U.S. Department
of Transportation
Federal Highway
Administration

Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model (FHWA TNM®), Version 1.0

FHWA-PD-96-008
DOT-VNTSC-FHWA-96-2

Final Report
November 1995

Prepared for

U.S. Department of Transportation
Federal Highway Administration
Office of Engineering and Highway
 Operations Research and Development
McLean, VA 22101-2296

Prepared by

U.S. Department of Transportation
Research and Special Programs Administration
John A. Volpe National Transportation Systems Center
Acoustics Facility, DTS-75
Kendall Square
Cambridge, MA 02142-1093

FOREWORD

Noise is an important environmental consideration for highway planners and designers. It can annoy and cause psychological or physiological harm, depending on frequency characteristics and loudness. The U.S. Department of Transportation and State transportation agencies are charged with the responsibility of optimizing compatibility of highway operations with environmental concerns. Highway noise problems have been addressed by numerous investigations, including evaluations of the following:

(1) noise sources, and highway noise reference energy mean emission levels;
(2) noise impacts at receptor locations;
(3) effects of site geometry, meteorology, ground surface conditions, and barriers on noise propagation; and
(4) alternative methods of mitigating noise impacts.

An accurate, state-of-the-art, prediction model for assessing noise impacts in the vicinity of roadways, and for designing effective, cost-efficient noise barriers, is a recognized need in the highway noise community. Such a tool requires the development of a nationally-representative, standardized noise data base, around which acoustic algorithms can be structured. In an effort to develop a data base for a new prediction model, the Federal Highway Administration's Traffic Noise Model (FHWA TNM®), Version 1.0, the FHWA along with 25 sponsoring State transportation agencies initiated the National Pooled-Fund Study (NPFS), titled "Highway Noise Model Data Base Development." The multi-year study was conducted by the Research and Special Programs Administration, John A. Volpe National Transportation Systems Center (Volpe Center), Acoustics Facility.

This report presents the measurement, data reduction, and analysis procedures, along with the results of the study. It will be of interest to engineers and other individuals involved in the mitigation of highway noise.

All data pertaining to the experimental conditions and measurements performed during the course of the NPFS have been archived at the Volpe Center in Cambridge, MA.

NOTICE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE November 1995	3. REPORT TYPE AND DATES COVERED Final Report July 1993 - November 1995

4. TITLE AND SUBTITLE
DEVELOPMENT OF NATIONAL REFERENCE ENERGY MEAN EMISSION LEVELS
FOR THE FHWA TRAFFIC NOISE MODEL (FHWA TNM®), Version 1.0

5. FUNDING NUMBERS
HW627/H6005/4K2

6. AUTHOR(S)
Gregg G. Fleming, Amanda S. Rapoza, Cynthia S.Y. Lee

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Research and Special Programs Administration
John A. Volpe National Transportation Systems Center
Acoustics Facility, DTS-75
Kendall Square
Cambridge, MA 02142-1093

8. PERFORMING ORGANIZATION REPORT NUMBER
DOT-VNTSC-FHWA-96-2

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Federal Highway Administration
Office of Environment and Planning
McLean, VA 22101-2296

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
FHWA-PD-96-008

11. SUPPLEMENTARY NOTES
FHWA Program Manager: Howard A. Jongedyk, HNR-20, Office of Engineering Research and Development; FHWA Contacts: Robert E. Armstrong and Steven A. Ronning, HEP-41, Office of Environment and Planning. This study, through pooled funds, was supported by the highway agencies of the following states: AZ, CA, FL, GA, HI, IL, IN, IA, MD, MA, MI, MN, MO, NJ, NY, NC, OH, OR, PA, TN, TX, UT, VA, WA, and WI.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
This document is available to the public through the National Technical Information Service, Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

During the period, July 1993 through November 1995, the U.S. Department of Transportation, Research and Special Programs Administration, John A. Volpe National Transportation Systems Center (Volpe Center), Acoustics Facility, in support of the Federal Highway Administration (FHWA) and 25 sponsoring state transportation agencies, conducted the National Pooled-Fund Study (NPFS), SP&R 0002-136, titled "Highway Noise Model Data Base Development." This report presents the results of the study, including the measurement, data reduction and analysis procedures used to develop the Data Base. It discusses data for constant-flow and interrupted-flow roadway traffic, and data related to vehicle subsource heights. The Data Base is the foundation around which the acoustic algorithms in the FHWA's Traffic Noise Model (FHWA TNM®), Version 1.0 are being structured.

This report also presents the statistical methodology used to establish the Data Base for the FHWA TNM. Sound level regressions are presented as a function of several parameters, including vehicle speed, vehicle type, one-third octave-band frequency, roadway pavement type, roadway grade, traffic-flow condition and vehicle subsource height.

14. SUBJECT TERMS
Noise, Highway Noise, Noise Prediction, Noise Model, Traffic Noise Model, FHWA TNM, Noise Barrier, Parallel Noise Barrier, Insertion Loss, Vehicle Noise Emission, REMEL

15. NUMBER OF PAGES
452

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

ACKNOWLEDGMENTS

During the period of July 1993 through November 1995, the U.S. Department of Transportation, Research and Special Programs Administration, John A. Volpe National Transportation Systems Center (Volpe Center), Acoustics Facility, in support of the Federal Highway Administration (FHWA), Office of Engineering and Highway Operations Research and Development and Office of Environment and Planning, and 25 sponsoring state transportation agencies (AZ, CA, FL, GA, HI, IL, IN, IA, MD, MA, MI, MN, MO, NJ, NY, NC, OH, OR, PA, TN, TX, UT, VA, WA, and WI) conducted the National Pooled-Fund Study (NPFS), titled "Highway Noise Model Data Base Development."

Major contributions of the Acoustics Facility staff members are as follows: Dave R. Read and Christopher J. Roof provided field measurement support, as well as data reduction and processing support. Shamir Patel and Antonio Godfrey provided data reduction support.

Special thanks go to Kenneth D. Polcak of the Maryland State Highway Administration. Whereas most states contributed financial support to the study, Kenneth participated in the majority of the field measurements, and provided valuable assistance and insight throughout the study, as well as several high-quality measurement sites in Maryland.

Rudy Hendriks of Caltrans also deserves special thanks for his unmatched site scoping process and informed suggestions. Rudy's experience and knowledge are the reasons the study began in California.

Thanks also go to all the individuals who assisted in the site selection process. They include Paul Dickey (Connecticut DOT) Win Lindeman and Kenneth Cambell (Florida DOT), Roger Wayson (University of Central Florida), Barry Adkins (Kentucky DOT), Tim Roache (Massachusetts Highway Department), Leo DeFrain and Fred Harwood

(Michigan DOT), Domenick Billera and Robert Sasor (New Jersey DOT), Harvey Knauer (Pennsylvania DOT), Raymond Brisson (Tennessee DOT), George Reeves and Wayne Young (Texas DOT), John Neil (Utah DOT), and William Bowlby (Vanderbilt University).

The authors would also like to acknowledge the Vibro-Acoustic Group at Harley-Davidson Motor Corporation for its contribution of motorcycle data.

The information provided by the FHWA and each of the 25 sponsoring state transportation agencies materially contributed to the success of the study. The authors are grateful to members of the FHWA, as well as members of the state agencies for their support and timely commentary. Special thanks go to Robert E. Armstrong, Steven A. Ronning, and Howard A. Jongedyk for their guidance and support.

Finally, thanks also go to the Virginia DOT which was responsible for the printing of this document.

TABLE OF CONTENTS

SECTION PAGE

TABLE OF CONTENTS (continued)

SECTION PAGE

TABLE OF CONTENTS (continued)

SECTION PAGE

TABLE OF CONTENTS (continued)

SECTION PAGE

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF TABLES

LIST OF TABLES (continued)

LIST OF TABLES (continued)

LIST OF TABLES (continued)

LIST OF TABLES (continued)

LIST OF TABLES (continued)

TABLE PAGE

LIST OF TABLES (continued)

LIST OF TABLES (continued)

1. INTRODUCTION

During the period July 1993 through November 1995, the U.S. Department of Transportation, Research and Special Programs Administration, John A. Volpe National Transportation Systems Center (Volpe Center), Acoustics Facility, in support of the Federal Highway Administration (FHWA), Office of Engineering and Highway Operations Research and Development and Office of Environment and Planning, and 25 sponsoring state transportation agencies (AZ, CA, FL, GA, HI, IL, IN, IA, KY, MD, MA, MI, MN, NJ, NY, NC, OH, OR, PA, TN, TX, UT, VA, WA, and WI) conducted the National Pooled-Fund Study (NPFS), SP&R 0002-136, titled "Highway Noise Model Data Base Development." This document presents the results of the Study.

Section 2 details the field measurement sites used in the Study. Section 3 identifies the field measurement instrumentation, including manufacturer and model number. Section 4 describes the field measurement procedures. Section 5 and 6, respectively, describe the field data reduction and analysis processes. Section 7 presents the results of the Study. Section 8 describes the benefits resulting from the Study.

1.1 BACKGROUND

The existing FHWA highway traffic noise prediction computer software, STAndard Method In Noise Analysis (STAMINA, Version 2.0), which also contains a component that performs optimization of barrier analysis and design (OPTIMA), has been in use for over thirteen years.[1] Much of the computer architecture and source code comprising this software dates to the early 1970s. Since that time, significant advancements have been made in the methodology and technology of noise prediction, barrier analysis and design, and computer software design and coding. Consequently, the FHWA identified the need to design, develop, test, and document a new highway traffic noise prediction model which utilizes these advancements. The new model is the FHWA's Traffic Noise Model (FHWA TNM®), Version 1.0.

STAMINA's core Data Base dates to the middle 1970's, when the Volpe Center, then the Transportation Systems Center (TSC), performed the so-called "Four-State Study."[2] Since then, vehicle sound level regulations have been made significantly more stringent, and the greater emphasis on fuel economy, coupled with the higher costs of fuel, has resulted in significant changes in types and mixes of motor vehicles. As a result, vehicle sound levels have likely changed. Related studies[3,4,5,6,7,8] support this contention. In addition, the parameters examined in the Four-State Study were limited, primarily due to limitations in modeling capabilities and requirements at the time. The Four-State Study included measurement over limited speed ranges, pavement types, and vehicle types. It was also limited to measurement of constant-speed traffic on level roadways.

Recognizing the limitations of the STAMINA Data Base, and the potential for it to be scrutinized due to its age, the FHWA, several state transportation agencies, and the Volpe Center considered it essential to develop a new, nationally-representative data base for the FHWA TNM.

The components identified as essential for the Reference (i.e., the data will be measured with standardized field measurement procedures and will provide the reference data base in the FHWA TNM) Energy Mean (i.e., the mean value of the statistical regression to be developed will be based on the acoustic energy, not the sound level in decibels) Emission Level (REMEL) Data Base were as follows: (1) constant-flow REMEL data; (2) interrupted-flow REMEL data; and (3) individual vehicle subsource-height data.

The field-measurement portion of this document (Sections 2 through 4) focuses primarily on the constant-flow measurements, with a lesser emphasis on the interrupted-flow and subsource-height measurements. Readers interested in more detail on the interrupted-flow and subsource-height measurements are directed to References 15 through 18. Sections 5 through 7 present a detailed explanation of how these three types of data were integrated to form the Data Base for the FHWA TNM.

1.2 OBJECTIVES

The objectives of the study were as follows:

(1) Establish through field measurements a sound level data base for vehicles representative of those traveling on the interstate highway system in the United States.

(2) Develop a set of statistical relationships between vehicle sound level, vehicle speed, and one-third octave-band frequency. These relationships should consider the following parameters: roadway pavement type, roadway grade, traffic-flow condition, and vehicle subsource height.

(3) Integrate the relationships developed above with the FHWA TNM in the form of a matrix of regression coefficients.

The methods and criteria used to accomplish these objectives were generally consistent with References 9, 10 and 11.

2. MEASUREMENT SITES

This section describes the measurement sites used to develop the FHWA TNM Data Base, including a discussion of site characteristics (Section 2.1), and a definition of vehicle types (Section 2.2), pavement types (Section 2.3), and roadway grade (Section 2.4). These general characteristics and definitions were consistent for constant-flow, interrupted-flow, and subsource-height measurements. In addition, a detailed description of specific site locations is included (Section 2.5).

2.1 SITE CHARACTERISTICS

Participating states in the National Pooled-Fund Study were asked to identify 10 to 15 potential measurement sites which had the following characteristics:

(1) A flat open space free of large reflecting surfaces, such as parked vehicles, signboards, buildings, or hillsides located within 30 m (100 ft) of either the vehicle path or the microphones.

(2) The ground surface at the microphones no more than 0.6 m (2 ft) above roadway elevation. In addition, the ground surface elevation along a line from the microphones, perpendicular to the roadway should not vary by more than 0.6 m parallel to the plane of the pavement.

(3) The line-of-sight from the 30-meter microphone position to the roadway unobscured within an arc of 150 degrees.

(4) The ground surface within the measurement area free of snow and representative of acoustically hard, e.g., pavement, or acoustically soft, e.g., grass, terrain.

(5) The vehicle path, i.e., roadway lane, comprised of smooth, dry dense-graded asphalt, concrete, or open-graded asphalt, and free of extraneous material such as gravel or road debris.

(6) A predominant, ambient noise level at the measurement site low enough to enable the measurement of uncontaminated vehicle pass-by sound levels. Specifically, the

difference between the lowest-anticipated, vehicle pass-by, maximum A-weighted sound-pressure level (L_{AFmx}) and the A-weighted ambient noise level, as measured at the 15-meter microphone, should be at least 6 dB, with 10 dB being preferable.

(7) The site to be located away from known sound sources, such as airports, construction sites, rail yards, or other heavily travelled roadways.

(8) The site to exhibit constant-speed roadway traffic operating under cruise conditions at speeds between 15 and 110 km/h (10 to 70 mph), or interrupted-speed traffic, such as at a stop sign or tollbooth. In addition, the traffic should be representative of the population of interstate, roadway traffic in the state as a whole.

(9) For constant-speed measurements, the site to be located away from intersections, lane merges or any other features that would cause traffic to accelerate or decelerate.

2.2 VEHICLE TYPES

Sites were selected with traffic volumes low enough for measurement of individual vehicle pass-bys, and diverse enough for measurement of many different types of vehicles. Roadway vehicles were grouped into five acoustically significant types, i.e., differing vehicles within each type exhibit statistically similar acoustic characteristics. These vehicle types are defined as follows:

<u>Automobiles (A)</u>: All vehicles having two axles and four tires and designated primarily for transportation of nine or fewer passengers, i.e., automobiles, or for transportation of cargo, i.e., light trucks. Generally, the gross vehicle weight is less than 4500 kg (9900 lb).

<u>Medium Trucks (MT)</u>: All cargo vehicles having two axles and six tires. Generally, the gross vehicle weight is greater than 4500 kg (9900 lb) but less than 12,000 kg (26,400 lb).

<u>Heavy Trucks (HT)</u>: All cargo vehicles having three or more axles. Generally, the gross vehicle weight is greater than 12,000 kg (26,400 lb).

<u>Buses (B)</u>: All vehicles having two or three axles and designated for transportation of nine or more passengers.

<u>Motorcycles (MC)</u>: All vehicles having two or three tires with an open-air driver and/or passenger compartment.

2.3 PAVEMENT TYPE, AGE, TEXTURE AND TEMPERATURE

Sites were also selected based on roadway pavement type. The FHWA TNM will contain the capability to account for four pavement types, an "average" pavement (made up of data collected for dense-graded asphaltic concrete (DGAC) and portland cement concrete (PCC), as defined in Section 6.4), DGAC, PCC, and open-graded asphaltic concrete (OGAC). In each state, an attempt was made to measure data at a high-speed DGAC site, a high-speed PCC site, and at a low-speed site.

In addition, an attempt was made to collect data for a range of pavement ages and from a variety of representative PCC textures. The effect ambient air temperature has on tire/pavement noise was also a consideration.[12] As such, an attempt was made to measure the majority of the data when the ambient air temperature was between 55 and 85 degrees Fahrenheit.

2.4 ROADWAY GRADE

Another important parameter in the site selection process was roadway grade. Measurement at grade sites was limited to the state of California, at sites identical to those used in an emission level study conducted by the California Department of Transportation (Caltrans) between 1982 and 1985.[3] For the purpose of possible inclusion of the older Caltrans grade data in the Data Base of the FHWA TNM, measurements were made at most of the sites used in the earlier Caltrans study (See Tables 1 and 2 for a description of the grade sites).

Figure 1, reproduced from Reference 3, presents the distance needed for a heavy truck to sustain crawl speed at some point on a constant-percentage grade. Crawl speed is the maximum sustained speed which heavy trucks can maintain on an extended upgrade. The California sites had grades ranging from 3 to 7 percent. An essential characteristic of these grade sites was that they were located at a large enough distance from the start of the grade that a constant crawl speed for heavy trucks was ensured.

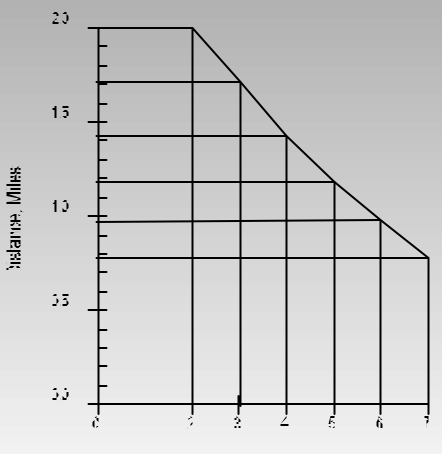


Figure 1. Distance Versus Grade Criteria

2.5 MEASUREMENT SITE LOCATIONS AND DESCRIPTIONS

Out of the "pool" of potential sites submitted to the Volpe Center, a total of 40 sites were chosen for constant-flow REMEL measurements, of which five were also used for interrupted-flow measurements. The subsource-height measurement sites are documented in References 16 and 17. The constant/interrupted-flow sites were located on the outskirts of the following major metropolitan areas:

CA:	Sacramento/San Francisco and Los Angeles
FL:	Ft. Lauderdale/West Palm Beach and Orlando
MD:	Baltimore
MA/CT:	Boston
MI:	Lansing
NJ:	Atlantic City
TN/KY:	Nashville

Figure 2 presents the general areas covered by these measurement sites on a map of the United States. Each circle on the map represents approximately one week of measurements. Eleven weeks of constant-flow measurements and three weeks of interrupted-flow measurements were performed. In total, over 6000 individual pass-by events were measured.

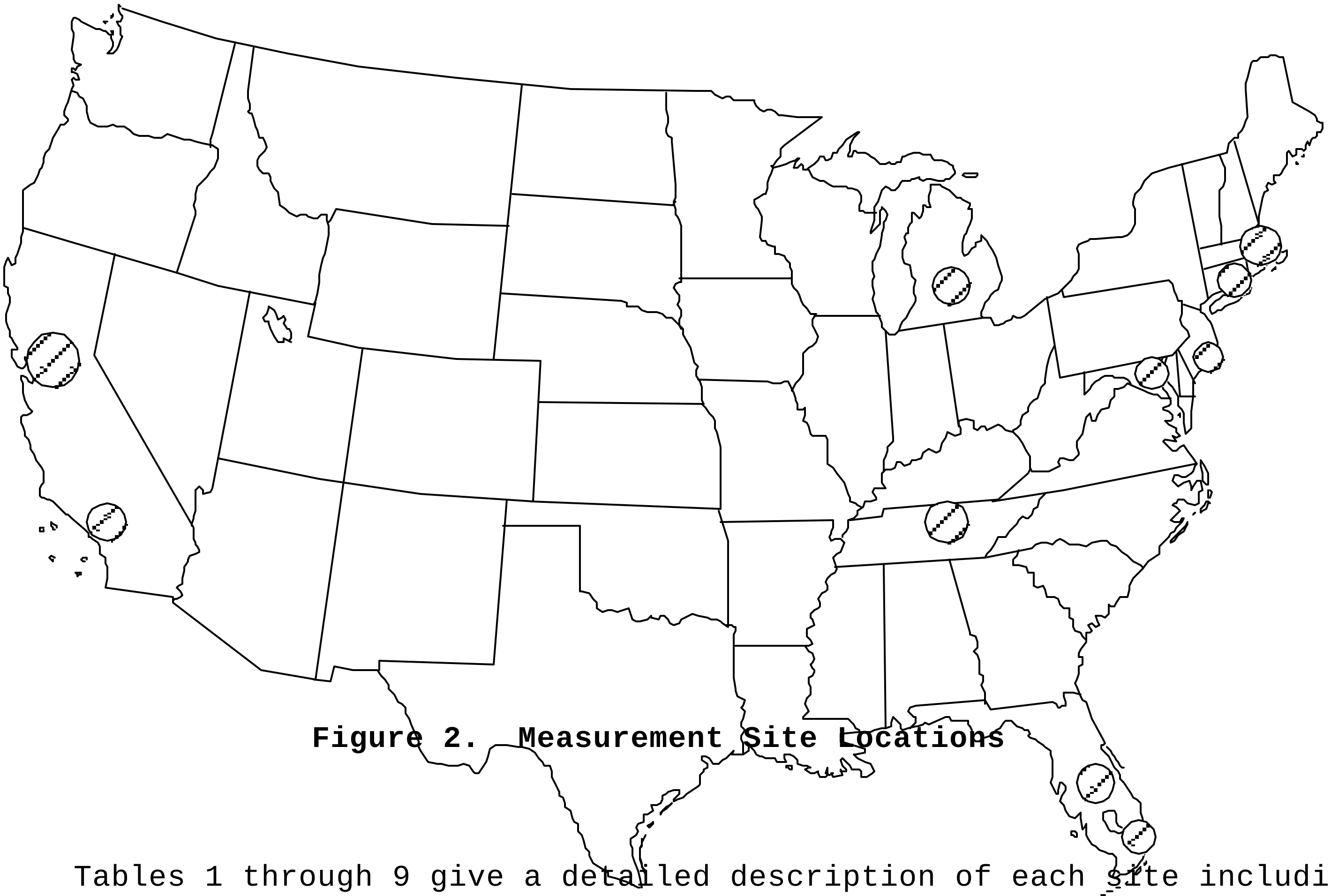


Figure 2. Measurement Site Locations

Tables 1 through 9 give a detailed description of each site including its numerical designator, location, roadway grade, roadway pavement type and year constructed or last overlaid (whichever year is more recent), acoustic characteristics of the site surface, and dates of measurement. Appendix A contains a plan and profile for each site.

Table 1. Measurement Sites and Characteristics
Sacramento/San Francisco, California

Site #	Location (Closest City in Parentheses)	Grade	Pavement		Site Surface	Date
			Type	Year		
1	Rt. 37 EB, 0.4 km east of Lakeville Rd. at Weigh Station, 9.7 km east of Rt. 101 (Novato, CA)	0	DGAC	1989	Hard	2/28/94
2	I-580 EB, 0.6 km west of North Flynn Rd. (Altamonte, CA)	3%	PCC	1986	Hard/ Soft	3/1/94
3	I-680 SB, 1.8 km south of Mission Blvd., north of exit sign located in center median (Milpitas, CA)	0	DGAC	1992	Soft	3/2/94
4	Elkhorn Blvd. EB, 0.8 km east of Rt. 99 (Sacramento, CA)	0	DGAC	1991	Hard/ Soft	3/3/94 3/4/94
5	I-5 SB, 2.4 km south of Pocket Rd. (Sacramento, CA)	0	PCC	1990	Soft	3/5/94

Table 2. Measurement Sites and Characteristics
Los Angeles, California

Site #	Location (Closest City in Parentheses)	Grade	Pavement		Site Surface	Date
			Type	Year		
6	I-15 NB, 16.7 km north of I-215 (Cajon, CA)	5.6%	PCC	1970	Soft	5/2/94 5/4/94
7	I-15 NB, 18.5 km north of I-215 (Cajon, CA)	4.5%	PCC	1969	Soft	5/3/94
8	Rt. 101 SB, 1.2 km southeast of Camarillo Springs (Camarillo Springs, CA)	7%	DGAC	1990	Soft	5/5/94 5/6/94

Table 3. Measurement Sites and Characteristics
Ft. Lauderdale/West Palm Beach, Florida

Site #	Location (Closest City in Parentheses)	Grade	Pavement		Site Surface	Date
			Type	Year		
9	Sample Road WB, Approx. 1.6 km east of US 441 (Coconut Creek, FL)	0	DGAC	1991	Soft	3/21/94
10	I-75 NB, 0.8 km south of I-595 (Davie, FL)	0	DGAC	1993	Soft	3/22/94
11	US 1, Federal Highway SB, 0.8 km north of County Line Road (Hobe Sound, FL)	0	DGAC	1991	Soft	3/23/94 3/25/94
12	Florida Turnpike NB, 2.4 km south of Rt. 806 (Delray Beach, FL)	0	DGAC	1994	Soft	3/24/94

Table 4. Measurement Sites and Characteristics
Orlando, Florida

Site #	Location (Closest City in Parentheses)	Grade	Pavement		Site Surface	Date
			Type	Year		
13	State Road 417 NB, 0.8 km south of Red Bug Lake Road (Oviedo, FL)	0	DGAC	1989	Soft	4/11/94
14	State Road 419 EB, 0.8 km west of Lockwood Road (Oviedo, FL)	0	DGAC	1990	Soft	4/12/94 4/15/94
15	Mellonville Ave. SB, Sanford Municipal Airport, 152 m south of Catapult Rd. (Sanford, FL)	0	DGAC	1987	Soft	4/13/94
16	Tuskawilla Rd. SB, 0.3 km south of Eagle Blvd., Amherst Way (Winter Springs, FL)	0	DGAC	1986	Soft	4/14/94
17* **	State Rd. 417 SB, 1.6 km past tollbooth J (Orlando, FL)	0	DGAC	1994	Hard/ Soft	1/31/95 2/2/95
18*	Challenger Rd., 61 m west of toll road sign at UCF (Orlando, FL)	0	DGAC	1993	Soft	2/1/95

* Used for both constant-flow and interrupted-flow measurements.

** Measurements were also made on State Rd. 417 NB, 0.8 km past tollbooth J. However, only the interrupted-flow portion of the data were used because the ground elevation beneath the 15-m microphones at the constant-flow site was 1 m below roadway elevation, 0.5 m greater than our allowed criteria.

Table 5. Measurement Sites and Characteristics Baltimore, Maryland

Site #	Location (Closest City in Parentheses)	Grade	Pavement		Site Surface	Date
			Type	Year		
19	Truck Stop Access Rd. off Elkton Blvd. at Motel 6 (Elkton, MD)	0	DGAC	N/A	Soft	6/20/94
20	I-895 WB, 1.6 km east of Rt. 1 (Halethorpe, MD)	0	OGAC	1990	Soft	6/21/94 6/23/94
21	I-70 WB at mile marker 81, west of Sand Hill Road Overpass (West Friendship, MD)	0	OGAC	N/A	Soft	6/22/94
22	I-895 EB, 1.6 km east of I-695, near Colt 45 Plant (Halethorpe, MD)	0	OGAC	1990	Soft	6/24/94
23	MD 140 WB, at State Police Barrack "G" (Westminster, MD)	0	PCC	1951	Soft	7/18/94 7/21/94
24	US 301 NB, 0.4 km north of MD 299 (Sassafras, MD)	0	DGAC	1992	Soft	7/19/94
25	Ambassador Rd. at Baltimore Gas and Electric Offices (Baltimore, MD)	0	DGAC	1975	Soft	7/20/94
26	US 301 NB, 0.4 km north of US 50 (Queenstown, MD)	0	DGAC	1985	Soft	7/22/94

Table 6. Measurement Sites and Characteristics
Boston, Massachusetts

Site #	Location (Closest City in Parentheses)	Grade	Pavement		Site Surface	Date
			Type	Year		
27	Rt. 117 WB, 6.4 km east of I-495 (Stow, MA)	0	DGAC	1979	Soft	8/8/94
28	Rt. 30 WB, 1.6 km east of Rt. 27 (Wayland, MA)	0	DGAC	N/A	Soft	8/9/94
29	Rt. 2 WB, 4 km east of Foxwoods Casino, 19.3 km northwest of I-95 (Preston, CT)	0	DGAC	1993	Soft	8/16/94 8/17/94 8/18/94
30	I-495 NB, 3.2 km north of I-95 (Wrentham, MA)	0	PCC	1965	Hard/ Soft	8/23/94 8/24/94 8/30/94 10/26/94
31	Rt. 37 SB, at Mass. Respiratory Hospital, 6.4 km south of I-93 (Holbrook, MA)	0	DGAC	1938 (?)	Soft	8/25/94 9/2/94
32	Playstead Rd. SB, near Century Rd., 0.8 km north of Rt. 60 (Medford, MA)	0	DGAC	1988	Soft	9/1/94 9/21/94 9/29/94 10/13/94

Table 7. Measurement Sites and Characteristics
Lansing, Michigan

Site #	Location (Closest City in Parentheses)	Grade	Pavement		Site Surface	Date
			Type	Year		
33	I-94 WB, at junction M-99 (Albion, MI)	0	PCC	1991	Soft	6/6/94 6/10/94
34	M-60 WB, at Spring Arbor College (Spring Arbor, MI)	0	DGAC	1977	Soft/ Hard	6/7/94 6/9/94
35	I-96 EB, 4 km east of Okemos Rd. between mile markers 112 and 113 (Okemos, MI)	0	DGAC	1993	Soft	6/8/94

Table 8. Measurement Sites and Characteristics
Atlantic City, New Jersey

Site #	Location (Closest City in Parentheses)	Grade	Pavement		Site Surface	Date
			Type	Year		
36	Garden State Pkwy SB at mile marker 47.4, 16 km north of Atlantic City Expwy (Atlantic City, NJ)	0	DGAC	1991	Soft	9/12/94 9/13/94
37	Garden State Pkwy NB at mile marker 46.6, 14.5 km north of Atlantic City Expwy (Atlantic City, NJ)	0	DGAC	1991	Soft	9/12/94 9/13/94

Table 9. Measurement Sites and Characteristics
Nashville, Tennessee

Site #	Location (Closest City in Parentheses)	Grade	Pavement		Site Surface	Date
			Type	Year		
38*	I-65 SB, Approximately 1.6 km south of exit 6 (Franklin, KY)	0	PCC	1965	Soft	11/14/94 11/15/94 11/17/94 11/18/94
39*	Rt. 41A NB, 2.4 km north of junction of Rt. 49 (Pleasantview, TN)	0	DGAC	1988	Soft	12/6/94
40*	I-24 EB, 0.8 km east of Tennessee Welcome Center at Exit 1 (Clarksville, TN)	0	DGAC **	1990	Soft	12/7/94 12/8/94

* Used for both constant-flow and interrupted-flow measurements.

** The pavement type for the interrupted-flow portion of Measurement Site 40 was PCC.

3. MEASUREMENT INSTRUMENTATION

This section identifies the field measurement instrumentation, including manufacturer and model number used in the constant-flow measurements. Readers are directed to Section 4 and to References 15 and 18 for a detailed description of the instrumentation used in the interrupted-flow and subsource-height measurements.

3.1 ACOUSTIC INSTRUMENTATION

The acoustic data acquisition system consisted of two General Radio Model 1962-9610 pressure-response electret-condenser microphones, each connected to a General Radio Model 1560-P42 preamplifier. The microphone/preamplifier combinations were mounted in insulated nylon holders and fastened to tripods. The diaphragms of the microphones were positioned for grazing incidence at a height of 1.5 m (5 ft), relative to roadway elevation, at distances of 7.5 and 15 m (25 and 50 ft, respectively) from the centerline of the near travel lane.

If site topography allowed, measurements were also simultaneously performed at a distance of 30 m (100 ft) so that drop-off rates at each measurement site could be quantified. It was also intended that the 30-meter data be used for evaluating the FHWA TNM. For the 30-meter microphone, a Brüel and Kjær Model 4155 free-field, electret-condenser microphone, connected to a Larson Davis Model 827-0V preamplifier, was mounted in an insulated nylon holder and fastened to a tripod. The diaphragm of the 4155 microphone was also positioned for grazing incidence at a height of 1.5 m (5 ft), relative to roadway elevation. A Brüel and Kjær Model UA0237 windscreen was placed atop each microphone to reduce the effect of wind-generated noise on the microphone diaphragm.

The microphone/preamplifier systems deployed at the 7.5-meter and 15-meter positions were connected via cables no greater than 150 m (500 ft) in length, to a Larson Davis Model 2900, two-channel, One-Third-Octave-Band Analyzer (LD2900) and a Brüel and Kjær Model 2306 Graphic Level Recorder (GLR), set-up at the observers' station, approximately

120 m (400 ft) upstream of traffic flow, relative to the measurement microphones. The electrical signal from each microphone/preamplifier system was fed directly into the LD2900. The A-weighted output signal from the LD2900, which was analogous to the acoustic signal measured at the 15-meter microphone, was input to the GLR. For the 30-meter (100 ft) position, the microphone/preamplifier system was connected to a modified Larson Davis Model 820 Sound Level Meter (SLM). The SLM was specially modified by the manufacturer to provide American National Standards Institute (ANSI), Type I, A-weighted response, when used with a Brüel and Kjær Model 4155 free-field microphone at grazing incidence.

Pre-processing and storage of the measured acoustic data was accomplished by the LD2900, which was programmed to measure and store the maximum A-weighted sound pressure level with fast-response time-weighting characteristics (L_{AFmx}), the A-weighted one-third octave-band spectrum associated with L_{AFmx}, and the A-weighted, spectral time-history every ½-second. The data in the internal memory of the LD2900 were periodically transferred to a floppy disk for later off-line processing and analysis. Data from the 30-meter (100 ft) measurement system included the maximum A-weighted sound-pressure level with fast-response time-weighting characteristic (L_{AFmx}), and the A-weighted time-history stored as sequential ½-second equivalent sound levels ($L_{Aeq0.5s}$). These data were downloaded from the LD820's internal storage, using a notebook computer, and saved to disk for later off-line processing and analysis.

The GLR produced a graphic time-history recording (A-weighted sound level versus time) at a paper transport speed of 1 mm/s. These recordings served as on-site visual verification of the acoustic integrity of each pass-by event.

3.2 SUPPORT INSTRUMENTATION

A CMI Model K-15II doppler radar-gun was set up at the observers' station, approximately 120 m (400 ft) upstream of traffic flow, relative to the array of microphones, and used to measure vehicle speed during each pass-by event. The unit was positioned at a distance of no greater than 10 m (35 ft) from the centerline of the near travel lane. This ensured that the angle subtended by the axis of the radar antenna and the direction of travel of the vehicle being measured was less than 5 degrees, when the vehicle was at the microphone pass-by point. The resulting uncertainty in vehicle speed readings, due to angular effects on doppler accuracy, did not exceed 0.5 km/h (0.28 mph) over the entire speed range from 15 to 110 km/h (10 to 70 mph).[13]

A sling psychrometer and wind cup anemometer were used to measure meteorological conditions, including temperature (wet and dry bulb) and wind speed. Wind direction was also noted.

The entire acoustic measurement system was calibrated using a General Radio Model 1562-A sound level calibrator for measurements made at all sites, with the exception of those in Connecticut, Massachusetts, Kentucky, New Jersey, and Tennessee. For measurements at sites within those states, a General Radio Model 1987 sound level calibrator was used. Both calibrators produce a signal of 1000 Hz at a sound-pressure level of 114 dB re: 20 micropascal. In addition, the electronic noise floor of the acoustic measurement system was established daily by substituting the measurement microphone with a passive microphone simulator (dummy microphone). The frequency response characteristics of the system were determined on a daily basis using a Cetec Ivie Model IE-20B random-noise generator. Calibration of the doppler radar was periodically checked in the field for accuracy using a calibrated tuning fork.

4. MEASUREMENT PROCEDURES

This section describes the procedures used for the measurement of constant-flow and interrupted-flow REMEL data, as well as subsource-height data. For all three sets of measurements, similar methodologies were used to determine event quality and document vehicle type.

4.1 EVENT QUALITY

Event quality was determined in the field and was logged for each event both on the data-log sheets and on the GLR output. The GLR produced a graphic, time-history output of A-weighted sound level measured at the 15-meter microphone. Optimally, a rise and fall of at least 10 dB between subsequent vehicles measured at the 15-meter microphone was desired. Rise and fall is defined as the difference between L_{AFmx} and the minimum measured level associated with either the start or end of a given event (whichever difference was smaller). The 10-dB criterion ensured that contamination due to other vehicles was essentially negligible.

Events with a rise and fall of at least 10 dB were designated as Type 2, the highest quality event. It was decided that accepting events of Type-2 quality only, may erroneously bias the results towards noisier vehicles. Therefore, events with a rise and fall of between 6 and 10 dB were also accepted, and designated a Type-1 event. Events with a rise and fall of between 3 and 6 dB were designated Type-0 events, and in most cases not used. Events with less than a 3 dB rise and fall were discarded. This designation methodology is consistent with the previously cited Caltrans study.

4.2 VEHICLE TYPES

The FHWA TNM will contain five, standard vehicle types (A, MT, HT, B, and M, as defined in Section 2.2). While collecting data, however, these five vehicle types were broken down into twelve numerical designations for the purpose of possible future, more-detailed analysis.

These twelve designations are as follows:

0 - Compact Automobiles;
1 - Standard Automobiles;
2 - Medium Trucks;
3 - 3-Axle Heavy Trucks;
4 - 4-Axle Heavy Trucks;
5 - 5-Axle Heavy Trucks;
6 - Heavy Trucks with 6 or more axles;
7 - Motorcycles;
8 - 2-Axle Buses;
9 - 3-Axle Buses;
10 - Motor Homes; and
11 - Miscellaneous.

In addition to the above numerical designations, additional, potentially important information was recorded, including any unique characteristics observed during the pass-by. For automobiles, the make, model and any distinguishing characteristics, i.e., irregular-sized tires or absence of a muffler, were documented on the field-data log sheets. For medium trucks, the trailer type, i.e., box or flatbed, and the location of the stack (high or low) were documented. For heavy trucks the trailer type, i.e., box, flatbed, tanker, or car carrier, and, if possible, the cargo state (empty or full) were documented.

4.3 CONSTANT-FLOW DATA MEASUREMENT PROCEDURE

Microphones were positioned at offset distances of 7.5, 15, and 30 m (25, 50, and 100 ft, respectively) from the centerline of the near travel lane (See Figure 3). The 15-meter data were used in the analysis described in Section 6.0 and make up the Data Base of the FHWA TNM. The 7.5- and 30- meter data were collected to characterize the drop-off rate at each site and also to evaluate the TNM.

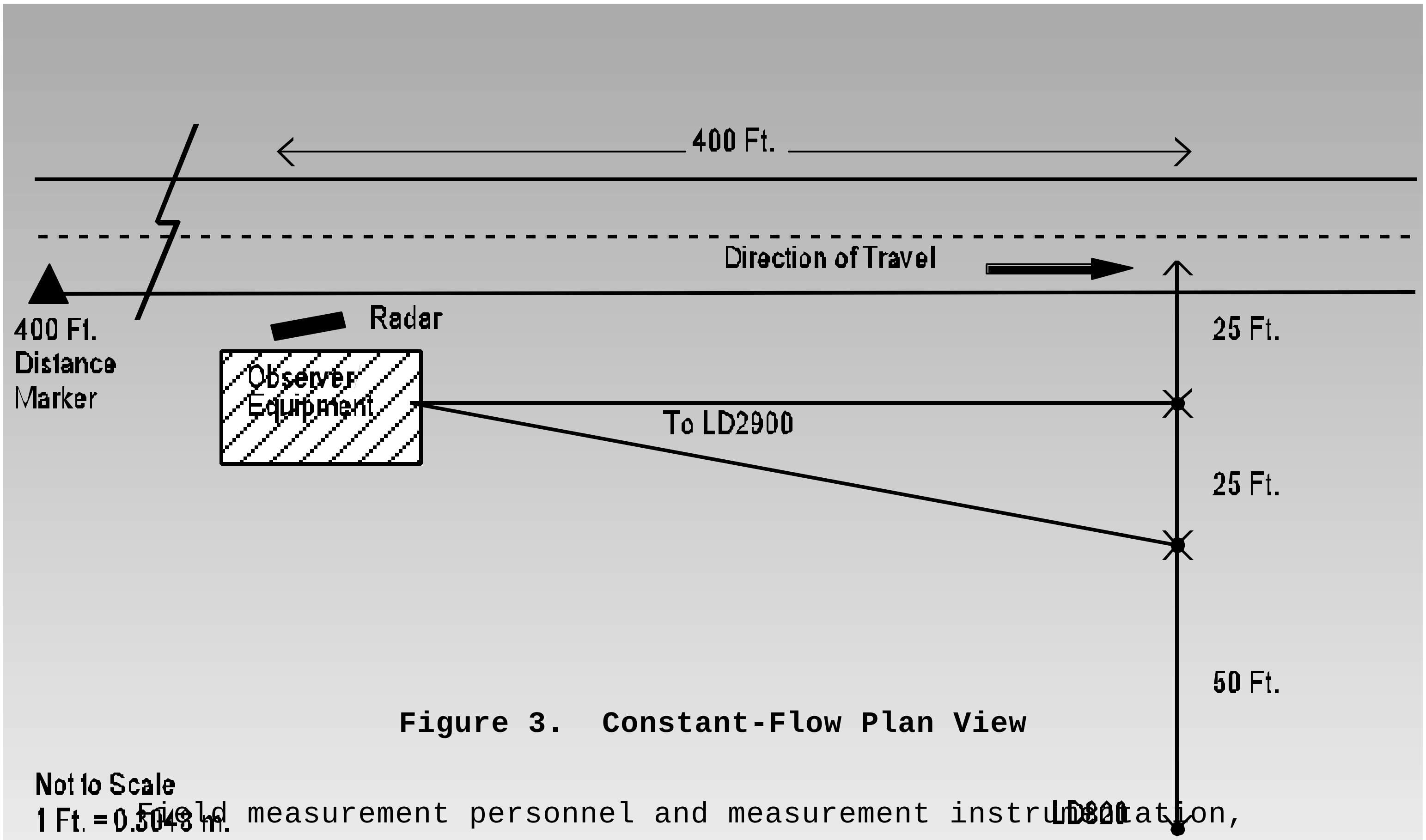


Figure 3. Constant-Flow Plan View

Field measurement personnel and measurement instrumentation, excluding the microphones and preamplifiers, were positioned approximately 120 m (400 ft) upstream from the microphones at the observers' station. Positioning of the observers' station upstream from the microphones, as opposed to at or beyond the microphones, served several purposes: (1) it minimized potential negative effects due to driver curiosity; (2) it provided a visual gauge of potentially good events, based on the separation-distance criteria defined below; (3) it ensured that the resultant uncertainty in vehicle speed readings, due to angular effects on doppler accuracy, did not exceed 0.5 km/h over the entire speed range from 15 to 110 km/h; and (4) it essentially eliminated vehicle braking associated with detection of the radar signal prior to, or in the vicinity of the microphones. Orange highway cones were set up at a distance of 120 m upstream from traffic flow, relative to the observers' station, to aid in determining vehicle separation distance.

Prior to initial data collection and at hourly intervals, thereafter, the entire acoustic measurement system was calibrated. In addition, the electronic noise floor was established daily using a passive microphone simulator. The frequency response characteristics were also determined daily by measuring and storing 20 seconds of pink noise. Concurrently, the LD2900 Analyzer's battery level and available memory space were also noted and documented.

Also, prior to data collection, at 15-minute intervals thereafter, and during noticeable weather changes, meteorological data were observed and documented. Temperature (wet and dry bulb), wind speed and direction, and cloud cover were recorded. Data were not collected when wind speeds exceeded 19 km/h (12 mph). The previously cited Caltrans study, in which wind data were carefully recorded and analyzed, concluded that wind speeds below 19 km/h have no apparent effect on sound-level measurements made at distances up to 30 m (100 ft). Appendix B contains a summary of the meteorological data measured in support of the current Study.

Data acquisition required a minimum of two observers: a vehicle observer and an acoustic observer. A potential event was identified for measurement when there were no other like vehicles observed within a distance of 120 m (400 ft). For example, an automobile was considered a potential event for measurement if there were no other automobiles within a distance of 120 m, or trucks within a distance of 300 m (1000 ft). A truck was considered a potential event for measurement if there were no other trucks within a distance of 120 m, and there were less than three automobiles within 120 m. The technical basis for the separation-distance criteria is presented in Appendix C.

It is extremely important to note that the constant-flow pass-by events measured in the field were truly random. That is to say that the only deciding factor in selecting an event for measurement was the separation distance. As such, extremely loud vehicles, vehicles without mufflers, or vehicles with relatively unique noise signatures were not excluded from the measurements, or the subsequent analysis, since they were considered to be part of a random sample. The is also true for the interrupted-flow and the subsource-height measurements.

When the above separation-distance criteria were met, the vehicle observer announced the event number and began monitoring the vehicle's speed as it passed the observers' station. Concurrently, the acoustic observer began data capture on the LD2900 analyzer, and observation of the GLR trace to determine event quality. Acoustical data, including the A-weighted maximum sound level fast response, denoted by the descriptor L_{AFmx}, the one-third octave-band spectrum at the time of L_{AFmx}, and the spectral time-history data, were measured and stored. After the vehicle passed the line of microphones and before subsequent vehicles entered the vicinity of the microphones, the acoustic observer ended data capture.

After each event, the vehicle observer recorded the following information on a data-log sheet: event number, event end-time, vehicle type and speed, and other observations, i.e., vehicle make and model, high/low exhaust stack, etc. The acoustic observer recorded the following information: event number (on both a data log sheet and on the GLR chart), event end-time, event duration, and GLR event quality. The careful field data recording procedure helped to simplify off-line event correlation.

The GLR and the LD820 SLM were set to run continuously; however, due to internal memory limitations, the LD2900 Analyzer was manually triggered to begin and end data collection for each individual event.

4.3.1 Idle Sound-Level Data Measurement Procedure

During the week of 25 January, 1995, in Orlando, FL, REMEL data were measured for idling automobiles, and a single idling motorcycle. The idle measurement site was located directly adjacent to constant-flow Site 18 (See Figure 23, Appendix A). One of the many concerns during the development of the FHWA TNM was the characterization of sound level versus speed as a linear function down to a vehicle speed of zero. The idle data will allow the FHWA TNM to more accurately characterize automobile sound levels at low speeds (See Section 6.1.1).

For these measurements, a LD820 SLM was positioned 3.8 m (12.5 ft) from the center of the near travel lane where vehicles were positioned idling. A distance of 3.8 m was chosen to ensure the idle sound level was at least 10 dB above the ambient level. For each event, ½-second equivalent sound levels, designated by the symbol $L_{Aeq0.5s}$, of ambient were recorded for approximately 20 seconds, followed by a 30-second sample of idle.

4.3.2 Supplementary Motorcycle Data Acquisition

Due to the small number of measured motorcycle pass-by events, an attempt was made to contact several motorcycle manufacturers for relevant emission level data. Of the many manufacturers contacted, Harley-Davidson Motor Company was the only one able to supply appropriate data.[14]

Harley-Davidson conducted a set of measurements at its Milwaukee Engine and Transmission Facility. A Norsonic Vehicle Noise Analyzer Model VNA-836 was used to measure a 1994 Model FLTCU Tour Glide Ultra motorcycle. Microphones were positioned at 7.5- and 15-m (25-ft and 50-ft) offset distances from the center of the near travel line. Acoustical data, including L_{AFmx} and the one-third octave-band spectrum at the time of L_{AFmx}, were obtained.

The motorcycle was measured for pass-bys at constant-speeds of 48 to 88 km/h in 8 km/h (30 to 55 mph in 5 mph) increments. This supplementary data proved to be in the same emission level range as the random motorcycle data collected by the Volpe Center, and was therefore included in the analysis.

4.4 INTERRUPTED-FLOW MEASUREMENT PROCEDURE

Interrupted-flow measurements were performed with the assistance of Vanderbilt University (VU), the University of Central Florida (UCF), and Ohio University (OU) at sites which contained some type of flow-control device, such as a stop sign, toll booth, or on/off ramps. Measurement systems were placed at 15-meter offset positions from the centerline of the near travel lane at various points along the roadway. These points were typically 15, 30, 60, 120, 240, 300, 360 m (50, 100, 200, 400, 800, 1000, and 1200 ft, respectively) from the stop line (See Figure 4). An observer was stationed with each system.

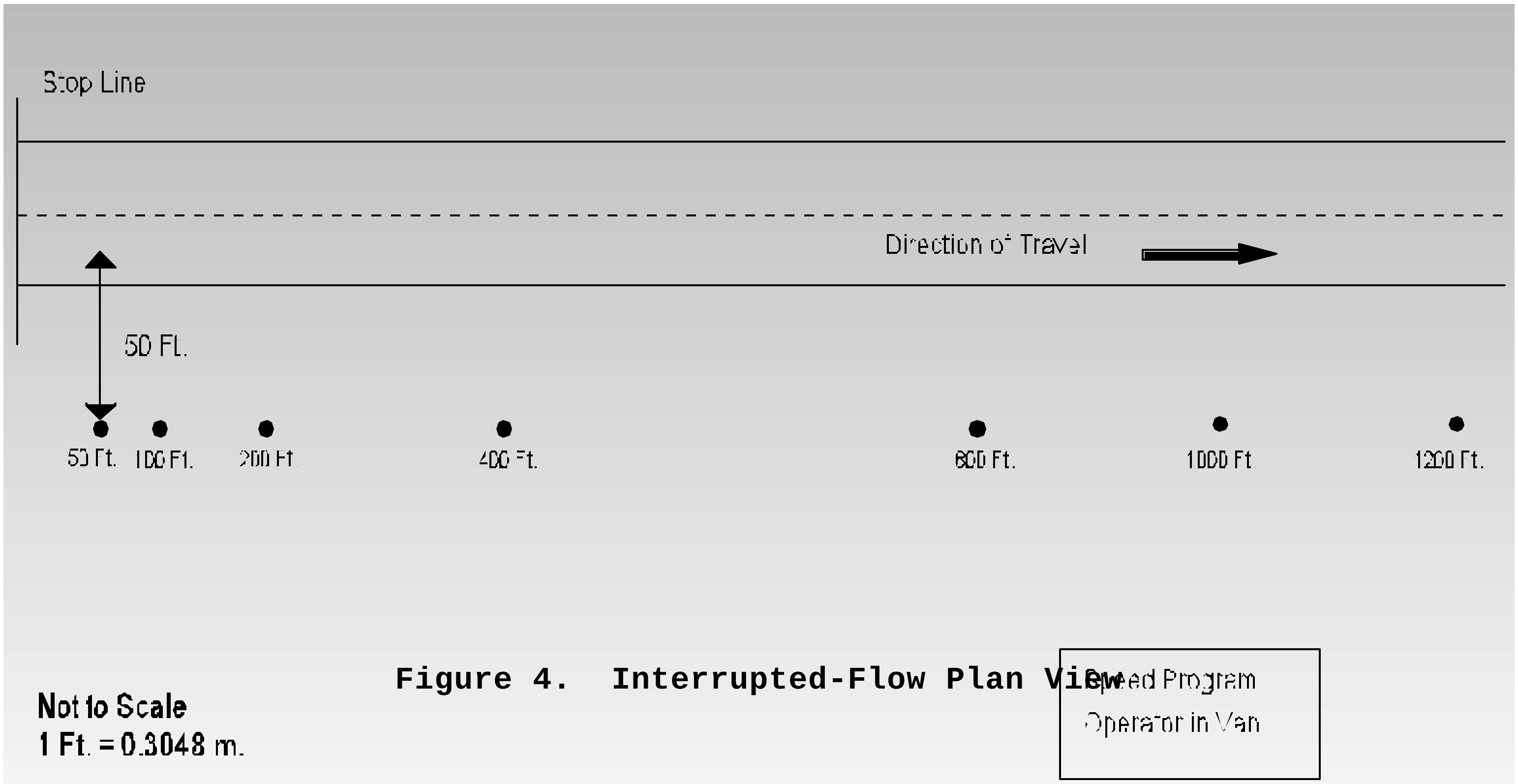


Figure 4. Interrupted-Flow Plan View

Each measurement system consisted of either a Metrosonics Model dB-308 sound level meter with built-in microphone, or a Rion Model SA-27 one-third octave-band analyzer. Prior to initial data collection and at hourly intervals, thereafter, all acoustic measurement systems were calibrated using a Metrosonics Model cl-304.

The observer at each station was also equipped with a CB radio and an orange signalling flag. As a potential event approached the stop line, the test coordinator announced the event number and vehicle description over the CB radio to both the interrupted-flow observers, as well as the observers at a constant-flow measurement site, typically located several miles beyond the interrupted-flow site. At the instant the test vehicle crossed the stop line, the test coordinator lowered the orange signalling flag. As the vehicle approached each subsequent measurement position, the observer at each location would begin measuring data with the sound level meter or analyzer. At the instant the vehicle's front axle crossed a line marked in the pavement opposite each microphone, the associated observer would lower his/her signalling flag.

After the vehicle passed the observer's station and before subsequent vehicles approached, the observer ended data capture and recorded the L_{AFmx}, the sound exposure level (SEL), denoted by the symbol L_{AE}, and a leading and trailing level associated with the rise and fall of the event, to determine event quality. The same event quality designators used for the constant-flow measurements were also used for the interrupted-flow measurements.

The lowering of the orange signaling flag at each observer position indicated to a vehicle speed operator running a computer program in a nearby van to press "enter" on a laptop computer. At the instant the observer pressed "enter" the program would read and store the time-of-day (TOD). The TOD data, along with the known distances between measurement points were used to compute average vehicle speed along various segments of the acceleration path.

The interrupted-flow measurements and analyses are chronicled in more detail in Reference 15.

4.5 SUBSOURCE-HEIGHT MEASUREMENT PROCEDURE

Florida Atlantic University (FLAU), with the assistance of Florida Department of Transportation, who provided supplementary financial support, measured vehicle subsource-height data for constant-flow traffic on PCC and DGAC pavement, as well as on graded roadways.

The vehicle subsource-height measurements are chronicled in detail in References 16, 17 and 18.

5. DATA REDUCTION

With the measurements completed, the constant-flow data, the interrupted-flow data, and the subsource-height data were amalgamated into a single, master spreadsheet. This section describes the data reduction process, including assembly of the final data base used for the analysis described in Section 6.0.

It is important to note that extremely loud vehicles, vehicles without mufflers, or vehicles with relatively unique noise signatures were not excluded from the analysis, since they were considered to be part of a random sample (See Section 4.3).

All analyses described in Sections 5 through 7 were performed with data adjusted for calibration drift, as required.

5.1 EVENT QUALITY

The GLR output measured at the 15-meter microphone position for each vehicle pass-by (A-weighted sound level versus time) was examined. When the rise and fall in sound level associated with an event was greater than 10 dB (Type-2 event quality), the L_{AFmx} (measured and stored by the LD2900) was included as-is in the spreadsheet.

When the rise and fall in sound level associated with an event was between 6 and 10 dB, due entirely to nearby vehicles (Type-1 event quality), the L_{AFmx} was included as-is in the spreadsheet.

In most cases, a primary criterion for a good event was that the difference between the L_{AFmx} and the ambient level measured at the 15-meter microphone position be at least 10 dB (See Criterion 6 in Section 2.1). However, due to the small amount of low speed (primarily less than 40 km/h, 25 mph), automobile data, this level-difference criterion was relaxed to 6 dB for data measured at five sites (Sites 25, 31, 32, 36, and 37). For automobile data measured at these sites, the L_{AFmx} was corrected for ambient via energy-subtraction, as required, and the associated event designated as Type

1A. The ambient-corrected L_{AFmx} data were also included in the spreadsheet.

Due to the small amount of bus pass-by events, bus data which had a rise and fall of between 3 and 6 dB, due entirely to nearby vehicles (Type-0 event quality), were also corrected. This correction was performed by subtracting from the measured L_{AFmx}, the sound energy due to "contaminating" vehicle(s). The Type-0, corrected, L_{AFmx} bus data were designated as Type 1B, and included in the spreadsheet.

All other events in which the rise and fall due to nearby vehicles were less than 6 dB, or events in which the associated L_{AFmx} was not at least 10 dB above the ambient noise level, were excluded from the spreadsheet. All data in which the rise and fall was 3 dB or less were discarded.

5.2 VEHICLE TYPES

Each vehicle was assigned an FHWA vehicle designation corresponding to one of the five acoustically significant types described in Section 2.2. These five vehicle types are consistent with the standard vehicle types in the FHWA TNM. The designations are as follows: Type 1 for all automobiles (previously Type 0 and 1); Type 2 for all medium trucks; Type 3 for all heavy trucks (previously Types 3 through 6); Type 4 for all buses (previously Type 8 and 9); and Type 5 for motorcycles (previously Type 7). Due to a lack of measured events, motor homes were excluded from all subsequent analyses.

The FHWA TNM definitions for automobiles, medium trucks and heavy trucks are consistent with the FHWA Report Number FHWA-RD-77-108.[19] The inclusion of two additional vehicle types (buses and motorcycles) provides a significant amount of flexibility to the TNM, not previously available with STAMINA.

5.3 IDLE DATA

As stated in Section 4.3.1, due to the low sound levels generated by idling automobiles, the measurement microphone at the idle site, Site 18, was positioned at a distance of 3.8 m (12.5 ft) from the center of the near travel lane. This system was set up to measure contiguous $L_{Aeq0.5s}$ data for a 30-second time period. The $L_{Aeq0.5s}$ data were energy-averaged to obtain a single L_{Aeq30s} for each idle event. The L_{Aeq30s} for each vehicle was adjusted to a distance of 15 m (50 ft) using the average drop-off rate measured at the adjacent constant-flow site (7.5 to 15 m) (25 to 50 ft). Due to the close proximity of the constant-flow site to the idle site, it is reasonable to assume that they have similar flow-resistivity (i.e., sound absorption) characteristics, and therefore similar drop-off rates. This data was merged into the spreadsheet but flagged as "special" since it was already energy averaged.

Data acquired from Harley-Davidson Motor Company were entered into the spreadsheet without any adjustments.

5.4 DATA BASE SPREADSHEET

The following information is included in the spreadsheet:

Event ID:	Volpe numerical event designation
Volpe Type: (used during data acquisition)	Numerical designation for vehicle type: 0 - Compact Automobiles; 1 - Standard Automobiles; 2 - Medium Trucks; 3 - 3 Axle Heavy Trucks; 4 - 4 Axle Heavy Trucks; 5 - 5 Axle Heavy Trucks; 6 - Heavy Trucks with 6 or more axles; 7 - Motorcycles; 8 - 2 Axle Buses; 9 - 3 Axle Buses 10 - Motor Homes 11 - Miscellaneous
FHWA Type:	Numerical designation for vehicle type: 1 - Automobiles; 2 - Medium Trucks; 3 - Heavy Trucks; 4 - Buses; 5 - Motorcycles
Vehicle Speed:	Vehicle Speed (mph)
Adj 50' Amax:	15-meter L_{AFmx}, including calibration, ambient noise, and contaminating vehicle adjustments, if applicable (dB)

GLR Code: Numerical designation for event quality:
  1A - Low speed (primarily less than 40 km/h, 25 mph) automobile data corrected for ambient noise;
  1B - Type 0 (3 to 6 dB) bus data corrected for noise caused by other vehicles;
  1 - 6 to 10 dB rise and fall;
  2 - greater than or equal to 10 dB rise and fall

Grade (%): Percent Grade to the nearest tenth, 0 if less than 1.5 percent

Pavement Type: DGAC - Dense-Graded Asphaltic Concrete;
PCC - Portland Cement Concrete;
OGAC - Open-Graded Asphaltic Concrete

Pavement Year: The year of the roadway's construction or last pavement overlay (whichever year is more recent)

Max A-weighted Spectrum 50 Hz to 10 kHz: Calibration-adjusted, one-third octave-band A-weighted spectrum measured at the 15-meter measurement position, at the time of L_{AFmx}. The spectrum is included for events with a GLR code of 1 and 2 only, i.e., no attempt was made to correct the spectral data for contamination. As will be discussed in Section 6.0, only the spectral data having an associated GLR quality of 2 were used in the one-third octave-band analyses.

Appendix D contains the complete, constant-flow REMEL Data Base as it was entered into the spreadsheet. The interrupted-flow and subsource-height data are presented in References 15 through 17.

6. DATA ANALYSIS

The analysis methodology presented in Section 6.0 is primarily based on a procedure developed jointly by Harris Miller Miller and Hanson Inc., Vanderbilt University, the University of Central Florida, and the Volpe Center.[20]

6.1 METHODOLOGY FOR DETERMINATION OF REMELs

This section describes the basic methodology employed for the determination of the Reference Energy Mean Emission Levels (REMELs) used in the FHWA TNM®. In determining the REMELs, the level-mean emission levels are first computed by regressing the measured L_{AFmx} values as a function of vehicle speed (Section 6.1.1). The REMELs are then computed by adjusting the level-mean emission levels upward by a fixed value, which is a function of the relationship between the level-mean regression and the individual L_{AFmx} values (Section 6.1.2).

6.1.1 Level-Mean Emission Level Regression

To compute the level-mean emission levels, the L_{AFmx} data measured at 15 m (50 ft) were regressed as a function of speed for each vehicle type, roadway surface, etc. The functional form of the level-mean regression equation is as follows:

$$\begin{aligned} L(s) &= 10\log_{10}(10^{C/10} + 10^{(A\log s+B)/10}) \\ &= 10\log_{10}(10^{C/10} + s^{A/10}10^{B/10}) \end{aligned}$$

In the above equation, L(s) is the logarithm to the base-10 of the coefficient C (an engine/exhaust coefficient, which is independent of vehicle speed); and, the term $A\log_{10}(s) + B$ (a tire/pavement-term, which increases with increasing vehicle speed).

The $A\log_{10}(s) + B$ term is consistent with that used in previous REMEL studies, as well as employed by STAMINA. The C coefficient has been added in this study to eliminate the prediction of erroneously low sound levels at low vehicle speeds.

The general form of the equation allows for easy adjustments for specific pavement types, roadway grades, and interrupted-flow traffic, as discussed later in Sections 6.5, 6.6, and 6.7, respectively. Figure 5 graphically displays the functional form.

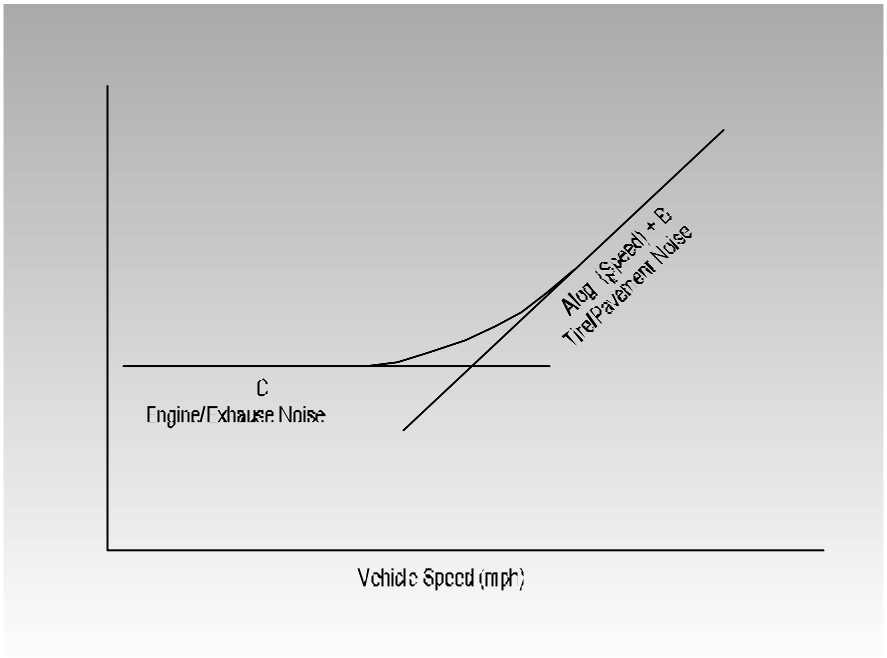


Figure 5. Graphical Form of the Level-Mean Regression Equation

6.1.2 Adjustment From Level-Mean to Energy-Mean

In previous REMEL studies, the adjustment from level-mean to energy-mean was computed using $0.115F^2$, where F is the standard error of the regression. This adjustment is correct only if the level-mean data are normally distributed about the level-mean regression, i.e., the level-mean data are Gaussian.   However, if the level-mean data are non-Gaussian, this adjustment is only an approximation. Since traffic noise data tend to be scattered more widely above the mean than below the mean, i.e., skewed upward, this adjustment is not quite correct. The following equation is a better method of approximating the level-mean to energy-mean adjustment factor when the distribution is non-Gaussian.

$$)E = 10\log_{10}((1/n)3RE_i) - (1/n)3RL_i$$

In the above equation, the RL_i values represent the level residuals, which are equivalent to the value of each data point, i, at its corresponding speed, s, minus the value of regression at s; and the RE_i values represent the energy residuals, which are equivalent to $10^{(RLi/10)}$.

To correctly account for this adjustment, it must be added to both the engine/exhaust term and the tire/pavement term of the L(s) equation, i.e., it must be added to both the C and B coefficients, as follows:

$$L_E(s) = 10\log_{10}[10^{(C+)E)/10} + (s^{A/10})(10^{(B+)E)/10})]$$

The)E adjustment converts the level-mean regression to an energy-mean regression. For several of the regressions developed in the current Study, computation of the engine/exhaust term and the tire/pavement term were performed separately. In these instances, computation of)E was performed twice, once during computation of the C coefficient, resulting in a)Ec term; and once during computation of the B coefficient, resulting in a)Eb term.

6.1.3 Confidence Interval

For each baseline (as defined in Section 6.4), energy-mean regression, the 95-percent confidence interval (CI) is defined as follows:

$$\text{95-percent CI}(s) = L_E(s) \pm 1.96g_{regr}(s)$$

In the above equation, the 95-percent CI defines the bounds within which we are 95 percent sure that the energy-mean regression lies. The $g_{regr}(s)$ term is the standard error of the energy-mean regression as a function of speed and is defined as follows:

$$(s) = \frac{1}{E}\{(s^{A/10}10^{B/10})^2[(\log_{10}s)^2\varepsilon_A^2+\varepsilon_B^2]+(10^{C/10})^2\varepsilon$$
$$+ 2(s^{A/10})^2(\log_{10}s)\rho_{AB}\varepsilon_A\varepsilon_B$$
$$+ 2(10^{C/10})(s^{A/10}10^{B/10})[(\log_{10}s)\rho_{AC}\varepsilon_A\varepsilon_B + \rho_{BC}\varepsilon$$
$$+ \frac{\sigma_{RL}^2\sigma_{RE}^2}{N(\overline{RE})^2}\}^{1/2}$$

In the above equation, $E = 10^{C/10} + s^{A/10}10^{B/10}$; g_A, g_B, and g_C are the standard errors of the A, B, and C coefficients, respectively; D_{AB}, D_{AC}, and D_{BC} provide a measure of the correlation between coefficients (i.e., the degree of relative correspondence); F_{RL} is the standard deviation of the level residuals; F_{RE} is the standard deviation of the energy residuals; 66 is the mean of the energy residuals; and N is the number of data points.

6.2 TESTS OF PRIOR DATA

As mentioned previously, a study was conducted by Caltrans from 1982 to 1985 for the purpose of determining California-specific REMELs. The Caltrans study included the measurement of 2734 vehicle pass-bys (A, MT, and HT) on level-grade roadways under constant-flow conditions; and 1769 vehicle pass-bys (HT only) on graded roadways under constant-flow conditions.

The procedures used for data measurement by Caltrans were essentially consistent with those used by the Volpe Center in the current REMEL study. Since the data set collected by Caltrans was quite extensive and considered by the authors to be of high quality, the possibility of including it in the FHWA TNM Data Base was examined. The data measured by the Volpe Center in the current study were purposely collected at eight sites in California which were also utilized in the Caltrans study. The intent was to compare the current Volpe Center data with the Caltrans data collected at the same sites to determine if the two data sets were statistically equivalent. Comparisons were made for automobiles, medium trucks and heavy trucks under average pavement (as defined in Section 6.4), level-grade, constant-flow conditions, and for heavy trucks under average pavement, grade, constant-flow conditions.

Emission level equations for each data set, $L_E(s)_{Volpe}$ and $L_E(s)_{Caltrans}$, and their standard errors were computed as in Section 6.1. The difference between the two regressions, and the associated difference in the standard error was computed as follows:

$$L_E(s)_{DIFF} = L_E(s)_{Volpe} - L_E(s)_{Caltrans}$$

$$g_{DIFF}(s) = (g_{Volpe}(s)^2 + g_{Caltrans}(s)^2)^{.5}$$

The difference in the standard errors was used to compute the associated 95-percent CI. Through graphical analysis, if it is found that the coordinate axis in the positive x direction (the vehicle speed axis) i.e., the zero difference line, lies outside the CI bounds, then it can be assumed that the measured difference in the two data sets is "real" rather than just due to chance. For the purposes of the current study it was decided that if the zero difference line lies totally within the CI bounds, then the two data sets are statistically the same and can be merged.

6.3 TESTS FOR INDIVIDUAL STATE REMELs

As mentioned above in Section 6.2, Caltrans performed a study for the purpose of determining California-specific REMELs. Similar to the Caltrans study, the Volpe Center performed a study for the purpose of determining if REMELs measured within a given state were unique, by comparing individual State REMELs with National REMELs, computed with data from all states combined.

The A-Level REMEL regression for each vehicle type, which included data from all states combined was compared with its associated State-specific regression. Using an analysis similar to that performed with the Caltrans data, it was decided that if the error bars defined by the 95-percent confidence interval associated with the National regressions encompassed the State-specific regressions, then the National REMELs were statistically equivalent to the State-specific REMELs.

Due to the large amount of data in the REMEL Data Base, the error bars associated with the National regressions fit relatively close about their regression lines. However, because different states were targeted for different vehicle types, speeds, pavement types, and grade conditions, State-specific regressions often contained a non-uniform distribution of data across the range of vehicle speeds. Consequently, in speed ranges where there was a large amount of data, the associated error was small. However, in speed ranges where only a few data points were measured, the error was quite large.

It was almost universally found that in those areas of the regression where large amounts of State-specific data were measured, the associated REMEL regressions were statistically equivalent to the National REMEL regressions. Conversely, in areas where only a small amount of data were measured, the State and National REMEL regressions were found to be statistically different. Thus, it was concluded that not enough State-specific data were measured to determine if REMELs measured within a given state were unique across the entire speed range of interest.

6.4 REMELs FOR BASELINE CONDITIONS

This section discusses the computation of REMELs for "baseline" conditions, which are defined as follows:

- Average Pavement
- Level Grade (1.5 percent or less)
- Constant-Flow Traffic

Average pavement is defined as a combination of both DGAC and PCC pavements. For A, MT, and HT this combination is made up of, on average, approximately 75 percent DGAC pavement and 25 percent PCC pavement.

Regression of the functional form for $L_E(s)$ requires the use of a non-linear regression model. The coefficients A, B, and C were estimated using the Simplex and/or Quasi-Newton, non-linear regression estimation methods, as programmed in the statistical analysis software package, SYSTAT Version 5.03 for DOS. SYSTAT was used for all statistical analyses described herein.[24]

6.4.1 Automobiles

Because the emission levels for automobiles are dominated by tire/pavement noise, the transition between the tire/pavement-portion of the regression and the engine/exhaust-portion occurs at a very low speed. The data collected for idling automobiles formed the basis for the engine/exhaust-portion of the regression. The level-mean regression for the baseline automobile data was computed as follows:

$L(s) = 10\log_{10}(10^{C/10})$, for zero speed (idle); and
$L(s) = 10\log_{10}(s^{A/10}10^{B/10})$, for speed greater than zero.

The adjustment from level-mean to energy-mean was computed as in Section 6.1.2, with)Ec computed from the zero speed regression and data set, and)Eb computed from the speed greater than zero regression and data set. The separate regression equations and adjustments were combined to form the final baseline REMEL equation for automobiles. The 95-percent CI was computed as in Section 6.1.3; g_{AC} and g_{BC} were equal to zero; F_{RL}, F_{RE}, $\overline{\boldsymbol{RE}}$ and N were computed using the data set associated with speeds greater than zero.

6.4.2 Medium Trucks

The baseline REMEL equation and 95-percent CI for medium trucks were computed as in Sections 6.1.1, 6.1.2, and 6.1.3.

6.4.3 Heavy Trucks

The baseline REMEL equation and 95-percent CI for heavy trucks were computed as in Sections 6.1.1, 6.1.2, and 6.1.3.

6.4.4 Buses

Due to the small amount of data measured for buses at low speeds, the nonlinear regression method used for A, MT, and HT could not be used to correctly identify an engine/exhaust transition in the bus sound-level data. However, inspection of the bus data set revealed that the tire/pavement-portion of the bus regression closely resembled that of the medium truck regression. Therefore, it was decided that the engine/exhaust-portion of the REMEL regression computed for medium trucks would be used for buses.

Level-mean regressions were computed as in Section 6.1.1. Specifically, the A and B coefficients were computed, and the value of the coefficient C from the medium truck, baseline regression was used. The adjustment from level-mean to energy-mean was computed as in Section 6.1.2, resulting in a)Eb value. Because the C coefficient from the medium truck regression was used, the associated value of)Ec was also used. The 95-percent CI was computed as in Section 6.1.3; g_{AC} and g_{BC} were equal to zero; F_{RL}, F_{RE}, **RE** and N were computed using the bus regression and data set.

6.4.5 Motorcycles

Due to the small amount of data measured for motorcycles at low speeds, the nonlinear regression method used for A, MT, and HT could not be used to correctly identify an engine/exhaust transition in the motorcycle sound-level data. However, at the site where data were measured for idling automobiles (Site 18), data for one idling motorcycle were also obtained. These data were used to determine the transition in the motorcycle data. The level-mean regression for the baseline motorcycle data was computed as follows:

$L(s) = 10\log_{10}(10^{C/10})$, for zero speed (idle); and
$L(s) = 10\log_{10}(s^{A/10}10^{B/10})$, for speed greater than zero.

The adjustment from level-mean to energy-mean was computed as in Section 6.1.2, with)Ec set equal to zero, and)Eb computed from the speed greater than zero regression and data set. Since there was only one data point at idle, the level-mean and energy-mean were equivalent and as such)Ec was set equal to zero. The separate regression equations and adjustments were combined to form the final baseline REMEL equation for motorcycles. The 95-percent CI was computed as in Section 6.1.3; g_{AC} and g_{BC} were equal to zero; F_{RL}, F_{RE}, $\overline{\boldsymbol{RE}}$ and N were computed using the data set associated with speeds greater than zero.

6.5 REMELs FOR SPECIFIC ROADWAY PAVEMENTS

This section discusses the computation of REMELs for level-grade, constant-flow conditions on specific roadway pavements. REMELs were computed for three types of pavements as follows: DGAC, PCC and OGAC.

The level mean, L(s), was computed by changing the coefficient which governs the vertical position of the tire/pavement portion of the regression, i.e., the B coefficient, while holding the other coefficients constant in the baseline regression. This method assumes that neither the engine/exhaust-portion of the curve nor the slope of the tire/pavement-portion of the curve changes with specific pavement type.

The adjustment from level-mean to energy-mean was computed as in Section 6.1.2. Specifically,)Eb was computed using the specific pavement data set and regression, and)Ec was taken from the baseline condition. The standard errors and 95-percent CI were computed as in Section 6.1.3, with D_{AB} and D_{BC} set equal to zero.

6.5.1 Automobiles

Specific pavement emission levels for automobiles were computed as in Section 6.5.

6.5.2 Medium Trucks

Specific pavement emission levels for medium trucks were computed as in Section 6.5.

6.5.3 Heavy Trucks

Specific pavement emission levels for heavy trucks were computed as in Section 6.5.

6.5.4 Buses

As stated in Section 6.4, the average pavement data set for A, MT, and HT consisted of approximately 25 percent PCC data. However, the data set for buses contained only 1 percent PCC data. Therefore, the DGAC REMEL regression was used as the baseline regression for buses, and was adjusted to approximate an average pavement regression. This adjustment was made by assuming that the difference between the vertical position of the tire/pavement-portion of the bus regression (baseline case versus specific pavement case) was the same as for medium trucks (i.e., $B+)Eb_{BUSAVG}-B+)Eb_{BUSDGAC} = B+)Eb_{MTAVG}-B+)Eb_{MTDGAC}$).

The baseline (i.e., DGAC) REMEL equation was adjusted to PCC and OGAC pavements using the same methodology.

6.5.5 Motorcycles

It was assumed that motorcycle REMELs are dominated by engine/exhaust noise. Therefore, no specific pavement adjustments were computed.

6.6 REMELs FOR VEHICLES ON GRADED ROADWAYS

This section discusses the computation of REMELs for constant-flow vehicles on average pavement and graded roadways. Vehicles on grade require an increased throttle setting to maintain a constant speed. Therefore, L(s) was computed by changing only the coefficient which governs the engine/exhaust-portion of the baseline regression, i.e., the C coefficient, while holding the other coefficients from the baseline regression constant. This assumes that the tire/pavement-portion of the regression does not change when vehicles are traveling on graded roadways.

The adjustment from level-mean to energy-mean was computed as in Section 6.1.2. Specifically, $)E_c$ was computed using the grade data set and regression, and $)E_b$ was taken from the baseline condition. The standard errors and 95-percent CI were computed as in Section 6.1.3, with D_{AB} and D_{BC} set equal to zero.

6.6.1 Automobiles

It was assumed that automobiles do not require a significant increase in throttle to maintain a constant speed when traveling on grades. Consequently, no grade adjustment was computed for automobiles.

6.6.2 Medium Trucks

It was assumed that medium trucks do not require a significant increase in throttle to maintain a constant speed when traveling on grades. Consequently, no grade adjustment was computed for medium trucks. However, a minimal amount of data were measured for medium trucks on grade. These data were used for deriving one-third octave-band spectral shapes for medium trucks and buses under interrupted-flow conditions, since no one-third octave-band data were obtained during the interrupted-flow measurements.

6.6.3 Heavy Trucks

The REMEL regressions and 95-percent CI for heavy trucks on grade was computed as in Section 6.6. Although the majority (83 percent) of data for heavy trucks on upgrade was measured on PCC pavement, it was assumed, when estimating the coefficient C, that the tire/pavement-portion of the curve was the same as for average pavement, i.e., the A, B, and)Eb coefficients were the same as in the average pavement case. This is a reasonable assumption, since tire/pavement noise should have little or no effect at the lower speeds, where engine/exhaust noise dominates.

6.6.4 Buses

It was assumed that buses do not require a significant increase in throttle to maintain a constant speed when traveling on grades. Consequently, no grade adjustment was computed for buses.

6.6.5 Motorcycles

It was assumed that motorcycles do not require a significant increase in throttle to maintain a constant speed when traveling on grades. Consequently, no grade adjustment was computed for motorcycles.

6.7 REMELs FOR VEHICLES UNDER INTERRUPTED-FLOW CONDITIONS

This section discusses the computation of REMELs for vehicles on level grade, average pavement, under interrupted-flow conditions. Vehicles under interrupted-flow conditions require an increased throttle setting to accelerate up to a desired constant speed. Therefore, the associated REMELs were computed by adjusting the engine/exhaust-portion of the baseline regression, i.e., the C coefficient, while holding the other coefficients from the baseline regression constant. This assumes that the tire/ pavement-portion of the regression is not affected by interrupted-flow conditions.

For automobiles, medium trucks, and heavy trucks, the level-mean regression was computed by using the A and B coefficients from the baseline regression, and solving the nonlinear regression for the coefficient C. The level and energy residuals were computed as in Section 6.1.2, resulting in a value for)Ec. The value of)Eb was taken from the respective roadway pavements. The standard errors and 95-percent CI were computed as in Section 6.1.3, with g_{AC} and g_{BC} set equal to zero.

For buses and motorcycles, the coefficient C and the associated)Ec were borrowed from medium trucks and automobiles, respectively. For buses under interrupted-flow conditions, use of the C coefficient and)Ec from medium trucks under interrupted-flow conditions appears reasonable based on the similarities between their REMELs for other like-measurement conditions. For motorcycles under interrupted-flow conditions, the choice of using the C coefficient and)Ec from automobiles under interrupted-flow conditions, although rather arbitrary, was based on conservative intuition.

6.8 ONE-THIRD OCTAVE-BAND REMELs

In order for the FHWA TNM to accurately predict sound levels, the REMELs will be propagated from source to receiver in one-third octave-bands. To correctly characterize these one-third octave-bands, spectral data at the time of L_{AFmx} were measured for each vehicle pass-by (see Section 3.1). These data were regressed as a function of speed and frequency to determine one-third octave-band REMELs for each vehicle type, pavement type, and throttle-condition combination.

In order to ensure that the data in any one-third octave-band were not significantly contaminated, data of GLR Type 2 only, i.e., greater than 10 dB rise and fall, were used in one-third octave-band analyses for automobiles, medium trucks, and heavy trucks. However, due to an insufficient amount of Type 2 data, GLR Type 1 data were also utilized for buses and motorcycles.

6.8.1 Speed Bands

To simplify the analysis, spectral data were grouped into speed bands, each having approximately the same number of pass-by events. The grouping was performed as follows: For each data set, divide the number of events by 50; if the quotient is less than 6, use 6 speed bands. If the quotient is greater than 6, use approximately 50 events per speed band for as many speed bands as necessary.

The spectral data for the events within each grouping were energy-averaged in each one-third octave-band (50 Hz to 10 kHz). The resultant energy-averaged spectrum was then associated with the mean speed encompassed by the group of events. Tables 10 through 25 present the speed bands used for each vehicle type, pavement, and grade condition. Note: No one-third octave-band data were measured for interrupted-flow conditions. The mean speed, minimum speed, maximum speed, and number of events in each speed-band for each data set are presented.

Table 10. Spectral Analysis Speed Bands Automobiles - Baseline Conditions

Mean Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	# of Events
25	14	28	62
30	29	31	50
32.5	32	33	48
35	34	36	50
38	37	39	54
42	40	44	58
45.5	45	46	49
48	47	49	50
50.5	50	51	56
52	52	52	31
53	53	53	43
54	54	54	55
55	55	55	53
56	56	56	54
57	57	57	72
58	58	58	57
59	59	59	62
60	60	60	69
61	61	61	60
62	62	62	49
63	63	63	45
64.5	64	65	73
66.5	66	67	55
68.5	68	69	51
72.5	70	85	58

Note: 1 mph = 1.609344 km/h

Table 11. Spectral Analysis Speed Bands
Automobiles - DGAC Pavement

Mean Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	# of Events
25	14	28	62
30	29	31	50
32.5	32	33	48
35	34	36	50
38	37	39	53
42	40	44	58
45.5	45	46	45
48	47	49	46
50.5	50	51	47
52.5	52	53	60
54	54	54	48
55	55	55	49
56	56	56	49
57	57	57	67
58	58	58	52
59	59	59	52
60	60	60	58
61	61	61	46
62	62	62	42
63.5	63	64	69
66	65	67	64
69	68	70	55
74	71	85	22

Note: 1 mph = 1.609344 km/h

Table 12. Spectral Analysis Speed Bands Automobiles - PCC Pavement

Mean Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	# of Events
49	39	52	22
54	53	55	21
57	56	58	15
59.5	59	60	21
61.5	61	62	21
63.5	63	64	17
65.5	64.5	66	18
68	67	69	16
72.5	70	81	21

Note: 1 mph = 1.609344 km/h

Table 13. Spectral Analysis Speed Bands Automobiles - OGAC Pavement

Mean Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	# of Events
51.5	48	53	32
54.5	54	55	32
56.5	56	57	41
58.5	58	59	37
60.5	60	61	40
62.5	62	63	34
65	64	67	36
71.5	60	89	21

Note: 1 mph = 1.609344 km/h

Table 14. Spectral Analysis Speed Bands
Medium Trucks - Baseline Conditions

Mean Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	# of Events
28.5	20	34	31
39	35	43	29
45	44	46	26
48.5	47	50	27
51.5	51	52	29
54	53	55	37
56.5	56	57	38
59	58	60	35
62.5	61	65	30
67.5	66	73	16

Note: 1 mph = 1.609344 km/h

Table 15. Spectral Analysis Speed Bands
Medium Trucks - DGAC Pavement

Mean Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	# of Events
27.5	20	32	27
37	33	41	26
44	42	46	24
48.5	47	50	20
52	51	53	27
54.5	54	55	21
56.5	56	57	34
59	58	60	28
62	61	63	19
66.5	64	73	19

Note: 1 mph = 1.609344 km/h

Table 16. Spectral Analysis Speed Bands
Medium Trucks - PCC Pavement

Mean Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	# of Events
45	44	46	9
49	47	51	8
52	52	52	7
54	53	55	10
57.5	56	59	9
65	60	70	10

Note: 1 mph = 1.609344 km/h

Table 17. Spectral Analysis Speed Bands
Medium Trucks - OGAC Pavement

Mean Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	# of Events
49.5	45	51	11
53.5	52	55	9
56.5	56	57	14
58.5	58	59	12
60.5	60	61	7
63	62	66	13

Note: 1 mph = 1.609344 km/h

Table 18. Spectral Analysis Speed Bands
Medium Trucks - Grade

Mean Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	# of Events
35.5	30	40	10
46.5	41	51	9
55.5	52	59	9

Note: 1 mph = 1.609344 km/h

Table 19. Spectral Analysis Speed Bands
Heavy Trucks - Baseline Conditions

Mean Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	# of Events
11	7	15	55
26	16	36	58
39	37	41	55
43	42	44	55
46	45	47	50
49	48	50	67
51.5	51	52	66
53	53	53	42
54	54	54	50
55	55	55	66
56	56	56	61
57	57	57	69
58	58	58	86
59	59	59	60
60	60	60	76
61	61	61	65
62	62	62	53
63	63	63	50
64	64	64	53
65.5	65	66	66
69.5	67	72	56

Note: 1 mph = 1.609344 km/h

Table 20. Spectral Analysis Speed Bands
Heavy Trucks - DGAC Pavement

Mean Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	# of Events
11	7	15	55
26	16	36	58
39	37	41	49
43.5	42	45	59
47.5	46	49	46
50.5	50	51	37
52.5	52	53	47
54.5	54	55	71
56	56	56	40
57	57	57	46
58	58	58	53
59	59	59	45
60	60	60	52
61	61	61	43
62.5	62	63	59
64.5	64	65	64
68	66	72	47

Note: 1 mph = 1.609344 km/h

Table 21. Spectral Analysis Speed Bands
Heavy Trucks - PCC Pavement

Mean Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	# of Events
46.5	38	50	52
52	51	53	44
54.5	54	55	49
56.5	56	57	45
58.5	58	59	50
60.5	60	61	48
62.5	62	63	45
65	64	66	45
68.5	67	72	24

Note: 1 mph = 1.609344 km/h

Table 22. Spectral Analysis Speed Bands
Heavy Trucks - OGAC Pavement

Mean Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	# of Events
49.5	46	51	21
52.5	52	53	23
54.5	54	55	26
56	56	56	20
57.5	57	58	30
59	59	59	20
60.5	60	61	21
63.5	62	67	23

Note: 1 mph = 1.609344 km/h

Table 23. Spectral Analysis Speed Bands
Heavy Trucks - Grade

Mean Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	# of Events
26	18	29	31
31.5	30	33	32
35.5	34	37	32
39.5	38	41	26
43	42	44	27
46	45	47	30
49	48	50	30
52	51	53	27
54.5	54	55	30
57	56	58	28
60.5	59	66	13

Note: 1 mph = 1.609344 km/h

Table 24. Spectral Analysis Speed Bands
Buses - Baseline Conditions

Mean Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	# of Events
27.5	17	35	39
41	37	45	39
51	46	55	37
57	56	58	31
60	59	61	36
64.5	62	72	36

Note: 1 mph = 1.609344 km/h

Table 25. Spectral Analysis Speed Bands
Motorcycles - Baseline Conditions

Mean Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	# of Events
35	31	39	5
42	40	44	5
51	46	54	5
58	55	60	6
62	61	64	5
70	65	80	6

Note: 1 mph = 1.609344 km/h

6.8.2 Analysis of Spectral Shape

To determine REMELs in terms of both frequency and speed, an analysis was first performed to determine what functional form would best fit the general shape of the vehicle sound-level spectra. The events making up each speed band were plotted and visually inspected to determine if there were any common characteristics.

The common characteristics for all of the spectra were: (1) an upside-down parabolic shape; and, (2) a "notch" of lost acoustic energy between 100 and 400 Hz due to ground effects between the source-vehicle and microphone. It was found that a sixth-order polynomial best described this shape. The general equation for the sixth-order polynomial is as follows:

$$L(f) = D+E\log_{10}f+F(\log_{10}f)^2+G(\log_{10}f)^3+H(\log_{10}f)^4+I(\log_{10}f)^5+J(\log_{10}f)^6$$

6.8.3 Analysis of Change in Spectral Shape Versus Speed

By analyzing the general changes in spectral shape as a function of speed, it was found, not surprisingly, that the level in each one-third octave-band increased with increasing vehicle speed. Each coefficient (D through J) in the above equation was replaced with a relatively empirical speed function: D(s) = D1+D2*s, E(s) = E1+E2*s, etc. The one-third octave-band, REMEL equation as a function of vehicle speed is as follows:

$$\begin{aligned} L(s,f) = {} & D1+D2*s + (E1+E2*s)\log_{10}f + (F1+F2*s)(\log_{10}f)^2 + \\ & (G1+G2*s)(\log_{10}f)^3 + (H1+H2*s)(\log_{10}f)^4 + \\ & (I1+I2*s)(\log_{10}f)^5 + (J1+J2*s)(\log_{10}f)^6 \end{aligned}$$

6.8.4 Spectral Shaping at Low Speeds

The coefficients (D1, D2, through J1, J2) in the above equation were estimated using non-linear regression methods. After examination of the regression fit, it was found that in those instances were there were little, if any, spectral data at low speeds, such as for vehicles on PCC and OGAC pavements, the computed spectral shape often behaved erratically. Specifically, the spectral shape did not always exhibit the expected characteristics, i.e., upside down parabola with a notch of lost acoustic energy. In such instances, additional spectral data at 8 or 16 km/h (5 or 10 mph) intervals were added, as required. The added spectral data were based on measured data and included in the following manner:

- If data were to be added at some speed in the low-speed range of the tire/pavement-portion of a data set, the spectral data from the lowest available speed were calibrated down in level so that its resultant A-weighted sound level at the lower speed was equal to the A-weighted sound level computed using the A-weighted sound level REMEL regression at the same speed.

- If the data were to be added at some speed in the engine/exhaust-portion of a data set, the spectral data from the closest available speed in the average pavement regression were calibrated in level so that the resultant A-weighted sound level was equal to the A-weighted sound level computed using the A-weighted sound level REMEL regression at the same speed.

A generalized example of this calibration for the 100 Hz one-third octave-band, using a known data point at a speed of 40.2 km/h (25 mph) and adjusting it for use at a speed of 16 km/h (10 mph) is as follows:

$$L_{AFmx(100Hz,10mph)} = 10\log_{10}[10^{[L_{AFmx(100Hz,25mph)}]/10} / 10^{[L_{AFmx(25mph)} - L_{AFmx(10mph)}]/10}]$$

The added spectral data and the source of that data, as a function of vehicle type, roadway pavement type, and grade condition are as follows:

<u>Automobiles</u>:

Average - Data were added at speeds of 1.6, 8, 16.1, 24.1, and 32.2 km/h (1, 5, 10, 15, and 20 mph), using the data from the average pavement case at a speed of 40.2 km/h (25 mph).

DGAC - Data were added at speeds of 8, 16.1, and 24.1 km/h (5, 10, and 15 mph), using data from the average pavement case at a speed of 40.2 km/h (25 mph); and data were added at a speed of 32.2 km/h (20 mph) using data from the DGAC case at a speed of 45.1 km/h (28 mph).

PCC - Data were added at speeds of 1.6, 8, and 16.1 km/h (1, 5, and 10 mph), using data from the average pavement case at a speed of 40.2 km/h (25 mph); and data were added at speeds of 24.1, 32.2, 40.2, 48.3, 56.3, 64.4, 72.4 km/h (15, 20, 25, 30, 35, 40, and 45 mph), using data from the PCC case at a speed of 78.9 km/h (49 mph).

OGAC - Data were added at speeds of 1.6, 8, 16.1, and 24.1 km/h (1, 5, 10, and 15 mph), using data from the average pavement case at a speed of 40.2 km/h (25 mph); and data were added at speeds of 24.1, 32.2, 40.2, 48.3, 56.3, 64.4, 72.4 km/h (20, 25, 30, 35, 40, and 45 mph), using data from the OGAC case at a speed of 83.7 km/h (52 mph).

Medium Trucks:

Average - Data were added at speeds of 1.6, 8, 16.1, 24.1, and 32.2 km/h (1, 5, 10, 15, and 20 mph), using data from the average pavement case at a speed of 46.7 km/h (29 mph).

DGAC - Data were added at speeds of 1.6, 16.1, and 32.2 km/h (1, 10, and 20 mph), using data from the average pavement case at a speed of 46.7 km/h (29 mph).

PCC - Data were added at speeds of 1.6, 16.1, and 32.2 km/h (1, 10, and 20 mph), using data from the average pavement case at a speed of 46.7 km/h (29 mph); and data were added at speeds of 48.3 and 64.4 km/h (30 and 40 mph), from the PCC case at a speed of 72.4 km/h (45 mph).

OGAC - Data were added at speeds of 1.6, 16.1, and 32.2 km/h (1, 10, and 20 mph), using data from the average pavement case at a speed of 46.7 km/h (29 mph); and data were added at speeds of 48.3 and 64.4 km/h (30 and 40 mph), using data from the OGAC case at a speed of 80.5 km/h (50 mph).

Grade - Data were added at speeds of 1.6, 16.1, 32.2 and 48.3 km/h (1, 10, 20, and 30 mph), using data from the heavy-truck, grade case at a speed of 41.8 km/h (26 mph). Note: Although no grade adjustment was computed for medium trucks (Section 6.6.2), it was intended that the one-third octave-band data measured for medium trucks on grade would provide a good representation of spectral shape for medium trucks under interrupted-flow conditions (See Section 7.8.2).

Heavy Trucks:

Average - No data needed to be added.

DGAC - No data needed to be added.

PCC - Data were added at speeds of 1.6, 8, 16.1, and 24.1 km/h (1, 5, 10, and 15 mph), using data from the average pavement case at a speed of 17.7 km/h (11 mph); and data were added at speeds of 32.2 and 40.2 km/h (20 and 25 mph), using data from the average pavement case at a speed of 82.1 km/h (26 mph); and data were added at speeds of 48.3, 56.3, and 64.4 km/h (30, 35, and 40 mph), using data from the PCC case at a speed of 75.6 km/h (47 mph).

OGAC - Data were added at speeds of 1.6, 8, 16.1, and 24.1 km/h (1, 5, 10, and 15 mph), using data from the average pavement case at a speed of 17.7 km/h (11 mph); and data were added at speeds of 32.2, 40.2, and 48.3 km/h (20, 25, and 30 mph), using data from the average pavement at a speed of case at 41.8 km/h (26 mph); and data were added at speeds of 56.3, 64.4, and 72.4 km/h (35, 40, and 45 mph), using data from the OGAC case at a speed of 78.8 km/h (49 mph).

Grade - Data were added at speeds of 1.6, 8, 16.1, 24.1 and 32.2 km/h (1, 5, 10, 15, and 20 mph), using data from the grade case at a speed of 41.8 km/h (26 mph).

Buses:

Average - Data were added at speeds of 1.6, 16.1, and 32.2 km/h (1, 10, and 20 mph), using data from the average pavement case at a speed of 45.1 km/h (28 mph). Note: For buses, due to insufficient data, the same spectral shape was assumed, regardless of pavement type or grade condition.

Motorcycles:

Average - Data were added at speeds of 1.6, 16.1, and 32.2 km/h (1, 10, and 20 mph), using data from the average pavement case at a speed of 56.3 km/h (35 mph). Note: It was assumed that motorcycle REMELs are dominated by engine/exhaust noise. Therefore, no specific pavement adjustment or grade adjustment was computed. Likewise, spectral shaping for different pavements or grade conditions was not necessary.

6.8.5 Final Calibration

Following the spectral-shaping process described in Section 6.8.4, the coefficients (D1, D2, through J1, J2) were re-computed using non-linear regression methods. The resultant one-third octave-band-based equations were then used to compute the A-level as a function of speed. The one-third octave-band-based A-level was then compared as a function of vehicle speed with the A-level, as computed in Section 6.1. Small differences were observed, not surprisingly, since the one-third octave-band based A-level regression was a linear function of speed, as compared with the A-level regression, which was non-linear. (Note: It was decided that a linear function of speed was required for the one-third octave-band-based A-level to significantly reduce functional complexity.)

A final calibration factor for the one-third octave-band REMEL equation was needed to improve agreement between the one-third octave-band-based A-level versus speed regression, and the A-level versus speed regression. This calibration factor was simply the equation for the A-level, energy-mean regression, $L_E(s)$, minus the one-third octave-band-based equation for the A-level, $L_{E\ 1/3}(s) = K1+K2*s$.

With this calibration, the final one-third octave-band REMEL equation is as follows:

$$
\begin{aligned}
L_E(s,f) \quad = \quad & 10*\log_{10}(10^{(C+)Ec)/10}+s^{A/10}10^{(B+)Eb)/10}) \\
& - (K1+K2*s) + (D1+D2*s) \\
& + (E1+E2*s)(\log_{10}f) + (F1+F2*s)(\log_{10}f)^2 \\
& + (G1+G2*s)(\log_{10}f)^3 + (H1+H2*s)(\log_{10}f)^4 \\
& + (I1+I2*s)(\log_{10}f)^5 + (J1+J2*s)(\log_{10}f)^6
\end{aligned}
$$

To simplify the above equation, D1 and K1 can be combined and D1*s and K2*s can be combined. The simplified version of the equation appears in the FHWA TNM. Specifically, in the TNM, $D1 = D1-K1$ and
$D2*s = (D2-K2)*s$.

The A-levels resulting from the above, one-third octave-band-based equation are within ±0.6 dB of the A-level REMEL regression across all vehicle speeds, and are within ±0.3 dB of the A-level REMEL regression at the primary speeds of interest between 64.4 and 112.6 km/h (40 and 70 mph).

6.9 SUBSOURCE-HEIGHT SPLITS

This section discusses the methodology used to split the one-third octave-band REMELs into two subsource heights, (1) a lower subsource height at 0 m above the pavement, and (2) an upper subsource height at 3.6 m (12 ft) above the pavement for heavy trucks, and 1.5 m (5 ft) above the pavement for all other vehicles. The lower subsource height is representative of tire/pavement noise while the upper height is representative of engine/exhaust noise.

These subsource-height splits were developed using data measured by Florida Atlantic University (FLAU). In total, FLAU measured 714 pass-by events. Events were grouped separately for automobiles, medium trucks, heavy trucks, buses, and motorcycles on average pavement (DGAC and PCC combined), level grade conditions; and for medium trucks and heavy trucks on average pavement, grade conditions. Due to an insufficient amount of data available at this time, subsource-height ratios (upper/ lower) were not computed for specific pavement types, although a cursory analysis indicated little, if any relationship between subsource height and pavement type.

As in the one-third octave-band analysis, spectral data from the subsource-height measurements were grouped into speed bands, each band containing approximately the same number of pass-by events. The spectral data for the events in each group, at each subsource height, were energy-averaged in each one-third octave-band. The resultant energy-averaged spectrum for each subsource height was then associated with the mean speed encompassed by the group of events. Tables 26 through 30 present the speed bands used for each vehicle type, pavement type and grade condition. The mean speed, minimum speed, maximum speed, and number of events in each speed-band for each data set are presented.

Table 26. Subsource-Height Speed Bands
Automobiles - Baseline Conditions

Mean Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	# of Events
32.5	24	36	21
38.5	37	42	19
45.5	43	51	20
57	53	59	21
60.5	60	61	25
63	62	64	22
65.5	65	66	17
69	67	75	16

Note: 1 mph = 1.609344 km/h

Table 27. Subsource-Height Speed Bands
Medium Trucks - Baseline Conditions

Mean Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	# of Events
30.5	28	33	2
39.5	35	44	3
55.5	54	57	2
62.5	62	63	5
65	64	66	3
69.5	67	71	2

Note: 1 mph = 1.609344 km/h

Table 28. Subsource-Height Speed Bands Heavy Trucks - Baseline Conditions

Mean Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	# of Events
52.5	46	54	14
56	55	57	12
58	58	58	12
59	59	59	12
60	60	60	14
61	61	61	12
62	62	62	14
63	63	63	16
64.5	64	65	16
66.5	66	67	12
71	68	76	12

Note: 1 mph = 1.609344 km/h

Table 29. Subsource-Height Speed Bands Buses - Baseline Conditions

Mean Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	# of Events
39	39	39	1
40	40	40	1
47	47	47	1
55	55	55	1
56	56	56	2
68	68	68	1

Note: 1 mph = 1.609344 km/h

Table 30. Subsource-Height Speed Bands Motorcycles - Baseline Conditions

Mean Speed (mph)	Minimum Speed (mph)	Maximum Speed (mph)	# of Events
60	60	60	1
58	58	58	1

Note: 1 mph = 1.609344 km/h

For each speed band, the subsource-height ratio (upper/lower) was computed in all one-third octave-bands. The product of subsource-height ratio and 100 percent represents the percentage of acoustic energy located at the upper subsource-height, i.e., 1.5 m (5 ft) for automobiles, medium trucks, buses, and motorcycles, and 3.7 m (12 ft) for heavy trucks. This ratio was then corrected to account for the difference in propagation effects between the FLAU microphones (7.5 m over hard ground), and the Volpe Center microphones (15 m over primarily soft ground). Table 31 presents these correction factors as a function of one-third octave-band (50 Hz to 10 kHz). The subsource-height ratios were simply multiplied by the corrections factors, which were derived from the FHWA TNM propagation algorithms, to obtain the corrected subsource-height ratios.

Table 31. Frequency Correction Factors

Frequency	50	63	80	100	125	160	200	250	315	400	500	630
Heavy Trucks	0.96	0.89	0.79	0.66	0.47	0.23	0.08	0.08	0.49	1.28	1.28	1.02
All other Vehicles	1.00	1.00	1.00	0.98	0.95	0.87	0.74	0.54	0.30	0.11	0.11	0.55

Frequency	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
Heavy Trucks	0.80	0.54	0.49	0.42	0.35	0.30	0.25	0.22	0.21	0.21	0.26	0.36
All other Vehicles	1.12	1.12	0.78	0.42	0.35	0.30	0.25	0.22	0.21	0.21	0.26	0.36

These corrected ratios were then plotted as a function of frequency to determine a general functional form. The plot of subsource-height ratio, r, versus frequency was characterized by a constant ratio at low frequencies, with an exponential transition at mid-frequencies to a lower constant ratio at high frequencies.

Upon examining this plot, it was found that the ratio at 3150 Hz did not fit the general trends of the data. FLAU states in its data report that "...above about 2.5 kHz, we are also running into some noise problems which we believe are from turbulence driven by the vehicle pass-by." For this reason, data at 3150 Hz were eliminated from further analysis.

In addition, data at 500 and 630 Hz also did not fit the general trend. FLAU states that measurements of source heights cannot be made for frequencies below 500 Hz. For this reason, it is believed that the data at 500 and 630 Hz are bordering on unusable, and may not be accurate; therefore it was also eliminated from further analysis.

Further examination of these plots showed minimal dependence of subsource-height ratio on vehicle speed. Based on the small number of data measured at low speeds, there was no indication of an intuitive relationship between subsource-height ratio and speed, i.e., the subsource-height ratio (upper/lower) was expected to increase at low frequencies with decreasing vehicle speed, as low-frequency engine/exhaust noise becomes more prevalent as compared with higher-frequency tire/pavement noise.

Additional low-speed measurements are scheduled by FLAU over the next one-to-two year period. If it is determined that there is a significant dependence of subsource-height ratio on vehicle speed, this effect may be reflected in a future version of the FHWA TNM. In addition, FLAU is planning to measure additional data on various pavement types, graded roadways, and for interrupted-flow conditions. If deemed necessary, these data will be reflected in a future version of the FHWA TNM.

The following functional form provided a "best-fit" to the subsource-height versus frequency data:

$$\text{Subsource-height-ratio } (f) = L + [1-L-M][1+e^{[(N\log f)+P]}]^{Q}$$

In the above equation, L is the subsource-height ratio at low frequencies, 1-M is the subsource-height ratio at high frequencies, and N, P and Q control the exponential transition at the mid-frequencies.

As mentioned in previous sections, the vehicle subsource-height measurements and analyses are chronicled in more detail in References 16, 17, and 18.

7. RESULTS/DISCUSSION

During measurements, an attempt was made to collect: (1) an equal number of events in each speed band over the range of speeds from idle to 112.6 km/h (70 mph); (2) data for three pavement types (DGAC, PCC, and OGAC); (3) data for representative PCC textures; and (4) data over a wide range of pavement ages in good condition. Table 32 presents a breakdown of the total number of pass-by events measured under constant-flow conditions. Of the total number of constant-flow events tabulated below, the distribution of these events by pavement type are as follows: 64.5 percent were collected on DGAC pavement; 23.6 percent were collected on PCC pavement; and 11.9 percent were collected on OGAC pavement.

**Table 32. Constant-Flow Data Base Totals
Distribution by Speed Band**

FHWA Vehicle Type		A			MT				HT				MC	BUS			
Pavement Type/Grade		DGAC	PCC	OGAC	DGAC	PCC	OGAC	GRADE	DGAC	PCC	OGAC	GRADE		DGAC	PCC	OGAC	GRADE*
SPEED MPH	0-10	75							29								
	11-15	1			1				52								
	16-20	5			2				11			2		3			
	21-25	45			7				13			7		10			
	26-30	129			21			1	17			32		14			1
	31-35	160			32			5	46			38	3	16			4
	36-40	120	3		45	1		4	70	7		35	3	22			1
	41-45	116	4	1	36	10	1	2	103	27	1	44	4	30			
	46-50	162	23	16	40	18	5	6	94	55	18	50	2	20	1		
	51-55	261	59	76	62	33	25	6	176	141	66	57	4	36	1	2	1
	56-60	404	78	139	86	24	40	4	290	204	115	35	5	96	1		
	61-65	289	101	92	46	18	18		195	156	38	3	6	59	1		
	66-70	134	57	30	13	11	1		51	48	4	1	4	15		1	
	71-75	27	24	6	1	1			3	5				2			
	76-80	9	5	4									1				
Subtotal		1862	354	364	392	116	90	28	1149	643	242	304	32	323	4	3	7
Total by Type		2342			626				2338				32	337			
Total		5906															

Note: 1 mph = 1.609344 km/h

* Data not used in the analysis.

Table 33 presents a breakdown of the total number and percentage of pass-by events measured as a function of GLR type.

Table 33. GLR Type Distribution by Number of Events

GLR Type *	A			MT				HT				MC	B			
	DGAC	PCC	OGAC	DGAC	PCC	OGAC	GRADE	DGAC	PCC	OGAC	GRADE		DGAC	PCC	OGAC	GRADE **
1A	57	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1B	0	0	0	0	0	0	0	0	0	0	0	0	110	0	0	0
1	613	182	91	147	63	24	16	296	241	58	211	14	134	2	4	6
2	1192	172	273	245	53	66	12	853	402	184	93	18	79	2	0	1

GLR Type Distribution by Percentage

GLR Type *	A			MT				HT				MC	B			
	DGAC	PCC	OGAC	DGAC	PCC	OGAC	GRADE	DGAC	PCC	OGAC	GRADE		DGAC	PCC	OGAC	GRADE **
1A	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1B	0	0	0	0	0	0	0	0	0	0	0	0	34	0	0	0
1	33	51	25	38	54	27	57	26	37	24	69	44	42	50	100	86
2	64	49	75	63	46	73	43	74	63	76	31	56	24	50	0	14

* GLR Type:
1A - Low speed (primarily less than 40 km/h, 25 mph) automobile data corrected for ambient noise
1B - Type 0 (3 to 6 dB) bus data corrected for noise caused by other vehicles
1 - 6 to 10 dB rise and fall
2 - greater than 10 dB rise and fall

** Data not used in the analysis.

Table 34 presents a breakdown of the total number of pass-by events measured under interrupted-flow conditions.

Table 34. Interrupted-Flow Data Base Totals Distribution by Speed Band *

FHWA Vehicle Type		A-ACCEL			MT-ACCEL			HT-ACCEL			MC-ACCEL **	B-ACCEL **
Pavement Type/Grade		DGAC	PCC	GRADE	DGAC	PCC	GRADE	DGAC	PCC	GRADE		DGAC
SPEED MPH	0-10											
	11-15											
	16-20											
	21-25	1										
	26-30	6										
	31-35	14	1								1	
	36-40	24									1	
	41-45	7	4		3			1	1			
	46-50	4	4		3			12	3	4		
	51-55	2	12		11	1	2	11	29	32		
	56-60	10	9	1	25	1	1	38	47	75		1
	61-65	3	3	1	15	3	1	33	21	49	1	1
	66-70	3	2	1	6			12	4	17		
	71-75			2					1	1		
	76-80	1		1								
Subtotal		75	34	6	63	5	4	107	106	178	3	2
Total by Type		115			72			391			3	2
Total		583										

Note: 1 mph = 1.609344 km/h

* Note: Distribution based on speed measured at the corresponding constant-flow measurement site.

** Data not used in analysis.

Table 35 presents a breakdown of the total number of pass-by events measured for the subsource-height portion of the study.

Table 35. Subsource-Height Data Base Totals Distribution by Speed Band

FHWA Vehicle Type		A			MT			HT			MC	B		
Pavement Type/Grade		DGAC	PCC	GRADE *	DGAC	PCC	GRADE	DGAC	PCC	GRADE		DGAC	PCC	GRADE *
SPEED MPH	0-10													
	1-15													
	16-20													
	21-25	1												
	26-30	3			1									
	31-35	13		7	2		3			1				1
	36-40	16		16			4			1		2		1
	41-45	21		36	2		11			3				
	46-50	5		43			8	2		15		1		
	51-55	4		47	1		10	16		37	2	1		4
	56-60	19	8	38		1	9	39	7	38	2	2		1
	61-65	23	26	15	2	5	5	37	21	11				1
	66-70	5	12	3		2		11	9	5			1	1
	71-75		5	2		1		2	2					
	76-80													
Subtotal		110	51	207	8	9	50	107	39	111	4	6	1	9
Total by Type		368			67			257			4	16		
Total		712												

Note: 1 mph = 1.609344 km/h

* Data not used in analysis.

As mentioned in Section 2.3, due to the effect of ambient air temperature on tire/pavement noise, an attempt was made to measure the majority of the data when the ambient air temperature was between 55 and 85 degrees Fahrenheit. Seventy-seven percent of the constant-flow and interrupted-flow data were measured within those bounds. The minimum and maximum temperatures were 43 and 103 degrees Fahrenheit, respectively; and the mean temperature averaged over all events was 72.7 degrees Fahrenheit.

The remainder of Section 7.0 presents and discusses the results of the REMEL analysis.

7.1 ADJUSTMENT FROM LEVEL-MEAN TO ENERGY-MEAN

As stated in Section 6.1.2, the adjustment from level-mean to energy-mean,)E, was computed in prior studies using a fixed value of $0.115F^2$. This fixed adjustment is correct only if the level-mean data are normally distributed about the level-mean regression, i.e., the level-mean data are Gaussian. However, if the level-mean data are non-Gaussian, this adjustment is only an approximation. Since traffic noise data tend to be scattered more widely above the mean than below, i.e., skewed upward, this adjustment is not quite correct. Thus, the true difference between the level-mean and energy-mean, derived from the regression line and the data points, was used to compute)E. Table 36 presents a comparison of the adjustments computed using the two methods.

Table 36. Comparison of Level-Mean and Energy-Mean Adjustments

Vehicle Type	$0.115F^2$	)E	Difference ()E minus $0.115F^2$)
Automobiles	0.7862	0.9247	0.1385
Medium Trucks	0.9710	1.095	0.1240
Heavy Trucks	0.6928	0.7136	0.0208

Comparison of the above adjustments shows that the differences are small, but in each case the upward skew is evident. The)E or residual method resulted in slightly higher adjustments. This upward skewness is most evident for automobiles and medium trucks where)E is 0.14 and 0.12 dB higher, respectively. The difference for heavy trucks is less significant because the data show less evidence of upward skewness.

To confirm that the residual method provided good representation of the actual energy-mean of the data, energy-mean values were computed and plotted in 8 km/h (5 mph) speed bands against $L_E(s)$ for automobiles, medium trucks, heavy trucks, buses, and motorcycles (See Figures 47 to 51, Appendix E). In general, these plots show excellent agreement between the energy-mean of the speed band data and $L_E(s)$ computed by using the residual method.

7.2 TESTS OF PRIOR DATA

As stated in Section 6.2, data measured previously by Caltrans were directly compared with data measured in the current Volpe Center study to determine if the data sets were statistically similar. If they were found to be similar at a 95-percent CI, the Caltrans data would be merged with the data from the current study for all further analyses.

Direct comparisons of these two data sets were made by computing an A-level regression for each data set. The difference between the two regressions was then computed and plotted. Figures 52 through 55 in Appendix F compare the Volpe Center REMELs and the Caltrans REMELs as a function of vehicle speed. These figures present the difference between the two regressions and the associated 95-percent CI for automobiles, medium trucks, and heavy trucks under average pavement, level grade conditions, and grade conditions (heavy trucks only) for constant-flow roadway traffic. Although the A-levels computed by using the two regressions are extremely close in level, these plots show that they were not statistically similar. In fact, the 95-percent CI encompasses the zero line for medium trucks only. Therefore, the Caltrans data were not included in the current Volpe Center study.

7.3 EMISSION LEVEL TRENDS: 1975 to 1995

Table 37 presents a comparison of REMELs computed at a speed of 88.5 km/h (55 mph) for automobiles, medium trucks, and heavy trucks under baseline conditions (as defined in Section 6.4). REMELs are presented for data measured in 1975 in support of STAMINA, 1982 through 1985 for Caltrans' update of the STAMINA REMELs, and in 1994 through 1995 for the FHWA TNM. Although the REMELs associated with the 1975, and the 1982 through 1985 studies were computed using a slightly different analysis procedure, the difference due to the procedure is expected to be negligible at a speed of 88.5 km/h (55 mph).

Table 37. Emission Level Trends
88.5 km/h (55 mph)

	A	MT	HT
1975 (STAMINA)	71.74	82.37	86.30
1982 through 1985 (Caltrans)	72.79	79.88	83.75
1994 through 1995 (FHWA TNM)	73.81	79.91	83.96

Note: 1 mph = 1.609344 km/h

This comparison shows that the emission levels for automobiles have increased by approximately 1 dB every 10 years since 1975. It is believed that this is most likely due to: (1) the increasing number of automobiles with high-revving four-cylinder engines; (2) the increasing number of larger, all-purpose vehicles included in the automobile classification; and (3) changes in tire-tread design.

The emission levels for medium and heavy trucks decreased by approximately 3 dB from 1975 to 1985 and have exhibited negligible change from 1985 to 1995. The lack of change from 1985 to 1995 is likely due to the much longer life cycle associated with trucks, as compared with automobiles. Specifically, many of the types of trucks measured in the Caltrans study are generally representative of trucks on the road today. This certainly is not the case for automobiles.

7.4 REMELs FOR BASELINE CONDITIONS

This section presents the results of the REMEL regressions for baseline conditions (as defined in Section 6.4). Figures 56 through 60 present the REMEL regressions for each vehicle type. Figure 61 presents an emission level comparison for all vehicles for baseline conditions.

7.4.1 Automobiles

Figure 56 of Appendix G presents the baseline REMEL regression, 95-percent CI, and the associated L_{AFmx} data for automobiles. The 95-

percent CI ranges from ±1.01 dB at 1.6 km/h (1 mph), to

±0.11 dB at 88.5 km/h (55 mph), to ±0.21 dB at 128 km/h (80 mph). Following are the regression coefficients and the statistics used to compute the 95-percent CI and the adjustments from level-mean to energy-mean:

A	41.740807	g_A	0.453464	D_{AB}	-0.997414	N	2216
B	0.223836	g_B	0.774396	D_{AC}	0.000000		
C	47.861067	g_C	0.513517	D_{BC}	0.000000		
$)E_b$	0.924710	F_{RL}	2.615613	$\overline{RL}$	-0.000000		
$)E_c$	2.267249	F_{RE}	1.132225	$\overline{RE}$	1.685485		

7.4.2 Medium Trucks

Figure 57 of Appendix G presents the baseline REMEL regression, 95-percent CI, and the associated L_{AFmx} data for medium trucks. The 95-percent CI ranges from ±2.47 dB at 1.6 km/h (1 mph), to ±0.22 dB at 88.5 km/h (55 mph), to ±0.64 dB at 128 km/h (80 mph). Following are the regression coefficients and the statistics used to compute the 95-percent CI and adjustments from level-mean to energy-mean:

A	33.918713	g_A	2.693016	D_{AB}	-0.999241	N	508
B	19.495961	g_B	4.764379	D_{AC}	0.795330		
C	66.907893	g_C	1.622173	D_{BC}	-0.809416		
$)E_b$	1.095085	F_{RL}	2.899997	$\overline{RL}$	-0.000001		
$)E_c$	1.095085	F_{RE}	1.797732	$\overline{RE}$	1.286792		

7.4.3 Heavy Trucks

Figure 58 of Appendix G presents the baseline REMEL regression, 95-percent CI, and the associated L_{AFmx} data for heavy trucks. The 95-percent CI ranges from ±0.44 dB at 1.6 km/h (1 mph), to ±0.10 dB at 88.5 km/h (55 mph), to ±0.30 dB at 128 km/h (80 mph). Following are the regression coefficients and the statistics used to compute the 95-percent CI and adjustments from level-mean to energy-mean:

A	35.879850	g_A	1.171595	D_{AB}	-0.999326	N	1793

B	20.306023	g_B	2.063356	D_{AC}	0.449340
C	73.584493	g_C	0.260971	D_{BC}	-0.463231
$)E_b$	0.713642	F_{RL}	2.453129	$\overline{RL}$	-0.000000
$)E_c$	0.713642	F_{RE}	0.796573	$\overline{RE}$	1.178594

7.4.4 Buses

Figure 59 of Appendix G presents the baseline REMEL regression, 95-percent CI, and the associated L_{AFmx} data for buses. The 95-percent CI ranges from ±3.18 dB at 1.6 km/h (1 mph), to ±0.38 dB at 88.5 km/h (55 mph), to ±0.56 dB at 128 km/h (80 mph). Following are the regression coefficients and the statistics used to compute the 95-percent CI and adjustments from level-mean to energy-mean:

A	23.479530	g_A	1.352102	D_{AB}	-0.998194	N	327
B	38.006238	g_B	2.326674	D_{AC}	0.000000		
C	66.907893	g_C	1.622173	D_{BC}	-0.000000		
$)E_b$	0.000000	F_{RL}	2.244492	$\overline{RL}$	-0.011503		
$)E_c$	1.095085	F_{RE}	0.804464	$\overline{RE}$	1.158313		

7.4.5 Motorcycles

Figure 60 of Appendix G presents the baseline REMEL regression, 95-percent CI, and the associated L_{AFmx} data for motorcycles. The 95-percent CI ranges from ±0 dB at 1.6 km/h (1 mph), to ±5.48 dB at 29 km/h (18 mph), to ±1.72 dB at 88.5 km/h (55 mph), to ±3.43 dB at 128 km/h (80 mph). Following are the regression coefficients and the statistics used to compute the 95-percent CI and adjustments from level-mean to energy-mean:

A	41.022542	g_A	7.775015	D_{AB}	-0.998009	N	38
B	7.333072	g_B	13.282470	D_{AC}	0.000000		
C	56.086099	g_C	0.000000	D_{BC}	-0.000000		
$)E_b$	2.680807	F_{RL}	5.028582	$\overline{RL}$	-0.000368		
$)E_c$	2.680807	F_{RE}	2.217101	$\overline{RE}$	1.876264		

Since there was only one motorcycle measured at idle, the level-mean and energy-mean were equivalent, and the resultant 95-percent CI at idle is zero.

7.5 REMELs FOR SPECIFIC ROADWAY PAVEMENTS

This section presents the results of the REMEL regressions for level grade, constant-flow conditions on specific roadway pavement types.

7.5.1 Automobiles

Figure 62 of Appendix G presents the REMEL regression and the associated L_{AFmx} data for automobiles on DGAC. Following are the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean:

A	41.740807	F_{RL}	2.360088	$\overline{RL}$	-0.066229	N	1862
B	-0.310763	F_{RE}	1.147847	$\overline{RE}$	1.184454		
C	47.861067						
)E_b	0.805461						
)E_c	2.267249						

Figure 63 of Appendix G presents the REMEL regression and the associated L_{AFmx} data for automobiles on PCC. Following are the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean:

A	41.740807	F_{RL}	1.927324	$\overline{RL}$	-0.005747	N	354
B	3.035771	F_{RE}	0.655913	$\overline{RE}$	1.116474		
C	47.861067						
)E_b	0.484233						
)E_c	2.267249						

Figure 64 of Appendix G presents the REMEL regression and the associated L_{AFmx} data for automobiles on OGAC. Following are the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean:

A	41.740807	F_{RL}	2.218887	$\overline{RL}$	0.001242	N	364
B	-1.673745	F_{RE}	0.709195	$\overline{RE}$	1.150790		
C	47.861067						
)E_b	0.608719						
)E_c	2.267249						

Table 38 presents the relative difference at 88.5 km/h (55 mph) between the baseline REMEL regression for automobiles and each of the three associated specific-pavement regressions. Figure 65 of Appendix G presents the relative differences as a function of speed.

Table 38. Specific Pavement Emission Level Differences Automobiles at 88.5 km/h (55 mph)

Pavement Type	Specific Pavement Minus Baseline (dB)
DGAC	-0.65
PCC	2.36
OGAC	-2.20

Note: 1 mph = 1.609344 km/h

7.5.2 Medium Trucks

Figure 66 of Appendix G presents the REMEL regression and the associated L_{AFmx} data for medium trucks on DGAC. Following are the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean:

A	33.918713	F_{RL}	2.841249	$\overline{RL}$	0.034877	N	392
B	18.718316	F_{RE}	2.310373	$\overline{RE}$	1.324444		
C	66.907893						
)E_b	1.185459						
)E_c	1.095085						

Figure 67 of Appendix G presents the REMEL regression and the associated L_{AFmx} data for medium trucks on PCC pavement. Following are the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean:

A	33.918713	F_{RL}	1.879804	$\overline{RL}$	0.003932	N	116
B	21.747675	F_{RE}	0.467689	$\overline{RE}$	1.095940		
C	66.907893						
$)E_b$	0.393936						
$)E_c$	1.095085						

Figure 68 of Appendix G presents the REMEL regression and the associated L_{AFmx} data for medium trucks on OGAC pavement. Following are the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean:

A	33.918713	F_{RL}	2.550326	$\overline{RL}$	-0.002799	N	90
B	18.589391	F_{RE}	0.746556	$\overline{RE}$	1.189330		
C	66.907893						
$)E_b$	0.755823						
$)E_c$	1.095085						

Table 39 presents the relative difference at 88.5 km/h (55 mph) between the baseline REMEL regression for medium trucks and each of the three associated specific-pavement regressions. Figure 69 of Appendix G presents the relative differences as a function of speed.

Table 39. Specific Pavement Emission Level Differences
Medium Trucks at 88.5 km/h (55 mph)

Pavement Type	Specific Pavement Minus Baseline (dB)
DGAC	-0.64
PCC	1.47
OGAC	-1.15

Note: 1 mph = 1.609344 km/h

7.5.3 Heavy Trucks

Figure 70 of Appendix G presents the REMEL regression and the associated L_{AFmx} data for heavy trucks on DGAC pavement. Following are the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean:

A	35.879850	F_{RL}	2.568958	$\overline{RL}$	0.022320	N	1150
B	19.552914	F_{RE}	0.896782	$\overline{RE}$	1.210014		
C	73.584493						
$)E_b$	0.805584						
$)E_c$	0.713642						

Figure 71 of Appendix G presents the REMEL regression and the associated L_{AFmx} data for heavy trucks on PCC pavement. Following are the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean:

A	35.879850	F_{RL}	1.823696	$\overline{RL}$	0.003668	N	643
B	21.402464	F_{RE}	0.578276	$\overline{RE}$	1.102560		
C	73.584493						
$)E_b$	0.420354						
$)E_c$	0.713642						

Figure 72 of Appendix G presents the REMEL regression and the associated L_{AFmx} data for heavy trucks on OGAC pavement. Following are the regression coefficients and the statistics used to compute the adjustments from level-mean to energy-mean:

A	35.879850	F_{RL}	2.522499	$\overline{RL}$	0.003808	N	242
B	18.222167	F_{RE}	1.106547	$\overline{RE}$	1.227098		
C	73.584493						
$)E_b$	0.884984						
$)E_c$	0.713642						

Table 40 presents the relative difference at 88.5 km/h (55 mph) between the baseline REMEL regression for heavy trucks and each of the three associated specific-pavement regressions. Figure 73 of Appendix G presents the relative differences as a function of speed.

Table 40. Specific Pavement Emission Level Differences
Heavy Trucks at 88.5 km/h (55 mph)

Pavement Type	Specific Pavement Minus Baseline (dB)
DGAC	-0.59
PCC	0.72
OGAC	-1.66

Note: 1 mph = 1.609344 km/h

7.5.4 Buses

As stated in Section 6.5.4, the REMEL equation for buses on DGAC was used as "baseline," and adjusted to approximate the associated REMEL equation for average pavement, PCC, and OGAC. This adjustment was based on the specific pavement adjustments for medium trucks. Following are the bus regression coefficients for each pavement type:

Pavement	A	B	)E_b	C	)E_c
Average	23.479530	38.006238	0.000000	66.907893	1.095085
DGAC	23.479530	36.669205	0.649762	66.907893	1.095085
PCC	23.479530	39.556803	0.000000	66.907893	1.095085
OGAC	23.479530	36.760406	0.000000	66.907893	1.095085

Table 41 presents the relative difference at 88.5 km/h (55 mph) between the baseline REMEL regression for buses and each of the three associated specific-pavement regressions. Note: The specific pavement differences for buses at 88.5 km/h are identical to the differences for medium trucks. Likewise, Figure 69 of Appendix G, which presents relative differences as a function of pavement type for medium trucks, is also applicable for buses.

Table 41. Specific Pavement Emission Level Differences
Buses at 88.5 km/h (55 mph)

Pavement Type	Specific Pavement Minus Baseline (dB)
DGAC	-0.64
PCC	1.47
OGAC	-1.15

Note: 1 mph = 1.609344 km/h

7.5.5 Motorcycles

As stated in Section 6.5.5, it was assumed that motorcycle REMELs are dominated by engine/exhaust noise. Therefore, no specific pavement adjustments were computed.

7.6 REMELs FOR VEHICLES ON GRADED ROADWAYS

This section presents the results of the REMEL regressions for average pavement, constant-flow conditions on graded roadways.

7.6.1 Automobiles

As stated in Section 6.6.1, it was assumed that automobiles do not require a significant increase in throttle to maintain a constant speed when traveling on grades. Consequently, no grade adjustment was computed for automobiles.

7.6.2 Medium Trucks

As stated in Section 6.6.2, it was assumed that medium trucks do not require a significant increase in throttle to maintain a constant speed when traveling on grades. Consequently, no grade adjustment was computed for medium trucks. However, a minimal amount of data were measured for medium trucks on grade. The data were used for deriving one-third octave-band spectral shape for medium trucks and buses under interrupted-flow conditions, since no one-third octave-band data were obtained during the interrupted-flow measurements.

7.6.3 Heavy Trucks

For heavy trucks, the difference in the emission level at 16.1 km/h (10 mph) between the baseline condition and grade condition (grade minus baseline) is 8.3 dB. This difference was attributed entirely to an increase in engine/exhaust noise associated with an increase in throttle.

It was decided that the increase in engine/exhaust noise for heavy trucks on grade would be arithmetically averaged with the increase in engine/exhaust noise for heavy trucks under interrupted-flow conditions; and the resultant average increase would be used for both conditions.

As discussed in Section 7.7.3 below, for heavy trucks, the difference in the emission level at 16.1 km/h (10 mph) between the baseline condition and interrupted-flow condition is 3.1 dB. Consequently, the average increase in emission level for heavy trucks under both conditions was 5.7 dB. As such, the C coefficient for heavy trucks under baseline conditions was increased by 5.7 dB, from 74.298135 to 80.000000, for heavy trucks subject to either interrupted-flow or grade conditions. Figure 76 of Appendix G shows the REMEL regression for heavy trucks under both conditions.

7.6.4 Buses

As stated in Section 6.6.4, it was assumed that buses do not require a significant increase in throttle to maintain a constant speed when traveling on grades. Consequently, no grade adjustment was computed for buses.

7.6.5 Motorcycles

It was assumed that motorcycles do not require a significant increase in throttle to maintain a constant speed when traveling on grades. Consequently, no grade adjustment was computed for motorcycles.

7.7 REMELs FOR VEHICLES UNDER INTERRUPTED-FLOW CONDITIONS

This section presents the results of the REMEL regressions for vehicles subject to interrupted-flow conditions.

7.7.1 Automobiles

The REMEL regression for automobiles under interrupted-flow conditions, due to an increase in throttle, was limited to the engine/exhaust-portion of the regression, i.e., the C coefficient. The C coefficient for automobiles under interrupted-flow conditions was 67.000000. Figure 74 shows the REMEL regression for automobiles subject to interrupted-flow conditions.

7.7.2 Medium Trucks

The REMEL regression for medium trucks under interrupted-flow conditions, due to an increase in throttle, was limited to the engine/exhaust portion of the regression, i.e., the C coefficient. The C coefficient for medium trucks under interrupted-flow conditions was 74.000000. Figure 75 shows the REMEL regression for medium trucks subject to interrupted-flow conditions.

7.7.3 Heavy Trucks

As stated in Section 7.6.3, it was decided that the increase in engine/exhaust noise for heavy trucks under interrupted-flow conditions would be arithmetically averaged with the increase in engine/exhaust noise for heavy trucks under grade conditions; and the resultant average increase would be used for both conditions. As such, the C coefficient for heavy trucks subject to either interrupted-flow or grade conditions is 80.000000. Figure 76 of

Appendix G shows the REMEL regression and L_{AFmx} data for heavy trucks under both conditions.

7.7.4 Buses

The REMEL regression for buses under interrupted-flow conditions, due to an increase in throttle, was limited to the engine/exhaust portion of the regression, i.e., the C coefficient. Due to the small amount of data measured for buses subject to interrupted-flow conditions, it was assumed that the magnitude of the adjustment to the engine/exhaust-portion of the regression is the same as for medium trucks under interrupted-flow conditions.

7.7.5 Motorcycles

The REMEL regression for motorcycles under interrupted-flow conditions due to an increase in throttle, was limited to the engine/exhaust-portion of the regression, i.e., the C coefficient. It was assumed that the C coefficient for motorcycles subject to interrupted-flow conditions was equivalent to the C coefficient for automobiles under the same conditions. This assumption, although rather arbitrary, was based on conservative intuition. Figure 77 shows the REMEL regression for motorcycles subject to interrupted-flow conditions.

7.8 ONE-THIRD OCTAVE-BAND REMELs

This section presents the results of the one-third octave-band emission level analysis.

7.8.1 Automobiles

Following are the regression coefficients and the statistics which define the sixth-order polynomial fit through the one-third octave-band spectra for automobiles on level grade, under constant-flow conditions, for average pavement, DGAC, PCC, and OGAC. Since one-third octave-band data were not measured under interrupted-flow conditions, the D1, D2 through K1, K2 interrupted-flow coefficients are borrowed from the appropriate pavement type. In other words, for automobiles subject to interrupted-flow conditions, the overall engine/exhaust component, C, is increased as discussed in Section 7.7.1, relative to level grade conditions; and the shape of the associated spectrum is consistent with the appropriate pavement type.

	D1	D2	E1	E2
Average	-7468.779575	-9.309929	16460.100000	11.659320
DGAC	-7264.636908	-19.281377	16009.500000	34.363901
PCC	-1978.652255	-70.206590	3728.329033	155.109567
OGAC	-9502.803330	-145.771940	21064.000000	340.622686
Interrupted-Flow	Use coefficients from appropriate pavement type			

	F1	F2	G1	G2
Average	-14823.900000	-1.233347	7009.474786	-4.327918
DGAC	-14414.400000	-22.462943	6814.317463	6.093141
PCC	-2768.001364	-138.780925	1030.541403	64.525774
OGAC	-19060.800000	-324.802942	9032.990872	161.886578
Interrupted-Flow	Use coefficients from appropriate pavement type			

	H1	H2	I1	I2
Average	-1835.189815	2.579086	252.418543	-0.573822
DGAC	-1783.723974	-0.252834	245.299562	-0.170266
PCC	-195.324560	-16.430316	16.418899	2.174350
OGAC	-2363.810485	-44.454426	324.077238	6.378783
Interrupted-Flow	Use coefficients from appropriate pavement type			

	J1	J2	K1	K2
Average	-14.268316	0.045682	47.800479	0.452371
DGAC	-13.864870	0.022131	49.348719	0.415642
PCC	-0.339616	-0.117021	49.185345	0.467972
OGAC	-18.211670	-0.373971	47.184521	0.401542
Interrupted-Flow	Use coefficients from appropriate pavement type			

Figure 78 of Appendix H presents the emission level spectra at 88.5 km/h (55 mph) for each of the above four pavement conditions. As can be seen, pavement type has a significant effect on the emission level spectra in the frequency range from 800 Hz to 10 kHz. The effect is relatively intuitive, i.e., OGAC provides a significant reduction in high frequency energy, as compared with DGAC and especially PCC. Figure 79 of Appendix H presents the emission level spectra on average pavement as a function of frequency and speed.

7.8.2 Medium Trucks

Following are the regression coefficients and the statistics which define the sixth-order polynomial fit through the one-third octave-band spectra for medium trucks on level grade, under constant-flow conditions, for average pavement, DGAC, PCC, and OGAC; and for medium trucks under interrupted-flow conditions. The D1, D2 through K1, K2 interrupted-flow coefficients are based on the one-third octave-band data measured under grade conditions, but adjusted to levels consistent with the interrupted-flow data.

	D1	D2	E1	E2
Average	-1172.343352	-67.978113	2532.436947	151.781493
DGAC	-164.363614	-82.556065	172.725033	186.801430

PCC	-73.288478	-131.933335	97.357937	296.574807
OGAC	-168.937079	-102.927675	162.036132	244.033651
Interrupted-Flow	-8922.408136	96.440897	19015.400000	-196.241744

	F1	F2	G1	G2
Average	-2124.165806	-140.388413	919.784302	68.545463
DGAC	131.655819	-174.718246	-207.664798	86.124810
PCC	65.350117	-273.981431	-104.555273	132.854390
OGAC	133.970948	-237.867685	-196.613672	121.527971
Interrupted-Flow	-16587.000000	162.569520	7627.874332	-70.394575

	H1	H2	I1	I2
Average	-215.745405	-18.551234	25.909788	2.634001
DGAC	95.139145	-23.513441	-18.966690	3.366475
PCC	47.637332	-35.600554	-9.424641	4.997542
OGAC	87.517298	-34.222359	-17.125620	5.031804
Interrupted-Flow	-1950.412341	16.876826	263.093464	-2.132793

	J1	J2	K1	K2
Average	-1.244253	-0.153272	66.010280	0.240831
DGAC	1.407549	-0.197472	66.076401	0.227133
PCC	0.689877	-0.287335	65.988692	0.273776
OGAC	1.253128	-0.301914	65.774278	0.220219
Interrupted-Flow	-14.645109	0.111404	75.566138	0.139194

Figure 80 of Appendix H presents the emission level spectra at 88.5 km/h (55 mph) for each of the above five conditions. As can be seen, pavement type has a significant effect on the emission level spectra in the frequency range from 800 Hz to 10 kHz. The effect is relatively intuitive, i.e., OGAC provides a significant reduction in high frequency energy, as compared with DGAC and, especially, PCC. In addition, the increase in throttle, associated with interrupted-flow conditions, generally results in an increase in the spectral levels from 125 Hz to 500 Hz. Figure 81 of Appendix H presents the emission level spectra on average pavement as a function of frequency and speed.

7.8.3 Heavy Trucks

Following are the regression coefficients and the statistics which define the sixth-order polynomial fit through the one-third octave-band spectra for heavy trucks on level grade, under constant-flow conditions, for average pavement, DGAC, PCC, and OGAC; and for heavy trucks both on graded roadways and under interrupted-flow conditions. The D1, D2 through K1, K2 grade/interrupted-flow coefficients are based on one-third octave-band data measured under grade conditions only, but adjusted to levels consistent with the C coefficient computed for both the interrupted-flow and grade data.

	D1	D2	E1	E2
Average	1540.953481	-235.108917	-3852.39321	537.981518
DGAC	-217.571747	-196.634999	156.854882	450.144699
PCC	158.860076	-223.893548	-497.410428	509.705253
OGAC	-186.933080	-255.033940	135.514216	587.489921
Grade/Interrupted-Flow	-6782.550530	-94.315686	14368.700000	226.701375

	F1	F2	G1	G2
Average	3886.430673	-502.160068	-1986.85878	244.714955
DGAC	151.082001	-420.250062	-168.033708	204.806845
PCC	579.584033	-473.326603	-298.568995	229.580900
OGAC	132.973712	-552.824216	-151.366531	272.102657
Grade/Interrupted-Flow	-12459.200000	-220.015419	5710.525999	110.518825

	H1	H2	I1	I2
Average	549.002247	-65.686556	-78.239429	9.217734
DGAC	60.772941	-54.968455	-9.681901	7.711617
PCC	78.021585	-61.374037	-10.058424	8.584030
OGAC	57.669240	-73.912732	-9.928293	10.514055
Grade/Interrupted-Flow	-1458.340416	-30.365892	196.811136	4.337165

	J1	J2	K1	K2
Average	4.509121	-0.529106	72.512832	0.210200
DGAC	0.570105	-0.442469	72.705285	0.193916
PCC	0.498685	-0.491490	71.481738	0.238763
OGAC	0.649271	-0.612569	72.008268	0.172006
Grade/Interrupted-Flow	-10.977676	-0.252197	82.036316	0.064162

Figure 82 of Appendix H presents the emission level spectra at 88.5 km/h (55 mph) for each of the above five conditions. As can be seen, pavement type has a significant effect on the emission level spectra in the frequency range from 800 Hz to 10 kHz. The effect is relatively intuitive, i.e., OGAC provides a significant reduction in high frequency energy, as compared with DGAC and especially PCC. In addition, an increase in throttle generally results in a broadband increase in the spectral levels from 50 Hz to 10 kHz. Figure 83 of Appendix H presents the emission level spectra on average pavement as a function of frequency and speed.

7.8.4 Buses

Following are the regression coefficients and the statistics which define the sixth-order polynomial fit through the one-third octave-band spectra for buses on level roadways, under constant-flow conditions for average pavement. Due to the small amount of data, these regression coefficients were assumed to be the same for DGAC, PCC, OGAC; and for buses subject to interrupted-flow conditions.

	D1	D2	E1	E2
Average	4688.569098	-122.935195	-11601.500000	284.796174
	F1	F2	G1	G2

Average	11535.300000	-267.623062	-5896.461017	130.822488
	H1	H2	I1	I2
Average	1645.797051	-35.139019	-238.929963	4.927783
	J1	J2	K1	K2
Average	14.139828	-0.282557	67.203674	0.205371

Figure 84 of Appendix H presents the emission level spectra at 88.5 km/h (55 mph) for all conditions. Figure 85 of Appendix H presents the emission level spectra on average pavement as a function of frequency and speed.

7.8.5 Motorcycles

Following are the regression coefficients and the statistics which define the sixth-order polynomial fit through the one-third octave-band spectra for motorcycles on level roadways, under constant-flow conditions for average pavement. It was assumed that motorcycle REMELs are dominated by engine/exhaust noise. Therefore, no specific pavement adjustments were computed. For motorcycles subject to interrupted-flow conditions, the D1, D2 through K1, K2 coefficients are based on the following coefficients for average pavement, but adjusted to levels consistent with the C coefficient for automobiles subject to interrupted-flow conditions (See Section 7.7.5).

	D1	D2	E1	E2
All Pavements	7604.474238	-8.465503	-17396.000000	7.899209
	F1	F2	G1	G2
All Pavements	16181.800000	2.526152	-7828.63253	-5.314462
	H1	H2	I1	I2
All Pavements	2085.468458	2.344913	-290.816544	-0.435913
	J1	J2	K1	K2
All Pavements	16.614043	0.030050	57.815218	0.404674

Figure 86 of Appendix H presents the emission level spectra at 88.5 km/h (55 mph) for all pavements, as well as for interrupted-flow conditions. Figure 87 of Appendix H presents the emission level spectra for all pavement types as a function of frequency and speed.

7.9 SUBSOURCE-HEIGHT SPLITS

This section discusses the results of the subsource-height data analysis. As stated in Section 6.9, it was assumed that the subsource-height ratios do not change as a function of speed, pavement type, or throttle condition (.e., cruise or grade and interrupted-flow) The data measured thus far support this contention. However, more data are needed.

7.9.1 Automobiles

Figure 88 of Appendix I presents the subsource-height ratio versus frequency regression for automobiles along with the associated data points. Following are the related regression coefficients used to perform the percent-energy apportioning of the REMELs for automobiles:

L	0.373239	P	39.491299
M	0.976378	Q	-2.583128
N	-13.195596		

This regression shows that, at low frequencies, 37.3 percent of the energy associated with the REMELs for automobiles has a source height of 1.5 m (5 ft), and, at high frequencies, only 2.4 percent of the energy has a source height of 1.5 m.

7.9.2 Medium Trucks

Figure 89 of Appendix I presents the subsource-height ratio versus frequency regression for medium trucks on level-grade roadways along with the associated data points. Following are the related regression coefficients used to perform the percent-energy apportioning of the REMELs for medium trucks:

L	0.566933	P	80.239979
M	0.933520	Q	-0.234435
N	-25.497631		

This regression shows that, at low frequencies, 56.7 percent of the energy associated with the REMELs for medium trucks on level-grade roadways has a source height of 1.5 m (5 ft) and, at high frequencies, only 6.7 percent of the energy has a source height of 1.5 m.

7.9.3 Heavy Trucks

Figure 90 of Appendix I presents the subsource-height ratio versus frequency regression for heavy trucks on level-grade roadways, along with the associated data points. Following are the related regression coefficients used to perform the percent-energy apportioning of the REMELs for heavy trucks:

L	0.054276	P	102.627995
M	0.973749	Q	-132.679357
N	-36.503587		

This regression shows that, at low frequencies, 5.4 percent of the energy associated with the REMELs for heavy trucks on level-grade roadways has a source height of 3.6 m (12 ft) and, at high frequencies, only 2.6 percent of the energy has a source height of 3.6 m.

7.9.4 Buses

Figure 91 of Appendix I presents the subsource-height ratio versus frequency regression for buses on level-grade roadways along with the associated data points. Following are the related regression coefficients used to perform the percent-energy apportioning of the REMELs for buses:

L	0.563097	P	99.099777
M	0.928086	Q	-0.263459
N	-31.517739		

This regression shows that, at low frequencies, 56.3 percent of the energy associated with the REMELs for buses on level-grade roadways has a source height of 1.5 m (5 ft) and, at high frequencies, only 7.2 percent of the energy has a source height of 1.5 m.

7.9.5 Motorcycles

Figure 92 of Appendix I presents the subsource-height ratio versus frequency regression for motorcycles along with the associated data points. Following are the related regression coefficients used to perform the percent-energy apportioning of the REMELs for motorcycles:

L	0.391352	P	60.404841
M	0.978407	Q	-0.614295
N	-19.278172		

This regression shows that, at low frequencies, 39.1 percent of the energy associated with the REMELs for motorcycles has a source height of 1.5 m (5 ft) and, at high frequencies, only 2.2 percent of the energy has a source height of 1.5 m.

7.9.6 Medium Trucks Under Interrupted-Flow Conditions

Figure 93 of Appendix I presents the subsource-height ratio versus frequency regression for medium trucks subject to interrupted-flow conditions, along with the associated data points. Note: The data and the associated regression are based on data measured for medium trucks under grade conditions, not interrupted-flow conditions. Following are the related regression coefficients used to perform the percent-energy apportioning of the REMELs for medium trucks subject to interrupted-flow conditions:

L	0.579261	P	558.980283
M	0.871354	Q	-0.026532
N	-177.249214		

This regression shows that, at low frequencies, 57.9 percent of the energy associated with the REMELs for medium trucks under interrupted-flow conditions, has a source height of 1.5 m (5 ft) and, at high frequencies, 12.9 percent of the energy has a source height of 1.5 m.

7.9.7 Heavy Trucks On Grade or Under Interrupted-Flow Conditions

Figure 94 of Appendix I presents the subsource-height ratio versus frequency regression for heavy trucks subject to both grade and interrupted-flow conditions, along with the associated data points. Note: The data and the associated regression are based on data measured for heavy trucks under grade conditions, not both grade and interrupted-flow conditions. Following are the related regression coefficients used to perform the percent-energy apportioning of the REMELs due to throttle increase for heavy trucks subject to both grade and interrupted-flow conditions:

L	0.047771	P	890.880597
M	0.972453	Q	-8519.429646
N	-309.046731		

This regression shows that, at low frequencies, 4.8 percent of the energy associated with the REMELs for heavy trucks subject to both grade and interrupted-flow conditions, has a source height of 3.6 m (12 ft) and, at high frequencies, 2.8 percent of the energy has a source height of 3.6 m.

7.9.8 Buses Under Interrupted-Flow Conditions

Figure 93 of Appendix I presents the subsource-height ratio versus frequency regression for buses subject to interrupted-flow conditions, along with the associated data points. The regression and the regression coefficients are identical to those used for medium trucks subject to interrupted-flow conditions.

7.10 ANALYSIS SUMMARY

In summary, this analysis and, consequently the FHWA TNM Data Base include the following:

- 10 subsource, one-third octave-band, average-pavement regressions for constant-flow vehicles on level grade;
- 24 subsource, one-third octave-band, specific-pavement regressions for constant-flow vehicles on level grade;

- 2 subsource, one-third octave-band, grade/interrupted-flow adjustment regressions (heavy trucks); and
- 8 subsource, one-third octave-band, adjustment regressions for interrupted-flow vehicles (autos, medium trucks, buses, and motorcycles).

These regressions exist in the FHWA TNM as a matrix of coefficients expressed as a function of vehicle type, vehicle speed, one-third octave-band frequency, pavement type, roadway grade condition, traffic-flow condition, and vehicle subsource height. Tables 42 through 46 present a summary of the coefficients for each vehicle type.

Table 42. Regression Coefficients for Automobiles

Coefficient	Average	DGAC	PCC	OGAC	Interrupted-Flow
A	41.740807	41.740807	41.740807	41.740807	*
B+)E_b	1.148546	0.494698	3.520004	-1.065026	*
C+)E_c	50.128316	50.128316	50.128316	50.128316	67.000000
D1	-7468.779575	-7264.636908	-1978.652255	-9502.803330	*
D2	-9.309929	-19.281377	-70.206590	-145.771940	*
E1	16460.100000	16009.500000	3728.329033	21064.000000	*
E2	11.659320	34.363901	155.109567	340.622686	*
F1	-14823.900000	-14414.400000	-2768.001364	-19060.800000	*
F2	-1.233347	-22.462943	-138.780925	-324.802942	*
G1	7009.474786	6814.317463	1030.541403	9032.990872	*
G2	-4.327918	6.093141	64.525774	161.886578	*
H1	-1835.189815	-1783.723974	-195.324560	-2363.810485	*
H2	2.579086	-0.252834	-16.430316	-44.454426	*
I1	252.418543	245.299562	16.418899	324.077238	*
I2	-0.573822	-0.170266	2.174350	6.378783	*
J1	-14.268316	-13.864870	-0.339616	-18.211670	*
J2	0.045682	0.022131	-0.117021	-0.373971	*
K1	47.800479	49.348719	49.185345	47.184521	*
K2	0.452371	0.415642	0.467972	0.401542	*
L	0.373239	0.373239	0.373239	0.373239	*
M	0.976378	0.976378	0.976378	0.976378	*
N	-13.195596	-13.195596	-13.195596	-13.195596	*
P	39.491299	39.491299	39.491299	39.491299	*
Q	-2.583128	-2.583128	-2.583128	-2.583128	*

* Use coefficient value from the appropriate pavement type.

Table 43. Regression Coefficients for Medium Trucks

Coefficient	Average	DGAC	PCC	OGAC	Interrupted-Flow
A	33.918713	33.918713	33.918713	33.918713	*
B+)E_b	20.591046	19.903775	22.141611	19.345214	*
C+)E_c	68.002978	68.002978	68.002978	68.002978	74.000000
D1	-1172.343352	-164.363614	-73.288478	-168.937079	-8922.408136
D2	-67.978113	-82.556065	-131.933335	-102.927675	96.440897
E1	2532.436947	172.725033	97.357937	162.036132	19015.400000
E2	151.781493	186.801430	296.574807	244.033651	-196.241744
F1	-2124.165806	131.655819	65.350117	133.970948	-16587.000000
F2	-140.388413	-174.718246	-273.981431	-237.867685	162.569520
G1	919.784302	-207.664798	-104.555273	-196.613672	7627.874332
G2	68.545463	86.124810	132.854390	121.527971	-70.394575
H1	-215.745405	95.139145	47.637332	87.517298	-1950.412341
H2	-18.551234	-23.513441	-35.600554	-34.222359	16.876826
I1	25.909788	-18.966690	-9.424641	-17.125620	263.093464
I2	2.634001	3.366475	4.997542	5.031804	-2.132793
J1	-1.244253	1.407549	0.689877	1.253128	-14.645109
J2	-0.153272	-0.197472	-0.287335	-0.301914	0.111404
K1	66.010280	66.076401	65.988692	65.774278	75.566138
K2	0.240831	0.227133	0.273776	0.220219	0.139194
L	0.566933	0.566933	0.566933	0.566933	0.579261
M	0.933520	0.933520	0.933520	0.933520	0.871354
N	-25.497631	-25.497631	-25.497631	-25.497631	-177.249214
P	80.239979	80.239979	80.239979	80.239979	558.980283
Q	-0.234435	-0.234435	-0.234435	-0.234435	-0.026532

* Use coefficient value from the appropriate pavement type.

Table 44. Regression Coefficients for Heavy Trucks

Coefficient	Average	DGAC	PCC	OGAC	Grade/Interrupted-Flow
A	35.879850	35.879850	35.879850	35.879850	*
B+)E_b	21.019665	20.358498	21.822818	19.107151	*
C+)E_c	74.298135	74.298135	74.298135	74.298135	80.000000
D1	1540.953481	-217.571747	158.860076	-186.933080	-6782.550530
D2	-235.108917	-196.634999	-223.893548	-255.033940	-94.315686
E1	-3852.393214	156.854882	-497.410428	135.514216	14368.700000
E2	537.981518	450.144699	509.705253	587.489921	226.701375
F1	3886.430673	151.082001	579.584033	132.973712	-12459.200000
F2	-502.160068	-420.250062	-473.326603	-552.824216	-220.015419
G1	-1986.858782	-168.033708	-298.568995	-151.366531	5710.525999
G2	244.714955	204.806845	229.580900	272.102657	110.518825
H1	549.002247	60.772941	78.021585	57.669240	-1458.340416
H2	-65.686556	-54.968455	-61.374037	-73.912732	-30.365892
I1	-78.239429	-9.681901	-10.058424	-9.928293	196.811136
I2	9.217734	7.711617	8.584030	10.514055	4.337165
J1	4.509121	0.570105	0.498685	0.649271	-10.977676
J2	-0.529106	-0.442469	-0.491490	-0.612569	-0.252197
K1	72.512832	72.705285	71.481738	72.008268	82.036316
K2	0.210200	0.193916	0.238763	0.172006	0.064162
L	0.054276	0.054276	0.054276	0.054276	0.047771
M	0.973749	0.973749	0.973749	0.973749	0.972453
N	-36.503587	-36.503587	-36.503587	-36.503587	-309.046731
P	102.627995	102.627995	102.627995	102.627995	890.880597
Q	-132.679357	-132.679357	-132.679357	-132.679357	-8519.429646

* Use coefficient value from the appropriate pavement type.

Table 45. Regression Coefficients for Buses

Coefficient	Average	DGAC	PCC	OGAC	Interrupted-Flow
A	23.479530	23.479530	23.479530	23.479530	*
B+)E_b	38.006238	37.318967	39.556803	36.760406	*
C+)E_c	68.002978	68.002978	68.002978	68.002978	74.000000
D1	4688.569098	*	*	*	*
D2	-122.935195	*	*	*	*
E1	-11601.500000	*	*	*	*
E2	284.796174	*	*	*	*
F1	11535.300000	*	*	*	*
F2	-267.623062	*	*	*	*
G1	-5896.461017	*	*	*	*
G2	130.822488	*	*	*	*
H1	1645.797051	*	*	*	*
H2	-35.139019	*	*	*	*
I1	-238.929963	*	*	*	*
I2	4.927783	*	*	*	*
J1	14.139828	*	*	*	*
J2	-0.282557	*	*	*	*
K1	67.203674	*	*	*	*
K2	0.205371	*	*	*	*
L	0.563097	*	*	*	0.579261
M	0.928086	*	*	*	0.871354
N	-31.517739	*	*	*	-177.249214
P	99.099777	*	*	*	558.980283
Q	-0.263459	*	*	*	-0.026532

* Use coefficient value from the average pavement type.

Table 46. Regression Coefficients for Motorcycles

Coefficient	Average	DGAC	PCC	OGAC	Interrupted-Flow
A	41.022542				*
$B+)E_b$	10.013879				*
$C+)E_c$	58.766906				67.000000
D1	7604.474238				*
D2	-8.465503				*
E1	-17396.000000				*
E2	7.899209				*
F1	16181.800000				*
F2	2.526152				*
G1	-7828.632535		Motorcycle coefficients independent of pavement type.		*
G2	-5.314462				*
H1	2085.468458				*
H2	2.344913				*
I1	-290.816544				*
I2	-0.435913				*
J1	16.614043				*
J2	0.030050				*
K1	57.815218				*
K2	0.404674				*
L	0.391352				*
M	0.978407				*
N	-19.278172				*
P	60.404841				*
Q	-0.614295				*

* Use coefficient value from the average pavement type.

The above matrix of coefficients, exclusive of the L, M, N, P, and Q coefficient, are substituted into the general REMEL equation to determine the composite emission levels. The L, M, N, P, and Q coefficients, along with the general subsource-height-ratio equation, are then used to perform the percent-energy apportioning of the composite emission levels.

The general REMEL equation is defined as follows:

$$\begin{aligned} L_E(s,f) = {} & 10\log_{10}[10^{(C+)Ec)/10} + (s^{A/10})(10^{(B+E)b)/10})] \\ & - (K1+K2*S) + D1+D2*s + (E1+E2*s)\log_{10}f \\ & + (F1+F2*s)(\log_{10}f)^2 + (G1+G2*s)(\log_{10}f)^3 \\ & + (H1+H2*s)(\log_{10}f)^4 + (I1+I2*s)(\log_{10}f)^5 \\ & + (J1+J2*s)(\log_{10}f)^6 \end{aligned}$$

where: A is the slope of the tire/pavement-portion of the regression;

B+)Eb is the height of the tire/pavement-portion of the regression;

C+)Ec is the height of the engine/exhaust-portion of the curve;

D1 through J2 are for the sixth-order polynomial fit through the one-third octave-band spectral data as a function of speed; and

K1 and K2 calibrate the A-levels resulting from the sixth-order polynomial fit, such that they are essentially equal to the A-levels from the A-level REMEL equations, $L_E(s)$.

The general subsource-height-ratio equation is defined as follows:

$$\text{Subsource-height-ratio } (f) = L + [1-L-M][1+e^{[(N\log f)+P]}]Q$$

where: L is the subsource-height ratio at low frequencies;

1-M is the subsource-height ratio at high frequencies; and

N, P, and Q control the exponential transition at the mid-frequencies.

7.11 FHWA TNM DATA BASE

The matrix of coefficients presented in Section 7.10 has been integrated into the Data Base of the FHWA TNM program for computing sound levels in the vicinity of a roadway, and for designing noise barriers. Readers are directed to two related reports for a detailed description of how the Data Base is used by the FHWA TNM, "FHWA Traffic Noise Model (FHWA TNM®), Version 1.0: User's Guide"[21] and "FHWA Traffic Noise Model (FHWA TNM®), Version 1.0: Technical Manual."[22]

7.12 USER-DEFINED VEHICLES IN THE FHWA TNM

The FHWA TNM will allow user-defined vehicles to be entered. However, it is anticipated that the capability to input user-defined vehicles will not be used for entering state-specific emission levels. In fact, it is likely that the FHWA will not allow the use of state-specific REMELs in the near future. Based on the work performed in the current Study, there is no indication of a need or justification for developing state-specific REMELs at this time. Although REMELs developed in the current study were found to be statistically different from those developed previously by Caltrans, the practical difference was less than 1 dB, or essentially negligible. Until the design of highway vehicles change incrementally, or regulatory requirements warrant lower noise emission levels, development of state-specific REMELs is unnecessary.

However, the user-defined vehicle capability in the FHWA TNM is intended for describing vehicles which differ significantly from automobiles, medium trucks, heavy trucks, buses, or motorcycles, e.g., motor homes or electric cars. The first step to developing user-defined REMELs for use in the FHWA TNM is to carefully adhere to fielc measurement procedures, as discussed in Reference 23.

As required under these procedures, unique vehicles shall be measured under the following reference conditions: constant-flow roadway traffic; level grade; and DGAC pavement. Next, data analysis procedures, as described in Section 6.1.1 and 6.1.2, shall be used to determine the regression equation which characterizes the A-weighted emission levels as a function of speed, $L_E(s)$.

From the data analysis, four parameters are required to define the user-defined vehicle type: (1) a minimum level (the C+)Ec coefficient); (2) a reference level (the emission level at 80.5 km/h, 50 mph); (3) a slope (the A coefficient); and (4) the TNM vehicle type which is most similar to the user-defined vehicle. In determining the most similar vehicle type, the factors to be considered are listed in order of importance as follows: estimated subsource heights; estimated acceleration characteristics; and estimated, one-third octave-band frequency spectrum.

8. BENEFITS

The current Volpe Center study has resulted in three primary benefits as follows:

- A standardized procedure has been established and documented for developing an emission level data base for the FHWA TNM. In addition, the measurement and analysis procedures used in the current study will make up the foundation of an updated version of the FHWA's "Sound Procedures" report. The new document, currently being prepared by the Volpe Center, will be titled "Recommended Practice for the Measurement and Assessment of Highway Traffic Noise."[23]

- The Data Base developed as part of the study offers much greater flexibility in predicting traffic noise levels as compared to the Data Base in the FHWA's previous noise prediction computer software, STAMINA. It includes data for both constant-flow and interrupted-flow roadway traffic. It includes a much wider range of vehicle operating speeds (0 to 112.6 km/h, 0 to 70-plus mph), and it includes data for vehicles on graded roadways. It also includes data for five vehicle types (automobiles, medium trucks, heavy trucks, buses, and motorcycles) with their emissions energy-apportioned to two subsource heights.

- It is expected that the flexibility discussed above will translate into a significant improvement in predictive accuracy. The two-part emission level equation, which includes noise from both engine/exhaust and tire/pavement effects, will result in more reliable noise barrier designs and provide a higher level of confidence to the public.

APPENDIX A:

MEASUREMENT SITE PLANS AND PROFILES

This appendix presents the plans and profiles for the constant-flow measurement sites as listed in Tables 1 through 9. The plans and profiles for the interrupted-flow and subsource-height measurement sites are presented in References 15 and 17, respectively. Note: In the notation for microphone position, AGL refers to the height of the microphone diaphragm "above ground level." As mentioned in Section 3.1, all microphones were positioned for grazing incidence at a height of 1.5 m (5 ft), relative to roadway elevation. The notation "6 Near Lane" indicates the "center-line of the near travel lane."

APPENDIX B:
METEOROLOGICAL DATA

This appendix presents the tabulated meteorological data obtained during constant-flow and interrupted-flow measurements, as discussed in Section 4.3. The following information is included (Note: Some meteorological entries were interpolated from the measured data):

Date: Date of data acquisition
Time: Time (HH:MM) of data acquisition
Ambient Temp: Psychrometer dry bulb temperature, °F (°C=[°F - 32]/1.8)
Relative Humidity: Relative humidity in percent
Wind Speed: Anemometer indicated wind speed, mph (1 mph = 1.609344 km/h)
Wind Dir: Predominant wind direction
Cloud Cover: Estimated percentage of cloud cover

As mentioned in Section 2.3, due to the effect of ambient air temperature on tire/pavement noise, an attempt was made to measure the majority of the data when the ambient air temperature was between 55 and 85 degrees Fahrenheit. Seventy-seven percent of the data measured were within those limits. The minimum and maximum temperatures were 43 and 103 degrees Fahrenheit, respectively; and the mean temperature averaged over all events was 72.7 degrees Fahrenheit.

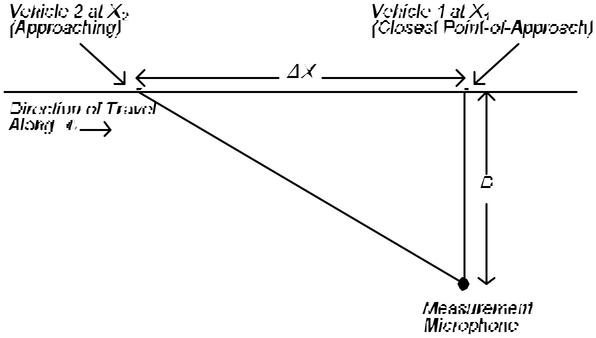
APPENDIX C:
MINIMUM SEPARATION-DISTANCE CRITERIA

The minimum separation-distance criteria used in the current Study were based on work performed by Caltrans during their California REMEL study.[3]

In the Caltrans study, the following assumptions were made: (1) the vehicle behaves as a point source, i.e., spherical divergence is assumed; and (2) there is no ground attenuation of the emission level. In addition, the ambient noise level was at least 10 dB less than the L_{AFmx} of observed vehicles.

In general, when a vehicle approaches a measurement microphone at a constant speed, the observed noise level at the microphone is related to the vehicle position as follows:

$$L_2 = L_1 - 20\,Log_{10}\frac{\sqrt{\Delta X^2 + D^2}}{D}$$



where: L_2 is the contribution to the measured emission level of the subject vehicle, Vehicle 1, due to a subsequent vehicle, Vehicle 2, at X_2;

L_1 is the contribution to the measured emission level of the subject vehicle, Vehicle 1, due entirely to Vehicle 1 at X_1;

ΔX is the distance between X_1 and X_2, or the minimum separation distance we're interested in determining; and

D is the distance from the microphone to X_1, or 15 m in this case.

If other vehicles are in proximity of the subject vehicle to be measured, the measured sound level at the microphone for the subject vehicle may increase due to contamination. For the current study, it was decided that a maximum of 0.5 dB contamination would be allowable.

Based on the 0.5-dB criterion, the next step was to determine an associated separation-distance criteria. Potential sources of contamination included contamination due to ambient noise, as well as contamination due to other vehicles in proximity of the subject vehicle (See Figure 46 on the following page).

The maximum contamination due to ambient noise was determined to be 0.4 dB, assuming the ambient noise level was 10 dB less than the L_{AFmx} of observed vehicles. Consequently, we could allow as much as 0.1-dB contamination due to subsequent vehicles based on the 0.5-dB contamination criterion.

To ensure no more than 0.1-dB contamination due to subsequent vehicles, it was determined that the emission level due to a subsequent vehicle, Vehicle 2 in the case of Figure 46, must be at least 15.9 dB below that of the subject vehicle, Vehicle 1. The next step was to determine the separation distance associated with the 15.9-dB requirement.

Using the above equation and substituting in the following values:

$L_2 = L_{AFmx} - 15.9$
$D = 15$ m,

)X was solved for.

Based on the above, it was determined that for REMELs measured at 15 m (50 ft), a minimum separation distance of 93.9 m (308 ft) between similar vehicles was required to ensure that the total contamination was not greater than 0.5 dB. For measuring automobiles in the vicinity of heavy trucks, it was determined that a minimum separation distance of 300.2 m (985 ft) between the automobile and heavy truck was required, assuming a heavy truck is 10 dB louder than an automobile at comparable speeds.

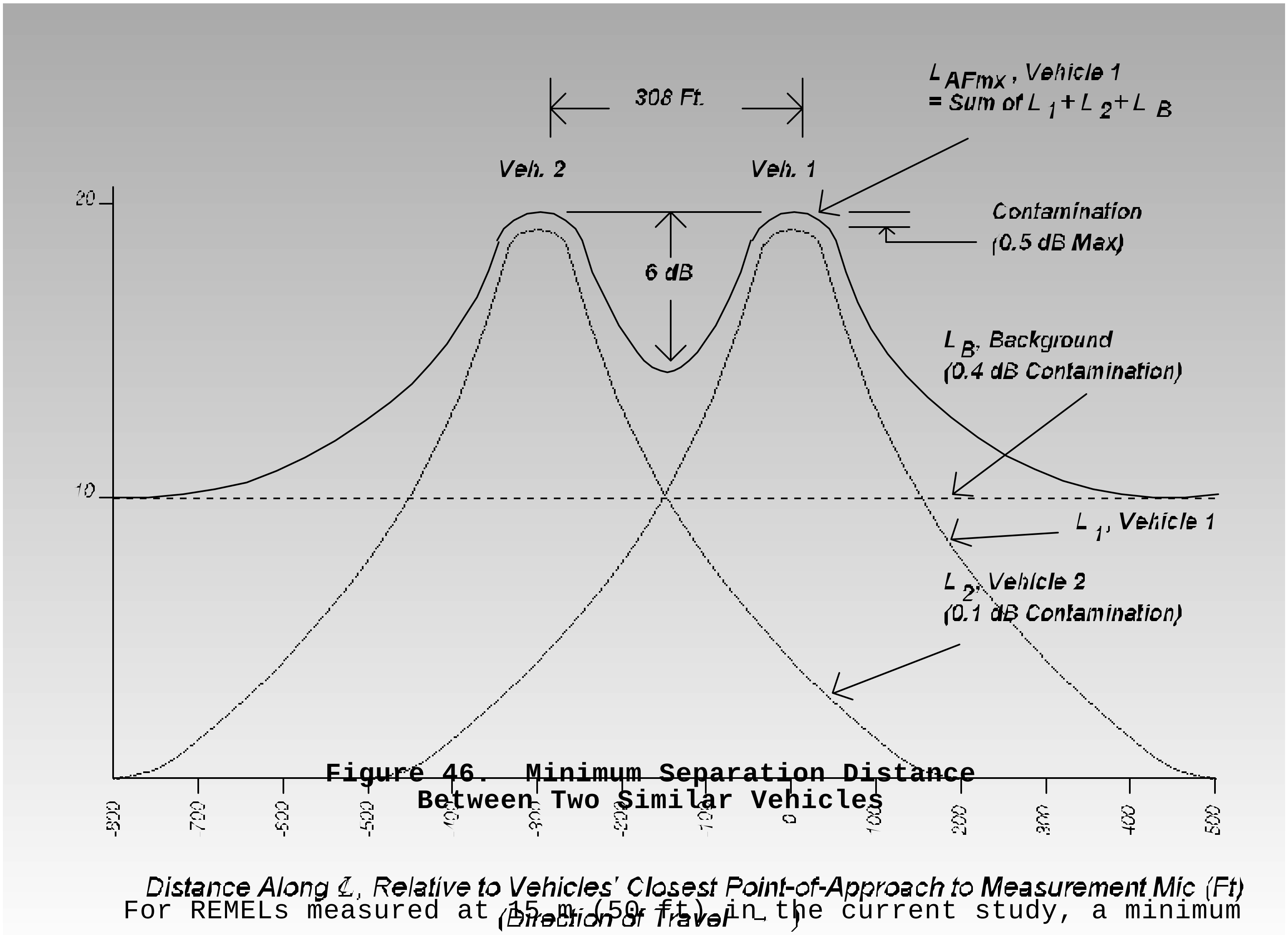


Figure 46. Minimum Separation Distance Between Two Similar Vehicles

For REMELs measured at 15 m (50 ft) in the current study, a minimum separation-distance criterion of 121.9 m (400 ft) was conservatively established; and 304.8 m (1000 ft) between automobiles and heavy trucks was observed. As discussed in Section 4.3, an orange highway cone was positioned 120 m upstream from the observers' position to aid in identifying potentially acceptable events. The 304.8 m distance was left to observers' judgement.

APPENDIX D:
FIELD DATA

This appendix presents the 15-m (50-ft) field data measured during constant-flow measurements, as discussed in Sections 4.3 and 5.0. The data are sorted by FHWA vehicle type, and within the same vehicle type, sorted by speed. The following information is included:

Event ID: Volpe numerical event designation

Volpe Type: (used during data acquisition) Numerical designation for vehicle type:
- 0 - Compact Automobiles;
- 1 - Standard Automobiles;
- 2 - Medium Trucks;
- 3 - 3 Axle Heavy Trucks;
- 4 - 4 Axle Heavy Trucks;
- 5 - 5 Axle Heavy Trucks;
- 6 - Heavy Trucks with 6 or more axles;
- 7 - Motorcycles;
- 8 - 2 Axle Buses;
- 9 - 3 Axle Buses
- 10 - Motor Homes
- 11 - Miscellaneous

FHWA Type: Numerical designation for vehicle type:
- 1 - Automobiles;
- 2 - Medium Trucks;
- 3 - Heavy Trucks;
- 4 - Buses;
- 5 - Motorcycles

Vehicle Speed: Vehicle Speed (mph)

Adj 50' Amax: 15-meter L_{AFmx}, including calibration, ambient noise, and contaminating vehicle adjustments, if applicable (dB)

GLR Code: Numerical designation for event quality:
- 1A - Low speed (primarily less than 40 km/h, 25 mph) automobile data corrected for ambient noise;
- 1B - Type 0 (3 to 6 dB) bus data corrected for noise caused by other vehicles;
- 1 - 6 to 10 dB rise and fall;
- 2 - greater than or equal to 10 dB rise and fall

Grade (%): Percent Grade to the nearest tenth, 0 if less than 1.5 percent

Pavement Type: DGAC - Dense-Graded Asphaltic Concrete;
PCC - Portland Cement Concrete;
OGAC - Open-Graded Asphaltic Concrete

Pavement Year: The year of the roadway's construction or last pavement overlay (whichever is more recent)

Max A-weighted Spectrum (50 Hz to 10 kHz): Calibration-adjusted, one-third octave-band A-weighted spectrum measured at the 15-meter measurement position, at the time of L_{AFmx}. The spectrum is included for events with a GLR code of 1 and 2 only, i.e., no attempt was made to correct the spectral data for contamination. As was discussed in Section 6.0, only the spectral data having an associated GLR quality of 2 were used in the one-third octave-band analyses.

APPENDIX E:

SPEED BAND ENERGY-MEAN VERSUS REGRESSION LINE

This appendix presents a comparison between the energy-mean of the L_{AFmx} data, computed in 8 km/h (5 mph) speed bands, and the energy-mean regression line, $L_E(s)$, derived from the level-mean emission levels, after applying the)E adjustment, as discussed in Section 6.1.2.

APPENDIX F:
COMPARISON OF VOLPE CENTER AND CALTRANS DATA

This appendix presents comparisons of the Volpe Center and the Caltrans emission level data for automobiles, medium trucks, and heavy trucks (baseline conditions), and heavy trucks on grade, as discussed in Section 7.2. These comparisons were performed to determine if the data sets were similar within a 95-percent CI. Figures 52 through 55 show the difference curves, and the associated 95-percent CI, as a function of speed, computed using these two data sets.

APPENDIX G:
EMISSION LEVEL REGRESSIONS

This appendix presents the emission level regression, $L_E(s)$, 95-percent CI, and the measured data points as a function of speed for automobiles, medium trucks, heavy trucks, buses, and motorcycles on all pavements. Figures 56 through 61 present the results for baseline conditions, as discussed in Section 7.4. Figures 62 through 73 present the results for vehicles on specific pavements, as discussed in Section 7.5. Figures 74 through 77 present the results for grade and interrupted-flow conditions, as discussed in Sections 7.6 and 7.7, respectively.

APPENDIX H:
EMISSION LEVEL SPECTRA

This appendix presents the emission level spectra measured at the time of L_{AFmx}, as a function of one-third octave-band center frequency for automobiles, medium trucks, heavy trucks, buses, and motorcycles at 55 mph (88.5 km/h), as discussed in Section 7.8. Note: Because motorcycle emission levels are dominated by engine/exhaust noise, and the number of data measured for PCC and OGAC was minimal, only one spectrum representative of all pavement types is presented.

In addition, this appendix presents the emission level spectra measured on average pavement as a function of one-third octave-band center frequency and speed, for all vehicles types.

APPENDIX I:
SUBSOURCE-HEIGHT RATIO VERSUS FREQUENCY

This appendix presents the subsource-height ratio (upper/lower), and associated data points as a function of one-third octave-band center frequency, as discussed in Section 7.9.

REFERENCES

1 Menge, C.W. (Bowlby, W., Higgins, J., Reagan, J., Editors), Noise Barrier Cost Reduction Procedures, STAMINA 2.0/OPTIMA User's Manual, Report No. FHWA-DP-58-1, Washington, DC: Federal Highway Administration, April 1982.

2 Rickley, E.J., Ford, D.W., Quinn, R.W., Highway Noise Measurements for Verification of Prediction Models, Report No. DOT-TSC-OST-78-2 and DOT-TSC-FHWA-78-1, Cambridge, MA: Transportation Systems Center, January 1978.

3 Hendriks, R.W., California Vehicle Noise Emission Levels, Report No. FHWA/CA/TL-87/03, Sacramento, CA: California Department of Transportation, Division of New Technology, Materials, and Research, January 1987.

4 Dunn, S.E., Smart, R.C., Determination of Vehicle Noise Levels for Highway Noise Computer Models, Report No. FL-ER-31-86, Boca Raton, FL: Florida Atlantic University, June 1986.

5 Wayson, R.L., Ogle, T.A., Extension of Reference Emission Factors for the STAMINA 2.0 Model to Include 55 and 65 MPH, Report No. FL-ER-51-92, Orlando, FL: University of Central Florida, July 1992.

6 Bowlby, W., O'Grady, T., Vehicle Noise Emission Tests for I-440 Noise Barrier Evaluation Project, Nashville, TN: Vanderbilt University, April 1991.

7 Innes, J.D., Levesque, S.L., Highway Traffic Noise Model Evaluation Study, New Brunswick, Ontario: University of New Brunswick, 1995.

8 Jung, F.W., Blaney, C.T., Noise Emission Levels of 8 Vehicles in Ontario, Toronto, Ontario: Ministry of Transport, 1978.

[9] Fleming, G.G., Rickley, E.J., Development of National Reference Energy Mean Emission Levels for Constant-Flow Roadway Traffic, Test Plan, Letter Report No. DTS-75-HW327-LR2, Cambridge, MA: John A. Volpe National Transportation Systems Center, Acoustics Facility, September 1993.

[10] Bowlby, W., Editor, Sound Procedures for Measuring Highway Noise: Final Report, Report No. FHWA-DP-45-1R, Arlington, VA: Federal Highway Administration, August 1981.

[11] Regan, J.A., Determination of Reference Energy Mean Emission Levels, Report No. FHWA-OEP/HEV-78-1, Washington, DC: Federal Highway Administration, July 1978.

[12] International Organization for Standardization, Method for Measuring the Influence of Road Surfaces on Traffic Noise: "The Statistical Pass-By Method," Draft Standard ISO/CD 11819-1, Delft, Netherlands: ISO/TC 43/SC 1/WG 33 N 62, November 1994.

[13] Operator's Manual for Stationary Radar, Model K-15 II Hand Held Unit, Owensboro, KY: MPH Industries, Inc., 1985.

[14] Protheroe, A., Jaeger, D., Harley-Davidson Motor Company Letter Report, Milwaukee, WI: Harley Davidson, Inc., November 1994.

[15] Bowlby, W., Wayson, R.L., Chiguluri, S., Martin, M., Herman, L.A., Interrupted Flow Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model, Nashville, TN: Vanderbilt University, December 1995.

[16] Coulson, R.K., Evaluation of Vehicle Sub-Source Spectra for Noise Barrier Design, Boca Raton, FL: Florida Atlantic University, January 1994.

[17] Armstrong, J., Coulson, R.K., Vehicle Noise Source Heights & Sub-Source Spectra, Boca Raton, FL: Florida Atlantic University, April 1995.

[18] Coulson, R.K., Development of a Turn-Key System for the Rapid Acquisition, Analysis and Presentation of Field Data for Vehicle Sub-Source Noise Spectra, Boca Raton, FL: Florida Atlantic University, June 1995.

[19] Barry, T.M., Reagan, J.A., FHWA Highway Traffic Noise Prediction Model, Report No. FHWA-RD-77-108, Washington, DC: Federal Highway Administration, December 1978.

[20] Anderson, G.S., Rapoza, A.S., Bowlby, W., Wayson, R., FHWA Traffic Noise Model: Field Data Requirements Report, Draft Report, Cambridge, MA: John A. Volpe National Transportation Systems Center, Acoustics Facility, March 1995.

[21] Anderson, G.S., Menge, C.W., FHWA Traffic Noise Model (FHWA TNM®), Version 1.0: User's Guide, Report No. FHWA-PD-96-009, Cambridge, MA: John A. Volpe National Transportation Systems Center, Acoustics Facility, 1996.

[22] Menge, C.W., C.F. Rossano, Anderson, G.S., Bajdek, C.J., FHWA Traffic Noise Model (FHWA TNM®), Version 1.0: Technical Manual, Report No. FHWA-PD-96-010, Cambridge, MA: John A. Volpe National Transportation Systems Center, Acoustics Facility, 1996.

[23] Lee, C.S., Fleming, G.G., Recommended Practice for the Measurement and Assessment of Highway Traffic Noise, Cambridge, MA: John A. Volpe National Transportation Systems Center, Acoustics Facility, 1996.

[24] Wilkinson, L., SYSTAT: The System of Statistics, Evanston, IL: SYSTAT, Inc., 1990.

INDEX