Machine	90	91	90
Puller Fan Fitted	90	91	90
End Ducts and Undertray	90	86	86
Muffler Changed	86.5	86	86
Viscous Fan:			
Clutched-In	86.5	84.5	84.5
Clutched-Out	80.5	80.5	83
Total Reduction	9.5	10.5	7

- A complete square edge orifice shroud placed over the standard shroud reduced the A-weighted sound level by an additional 2.5 dB at the second blade pass frequency.
- An acoustic shield constructed from sheet steel and 1-inch acoustic foam was installed in front of the radiator, reducing cooling system noise by 5.5 dB as measured at 4m.
- Obstructions of airflow behind the fan were determined to increase cooling system noise by 3 dB as measured 7m from the front of the vehicle.

Much of the research reported by Mann in 1973 is still applicable to current equipment designs. However, it is not clear from the literature which are available on a retrofit basis. The EPA Background Document[127] indicates that the most promising approaches to reducing fan noise are:

- Improved fan shrouds and reduced fan tip clearance
- Increased radiator-to-fan-to-engine clearance
- Radiator redesign
- Fan redesign

Baranski, et al.,[6] state that much of what was learned through the Quiet Truck Program on cooling system noise reduction is being incorporated into today's designs by construction equipment manufacturers. However, the specific designs employed are not clearly delineated in the literature. It is apparent, however, that reductions in component noise of 4 to 17 dB are achievable through cooling system modification.

Exhaust Noise

Exhaust noise on construction equipment has been evaluated extensively, as this is a primary noise source for which immediate reductions can be achieved on in-use vehicles through retrofitting. Examples of equipment quieting through the use of new and/or improved muffling systems are numerous.[5,24,106,107,122,127] A survey of major manufacturers of construction equipment mufflers reveals that a wide range of adequate exhaust systems which will reduce exhaust noise levels to those levels exhibited by the fan or engine exists for diesel engines.* Muffler manufacturer data indicates that exhaust noise levels of 69 to 90 dB (measured at 50 feet) are achievable on construction equipment through the application of effective mufflers. Obviously, the minimum achievable level is

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* Based on information compiled from Donaldson, Stemco, and Walker muffler manufacturers as part of efforts undertaken in Task B of this study.

dependent upon the size and type of engine. Generally, a 5 to 10 dB reduction in equipment noise levels can be realized by fitting a muffler to the exhaust.[19,38]

Other key points regarding exhaust system design are as follows:[139]

- Exhaust back pressures (a difficulty cited by some manufacturers) of most mufflers are so low that the effect on net horsepower is not measurable with ordinary instruments.
- The sound reduction properties of mufflers depend more on their internal design, materials, etc., than on physical size.
- Exhaust pipe should be of heavy material. Flexible joints and pipes should be avoided.

Engine Casing Noise

Perhaps the most successful attempts to reduce engine noise occurred during the DOT Quiet Truck Program. The most common methods for reduction of engine noise are:

- Engine enclosure
- Vibration isolation

Use of adaptive engine enclosures and lining of existing hoods with absorptive material would seem to represent the most feasible approach to reducing engine noise. The EPA Background Document[127] states that noise level reductions of 2 to 10 dB are possible through the use of side panels and belly pans on wheeled and crawler tractors. Rudny[106,107] indicates that side panels may be necessary on front-end loaders to meet future, more stringent European noise regulations. Experimental application of side panels to a front-end loader is discussed by Rudny,[106] but data showing the resultant effect on exterior noise levels are not presented. Overall, the literature provides few examples as to the use of engine enclosures on construction equipment, and gives no indication as to the availability of engine covers and enclosures for use as a retrofit item on existing equipment. Discussions with one manufacturer, Caterpillar, revealed that their current design heavy front-end loaders can be adapted with louvered panels and acoustically treated undertrays. Such enclosures are fitted to equipment shipped to Europe, and can be retrofitted to current design machines used domestically. Thus it would appear that the availability of engine enclosures for construction machinery is equipment specific.

Isolation of components attached to the engine, as well as of the engine itself, can reduce noise caused by engine vibration. The literature suggests that noticeable reductions can be achieved when vibration isolation is applied to valve covers, manifolds, crankcases, covers, and oil pans. The EPA Background Document[127] suggests that a 3 to 5 dB reduction is achievable, although specific examples are not cited. Problems with durability and sealing performance must be considered in applying this technique. Rudney[106] indicates successful results when neoprene isolation mounts were used on the engine and transmission of a front-end loader. Suggestions as to whether it is feasible to apply this treatment on a retrofit basis are not made in the literature. However, conversations with several major equipment manufacturers indicate that isolation mounting of the engine and transmission is widely used on new equipment designs, but is not recommended for use in retrofitting older equipment.

Air Intake Noise

The nature of the operating environment for construction equipment requires a high level of filtration for intake air. That intake filter elements tend to act as silencers for air intake noise results in this being a secondary source in comparison to others.[127]

Transmission Noise

If properly designed, the transmission will radiate noise levels significantly below those exhibited by other sources.[127] However, as previously illustrated in Figure 1, transmission noise measured for a moving front-end loader was found to be the second loudest component noise source.[122] Transmission noise abatement through redesign is not discussed in the literature and is not considered here as a feasible approach. Limited reference is made to the use of shielding.[127] Examples of transmission enclosures as used on heavy trucks are provided through the DOT Quiet Truck Program.[148] However, the application of such enclosures to construction equipment is questionable due to obvious differences in both design and use of the equipment. No direct examples of the use of shielding to reduce construction equipment noise levels were identified in the literature. This would suggest that, in most instances, transmission noise is considered a secondary source.

As noted previously, isolation mounting has been proven beneficial in reducing noise due to vibration transmitted to the main frame.[106] Transmissions on Caterpillar's heavy front-end loaders currently utilize isolation mounts. No information is given as to the precise effect on exterior noise levels.

Hydraulic Noise

Hydraulic noise on construction equipment is typically a secondary source. Thus hydraulic noise reduction has been given only limited attention in the literature. Methods identified for reducing hydraulic system noise include:[19,64,122,127]

- Use of quieter pumps;
- Use of in-line silencers;
- Replacement of rigid piping with hydraulic rubber hoses;
- Vibration-isolation of large hydraulic valves.

Examples of applications of these techniques are limited. Kamperman[64] notes that a 2 to 5 dB reduction in hydraulic noise can be achieved by replacing rigid piping with hydraulic rubber hoses. It is also noted that structure-borne transmission of hydraulic noise will be minimized through the use of isolation mounts.

Stephenson and Thomas[122] cite a case in which resonance from a rigid hydraulic pipe located near the operator's cab of a crawler excavator resulted in an annoying whine which dominated the cab noise. Subsequent replacement of this pipe with a flexible hose eliminated this problem in the cab, but had no apparent effect on exterior noise levels.

Track Noise

Attempts to limit track squealing have been made through the use of improved lubrication systems. However, this has not resulted in total elimination of track noise. Specifically, the problem of track impact noise, which is highly dependent on soil conditions, still remains. No practical solutions for reducing this source of noise were identified in the literature.

Equipment maintenance must also be considered as a potentially useful noise preventive strategy. FHWA[102] points out that poor maintenance can lead to abnormally high equipment noise levels. It is suggested that "significant" reductions in noise are achievable through correction of maintenance problems. However, little or no data is reported which enables definition of what may be deemed significant reductions. Regardless, maintenance of noise sensitive components appears to be highly cost effective since it typically can be incorporated into the normal maintenance process. Faulty and damaged exhaust mufflers, hydraulic system problems, loose engine parts, and slack or dry tracks are prime candidates for causing increased equipment noise levels.[14] It is recommended by FHWA[102] that requirements for proper maintenance of all construction equipment be included in the specifications given to the contractor,[102] thereby making the contractor fully aware of the need to maintain those components which might affect the noise level of the equipment.

4.1.2 Construction Equipment Noise Control - Impact Equipment and Power Tools

Considerably less literature exists pertaining to noise reduction techniques for impact equipment and power tools than for medium/heavy equipment. This is due to two reasons: (1) this equipment does not benefit from a wealth of related research such as the DOT Quiet Truck Program, and (2) the equipment does not have as significant an impact on the noise environment as machinery which utilizes internal combustion engines. This is not to say that impact equipment and power tools do not present a serious noise problem on the construction site. Kessler and Gray[140] note that pavement breakers and rock drills rank among the top ten in total acoustic energy emitted by construction tools.

Greatest attention has been focused upon impact equipment, i.e., breakers, rock drills, and pile drivers. With respect to breakers and rock drills, noise control methods are currently limited to mufflers for pneumatic tools, and damped moils for portable breakers. Kessler and Gray[140] identify the four primary types of mufflers in commercial use today:

- Strap-on muffler
- Integral muffler
- Remote muffler connected to the tool by a hose
- Internal compartment for expansion of exhaust air

Of these four, the strap-on muffler, which fits over the exhaust ports and surrounds part or all of the cylinder case, represents the most common type of muffler utilized. Strap-on mufflers range in size from those which just cover the exhaust port to those which enclose the entire cylinder case. Data presented by Kessler and Gray[140] indicate that a 5 dB reduction in noise level of a portable pavement breaker is achievable using a strap-on muffler which covers only the exhaust ports.

Hallman[38] also cites the availability of proprietary mufflers for use in reducing exhaust and cylinder casing noise of pneumatic tools. For example, the A-weighted sound level of a pneumatic concrete breaker (measured at 7m) was reduced from 101 dB to 93 dB through the use of an exhaust silencer. Similarly, the noise level of a pneumatic rock drill was reduced from 124 dB to 116 dB. Hallman points out that noise control measures for such tools have been designed primarily for protection of operators, but these abatement measures can also lead to noticeable reductions in site boundary noise levels.

Kessler and Gray[140] also note that several manufacturers provide mufflers for pavement breakers which enclose the entire cylinder case, thus acting to attenuate both exhaust and cylinder casing noise. Such a device typically provides 7 dB in noise reduction for the breaker.

It should be noted that all of the mufflers discussed above apply to pneumatic equipment; exhaust noise on hydraulic and electric breakers is, of course, not a problem.

Reduction of ringing noise associated with the tool steel can be accomplished through the use of damped moils, which are available commercially. However, Kessler and Gray[140] point out that moil damping has only a minimal effect unless the other primary noise sources (i.e., exhaust, cylinder casing, and front head) are first attenuated. For example, only one decibel reduction in A-weighted sound level is achieved when moil damping is applied to a tool with only a strap-on muffler.

Through the combined use of an exhaust silencer and damped moil, Hallman[38] indicates that 12 dB in noise reduction (measured at 7m) is possible for a portable breaker. While this represents a substantial reduction in noise, it is evident that the A-weighted sound level of such pneumatic equipment is still in the 90 to 100 dB range. Further, Hallman[38] notes three disadvantages associated with utilizing such noise control methods:

- Damped moils cost twice as much as conventional steels
- Mufflers can be ruined during heat treatment of the moil after resharpening
- Mufflers can be bulky and act to reduce operating efficiency

This may help to account for the limited use of such noise reduction treatments at present.

With respect to pile drivers, the literature provides little insight into potential methods for reducing noise. Alternative pile-driving techniques have been suggested and are reviewed in Section 4.1.4.

It appears very difficult to achieve a reduction in pile-driving noise in excess of 10 dB due to the fact that the pile is free to resonate and therefore transmits airborne noise. Application of shrouds appears to be the most effective approach to noise reduction. Hallman[38] presents two examples of noise control methods demonstrated in the United Kingdom on drop hammer rigs. The first, called a "Hush" piling rig, utilizes a complete enclosure around the crane-supported drop hammer and pile. The enclosure consists of multilaminated bonded steel/rubber panels. A manually operated door on the side of the enclosure allows access for the piles. Sand bags can be placed around the bottom to provide an acoustic seal. With the enclosure installed, individual hammer blows measured 80 dB at 7m. The level rose to 94 dB when the door to the enclosure was opened (comparable to the level exhibited by standard pile drivers).

Hallman also describes a noise-reduced method of sheet piling which was developed by W.A. Dawson, Ltd. This device consists of a cast iron hammer weighing 5 tons which is dropped over a short distance, usually less than a meter. The hammer is completely enclosed in a 6mm-thick steel shroud which is lined at the bottom with a resilient cushion. The piles remain exposed, although those being driven are partially damped by tight-fitting plastic rollers. The range of noise levels measured for individual hammer blows was 85 to 92 dB at 7m, with a mean value of 88 dB.

Each of the above pile-driving methods appear promising as a viable alternative. However, Hallman provides no indication as to the availability of such equipment in the U.S. Thus their applicability to highway construction here is not known.

With respect to pneumatic power tools, such as grinders, hoists, and tampers, noise control methods have generally been developed to reduce the main source of noise – exhaust. Information acquired from manufacturers verifies the availability of silencers for several types of hand-held equipment.* The literature, however, provides little detail as to the level of actual noise reduction that is achievable through the use of such silencing techniques. Again, it would appear that noise control methods for such tools have been developed primarily for the sake of reducing operator exposure.

Hallman[38] also notes that it is possible to reduce the high-pitched whine associated with circular saw blades. Integrally damped saw blades are commercially available and can be used to reduce noise during both idling and cutting. Spring-loaded felt-tipped damping pegs were shown to reduce noise at the operator's position of a circular saw (idling) from 110 dB to 91 dB. Similar research into the control of saw blade noise has been conducted by Wyle.[150]

In total, literature pertaining to noise reduction techniques for impact equipment and power tools is limited. Several abatement treatments have been identified as being commercially available. Two potentially useful techniques for reducing conventional pile-driving noise have been demonstrated in the United Kingdom, but their availabiity in the U.S. is not known. It is apparent that additional information from equipment manufacturers will have to be obtained.

4.1.3 Construction Site Noise Control

In situations where construction noise levels pose a problem over a small area near the site, use of site noise controls such as the following can prove beneficial:

- Sound barrier
- Earth berm
- Equipment enclosures
- Equipment location
- Site maintenance

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* Information obtained as part of efforts undertaken in Task B of this study.

The attenuation provided by a sound barrier will be dependent upon (1) the noise characteristics of the source, (2) the barrier location, and (3) the barrier material and design. For a highway construction site where the activity moves over a large area, the effectiveness of the barrier may vary.[19] Generally, a construction site barrier will not prove as efficient as a highway barrier, but still holds the potential for reducing noise by 5 to 10 dB (the actual level of attenuation being dependent upon barrier geometry, barrier construction and source characteristics).[29]

Use of timber wall barriers appears to be the most effective approach, as timber exhibits relatively high transmission loss characteristics, has a comparatively low initial cost,[110] and the walls are easy to construct. Timber walls may be easily constructed in segments such that a barrier may be dismantled and reused at another location, thus improving the cost-effectiveness.

Several articles outline the most effective approach to employing barriers at a construction site.[7,19,29,33,35] However, few examples regarding actual implementation of such barriers could be found. Fuller, et al.,[149] presented an analysis of the effectiveness of a construction noise barrier designed by Wyle for a portion of haul road at a dam construction site. Barriers 20 feet long and 470 feet in length were constructed along each side of a specified segment of the haul road. Measurements taken at the construction site revealed that the barrier provided 10 dB reduction in the A-weighted sound level (measured at 100 feet) for loaded heavy earthmoving equipment operating on the haul road.

Data on the costs of applying construction site barriers and berms are limited. A first estimate of the cost is provided through evaluation of costs associated with construction of highway noise barriers. Data compiled by FHWA[117] reveal the following costs:

- Earth Berm – cost to construct is estimated to vary from $1.00 to $2.00 per cubic yard (based on data for 1970 to 1974). The cost of a 10-foot-high berm with 1:2 side slopes ranged from $15.00 to $30.00 per linear foot.
- Timber Wall – cost to construct ranges from $3.00 to $5.00 per square foot for normal wall heights of 8 to 14 feet.

Kessler[67] reported that the cost in 1977 of a plywood barrier was approximately $650 per 1000 square feet. This is significantly lower than the construction cost figures presented by FHWA. The Wyle-designed plywood construction barrier described above cost approximately $1.40 per square foot ($28.00 per linear foot) to build in 1977.[149]

At the FHWA Symposium on Highway Construction Noise,[19] it was suggested that if barriers are to eventually be used for highway traffic noise control, they might be erected early in the construction process to reduce construction noise as well. It would appear that many contractors today are pursuing this approach.*

An earth berm can provide noise attenuation levels similar to those possible with a barrier, but is not as practical in its application. Development of an earth berm which is acoustically effective requires large amounts of excavated material and sufficient right-of-way width. Assuming most berms will be built with approximately a 2:1 slope, then as a rule of thumb one may assume that the width of the berm at the base will be 4 times its height (e.g., an earth berm 20 feet in height will require an 80-foot right-of-way). Further, the construction of a berm can only be considered feasible when there is sufficient excavated material available for its construction without requiring the handling of significant amounts of additional borrow material.[29]

Many pieces of equipment found on site remain stationary for long periods of time, and can be quietened by erecting a simple enclosure. Such enclosures must be designed, however, with consideration for equipment operational efficiency and enclosure acoustical effectiveness. Schomer, et al.,[100] summarized the basic guidelines for application of equipment enclosures. Examples aimed at demonstrating the effectiveness of such enclosures at an actual construction site were not found in the literature.

Consideration for positioning of construction equipment as far as possible from impacted areas is cited as a potentially useful abatement method.[19,33,67,109] Fuller, et al.,[29] found that repositioning of stationary equipment generally has little effect on reducing overall site L_{eq} values, due to the fact that the construction noise environment is typically dominated by the mobile equipment sources. However, Schomer, et al.,[110] point out that with respect to specific noise-sensitive areas adjacent to a site, location of noisy equipment at a significant distance will help minimize overall annoyance. Goff, et al.,[33] suggest that the location of noisy activities can be changed according to time of day. For instance, noisy operations at night could be performed near areas inhabited only during the day. This strategy could be used to produce positive effects if employed properly. However, as with equipment enclosures, evaluation of their effectiveness through in-situ demonstration is not provided in the literature.

Site maintenance refers specifically to the upkeep of haul roads used by rolling stock. Periodic grading of the road surface will eliminate surface irregularities which can

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* Based on a survey of five major construction equipment manufacturers undertaken as part of Task B of this study.

generate unnecessary chassis noise (especially on unloaded vehicles). Soil or rocks lying in the haul road should be removed so as not to cause vehicles to decelerate/accelerate more than is necessary. Crews conducting traditional site maintenance could be instructed to consider noise abatement in performing their duties. Costs beyond those already allocated for general site maintenance would be negligible.

In summary, construction site noise control methods represent potentially useful techniques for reducing construction noise impact in small areas near the site. Numerous articles have been identified which recommend the use of site control methods and provide guidelines for their implementation. However, examples relating to direct implementation and evaluation of these methods are quite limited.

4.1.4 Construction Strategy Modifications

Modification of the strategies associated with highway construction for the purpose of reducing the noise impact includes the following possibilities:

1. Substitution of alternative equipment for performance of a particular task;
2. Rescheduling of noisy operations to coincide with periods of least noise sensitivity.

Equipment substitution for the purpose of reducing total noise emissions may occur in one of three forms:

1. Replacement of existing equipment with smaller, less noisy equipment;
2. Introduction of alternative types of construction equipment;
3. Replacement of older equipment with newer, less noisy machinery.

The effectiveness of replacing equipment with smaller, less noisy machinery is questionable. From the construction standpoint, there appears to be little incentive for a contractor to substitute smaller equipment when larger machinery can be used. Thus the practicality of the abatement must be questioned immediately. Schomer, et al.,[109] attempted to assess the effectiveness of using smaller equipment as a noise control method by developing hypothetical replacement scenarios. It was discovered that for the case of a grading-site preparation task, total noise exposure and cost were both minimized when utilizing the largest capacity machines. For a trenching operation, however, the optimum size machine was shown to be neither the largest nor smallest capacity equipment, but rather a machine of medium trenching capability. Using a measurement scale in which duration of exposure is weighted equally with intensity of exposure (this is valid as long as one is defining noise exposure in terms of L_{eq}), it was shown that, for the most part, the reduction in noise intensity associated with a smaller machine is usually offset by an equivalent increase in the time required to accomplish a prescribed task. However, further calculations performed by Wyle upon hypothetical construction task situations show that the effectiveness of equipment replacement as a noise abatement strategy is dependent upon (1) the variation in sound level between equipment used, and (2) the variation in usage factors (i.e., a function of total operation time that a piece of equipment is in its noisiest mode).*

Substitution of alternative equipment may be useful in reducing the noise emission levels of some power tools. In particular, substitution of hydraulic, electric, or gasoline engine powered tools for pneumatic equipment can have a noticeable effect on noise levels. As an example, Hallman[38] presents data which suggest that a 12 dB reduction in noise emissions is possible when a gasoline engine 36 kg concrete breaker is substituted for the pneumatic equivalent. Reductions of 8 to 10 dB appear feasible when the pneumatic breaker is replaced by a hydraulic or electric tool, respectively (the actual level of noise reduction is highly dependent upon operating conditions and the type of material being penetrated). It would appear that similar substitutions could be made for other types of power tools, although the levels of noise reduction may or may not be great.[19] Examples demonstrating the feasibility and effectiveness of such substitutions were not found in the literature.

Ancillary construction operational considerations must be taken into account when assessing the feasibility of equipment replacement. Specifically, most contractors will not have spare equipment available to substitute for other equipment during a project. Therefore equipment replacement represents an abatement strategy which is best applied prior to project initiation. This would seem to reduce the flexibility of this abatement method.

Introduction of alternative construction processes is also suggested as a potentially useful noise preventive strategy. However, little work has been done in comparing the noise emissions of alternative construction processes. For cut and fill operations (the two most prevalent processes during the earthwork phase), Martin and Solani[77,78] conducted site boundary noise measurements which revealed very little difference in sound level for a scraper/dozer versus dump truck/loader operation. It was also noted that very quiet earthmoving can be achieved by using conveyors, although there is likely to be some loss of operating flexibility.[77]

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* Based on calculations performed as part of efforts undertaken in Task B of this program.

Utilization of alternative construction techniques generally means utilization of alternative equipment types. Therefore alteration of major construction processes is not considered feasible once work has been initiated. Rather, selection of the most effective construction process must occur during the design and processing stage of a project.[102] Thus construction noise can potentially be minimized through proper preconstruction planning.

Schomer, et al.,[109] present a summary of recommeded construction operational processes for reducing noise emissions. Additional recommended equipment and process substitutions were outlined at the FHWA Symposium on Highway Construction Noise.[19]

Various alternatives to the traditional pile-driving process were outlined at the FHWA Symposium, and are elaborated to varying degrees by Hallman,[38] Schomer, et al.,[110] Goodfriend,[35] Barnes, et al.[7] The primary alternatives are as follows:[19]

- Vibrating pile driver method. Instead of impact pile drivers, vibrating units are used. This possibility is limited since vibrating pile drivers can only be used in certain types of soil. Earth vibrations caused by vibrating pile drivers may also be undesirable.
- The "English" pile driver method. Steel piles are driven into the ground hydraulically.
- The slit trench method. Deep, narrow ditches are dug, which are then filled with concrete, eliminating the need for piles. This method is limited to the proper structure of supporting rock and soil and bearing weight required.
- The "Benoto" method. Piles are hydraulically inserted into the ground using rotation.

The literature provides little insight into the limitations associated with application of these alternative techniques as well as the anticipated noise reduction. As mentioned above, soil conditions will play a major part in determining whether a specific pile driving technique can be utilized.

Barnes, et al.,[7] suggest that use of sonic or vibrating pile drivers can provide "substantial" reductions in noise levels. Data to support this is not presented. Additional information was not found in the literature.

Hallman[38] discusses the use of the Taywood Pilemaster, a system for driving sheet piles which consists of eight hydraulic rams arranged in a crosshead side by side. Provided a quiet generator is used, there is little noise at the rig except the hum of the electric motor. Although specific noise levels are not cited by Hallman, an earlier paper by Page, et al.,[91] showed the noise level of the Pilemaster to be 69 dB measured at only 5 feet from the rig. Availabiity of such a rig in the U.S. is not indicated.

No additional information on slit trenching or the "Benoto" method of driving pile could be identified in the literature.

It may be feasible to replace existing older equipment with newer machinery having identical work capacity but reduced noise levels. This implies that (1) noise levels of certain equipment increase with time, or (2) newer equipment employs designs which reduce noise emissions. EPA[127] presents data which suggest that there is no clearly observable trend regarding the increase of wheel or crawler tractor noise levels with time, assuming periodic maintenance of equipment. However, it is questionable to what degree construction equipment is properly maintained since it is typically exposed to harsh operating conditions.

New equipment typically benefits from improved engineering designs, leading to noticeable reductions in exterior noise levels.* The cost of purchasing new equipment can be substantial. Thus equipment replacement as a direct form of noise control is not cost effective. Its effects will be seen, however, as older equipment becomes obsolete and is replaced by newer models.

4.1.5 Noise Control Incentives

It may be possible to reduce construction noise emissions through the use of contractual incentives which induce contractor cooperation in minimizing noise. Such incentives could take the following forms:[19]

1. Equipment and/or site noise specifications could be included in the bid documents.
2. Extended working hours could be granted to those contractors who meet the specified noise levels.
3. Bonuses could be allocated to those contractors willing to maintain reduced noise levels.

Inclusion of noise specifications in the bid documents will help assure that the contractor is fully cognizant of the need to mitigate noise. Such specifications may extend to include requirements for the use and maintenance of the best generally

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* Based on information derived from construction equipment manufacturers as part of the efforts undertaken in Task B of this program.

available mufflers on all gasoline or diesel engines. Reagen, et al.,[102] suggest that these specifications may also require equipment users to be properly trained in the use of construction equipment. Use of such specifications would seem feasible and effective if applied properly. However, these specifications will most likely prove to be weak if used by themselves, i.e., without the benefit of additional construction equipment and site noise control methods.

4.1.6 Community Relations

While public relations and community awareness do not represent a physical method of noise abatement, it can have a positive effect on reducing the impact of unavoidable construction-related noise and disturbances. Reagan and Grant[102] indicate that, depending on the scope of the construction project, the time involved in each particular phase, and the degree of unavoidable impact, the methods used to inform the public of upcoming noise impacts can be as simple as distributing flyers to adjacent property owners, or as complex as conducting public informational meetings. Regardless, it is emphasized that early communication is the primary consideration of any method. Information that should be provided by the contractor to the community should include:[19, 102]

- The importance of the highway project;
- The scope of the project and the scheduling of the construction phases;
- Actions taken which result in noise reduction;
- Procedures through which the contractor may receive and react to complaints.

Maintenance of community relations should be employed in unison with necessary physical abatement methods to minimize construction noise impact.

It is quite possible in many instances that public reaction to construction noise will come about as a result of initial annoyance to other aspects of the construction project. A survey conducted by Large, et al.,[68] revealed that some adverse response by surrounding communities to construction site noise is not directly associated with noise exposure but with perceived injurious effects attributable to the construction site. This points out the need for an overall program aimed at site maintenance and public awareness.

Examples aimed at assessing the effectiveness of community relations as a noise impact control technique were not found in the literature.

4.2 Field Demonstrations of Noise Abatement Measures

Four specific abatement measures were demonstrated and evaluated during the field measurement program described in Section 3.5. The objective of the demonstrations was to evaluate the effectiveness of each abatement measure in terms of acoustic, cost, and implementation factors. Specifically, each measure was evaluated in terms of:

a. measured reduction in L_{eq} at a specified position along the activity perimeter;
b. direct and indirect costs;
c. ease of implementation.

A brief description of each abatement measure demonstrated during the field measurements is provided in Section 4.2.1. An overview of the demonstration test procedures and a summary of the resulting data are presented in Sections 4.2.2 and 4.2.3, respectively.

4.2.1 Description of Abatement Measures

Demonstrations #1 and #2: Equipment Substitution

A series of equipment substitution demonstrations were performed at the I-95/395 (Baltimore) site. Tests were conducted on two types of equipment:

a. Portable Air Compressor – a unit meeting the specifications of the EPA Portable Air Compressor Noise Emissions Standards was substituted for an older compressor built prior to promulgation of the regulation. Tests were performed utilizing an Ingersoll-Rand XL750 Compressor (flow rate = 750 cubic feet per minute (cfm)) which was substituted for an older compressor of identical flow rate capacity.

b. Portable Pneumatic Breaker – hand-held units with and without exhaust mufflers were compared while breaking concrete. Chicago-Pneumatic CP-124 breakers fitted with standard concrete chiesels were used in each test.

Both the quiet compressors and portable breaker with muffler were leased through an equipment rental agency in the Baltimore area. Inquiries to other rental companies in the area verified that quiet compressors and breakers are readily available and can be obtained quite easily.

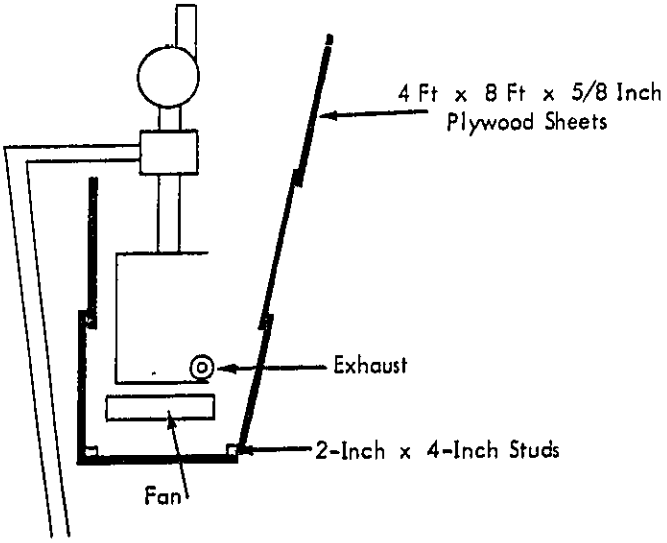

Figure 9. Enclosure Configuration (Plan View).

4.2.2 Description of Measurement Procedures

Demonstrations #1 and #2: Equipment Substitution

The basic procedure for demonstrating the equipment substitution abatement measures was as follows:

- The basic operational characteristics of the older equipment were documented and activity perimeter measurements were performed.
- Controlled, single equipment noise measurements were performed for the machine under observation. These measurements enabled comparison of the relative differences between new and old equipment noise levels, independent of operational factors which might bias the data.
- Where feasible, additonal measurements were performed on the equipment while under actual operating conditions.
- The above steps were repeated for the replacement equipment.

The above procedures yield A-weighted sound levels as a function of equipment operational mode as well as L_{eq} values of the prescribed activity. These L_{eq} values were compared to provide an estimate of the acoustic effectiveness of this abatement strategy.

Under conditions of actual equipment substitution, it is assumed that the contractor would purchase a new machine for replacement of the old equipment. Thus purchase price represents the primary cost factor associated with this abatement strategy. Such price information was obtained through discussions with representatives of the equipment manufacturers.

Demonstration #3: Exhaust System Retrofit

To assess the effectiveness of exhaust retrofit on reducing vehicle noise emissions, the following steps were followed:

- Once the specific equipment had been identified for observation, controlled, single equipment noise measurements were made to obtain A-weighted sound levels as a function of equipment operational mode.
- Each piece of equipment was then retrofitted with the best generally availabl muffler and associated connectors. As discussed earlier, care was taken in selecting the mufflers to ensure that engine performance was not degraded.
- Single equipment noise measurements were repeated for each machine.

Single equipment noise measurements provided comparative noise data which is independent of any operational-related bias. This enabled direct evaluation of the relative effectiveness of the muffler retrofits in reducing vehicle noise levels.

New exhaust system parts were considered here as a material cost, and were obtained when the mufflers used in this demonstration were purchased. Labor costs associated with retrofitting of the new systems were also accounted for. Arrangements were made with the on-site contractor to utilize his mechanics in replacing the systems. Total man-hours per machine were logged.

Demonstration #4: Equipment Enclosure

The basic evaluation procedures were as follows:

- Once the equipment had been identified for evaluation, activity perimeter measurements were made. Details regarding equipment operational characteristics were also obtained.
- Upon installation of the enclosure, the measurements were repeated, thus providing comparative A-weighted sound level data under controlled conditions. These data were utilized to provide an approximate value for the insertion loss associated with a given enclosure. Care must be taken to ensure that no major changes in construction activity operational characteristics have occurred between the "before" and "after" measurement cases.

As mentioned previously, material for the enclosures were obtained local to the prescribed test site. Thus material cost data were directly available. Total man-hours expended in constructing the enclosure were logged.

4.2.3 Summary of Results

Demonstrations #1 and #2: Equipment Substitution

Table 18 summarizes noise measurements performed on the standard and quieted compressors.

Table 18

Summary of Noise Measurements For Compressors

Equipment Description	Sound Level at 50 Feet	
	L_{eq} (dB)	L_{max} (dB)
Standard Compressor (Side Doors Open)	86	88
Quiet Compressor (Side Doors Open)	75	77
Quiet Compressor (Side Doors Closed)	65	67

Measurements revealed that substantial reductions in noise level are achievable through the introduction of a compressor which meets EPA Noise Emission Standards. With the quiet compressor operating in its recommended configuration (i.e., with the side doors closed), a 19 dB reduction in sound level (measured at 50 feet) was obtained. This is considered to be the maximum achievable noise reduction, as the standard compressor utilized here was relatively old and in poor condition. However, it is typical of many of the compressors used today on highway construction sites.

Data measured for the portable breakers is summarized below in Table 19.

Table 19

Summary of Noise Measurements For Portable Breakers

Equipment Description	Sound Level at 50 Feet	
	L_{eq} (dB)	L_{max} (dB)
Breaker Without Muffler	80	87
Breaker With Muffler	69	76
Total Noise Reduction	11	11

Significant reductions in construction site noise can be achieved through the introduction of mufflers to these demolition tools. An 11 dB reduction in A-weighted sound level (measured at 50 feet) was achieved when the quieted breaker was substituted for the standard model having no muffler. A noticeable reduction was anticipated since information derived from the literature indicated that exhaust noise is the predominant noise source on such tools.

Data from the two previously described abatement demonstrations is combined here on a hypothetical basis to assess the full potential of these equipment substitution techniques. Figure 10 illustrates the actual site where the compressor substitution was performed. (All compressor substitution measurements summarized in Table 18 were performed with all breakers shut down.) Sound levels as measured at 50 feet for each piece of standard and quieted equipment were extrapolated to Position D-1 assuming an attenuation rate of 6 dB per doubling of distance. The individual sound levels have been added on an energy basis to provide an estimate of the total noise level at Position D-1.

Based upon these calculations, a 16 dB reduction in noise level is afforded through substitution of the quieted equipment. Note that this sizeable reduction is achieved with no loss in work efficiency.

Cost data for the above-described abatement measures is as follows.

Quieted Compressors

1. Purchase Price = $46,000 (Rental = $2,600 per month).
2. No additional maintenance or operational costs as compared to standard compressor.

Quieted Portable Breaker

1. Purchase Price:

Breaker With Muffler	=	$965.00
Breaker Without-Muffler	=	895.00
Cost Differential	=	$ 70.00

2. Cost to rent breaker with or without muffler is identical.
3. No additional maintenance or operational costs when compared to standard breaker.

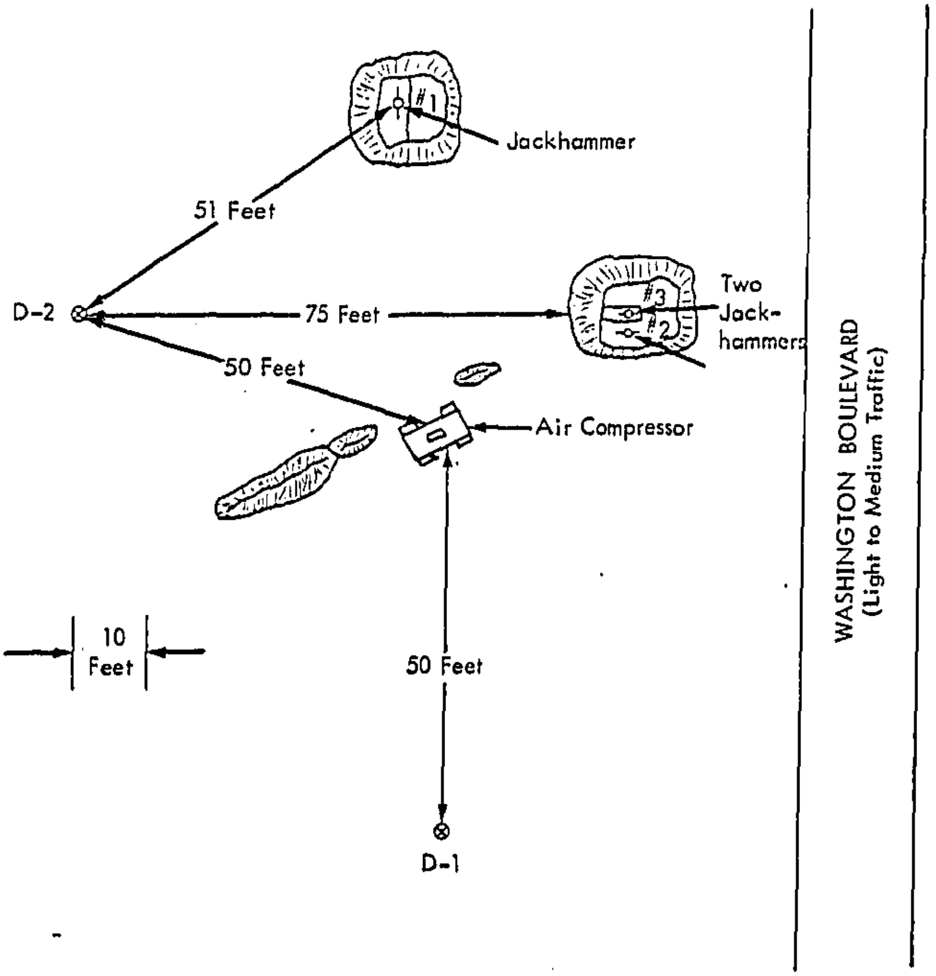

Figure 10. Site Configuration for Compressor Substitution.

Demonstration #3: Exhaust System Retrofit

Table 20 summarizes noise data acquired before and after retrofitting the three vehicles with new mufflers and clamps:

Table 20

Summary of Exhaust System Retrofit
Noise Measurements

Test Vehicle	A-Weighted Sound Level, dB		
	Before Exhaust System Retrofit	After Exhaust System Retrofit	Δ
Cat. D9G Dozer With Straight Stack	88	84	4
Cat. D9G Dozer With Muffler	84	81	3
Cat. 631B Scraper With Muffler	83	81	2

Noticeable reductions in vehicle sound levels were achieved for the two dozers. Reduction in sound level of the scraper, however, was minimal. This is due to the fact that the scraper was a much older piece of equipment, and mechanical noise appeared to contribute significantly to overall vehicle noise.

Costs associated with implementing new mufflers were as follows:

- Cat. D9G Dozer with Straight Stack:
  - Muffler = $171.85
  - Clamp = $ 7.35
- Cat. D9G Dozer with Muffler:
  - Muffler = $134.40
  - Clamp = $ 9.71
- Cat. 631B Scraper:
  - Muffler = $107.97
  - Clamp = $ 9.71

Approximately 3 manhours of mechanic's time was required to install each of the mufflers.

Numerous problems associated with fitting the new mufflers onto the vehicles were encountered. Specifically, these problems were noted:

- The muffler for the D9G with the straight stack interfered with the engine enclosure. Therefore part of the enclosure had to be cut away.
- The muffler for the other D9G did not fit the exhaust manifold even though it is the recommended stock muffler. It appeared that the manifold had been replaced at some time. Thus an alternate Cat. muffler had to be used.
- The stock muffler for the 631B scraper also did not fit, indicating that the exhaust system had been changed. A second muffler was ordered.

In talking with the mechanic, it became apparent that these types of problems are very common. Because they are older pieces of equipment (10 to 15 years old), many of the engine parts have been replaced using available hardware. But although these problems existed, it was still possible to obtain an adequate muffler which did not impede the performance of the machinery.

Demonstration #4: Equipment Enclosure

Measurements were made in a semicircle around the pump as shown in Figure 11. The resulting data are tabulated in Table 21 below. Note that the measurements were performed after construction along the right-of-way was stopped to ensure that background noise levels were at least 10 dB below the levels measured for the enclosed pump.

Table 21

Summary of Measurements of Well Point Pump
With and Without Enclosure

Test Condition	Average A-Weighted Sound Level (dB)						
	A (50 Ft)	B (50 Ft)	C (50 Ft)	D (50 Ft)	E (50 Ft)	F (25 Ft)	G (25 Ft)
Without Enclosure	74.5	76.2	74.8	76.4	72.1	--	--
With Enclosure	67.7	69.6	67.1	69.3	70.9	75.8	74.2
Change in Sound Level	-6.8	-6.6	-7.7	-7.1	-1.2	--	--

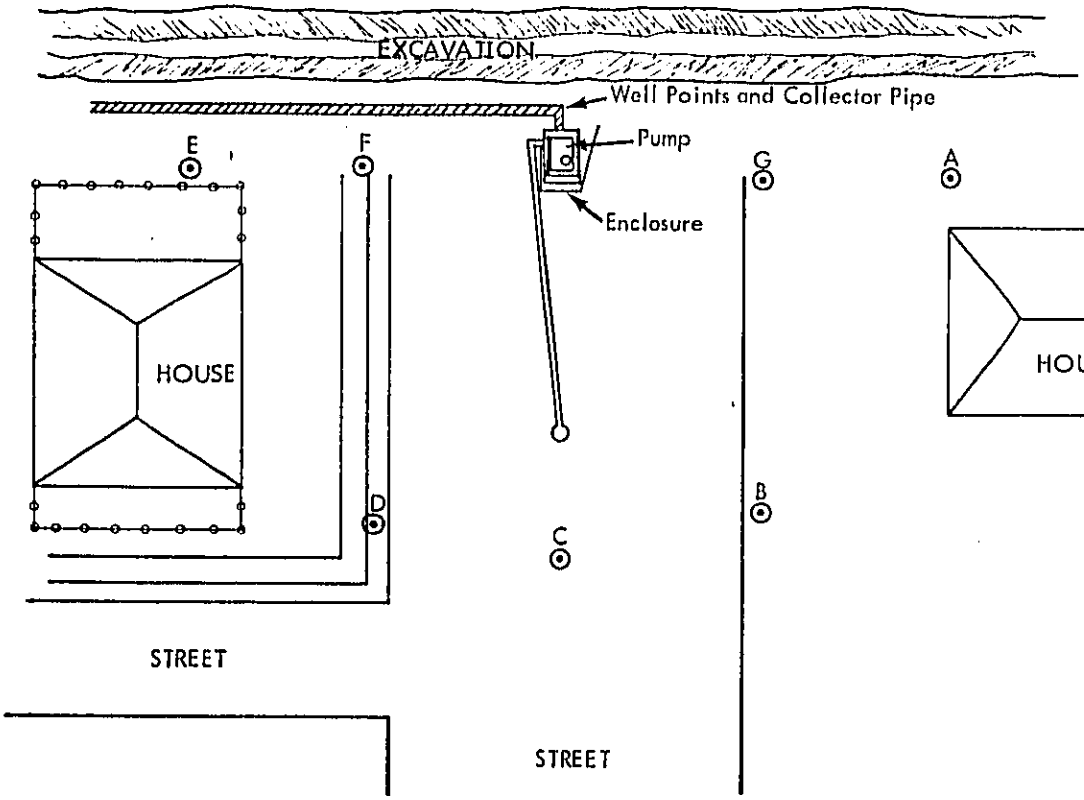

Figure 11. Description of Measurement Locations for Equipment Enclosure Evaluation.

The data reveals that a noise reduction of approximately 7 dB (at 50 feet) was possible at most points around the perimeter of the pump. At Point E, a reduction of only 1.2 dB was apparent. This was most likely due to the fact that the sidewall of the enclosure did not extend back far enough to prevent reflection of noise from the other sidewall.

Costs associated with implementing this simple enclosure were as follows:

Materials (Lumber)	= $90.00
Enclosure Surface Area	= 192 square feet
Total Cost Per Square Foot	= $0.47
Total labor man-hours	= 4

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	Construction Noise	Noise Prediction	Noise Metric	Construction Equipment Noise Data	Construction Equipment Noise Control	Construction Site Noise Control	Highway Construction Procedures	Construction Noise Measurement Procedures	Construction Cost Estimating	Noise Impact Assessment
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87. Newman, J.S., "Subjective Community Reactions to Construction Noise," Thesis submitted to Northwestern University, Evanston, Illinois, 1973.	X	X	X	X	X	X	X	X		X
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90. O'Neill, J.T., "Control of Construction Noise," Inter-Noise 72 Proceedings, Washington, D.C., 49-51 October 1972.	X			X	X	X	X	X	X	
91. Page, E.W.M. and Semple, W., "Silent and Vibration Free Sheet Pile Driving," Institution of Civil Engineering Proceedings, Institute of Civil Engineers, November 1968.				X	X		X		X	

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125. Thompson, S.E., "Chain Saw Safety, Vibration and Noise," Society of Automotive Engineers, Technical Paper 730702, August 1973.					X					
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139. Damkevala, R.J., Manning, J.E., Lyon, R.H., "Noise Control Handbook for Diesel-Powered Vehicles," U.S. Department of Transportation, DOT-TSC-OST-74-5, May 1974.					X			X		
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