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TIRE-PAVEMENT AND ENVIRONMENTAL TRAFFIC NOISE RESEARCH STUDY

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June 2012

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16. Abstract

In response to an interest in traffic noise, particularly tire–pavement noise, CDOT elected to conduct tire-pavement noise research. Following a rigid set of testing protocols, data was collected on highway traffic noise characteristics along with safety and durability aspects of the associated pavements. This report completes a comprehensive, long-term study to determine if particular pavement surface types and/or textures can be used as quieter pavements, and possibly be used to help satisfy FHWA noise mitigation requirements. The study addressed:

- The noise generation/reduction characteristics of pavements as functions of pavement type, pavement texture, age, time, traffic loading, and distance away from the pavement;
- Correlations between source measurements using on-board sound intensity (OBSI) and wayside measurements including both statistical pass-by (SPB) and time-averaged measurements; and
- The collection of data that can be used for validation and verification of the accuracy of the FHWA Traffic Noise Model (TNM) to use on future Colorado highway projects.

Implementation:

There are numerous findings from this study, along with associated implementation activities. The most promising finding is that each of the common pavement types in use by CDOT has the potential for quieter variants. As a result, implementation of this study could include the identification and specification of the specific asphalt mixtures and concrete textures that result in quieter pavements without compromising on safety or durability.

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EXECUTIVE SUMMARY

This report summarizes the final results of a field-testing program to evaluate tire-pavement and environmental noise of representative pavements throughout the State of Colorado. During the course of this research, tire-pavement noise was measured using two unique technologies: close-proximity (CPX) and on-board sound intensity (OBSI). In more recent years, testing focused on the latter technique since it has become the standard in the USA (AASHTO TP 76). Environmental noise was measured using wayside (roadside) microphones that capture traffic noise in a manner that is more relevant to the potential impacts to highway abutters. The test results provided in this final report include those collected from 2006, 2007, 2009, and 2011. Combined, the testing represents the culmination of a multi-year effort to assess the long-term acoustical durability of the various pavements being evaluated.

Implementation

As a result of this multi-year project, the Colorado DOT now has the data available to describe typical tire-pavement noise levels for a variety of pavements typically used in the state. Furthermore, measurements have been collected both in close proximity to the source, and at the wayside, which allow for two unique perspectives. The former can be used to assess spatial variability, and the latter as a means to include the effects of propagation and the noise generated by a more diverse set of traffic.

To implement these results, Colorado has a number of alternatives available. It is possible, for example, that Colorado can consider approaching the FHWA about entering a Quiet Pavement Pilot Program (QPPP). With this, CDOT could consider pavement effects as part of noise abatement studies where select pavement(s) are used. However, CDOT is advised to proceed with caution with this alternative. At the very least, the lessons learned from Arizona should be sought, as they remain the only state to have applied for this program. While some of the pavements that were evaluated in this study could be considered “quiet”, there was also significant variability in tire-pavement noise among any of the nominal pavement types. As a result, CDOT should make a determination about the viability of a QPPP which will effectively require a “maximum” tire-pavement noise level. The questions should be asked about the potential to construct a quiet enough surface with adequate acoustical durability to make a QPPP worthwhile.

Of considerable value to CDOT as an implementation activity is the ability to explore modifications to material and construction practices that can lead to the construction of quieter pavements that do not compromise on safety and durability. This can be done by comparing data collected on this project with better practices that have been developed by others over the course of the last several years. For example, the texture type on concrete pavement surfaces can be a significant factor in the resulting tire-pavement noise, with uniform and non-aggressive textures often leading to low tire-pavement noise. For asphalt mixtures, smaller nominal maximum aggregate size (NMAS) typically leads to lower tire-pavement noise. In both cases, however, CDOT must look at the implications to other factors such as friction and durability.

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ACRONYMS AND ABBREVIATIONS

AASHTO –	American Association of State Highway and Transportation Officials
ADT –	Average Daily Traffic
Amb. –	Ambient
ARFC –	Asphalt-Rubber Friction Course
ASTM –	American Society for Testing and Materials International
Avg. –	Average
CDOT –	Colorado Department of Transportation
CPX –	Close Proximity
CRM –	Crumb Rubber Modified/Modifier
CTIM –	Continuous-Flow Traffic Time-Integrated Method
DAP –	Data Acquisition Plan
dBA –	Decibel, A-weighted
Dia. –	Diamond
DD –	Doubling of Distance
EB –	Eastbound
FHWA –	Federal Highway Administration
Groov. –	Grooved
HMA –	Hot-Mix Asphalt
Hvy. –	Heavy
Lgt. –	Light
Long. –	Longitudinal
NB –	Northbound
NCHRP –	National Cooperative Highway Research Program
NMAS –	Nominal Maximum Aggregate Size
OBSI –	On-Board Sound Intensity
PG –	Performance Grade
QPPP –	Quiet Pavement Pilot Program
QPR –	Quiet Pavement Research
PCC –	Portland Cement Concrete

Ref. –	Reference
REMEL –	Reference Energy Mean Emission Level
SB –	Southbound
SEE –	Standard Estimate of the Error
SIL –	Sound Intensity Level
SIP –	Statistical Isolated Pass-By Method
SMA –	Stone Matrix Asphalt
SPB –	Statistical Pass-By
SPBI –	Statistical Pass-By Index
SPBI+ –	Environmental wayside measurements based on Statistical Pass-By method
SPL –	Sound Pressure Level
SRTT –	Standard Reference Test Tire
SX –	Designates ½-inch NMAS HMA
TA –	Time-Averaged Wayside
TNM –	Traffic Noise Model
Trk. –	Truck
Trlr. –	Trailer
WB –	Westbound

TERMS AND DEFINITIONS

A-weighted – Sound pressure levels measured with a specific filter, or frequency weighting, that emphasizes and de-emphasizes sound depending on frequency in a manner similar to human hearing. The filter is named A-weighting. A-weighting is almost always used when measuring surface transportation noise.

Acoustical durability – Refers to the ability of a pavement to maintain its acoustical performance over time in the presence of environmental effects, traffic, and age. An acoustically durable pavement has little change in tire-pavement noise with time.

Heavy trucks – Vehicle category comprised of vehicles with 3 or more axles and generally greater than 26400 lb (12000 kg).

Light vehicles – Vehicle category comprised of vehicles with 2 axles, 4 tires, and generally less than 9900 lb (4500 kg). Includes vehicles designated primarily for transportation of 9 or fewer passengers or for transportation of cargo, such as, cars, pick-up trucks, and sport utility vehicles.

Line source – Idealized acoustic source that can be considered localized along a line and sound radiates outward in a cylindrical pattern. A roadway with a continuous, steady stream of traffic (no isolated vehicles) can be treated as a line source.

Medium trucks – Vehicle category comprised of vehicles with 2 axles, more than 4 tires, and generally greater than 9900 lb (4500 kg) and less than 26400 lb (12000 kg).

Point source – Idealized acoustic source that can be considered localized at a point and sound radiates outward in a spherical pattern. A single, isolated vehicle can be treated as a moving point source.

p-value – A quantity calculated from a linear regression analysis and indicates the probability the regression coefficient is due to random chance. Range for p-value is zero to one. Generally, smaller p-value is better.

r-squared – Correlation coefficient squared. A quantity calculated from a linear regression analysis and indicates how well the regression line fits the data points. Range for r-squared is zero to one. Generally, higher r-squared is better.

Sample period – Period of time during which wayside noise is measured using the time averaged method, typically 60 to 90 minutes.

Sound propagation – The transmission of sound through the air from one location to another, usually from a generating source to a receiver.

Spatial variability – Variation in tire-pavement noise with position on the road, usually in reference to longitudinal position. Ideally, a pavement is has the same noise level independent of lane or location along the road. Real pavements have spatial variability, that is, the noise varies depending on position on the pavement.

Tire-pavement noise – The sound generated by the interaction of a tire and pavement surface as the tire traverses the pavement.

Wayside noise – Traffic noise occurring alongside a roadway.

INTRODUCTION

Background

Traffic noise pollution has become a growing concern to residents worldwide. This is particularly true in urban areas where the population density near major thoroughfares is much higher, and there is a greater volume of commuter traffic. To mitigate the noise – at least for residences directly adjacent to the highway – engineers at the Colorado Department of Transportation (CDOT) and elsewhere commonly resort to costly noise barriers. Although arguably the psychology of a noise wall is a factor, noise barriers including walls have not been shown to be an ideal solution for minimizing noise pollution in all cases. Sound tends to diffract over the top and around the ends of barriers, thus proving ineffective on arterial streets since the openings in the barrier required for side streets and driveways effectively defeat the benefits provided by the barrier. Furthermore, the mountainous terrain commonly found in the State of Colorado can further challenge the effectiveness of barriers.

In recent years, alternative solutions to noise barriers have been advanced – ones that may be able to mitigate noise for drivers, adjacent residences, and even for citizens farther from the highway. Driven in large part by public outcry, national policy, and eventually directives to reduce noise, engineers in the European Union and elsewhere have developed alternative pavement types and surfaces that reduce noise generated at the tire-pavement interface.

The noise produced from tire-pavement interaction is just one of several types of traffic noise. However, for many roads with low truck volumes, it becomes the primary source of traffic noise for vehicular speeds over 30 mph. While not a cure-all, certain pavement type and texture options have led to improvements in noise levels; in some cases, reducing the need for or height of noise walls and improving the quality of life.

For a more thorough discussion on these topics, one of the better sources is the FHWA *Little Book of Quieter Pavements*, which can be downloaded from the website http://www.tcpsc.com/LittleBookQuieterPavements.pdf and the publication *Questions and*

Answers About Quieter Pavements, developed under Transportation Pooled Fund TPF-5(135), and available from CDOT.

As a matter of federal policy (23 CFR 772), pavement type or texture cannot be considered as traffic noise abatement in projects receiving federal funding. For pavement effects to be considered in determining impacts or as a mitigation technique, a so-called Quiet Pavement Pilot Program (QPPP) must be approved and in place. Under a QPPP, a commitment must be made by the State Highway Agency to guarantee, in perpetuity, noise mitigation through use of a specified pavement type and/or texture. To date, Arizona is the only state that has accepted this challenge, opting for an asphalt-rubber friction course (ARFC) as the pavement (surface) of choice. A lot has been learned since 2003 when ARFC resurfacing began under the QPPP. However, any state that is interested in asphalt-rubber or any other specific pavement type should first evaluate its noise reducing capabilities under local conditions.

Every state has unique conditions, with differences in characteristics and issues such as climate, traffic, materials availability, and maintenance. Choosing a “quiet pavement” alternative that is best for any state must account for all of these factors along with durability, cost, and safety. Currently, the factors that CDOT considers in pavement selection emphasize safety and durability. Life-cycle cost analyses are performed to determine the most appropriate pavement type and/or rehabilitation technique for a given project. While noise is not currently a factor that is considered in CDOT pavement type selection process, it may eventually be used as a secondary consideration in environmentally sensitive areas and in cases where no significant differences in cost among alternatives have been determined.

Given the inherent issues with a QPPP, most states have instead opted to conduct Quiet Pavement Research (QPR). While the data that is collected under a QPPP and QPR is the same, no policy changes are made that would allow for a mitigation contribution from the pavements under investigation. Instead, if research is being conducted on a project that requires abatement, conventional means will need to be used until a QPPP is in place.

To meet the requirements of a Federal Highway Administration (FHWA) QPR program, the research should have an intended purpose, include a Data Acquisition Plan (DAP), and possess a reporting schedule frequent enough to demonstrate the various changes in the properties of the pavements under study over time. Within this research project, CDOT has drafted a DAP, which contains the various data collection, analysis, and reporting elements described in the FHWA model which, in turn, is based on that developed and implemented by the State of Arizona under their QPPP.

Within the current DAP, data are to be collected on tire-pavement and wayside noise, along with pavement, traffic, safety, and meteorological data. These data will be analyzed and reported in a fashion suitable to derive acoustic properties of various pavement types – by season, over time (and cumulative traffic), and correlated to the physical characteristics of the pavement and texture. Additionally, the data will be used to relate various noise measures to one another, particularly as standardization of these measures – at least, in the US – is an ongoing task within the industry.

Scope

This project is about examining current pavements in Colorado to determine their tire-pavement noise characteristics over a long period. In recent years, the FHWA has supported this through establishment of both a QPPP and guidelines for a QPR. For now, CDOT's emphasis will be on the latter, but to also be prepared for the possibility of entering the QPPP.

The scope of this project is to assist CDOT with the collection of tire-pavement surface and environmental (wayside) noise data. This data is then organized and reported in such a manner to help fulfill the Department's mission of conducting a proper Quiet Pavement Research program.

Project Objectives

The primary objective of this study is to provide CDOT with tire-pavement and environmental traffic data that are reliable, accurate, and representative given the sheer variety of conditions within the State of Colorado – from both traffic and climatic perspectives. Supporting data on traffic and climate are collected simultaneously with noise measurements. Ultimately, these will be compiled along with numerous other data being collected by CDOT, and interpreted and reported accordingly. The goal is to fulfill the overall QPR requirements as well as the desire of CDOT to learn what various pavement types and/or textures might do to address or supplement overall noise mitigation requirements.

To meet this objective, a specialized database has been developed. It has been populated by data collected from 34 select pavement sections, as described in a QPPP/QPR Data Acquisition Plan (DAP). Along with noise (and related) data collected by Transtec, a variety of other information about the pavement sections can continue to populate this database, including items related to design, materials construction, climate, traffic, and maintenance.

The database can be used to fulfill at least three specific objectives, as follows:

1. To establish relationships between the various noise measures, their change over time, and the variables that may be contributors to both.

2. To establish relationships between and within the various noise measurement techniques – near field (e.g., close proximity, CPX and on-board sound intensity, OBSI), wayside (e.g., statistical pass-by index, SPBI), and environmental (e.g., "SPBI+").

3. To assist in providing information suitable for validating and verifying the accuracy of the FHWA Traffic Noise Model (TNM) based on the pavements and other conditions unique to the State of Colorado.

DATA COLLECTION

Measurement Intervals

Data was collected in 2006, 2007, 2009, and 2011. Testing over these years under this project was conducted by Robert Whirledge, Eric Mun, R.P. Watson, and Robert Light of Transtec.

Measurement Sites

Thirty-four unique pavement sections were evaluated, representing the variety of pavement types and surface treatment textures that are currently used by CDOT. Table 1 lists the sites by number along with a description of the site location. Table 2 presents more detailed site information including type of pavement, test section start and end coordinates, and other identifying information.

Table 1. Site location information.

Site ID	Road	Direction	Location	Nearest City	Zip Code
1	SH 83	NB	Between CR-14 & Hess Rd.	Parker	80134
2	I-70	EB	Between Evergreen Pkwy. & CR-65	Golden	80439
3	I-70	WB	Between Federal Blvd. & Pecos St.	Denver	80221
4	US 50	WB	Between 35 6/10 Rd. & Bridgeport Rd.	Grand Junction	81527
5	SH 74	EB	Between Bergen Pkwy. & Lewis Ridge Rd.	Evergreen	80439
6	US 50	EB	Between 35 6/10 Rd. & Bridgeport Rd.	Grand Junction	81527
7	US 85	SB	Between Daniels Park Rd. & Happy Canyon Rd.	Sedalia	80135
8	I-70	EB	Between US 6 & Herman Gulch Rd.	Bakerville (E.Dillon)	80444
9	C-470	WB (N)	Between US 285 & Morrison Rd.	Morrison	80465
10	US 287	SB	Between Bonner Spring Ranch Rd. & SH 14	Laporte	80535
11	SH 82	EB	Between Hunter Logan & Lower River Rd.	Basalt	81654
12	SH 58	WB	Between McIntyre St. & 44th Ave.	Golden	80403
13	I-25	SB	Between CR-12 & CR-10	Erie	80516
14	US 285	NB	Between Surrey Dr. & Goddard Ranch Ct.	Indian Hills	80465
15	I-25	NB	Between Fontanero St. & Fillmore St.	Colorado Springs	80907
16	SH 121	NB	Between Chatfield Ave. & Ken Caryl Ave.	Littleton	80128
17	I-70	WB	Between SH 13 & US 6/24	Rifle	81650
18	US 285	NB	Between Turkey Creek Rd. & Chamberlain Rd.	Indian Hills	80465
19	I-70	WB	Between Camino Dorado Rd. & Trail Gulch Rd.	Gypsum	81637
20	US 40	WB	Between CR-8 & SH 94	Kit Carson	80862
21	US 285	SB	Between Kipling Pkwy. & C-470	Morrison	80227
22	US 160	WB	Between CR-103 & Threemile Rd.	Alamosa	81101
23	I-70	EB	Between 23 Rd. & 24 Rd.	Grand Junction	81505
24	I-76	WB	Between CR-49 & SH 52	Hudson	80642
25	I-76	EB	Between 88th Ave. & 96th Ave.	Henderson	80640
26	I-25	SB	Between SH 105 & Higby Rd.	Monument	80132
27	C-470	WB (N)	Between Morrison Rd. & Alameda Pkwy.	Morrison	80228
28	Powers Blvd.	NB (W)	Between Union Blvd. & Old Ranch Rd.	Colorado Springs	80908
29	Powers Blvd.	SB (E)	Between Old Ranch Rd. & Union Blvd.	Colorado Springs	80908
30	US 85	NB	Between Daniels Park Rd. & SH 67	Sedalia	80135
31	I-70	EB	Between 15th St. & US 40	Georgetown	80444
32	US 34	EB	Between 71st Ave. & 65th Ave.	Greeley	80634
33	US 34	EB	Between 65th Ave. & 59th Ave.	Greeley	80634
34	US 34	EB	Between 47th Ave. & 35th Ave.	Greeley	80634

Table 2. Detailed site information.

Site ID	Surface Type	Construction Accepted [1]	CPX [2]	OBSI	SPB	TA	Approx. Lat.	Approx. Lon.	Approx. Elev. (ft.)	Section Length (ft.)	Wayside Mic Pos. From Begin (ft.)
1	SMA (3/4")	2004	✓	✓		✓[2,3,6]	39.4883	104.7591	5960	1558	769
2	SMA (3/4")	1/2004	✓	✓		✓	39.7084	105.3511	7490	5308	4116
3	SMA (3/4")	10/2003	✓	✓			39.7841	105.0186	5330	3575	n/a
4	SMA (1/2")	8/2002	✓	✓	✓		38.8721	108.3385	5110	4847	1422
5	SMA (3/8")	7/2004	✓	✓			39.6702	105.3599	7680	3488	n/a
6	Asphalt (SX, 1/2")	8/2002	✓	✓	✓		38.8994	108.3666	5010	5333	1048
7	Asphalt (SX, 1/2")	2006	✓[8]	✓[8]	✓[2,3]	✓[4,6]	39.4288	104.9111	6000	2686	1864
8	Asphalt (SX, 1/2")	2005 [7]	✓	✓			39.6976	105.8703	10470	3535	n/a
9	SMA (1/2")	6/2006	✓	✓		✓	39.6410	105.1723	5760	3033	2460
10	Asphalt (S, 3/4")	10/2003	✓	✓	✓[2,4,6]		40.7113	105.1730	5470	3380	2649
11	NovaChip	10/2000	✓	✓			39.3389	106.9989	6880	3228	n/a
12	NovaChip	6/2003	✓	✓		✓	39.7706	105.1904	5600	3082 [2,3] 1010 [4,9]	653
13	Concrete (Long. Tining)	10/2005	✓	✓		✓	40.0667	104.9809	5060	3389	1054
14	Concrete (Long. Tining)	10/1999	✓	✓			39.5838	105.2258	7130	1613	n/a
15	Concrete (Long. Groov.)	11/2001	✓	✓[2]			38.8672	104.8340	6130	4485	n/a
16	Concrete (Carpet Drag)	8/2001	✓	✓		✓	39.5741	105.0837	5580	2422	1323
17	Concrete (Dia. Grinding)	11/2005	✓	✓		✓	39.5205	107.8229	5290	6368	1177
18	Concrete (Dia. Grinding)	10/1999	✓	✓			39.5980	105.2255	7050	2069	n/a
19	SMA (1/2")	8/1996	✓	✓	✓[2,3,4]		39.6528	106.8823	6630	3122	443
20	Concrete (Long. Tining)	4/2002	✓	✓	✓[2,4,6]	✓[3]	38.8328	103.0540	4520	5241	2668
21	Asphalt (S, 3/4")	11/2003	✓	✓		✓	39.6438	105.1318	5700	3599	1451
22	Asphalt (SX, 1/2”)	10/1999	✓	✓	✓		37.5177	105.9948	7610	2930	796
23	Asphalt (SX, 1/2”)	10/2004	✓	✓			39.1138	108.6193	4560	3623	n/a
24	Concrete (Long. Tining)	3/2001	✓	✓			40.0942	104.6143	4940	3345	n/a
25	Concrete (Long. Tining)	11/2002	✓	✓			39.8655	104.9059	5120	2495	n/a
26	Concrete (Long. Tining)	10/1996	✓	✓			39.0862	104.8614	7010	1493	n/a
27	Concrete (Long. Tining)	1/2001	✓	✓			39.6759	105.1869	5890	7873	n/a
28	Concrete (Drag)	12/2004	✓	✓			38.9796	104.7574	7010	1804	n/a
29	SMA (3/4”)	9/2005	✓	✓			38.9790	104.7575	7010	1724	n/a
30	Concrete (Burlap Drag)	2003 [7]	✓[8]	✓[8]		✓[3,4,6]	39.4365	104.9514	5870	3019	2657
31	SMA (3/4")	10/2006	✓				39.7286	105.6919	8560	5529	n/a
32	Asphalt (PG 64-28)	8/2009		✓[4,5]			40.3920	104.7896	4900	440	n/a
33	Asphalt (CRM, Wet Proc)	8/2009		✓[4,5]			40.3920	104.7764	4890	440	n/a
34	Asphalt (CRM, Terminal)	8/2009		✓[4,5]			40.3920	104.7474	4870	440	n/a

Notes: [1] Traffic loading may have begun prior to construction acceptance date;
[2] tested in 2006; [3] tested in 2007; [4] tested in 2009; [5] tested in 2010; [6] tested in 2011;
[7] Not confirmed;
[8] Testing conducted at 55 mph 2006-2007; all others at 60 mph;
[9] Same point of begin.

Measurement Methods

Over the course of the research program, the following measurements were conducted depending on the type of site:

1. **On-Board Sound Intensity (OBSI) –** a near-field technique that measures tire-pavement noise in close proximity to the source. Instead of measuring levels via sound pressure from a single microphone (as the ISO 11819-2 or "CPX" method does), OBSI measures tire-pavement noise using a phase-matched pair of microphones that are positioned in such a way to isolate sound generated near the tire-pavement contact patch. The OBSI technique was originally developed by General Motors and matured in large part by Dr. Paul Donavan, currently of Illingworth & Rodkin. The OBSI protocol was subsequently refined under sponsorship of Caltrans, and is now standardized nationally as AASHTO TP 76. The current standard tire for OBSI measurements is the ASTM F 2493 Standard Reference Test Tire (SRTT) (P225/60R16). The Goodyear Aquatred III (P205/70R15) tire has also been used for both OBSI and CPX testing in the past (2006 and 2007 testing). It was dropped from the test program since it is no longer in production and the test results between the two tires have been found to be highly correlated. The standard test speed used in OBSI measurements is typically 60 mph.

2. **Statistical Pass-By (SPB) and Time-Averaged (TA) Wayside –** these measurements are made using a tripod-mounted microphone located at a fixed position (50 ft. horizontal from and 5 ft. higher than the center of the outside lane). In 2009 and 2011, additional measurements were made at a 50 ft. offset and 12 ft. height; and at a 25 ft. offset and a 4 ft. height. In order to normalize for the traffic present during the measurements, there is a simultaneous collection of vehicle counts, classifications, and speeds. The SPB measurements collected in this effort have been made by adopting components of the ISO 11819-1 standard. The techniques also are in general compliance with the recently developed AASHTO provisional standards TP 98 and TP 99 describing the SIP (Statistical Isolated Pass-By Method) and CTIM (Continuous-Flow Traffic Time-Integrated Method) techniques, respectively. To assist in developing Reference Energy

Mean Emission Level (REMEL) type data for the various pavements under study, provisions of the FHWA "Measurement of Highway-Related Noise" have also been adopted, particularly those related to site selection, microphone positioning, data processing, and reporting (e.g., third-octave).

3. **Environmental Wayside –** these measurements are collected in the same manner as SPB/TA wayside measurements. They have been referred to as "SPBI+" by CDOT. The measurements are made with additional microphone positions at 100 and 200 ft. from the center of the outside lane. The reason this information is desired is to assess if the noise levels are significant at these distances, which would correspond to locations of residences in these areas. Although, industry experts have questioned the accuracy and usefulness of measurements at 200 ft. and greater. Conducting these SPBI+ tests during the project was difficult due to the inability to obtain the proper approvals for adjacent land access and/or contamination from other sound sources. Because of this, only one SPBI+ location was able to be selected, site 21, and SPBI+ measurements were conducted in 2009 and 2011.

4. **Supporting Data –** this includes climatic data via an on-site weather station, photographs and digital video, and site surveys to benchmark the begin/end points for each section along with the location of any wayside microphone positions.

Photographs of some of the test equipment can be found in Appendix A. Additional details for each site, along with the types of measurements collected are listed in Table 2.

Database

The work conducted under this project has resulted in a large database of information. In addition to the various site reference information, such as that contained in Table 1 and Table 2, it contains as-built plans and construction records for many of the 34 sites.

The noise data have been organized into the database, classified in a hierarchical folder structure for ready access.

RESULTS OF EVALUATIONS AND TRENDS

Appendix B contains a detailed listing of the more current data collected (in 2011) from each of the sites. This includes general information on the sites, followed by details of both the environmental and tire-pavement noise measurements.

Sites Resurfaced between 2009 and 2011

Three test sites were resurfaced during the time between the measurements conducted in 2009 and 2011:

1. Site 8, Asphalt (SX, 1/2”)
2. Site 11, NovaChip
3. Site 19, SMA. Wayside measurements not conducted.

These sites are called out by note (2) in Table 3, and their 2011 measurement results should not be used when evaluating trends of age and tire-pavement noise. For similar reasons, the wayside measurements (SPB) at site 19 were not conducted in 2011.

OBSI Results

A summary of the OBSI data (A-weighted sound intensity Level (SIL) in dB ref 1 pW/m^2) is given in Table 3. OBSI levels reported from the 2006, 2007, and 2009 testing are compared to those collected most recently in 2011. Calculated changes in level are also reported. Figure 1 shows a chart of the OBSI results for all four years, and grouped by pavement type (concrete, HMA, SMA, and NovaChip). In the chart, rank order within each nominal pavement type (color) is based on the levels measured in 2011. The final rows include different headings since they include no measurements in 2006 and 2007, but were measured independent of the other sites in 2010.

Table 3. OBSI test summary A-weighted overall SIL (dB ref 1pW/m²).

Site	2006	2007	2009	2011	Change ('07-'06)	Change ('09-'07)	Change ('11-'09)	Change ('11-'06)
1	102.7	102.0	102.8	102.9	–0.7	+0.8	+0.1	+0.2
2	102.9	105.5	104.9	105.0	+2.6	-0.6	+0.1	+2.1
3	104.0	105.1	104.5	104.7	+1.1	-0.5	+0.2	+0.7
4	101.4	102.4	102.0	102.6	+1.0	-0.5	+0.7	+1.3
5	102.3	102.7	102.8	103.2	+0.4	+0.1	+0.5	+0.9
6	101.6	102.7	102.3	103.0	+1.1	-0.5	+0.8	+1.4
7 (1)	104.8	104.3	104.3	105.0	–0.6	+0.1	+0.7	+0.2
8 (2)	104.0	106.0	104.6	103.1	+2.0	-1.3	n/a (2)	n/a (2)
9	100.6	101.7	102.4	102.7	+1.1	+0.7	+0.3	+2.2
10	102.5	102.9	102.5	102.4	+0.4	-0.4	-0.1	-0.1
11 (2)	104.3	104.6	103.5	102.3	+0.3	-1.0	n/a (2)	n/a (2)
12	101.8	101.7	100.9	102.8	–0.2	-0.8	+2.0	+1.0
13	101.8	101.5	101.4	101.6	–0.3	-0.2	+0.2	-0.2
14	104.3	104.8	105.1	105.3	+0.5	+0.3	+0.2	+1.1
15	102.4		102.8	104.1			+1.3	+1.7
16	102.8	103.3	103.3	103.7	+0.6	-0.1	+0.5	+1.0
17	101.6	103.5	103.6	105.1	+2.0	+0.1	+1.4	+3.5
18	104.5	104.7	104.5	105.1	+0.1	-0.1	+0.5	+0.5
19 (2)	104.7	105.0	104.2	103.8	+0.3	-0.8	n/a (2)	n/a (2)
20	101.9	102.1	101.3	101.6	+0.1	-0.8	+0.3	-0.3
21	104.7	105.1	104.8	105.9	+0.4	-0.3	+1.0	+1.2
22	103.4	103.2	102.0	102.7	–0.2	-1.2	+0.8	-0.7
23	101.6	103.2	102.7	103.7	+1.6	-0.5	+1.0	+2.1
24	102.2	101.0	101.6	102.0	–1.2	+0.6	+0.3	-0.3
25	102.2	102.2	102.2	103.1	0.0	0.0	+0.9	+0.9
26	102.1	101.8	102.8	104.6	–0.3	+1.0	+1.9	+2.5
27	102.4	103.5	103.1	104.1	+1.1	-0.4	+0.9	+1.6
28	101.4	101.9	102.2	102.0	+0.5	+0.3	-0.2	+0.6
29	101.4	102.3	103.2	104.8	+0.9	+0.9	+1.6	+3.4
30 (1)	102.4	102.8	102.5	103.0	+0.4	-0.3	+0.6	+0.6
31		104.9	105.3	106.2		+0.4	+0.9	

Site	2006 & 2007	2009	2010	2011	Change ('10-'09)	Change ('11-'10)	Change ('11-'09)	
32 (3)		100.5	101.1	101.6	+0.6	+0.5	+1.1	
33 (3)		100.4	100.7	101.4	+0.3	+0.7	+1.0	
34 (3)		99.3	100.3	100.9	+1.0	+0.6	+1.6	

Notes: (1) As needed, results normalized to standard test speed of 60 mph.
(2) Test section resurfaced between 2009 and 2011.
(3) Site first evaluated in 2009 and an extra, intermediate evaluation in 2010.

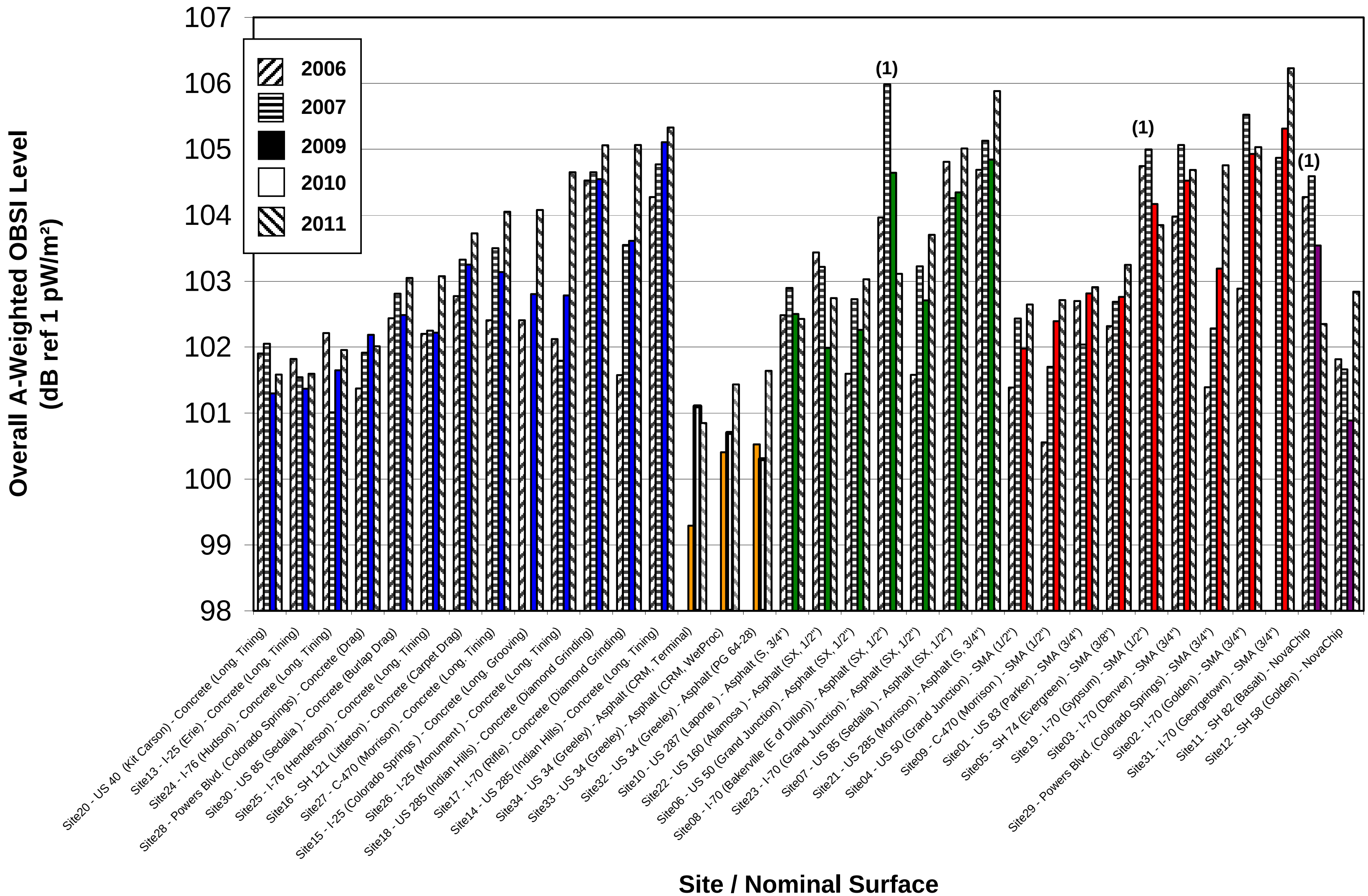

Figure 1. Summary of overall OBSI levels for test.

Notes: [(1)] Test section resurfaced between 2009 and 2011.

SPB Results

Table 4 contains a summary of the SPB wayside testing results for 2011 for both the car (which includes light trucks) and heavy truck vehicle categories at three microphone locations. In addition, the table includes the climatic conditions during the measurement periods. Wayside measurements at Site 19 were not conducted in 2011 because the test section was resurfaced since the last visit in 2009.

Table 5 contains SPB wayside testing results for all four measurement years and year-to-year changes in level. The results in Table 5 are for the 50×5 ft microphone because this microphone location was used consistently throughout the research project. Microphones located at 25×4 ft and 50×12 ft were initiated in 2009.

Table 4. SPB results and climatic conditions for 2011.

	SPB 50×5 mic		SPB 25×4 mic		SPB 50×12 mic		Environmental Conditions	
Site	Car	Hvy. Truck	Car	Hvy. Truck	Car	Hvy. Truck	Avg Temp (°F)	Avg Wind Speed (mph)
4[(1)]	73.5	81.0	80.9	88.2			82	4
6	75.6	83.1	81.7	89.0	75.8	83.4	66	12
10	73.0	82.5	80.5	89.8	74.6	84.1	78	2
19[(2)]								
20	73.7	82.4	80.1	89.0	73.7	82.9	60	17
22[(3)]	75.3		81.5		75.5		62	4

Notes: (1) 50×5 microphone position not feasible.
(2) Site not evaluated because of resurfacing.
(3) Too few heavy trucks for valid results. Results excluded.

Table 5. SPB (50×5 mic) test summary A-weighted SPL (dB ref 20 µPa).

	SPB 2006		SPB 2007		SPB 2009		SPB 2011		Change ('07-'06)		Change ('09-'07)		Change ('11-'09)		Change ('11-'06)	
	Car	Hvy. Truck	Car	Hvy. Truck	Car	Hvy. Truck	Car	Hvy. Truck	Car	Hvy. Truck	Car	Hvy. Truck	Car	Hvy. Truck	Car	Hvy. Truck
4	74.1	80.8	75.3	80.8	73.1	79.6	73.5	81.0	+1.2	0.0	-2.2	-1.2	+0.4	+1.4	-0.6	+0.2
6	74.4	83.0	75.0	82.2	74.6	83.0	75.6	83.1	+0.6	-0.8	-0.4	+0.8	+1.0	+0.1	+1.2	+0.1
10	74.8	83.7			74.0	82.2	73.0	82.5					-1.0	+0.3	-1.8	-1.2
19	76.0	83.0	76.5	82.2	76.3	82.8			+0.5	-0.8	-0.2	+0.6				
20	73.8	82.8			72.0	80.7	73.7	82.4					+1.7	+1.7	-0.1	-0.4
22	74.5	81.9	73.8	81.6	73.6	81.0	75.3		-0.7	-0.3	-0.2	-0.6	+1.7		+0.8	

TA Results

Table 6 contains a summary of the TA wayside testing results for 2011 at the three microphone locations. In addition, the table includes the climatic conditions during the measurement periods.

Table 7 contains TA wayside testing results for all four measurement years and year-to-year changes in level. The results in Table 7 are for the 50×5 ft microphone because this microphone location was used consistently throughout the research project. Microphones located at 25×4 ft and 50×12 ft were initiated in 2009.

Table 6. TA results and climatic conditions for 2011.

Site	50×5 mic	25×4 mic	50×12 mic	Environmental Conditions	
				Avg Temp (°F)	Avg Wind Speed (mph)
1	71.1	74.5	72.2	61	4
2(1)	78.2		78.6	74	4
7	71.6	75.0	72.5	66	9
9(2)	76.3	80.1		69	6
12	70.8	75.3	72.5	80	3
13	79.5	83.2	80.0	68	5
16(3)		73.2	70.8	68	5
17	74.9	80.2	77.0	83	2
21	74.9	78.4	75.4	74	4
30	67.7	71.3	69.3	70	2

Notes: (1) 25×4 microphone position not feasible.
(2) 50×12 microphone position not feasible.
(3) 50×5 microphone data not valid. Results excluded.

Table 7. TA results for 50x5 microphone and year-to-year change.

Site	2006	2007	2009	2011	Change ('07-'06)	Change ('09-'07)	Change ('11-'09	Change ('11-'06)
1	70.1	70.0		71.1	-0.1			1.0
2	75.6	78.1	76.9	78.2	2.5	-1.1	1.3	2.7
7			72.4	71.6			-0.8	71.6
9	75.2	77.6	75.5	76.3	2.4	-2.1	0.8	1.1
12	70.7	70.4	67.7	70.8	-0.3	-2.7	3.1	0.1
13	79.6	79.8	78.6	79.5	0.3	-1.2	0.9	0.0
16	69.8	69.1	70.7		-0.7	1.6		
17	72.4	75.4	74.2	74.9	3.0	-1.2	0.7	2.5
21	73.9	74.5	74.0	74.9	0.5	-0.4	0.9	1.0
30		68.9	68.1	67.7		-0.8	-0.4	67.7

Relationship between Wayside and OBSI Levels

The SPB results (as reported in Table 5) represent an estimate of the sound level of an "average" car traveling at 60 mph. The OBSI measurements are also conducted using a car at a vehicle speed of 60 mph. Therefore, by comparing the results from the sites at which both SPB wayside and OBSI testing are conducted, the relationship between sound levels at the wayside microphone location (50×5 ft) and OBSI levels can be investigated.

Figure 2 shows a plot of the SPB wayside versus OBSI levels for the five SPB wayside test locations in the 2011. Also shown in the figure, the solid line is a best-fit trend line with 1:1 slope. The offset for the best-fit is 28.3 dBA and the standard estimate of the error (SEE) is 1.1 dBA.

Figure 3 shows a similar plot but includes results from all the years data was collected. In this case, the best-fit trend line with 1:1 slope has offset of 28.2 dBA and SEE is 0.8 dBA.

These results indicated good correlation between tire-pavement noise levels using the OBSI method and wayside sound levels. Basically, wayside sound level is related to OBSI level by an offset of 28.2 dBA:

$$\text{Wayside sound level (dBA)} = \text{Overall OBSI level (dBA)} - 28.2$$

This offset is consistent with the offset of 28.5 dBA reported by Donavan and Lodico as part of the NCHRP 1-44 project (NCHRP Report 630).

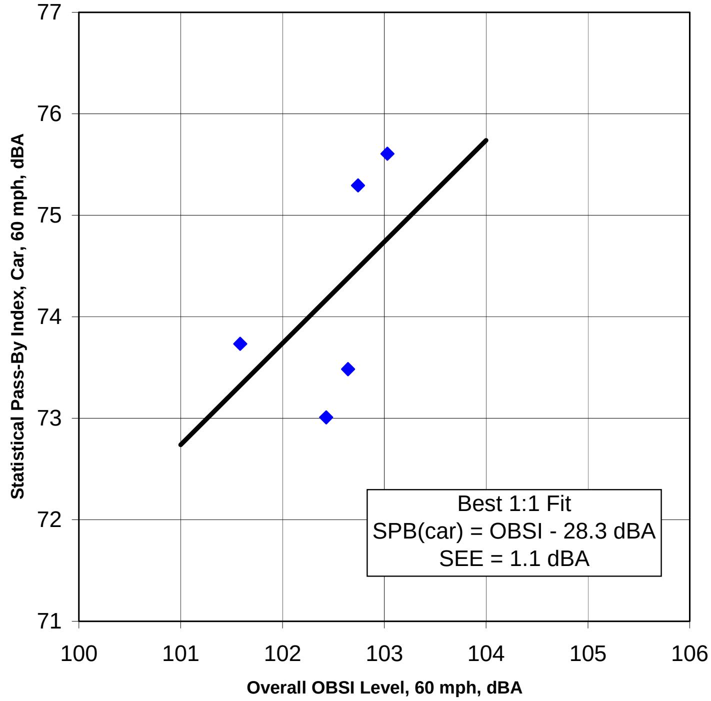

Figure 2. Comparison of the 2011 OBSI and SPBI sound levels for cars at 60 mph and the 50 ft x 5 ft microphone position.

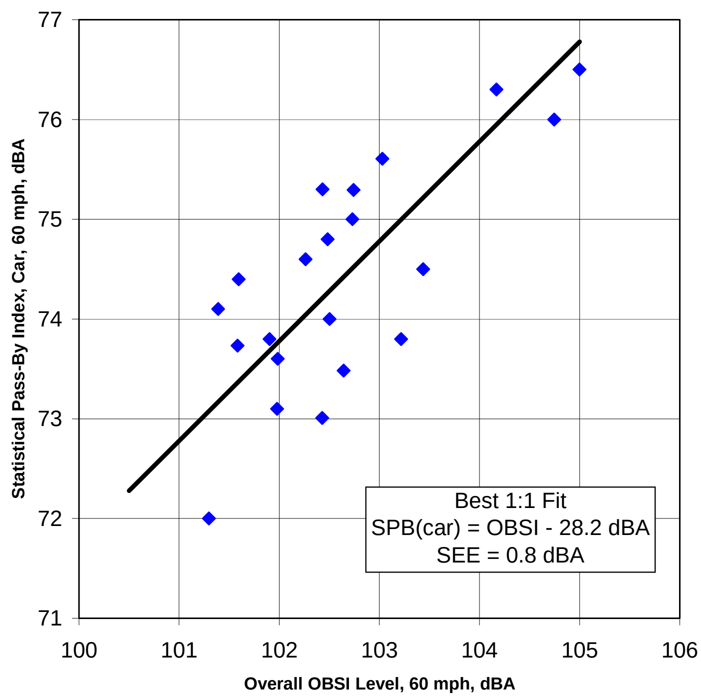

Figure 3. Comparison of the all the results (2006 to 2011) OBSI and SPBI sound levels for cars at 60 mph and the 50 ft x 5 ft microphone position.

Normalizing OBSI Levels for Temperature

Throughout this QPR program, OBSI measurements were conducted at different times of the year. In 2006, testing was conducted during the fall, from mid-September to early November. In 2007, testing occurred largely during the summer months; in 2009, testing was conducted in May-June, and again in September; and in 2011, testing was conducted in May and June. During these test intervals, average ambient air temperatures were 61°F in 2006, 78°F in 2007, 70°F in 2009, and 77°F in 2011. While temperatures during testing fell within the range of both specification and good practice, the differences are large enough to investigate an adjustment to the OBSI levels to compensate for the influence of temperature on the measured levels.

There are numerous published research results about the effects of ambient temperature on tire-pavement noise, including measured OBSI levels. All of the research concludes an inverse relationship, that is, tire-pavement noise increases with decreasing temperature. This is to be expected for several reasons. For one, tire hardness will increase with decreasing temperature, which will in turn affect the noise generated. An effect of temperature on the dynamic modulus of asphalt will also likely be present, with a level increase resulting from colder, stiffer pavements. Concrete pavement joints will open as temperatures decrease, which will in turn increase the overall level due to an increased contribution of “joint slap” noise. It is reasonable that all of these effects (and others) will vary from pavement to pavement.

An early study by Anfosso-Lédée and Pichaud concludes a linear relationship of -0.056 dBA/°F for dense-graded hot mix asphalt, and -0.033 dBA/°F for porous asphalt. More recently, Donavan and Lodico in the NCHRP 1-44(1) report conclude a relationship of -0.04 dBA/°F, which includes the effect of temperature on air density in the sound intensity calculation. The NCHRP 1-44(1) report is based on an exhaustive evaluation of pavements nationwide using the same OBSI test methodology as used here. As such, it serves as the basis for the temperature corrections adopted for this CDOT study.

With respect to the effect of air density on sound intensity, a discussion is warranted. To begin, it should be noted that sound intensity levels from OBSI measurements are actually calculated from sound pressure measurements. The equation for the calculation requires a value for the density of air, which in turn, is a function of temperature, atmospheric pressure, and relative humidity. Temperature and pressure have the strongest influence on density, while humidity is a less significant factor. At constant pressure and humidity, the effect of temperature on sound intensity due to changes in air density is -0.012 dBA/°F.

In following the most current (2011) AASHTO TP 76 procedure, all of the OBSI levels reported above in Table 3 and Figure 1 have had an acoustical correction factor applied so that the results are valid for the ambient temperature, pressure, and humidity at the time of the measurements. A subsequent temperature correction should also be applied to account for changes in the tire and pavement properties as they affect tire-pavement noise.

Since the temperature-sound intensity level relationship derived under NCHRP 1-44(1) combines these two temperature-dependent effects, the effect of temperature on tire-pavement noise generation that does not include the effect on air density is calculated to be:

$$-0.04 + 0.012 = -0.028 \text{ dBA/°F}. \tag{1}$$

This factor is employed in this study, and thus the tire-pavement noise levels measured at any ambient temperature can be normalized to a reference temperature of 68°F as follows:

$$OBSI_{68} = OBSI_{amb} - 0.028 \times (68 - T_{amb}) \tag{2}$$

Where:

$OBSI_{68}$ =	OBSI level normalized to 68°F,
$OBSI_{amb}$ =	OBSI level measured at the ambient conditions with environmental correction factor applied, and
T_{amb} =	ambient temperature when $OBSI_{amb}$ was measured.

Table 8 lists the OBSI levels normalized to 68°F for all the sites and years. Also shown in the table is the ambient temperature at the time of measurement and the OBSI levels measured at the ambient conditions (with the environmental correction factor applied). Figure 4 shows a chart of the OBSI levels normalized to 68°F. In the chart, the rank order within each nominal pavement type (color) is based on the normalized levels in 2011.

Table 8. Ambient temperature at the time of measurement (°F), measured overall OBSI levels (dBA), and OBSI levels normalized to 68°F (dBA).

Site	2006			2007			2009			2011		
	Temp (°F)	OBSI-amb. (dBA)	OBSI-68°F (dBA)	Temp (°F)	OBSI-amb. (dBA)	OBSI-68°F (dBA)	Temp (°F)	OBSI-amb. (dBA)	OBSI-68°F (dBA)	Temp (°F)	OBSI-amb. (dBA)	OBSI-68°F (dBA)
1	43.0	102.7	102.0	79.9	102.0	102.4	62.5	102.8	102.7	77.5	102.9	103.2
2	66.0	102.9	102.8	65.6	105.5	105.5	62.7	104.9	104.8	77.7	105.0	105.3
3	67.0	104.0	103.9	67.4	105.1	105.0	59.4	104.5	104.3	77.7	104.7	105.0
4	71.0	101.4	101.5	86.3	102.4	102.9	71.7	102.0	102.1	78.0	102.6	102.9
5	52.0	102.3	101.9	78.8	102.7	103.0	62.7	102.8	102.6	71.6	103.2	103.3
6	71.0	101.6	101.7	86.3	102.7	103.2	78.2	102.3	102.5	77.3	103.0	103.3
7	34.0	104.8	103.9	81.9	104.3	104.6	52.2	104.3	103.9	63.8	105.0	104.9
8	48.0	104.0	103.4	58.5	106.0	105.7	56.0	104.6	104.3	69.6	103.1	103.2
9	78.0	100.6	100.8	85.6	101.7	102.2	67.7	102.4	102.4	82.4	102.7	103.1
10	76.0	102.5	102.7	80.0	102.9	103.2	78.5	102.5	102.8	90.8	102.4	103.1
11	68.0	104.3	104.3	80.5	104.6	104.9	73.3	103.5	103.7	84.6	102.3	102.8
12	69.0	101.8	101.8	82.8	101.7	102.1	74.8	100.9	101.1	83.3	102.8	103.3
13	58.0	101.8	101.5	87.6	101.5	102.1	86.8	101.4	101.9	77.7	101.6	101.9
14	51.0	104.3	103.8	85.9	104.8	105.3	63.4	105.1	105.0	73.1	105.3	105.5
15	55.0	102.4	102.0				82.4	102.8	103.2	77.9	104.1	104.4
16	59.0	102.8	102.5	88.4	103.3	103.9	80.5	103.3	103.6	86.6	103.7	104.2
17	73.0	101.6	101.7	76.1	103.5	103.8	78.8	103.6	103.9	89.8	105.1	105.7
18	51.0	104.5	104.1	85.9	104.7	105.2	63.4	104.5	104.4	73.1	105.1	105.2
19	62.0	104.7	104.6	69.5	105.0	105.0	63.7	104.2	104.0	73.6	103.8	104.0
20	70.0	101.9	102.0	83.8	102.1	102.5	66.1	101.3	101.2	54.5	101.6	101.2
21	48.0	104.7	104.1	86.1	105.1	105.6	76.0	104.8	105.1	74.8	105.9	106.1
22	40.0	103.4	102.7	64.3	103.2	103.1	76.2	102.0	102.2	80.1	102.7	103.1
23	75.0	101.6	101.8	85.9	103.2	103.7	72.8	102.7	102.8	96.6	103.7	104.5
24	66.0	102.2	102.2	93.6	101.0	101.7	63.1	101.6	101.5	79.9	102.0	102.3
25	65.0	102.2	102.1	94.2	102.2	103.0	66.9	102.2	102.2	88.9	103.1	103.7
26	45.0	102.1	101.5	83.3	101.8	102.2	75.0	102.8	103.0	66.4	104.6	104.6
27	80.0	102.4	102.7	91.5	103.5	104.2	71.1	103.1	103.2	82.4	104.1	104.5
28	69.0	101.4	101.4	80.4	101.9	102.3	66.0	102.2	102.1	56.3	102.0	101.7
29	69.0	101.4	101.4	80.4	102.3	102.6	66.0	103.2	103.1	56.3	104.8	104.4
30	37.0	102.4	101.6	81.9	102.8	103.2	52.2	102.5	102.0	63.8	103.0	102.9
31				73.8	104.9	105.0	65.0	105.3	105.2	80.6	106.2	106.6

Site	2006 & 2007			2009			2010			2011		
32				53.6	100.5	100.1	76.0	101.1	101.3	87.5	101.6	102.2
33				53.6	100.4	100.0	76.0	100.7	100.9	87.5	101.4	102.0
34				53.6	99.3	98.9	76.0	100.3	100.5	87.5	100.9	101.4

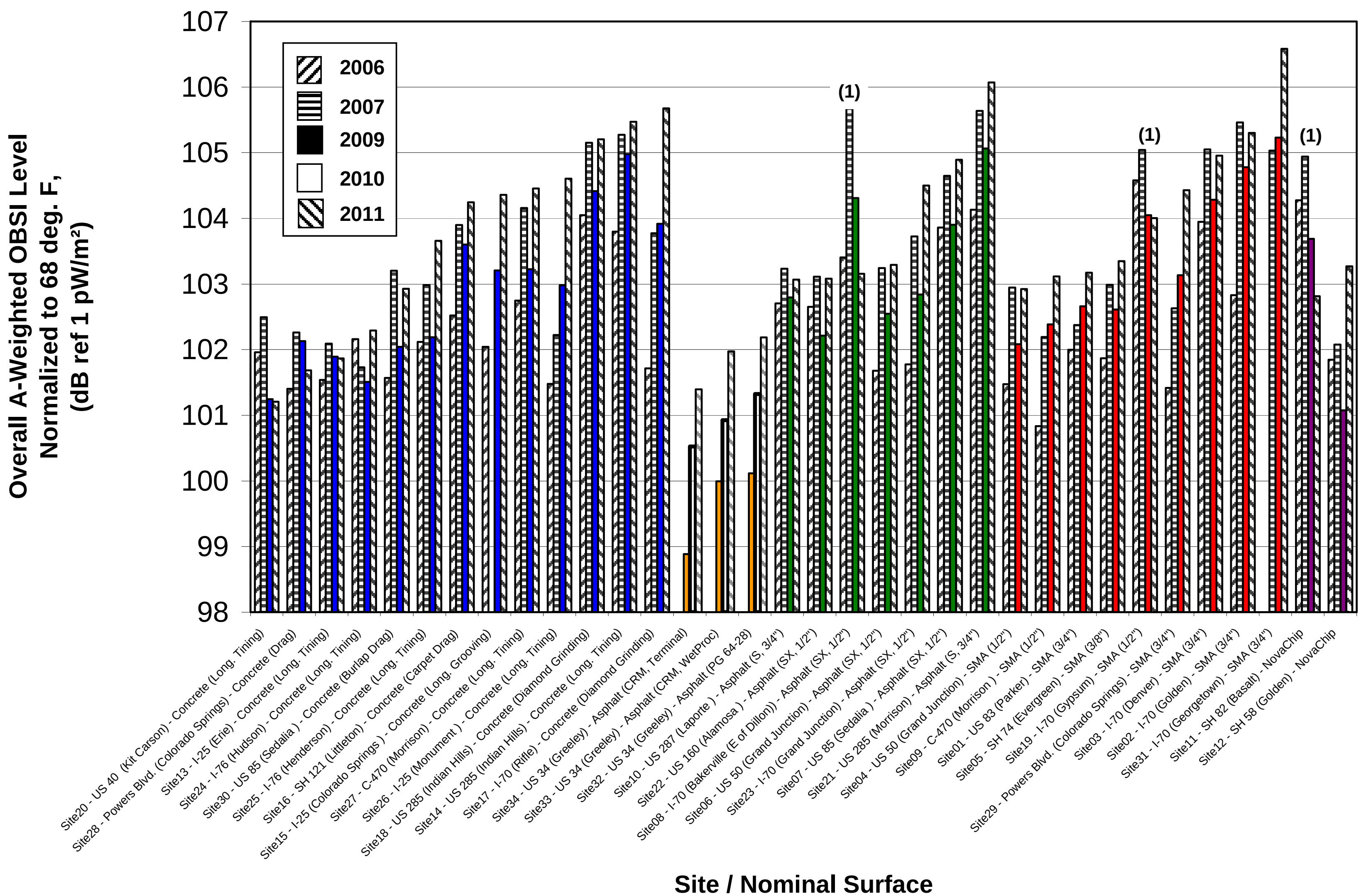

Figure 4. Summary of overall OBSI levels normalized to 68°F.

Notes: (1) Test section resurfaced between 2009 and 2011.

Acoustical Durability

For most of the sites, tire-pavement noise using the OBSI method was evaluated at four measurement times spanning five years, from 2006 to 2011. Table 9 lists the pavement age in years at the time of each OBSI measurement, along with the measured OBSI level and the OBSI level normalized to 68°F. Using these data, a linear regression analysis is conducted for each site to determine how the tire-pavement noise levels increase or decrease with pavement age, expressed in terms of sensitivity having units of dBA/year.

Table 10 through Table 14 show the results of the linear regression analyses for each site using measured and temperature normalized OBSI levels, and grouped and averaged by pavement type. The tables list the acoustic durability factor (dBA/year), the p-value, the correlation coefficient (r-squared), and the average durability factor for the pavement group. Figure 5 through Figure 9 graph the trend lines for each site using the temperature normalized OBSI levels. Also shown on the graph for each pavement type is the average trend for the group (solid red line).

General experience is for tire-pavement noise to increase with time. This is in part due to wearing and polishing of the pavement surface texture. In addition, raveling, cracking, and other material and structural distresses develop with age, and can lead to additional increases in tire-pavement noise.

Because increases in tire-pavement noise are a consequence of pavement behavior and distress, acoustic durability analysis should be considered as a function of traffic loading in addition to age. The different sites in this study have varied traffic loading (both ADT and mix), and thus it is reasonable that some of the site-to-site variation in acoustical durability can be attributed to this. Sites 32, 33, and 34 can be considered ideal for direct comparisons of acoustical durability since they are along the same road, and thus receive the same traffic loading (see reference Table 11 and Figure 6). Sites 28 and 29 can also be compared in this regard.

Table 9. Age, measured OBSI levels, and OBSI levels normalized to 68°F.

Site	2006			2007			2009			2011		
	Age (yr)	OBSI-amb. (dBA)	OBSI-68°F (dBA)	Age (yr)	OBSI-amb. (dBA)	OBSI-68°F (dBA)	Age (yr)	OBSI-amb. (dBA)	OBSI-68°F (dBA)	Age (yr)	OBSI-amb. (dBA)	OBSI-68°F (dBA)
1	1.3	102.7	102.0	2.1	102.0	102.4	4.3	102.8	102.7	5.9	102.9	103.2
2	2.7	102.9	102.8	3.6	105.5	105.5	5.4	104.9	104.8	7.5	105.0	105.3
3	3.1	104.0	103.9	3.8	105.1	105.0	5.6	104.5	104.3	7.7	104.7	105.0
4	4.2	101.4	101.5	5.1	102.4	102.9	6.9	102.0	102.1	8.9	102.6	102.9
5	2.3	102.3	101.9	3.0	102.7	103.0	4.9	102.8	102.6	7.0	103.2	103.3
6	4.2	101.6	101.7	5.1	102.7	103.2	6.9	102.3	102.5	8.9	103.0	103.3
7	1.3	104.8	103.9	2.1	104.3	104.6	4.2	104.3	103.9	5.9	105.0	104.9
8 (1)	1.3	104.0	103.4	2.1	106.0	105.7	3.9	104.6	104.3			
9	0.3	100.6	100.8	1.1	101.7	102.2	3.0	102.4	102.4	5.0	102.7	103.1
10	3.1	102.5	102.7	3.9	102.9	103.2	5.6	102.5	102.8	7.7	102.4	103.1
11 (1)	6.0	104.3	104.3	6.9	104.6	104.9	8.7	103.5	103.7			
12	3.4	101.8	101.8	4.2	101.7	102.1	6.0	100.9	101.1	8.1	102.8	103.3
13	1.1	101.8	101.5	1.9	101.5	102.1	3.6	101.4	101.9	5.7	101.6	101.9
14	7.0	104.3	103.8	7.7	104.8	105.3	9.7	105.1	105.0	11.7	105.3	105.5
15	5.0	102.4	102.0				7.6	102.8	103.2	9.6	104.1	104.4
16	5.2	102.8	102.5	6.0	103.3	103.9	7.8	103.3	103.6	9.8	103.7	104.2
17	0.9	101.6	101.7	1.8	103.5	103.8	3.6	103.6	103.9	5.7	105.1	105.7
18	7.0	104.5	104.1	7.7	104.7	105.2	9.7	104.5	104.4	11.7	105.1	105.2
19 (1)	10.2	104.7	104.6	11.1	105.0	105.0	12.9	104.2	104.0			
20	4.6	101.9	102.0	5.4	102.1	102.5	7.1	101.3	101.2	9.2	101.6	101.2
21	2.9	104.7	104.1	3.7	105.1	105.6	5.6	104.8	105.1	7.6	105.9	106.1
22	7.1	103.4	102.7	7.9	103.2	103.1	9.7	102.0	102.2	11.8	102.7	103.1
23	2.0	101.6	101.8	2.9	103.2	103.7	4.7	102.7	102.8	6.7	103.7	104.5
24	5.7	102.2	102.2	6.3	101.0	101.7	8.2	101.6	101.5	10.3	102.0	102.3
25	4.0	102.2	102.1	4.6	102.2	103.0	6.6	102.2	102.2	8.6	103.1	103.7
26	10.1	102.1	101.5	10.9	101.8	102.2	12.7	102.8	103.0	14.7	104.6	104.6
27	5.8	102.4	102.7	6.5	103.5	104.2	8.4	103.1	103.2	10.4	104.1	104.5
28	1.8	101.4	101.4	2.6	101.9	102.3	4.6	102.2	102.1	6.5	102.0	101.7
29	1.0	101.4	101.4	1.8	102.3	102.6	3.8	103.2	103.1	5.7	104.8	104.4
30	1.4	102.4	101.6	2.1	102.8	103.2	4.2	102.5	102.0	5.9	103.0	102.9
31				0.9	104.9	105.0	2.7	105.3	105.2	4.7	106.2	106.6

Site	2006 & 2007			2009			2010			2011		
32 (2)				0.1	100.5	100.1	1.0	101.1	101.3	1.8	101.6	102.2
33 (2)				0.1	100.4	100.0	1.0	100.7	100.9	1.8	101.4	102.0
34 (2)				0.1	99.3	98.9	1.0	100.3	100.5	1.8	100.9	101.4

Notes: (1) Test section resurfaced between 2009 and 2011.
(2) Site first evaluated in 2009 and an extra, intermediate evaluation in 2010.

Table 10. OBSI level and age trend analyses for the concrete sites.

Site	Description	Measured OBSI Levels			OBSI Levels Normalized to 68°F		
		dBA/yr	p-value	r-squared	dBA/yr	p-value	r-squared
26	Concrete (Long. Tining)	0.59	0.06	0.88	0.65	0.01	0.98
15	Concrete (Long. Groov.)	0.35	0.24	0.86	0.50	0.05	0.99
17	Concrete (Dia. Grinding)	0.62	0.09	0.82	0.71	0.07	0.86
20	Concrete (Long. Tining)	-0.11	0.34	0.43	-0.24	0.20	0.63
16	Concrete (Carpet Drag)	0.17	0.13	0.77	0.27	0.24	0.58
14	Concrete (Long. Tining)	0.21	0.07	0.87	0.25	0.30	0.49
25	Concrete (Long. Tining)	0.18	0.15	0.73	0.23	0.34	0.44
27	Concrete (Long. Tining)	0.26	0.20	0.64	0.23	0.39	0.38
18	Concrete (Dia. Grinding)	0.10	0.19	0.66	0.14	0.47	0.28
30	Concrete (Burlap Drag)	0.08	0.39	0.37	0.13	0.64	0.13
13	Concrete (Long. Tining)	-0.04	0.55	0.20	0.03	0.72	0.08
24	Concrete (Long. Tining)	0.04	0.83	0.03	0.04	0.77	0.05
28	Concrete (Drag)	0.12	0.30	0.49	0.01	0.94	0.00
Average		**0.20**			**0.23**		

Table 11. OBSI level and age trend analysis for the crumb rubber asphalt test sites.

Site	Description	Measured OBSI Levels			OBSI Levels Normalized to 68°F		
		dBA/yr	p-value	r-squared	dBA/yr	p-value	r-squared
33	Asphalt (CRM, Wet Proc)	0.60	0.16	0.94	1.16	0.03	1.00
32	Asphalt (PG 64-28)	0.66	0.00	1.00	1.22	0.05	0.99
34	Asphalt (CRM, Terminal)	0.92	0.10	0.98	1.48	0.10	0.98
Average		**0.73**			**1.3**		

Table 12. OBSI level and age trend analyses for the dense-graded asphalt sites.

Site	Description	Measured OBSI Levels			OBSI Levels Normalized to 68°F		
		dBA/yr	p-value	r-squared	dBA/yr	p-value	r-squared
23	Asphalt (SX, 1/2")	0.33	0.23	0.59	0.42	0.24	0.57
21	Asphalt (S, 3/4")	0.21	0.18	0.67	0.30	0.27	0.54
6	Asphalt (SX, 1/2")	0.22	0.27	0.53	0.22	0.38	0.39
7	Asphalt (SX, 1/2")	0.06	0.63	0.14	0.12	0.50	0.25
10	Asphalt (S, 3/4")	-0.05	0.52	0.23	0.03	0.76	0.06
8	Asphalt (SX, 1/2")	0.11	0.91	0.02	0.17	0.87	0.04
22	Asphalt (SX, 1/2")	-0.19	0.39	0.37	0.02	0.88	0.01
Average		**0.10**			**0.19**		

Table 13. OBSI level and age trend analyses for the SMA sites.

Site	Description	Measured OBSI Levels			OBSI Levels Normalized to 68°F		
		dBA/yr	p-value	r-squared	dBA/yr	p-value	r-squared
1	SMA (3/4")	0.11	0.40	0.37	0.23	0.02	0.96
29	SMA (3/4")	0.67	0.01	0.98	0.57	0.04	0.93
9	SMA (1/2")	0.42	0.09	0.82	0.41	0.11	0.80
31	SMA (3/4")	0.36	0.10	0.98	0.41	0.23	0.87
5	SMA (3/8")	0.17	0.05	0.90	0.22	0.26	0.55
2	SMA (3/4")	0.28	0.49	0.26	0.34	0.40	0.36
4	SMA (1/2")	0.19	0.30	0.49	0.19	0.45	0.31
19	SMA (1/2")	-0.26	0.39	0.67	-0.26	0.51	0.49
3	SMA (3/4")	0.07	0.70	0.09	0.12	0.55	0.20
Average		**0.22**			**0.25**		

Table 14. OBSI level and age trend analyses for the NovaChip sites.

Site	Description	Measured OBSI Levels			OBSI Levels Normalized to 68°F		
		dBA/yr	p-value	r-squared	dBA/yr	p-value	r-squared
12	NovaChip	0.18	0.53	0.22	0.23	0.46	0.29
11	NovaChip	-0.32	0.40	0.66	-0.29	0.57	0.40
Average		**-.07**			**-.03**		

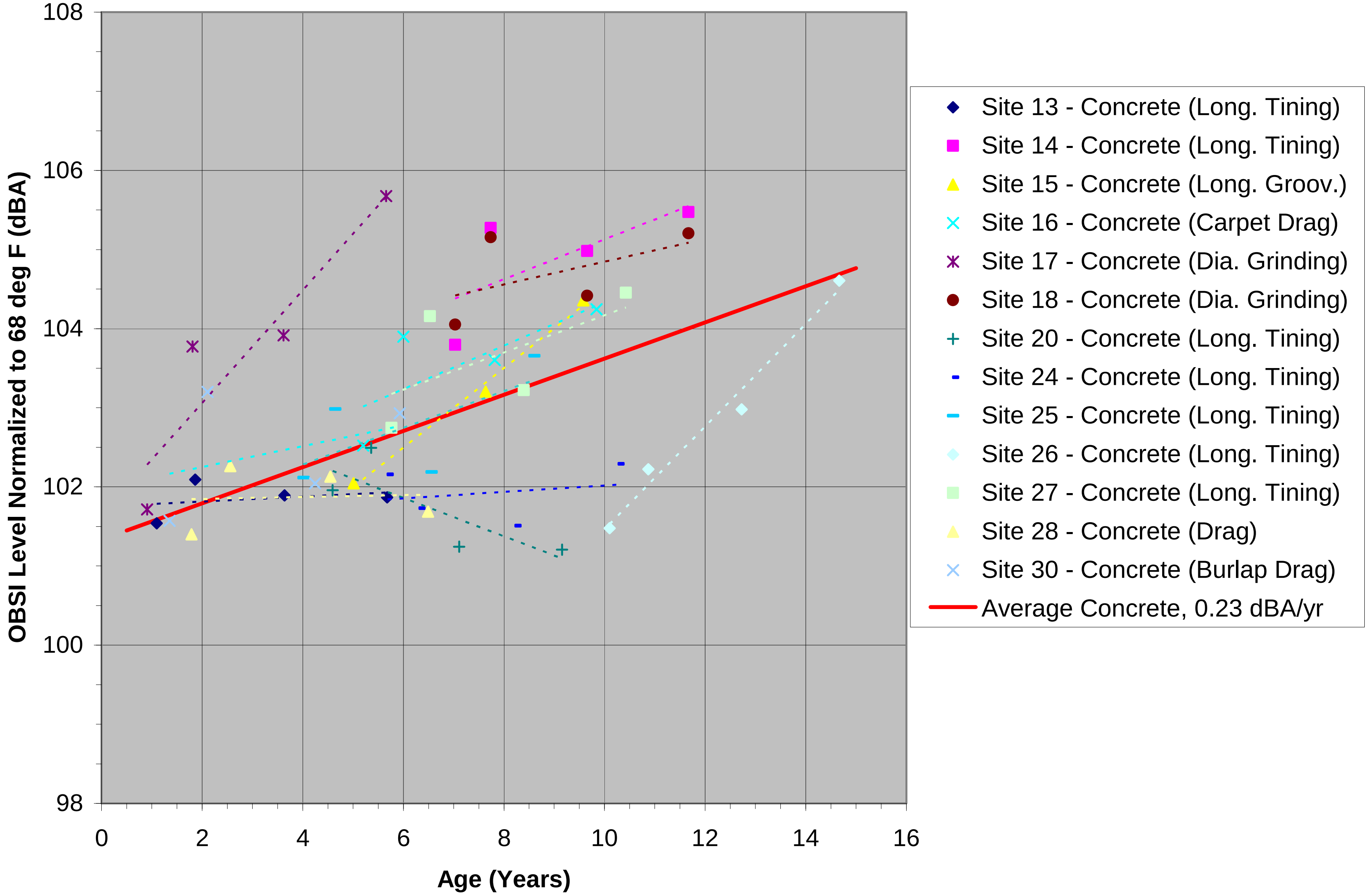

Figure 5. OBSI vs. age trend plots for the concrete sites.

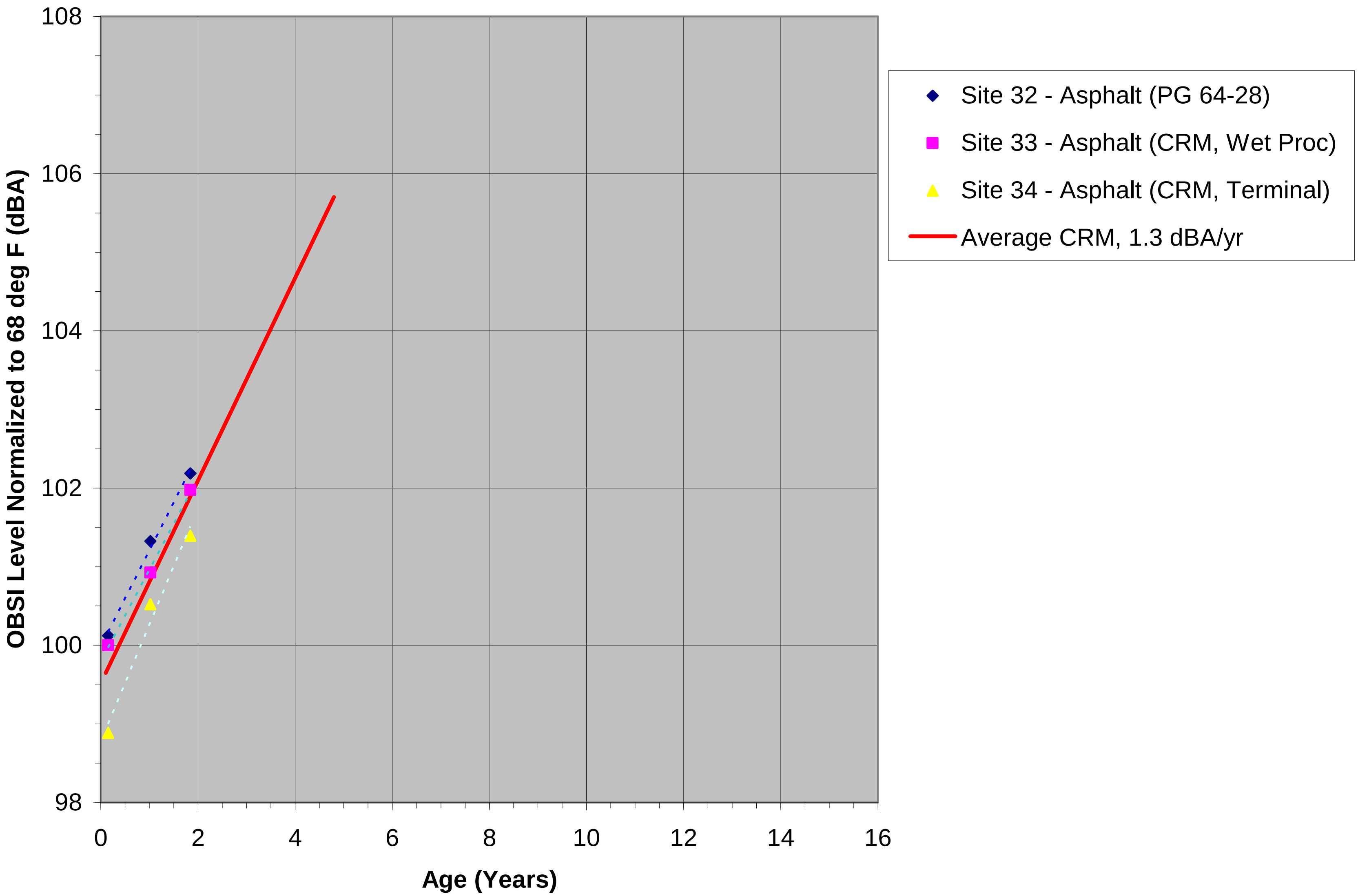

Figure 6. OBSI vs. age trend plots for the crumb rubber asphalt sites.

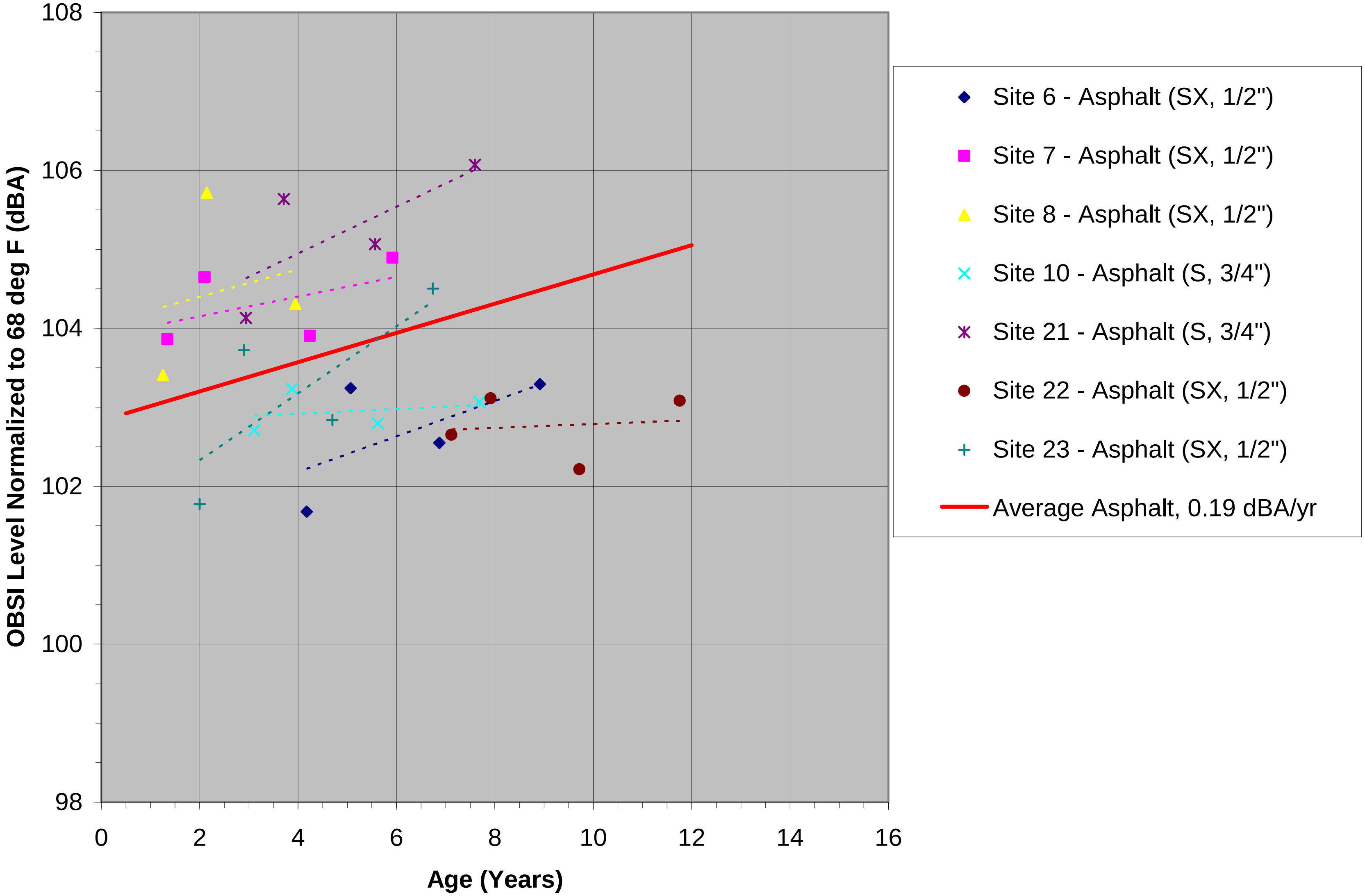

Figure 7. OBSI vs. age trend plots for the asphalt sites.

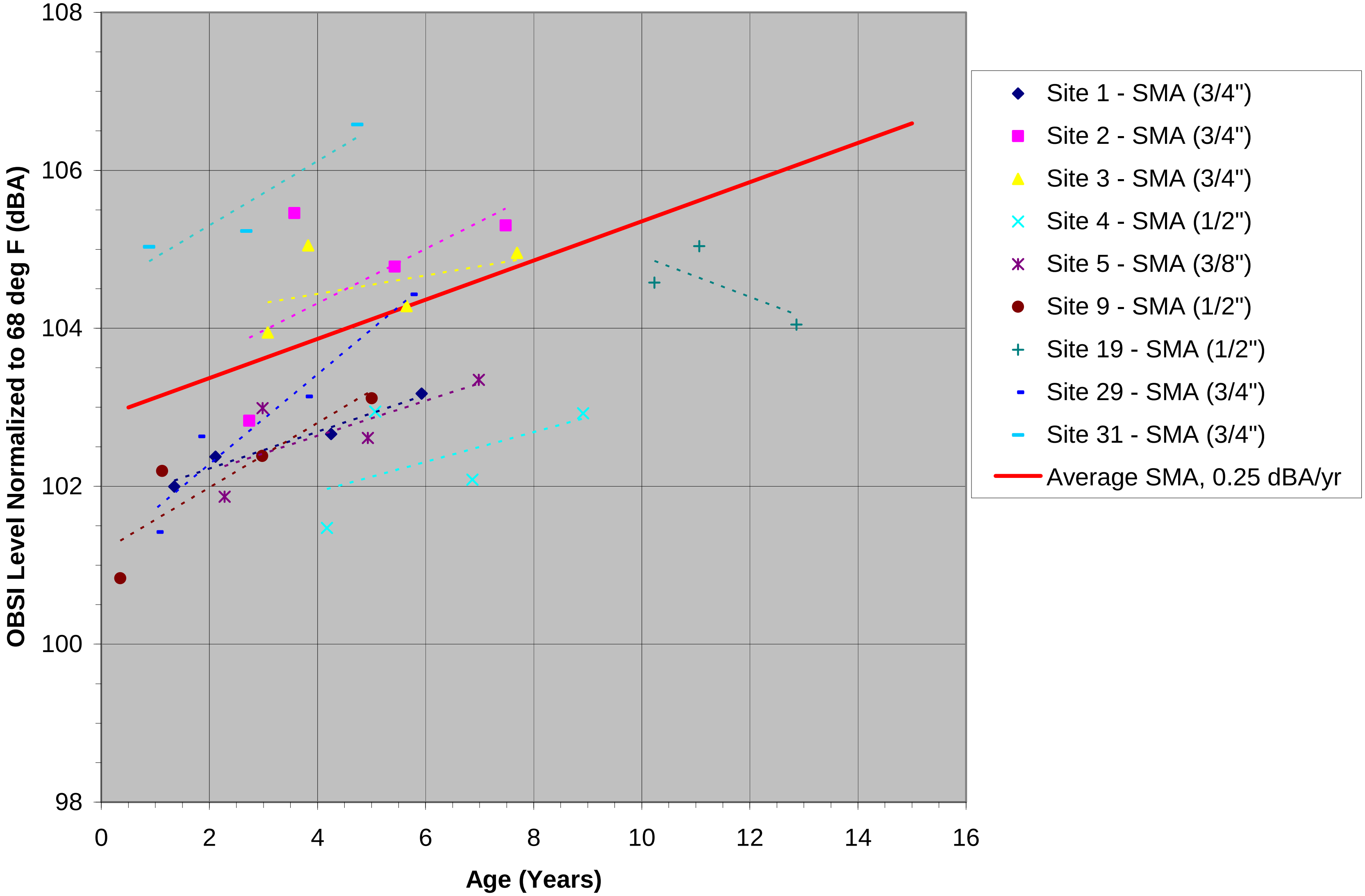

Figure 8. OBSI vs. age trend plots for the SMA sites.

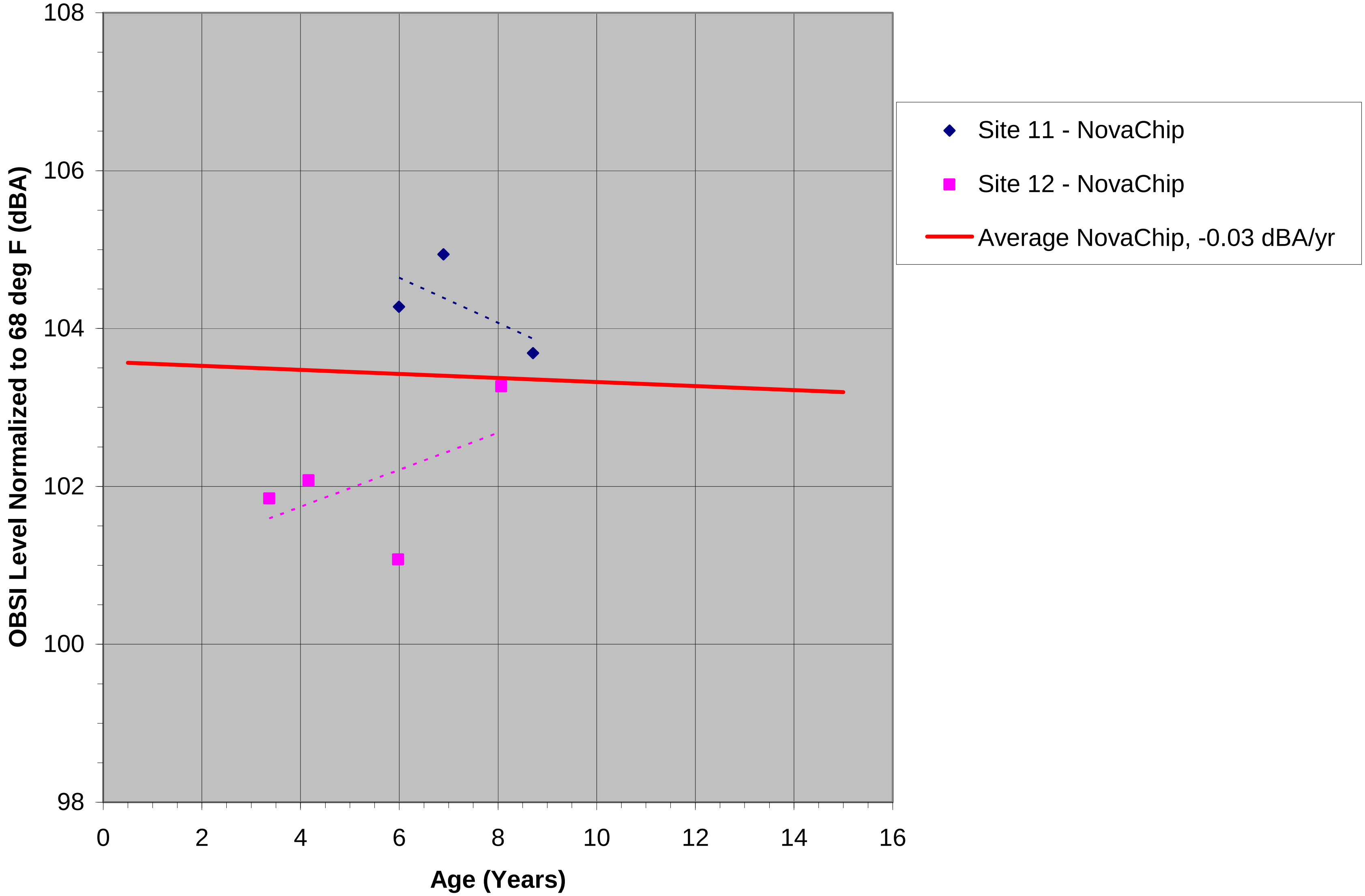

Figure 9. OBSI vs. age trend plots for the NovaChip sites.

Confidence Intervals and Extrapolation

Table 10 through Table 14 show the pavement durability factors for each pavement resulting from linear regression analyses, along with the r-squared and p-values statistics. The p-values (not the r-squared values) should be used to judge the significance of the pavement durability factor since the key metric is a slope. For example, from Table 13, the pavement durability factor for Site 1 (SMA 3/4") is 0.23 dBA/year with a p-value of 0.02. This means the probability of the factor arising by chance is only two percent (the p-value) or less, and the probability of the factor being real is 98 percent (one minus the p-value). This site is an example of a regression analysis resulting in a relatively low p-value for the pavement durability factor.

In addition to indicators such as r-squared and p-value, the linear regression analyses have associated confidence intervals. Figure 10 shows the regression results for Site 1 (SMA 3/4") and associated 90% confidence intervals. In Figure 10, the “regression bounds” indicate the range in which the regression line lies with 90 percent confidence. The “prediction bounds” show the range in which an OBSI level predicted from the linear model will lie with 90 percent confidence. Thus, the predicted OBSI level at the time of construction (year zero) is between 101.2 and 102.3 dBA with 90 percent confidence.

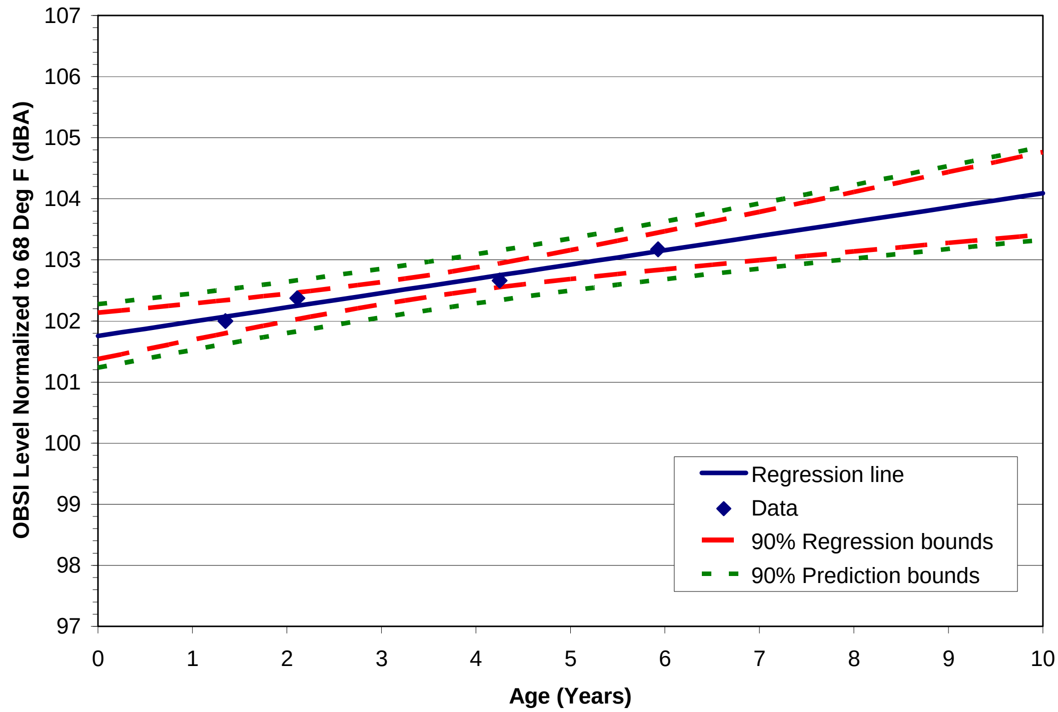

Figure 10. Linear regression analysis results for Site 1 (SMA 3/4") with the 90% confidence regression and prediction bounds.

Using the regression results to extrapolate and predict OBSI levels at times earlier or later than the measurement periods is not recommended. If done, it should be interpreted with an abundance of caution. This is because the prediction uncertainty increases with larger p-values. The uncertainty also increases outside the measurement periods. For example, Figure 11 shows the regression analysis and 90 percent confidence intervals for Site 16, PCC (carpet drag), with a p-value of 0.24 (Table 10). For this site, the predicted OBSI level at time of construction (year zero) is between 97.6 and 105.6 dBA with 90 percent confidence; an interval of 8 dB. Figure 12 shows a second example, Site 26, PCC (longitudinal tining), with the lowest p-value (0.01) and at which the first measurement period (2006) occurred when the pavement was already ten years old. Extrapolating back to year zero, the predicted OBSI level has a 90 percent confidence interval of 92.4 to 97.5 dBA, a range of 5.1 dB. Worth noting too is that these trends are likely not linear, as is assumed in this cursory analysis.

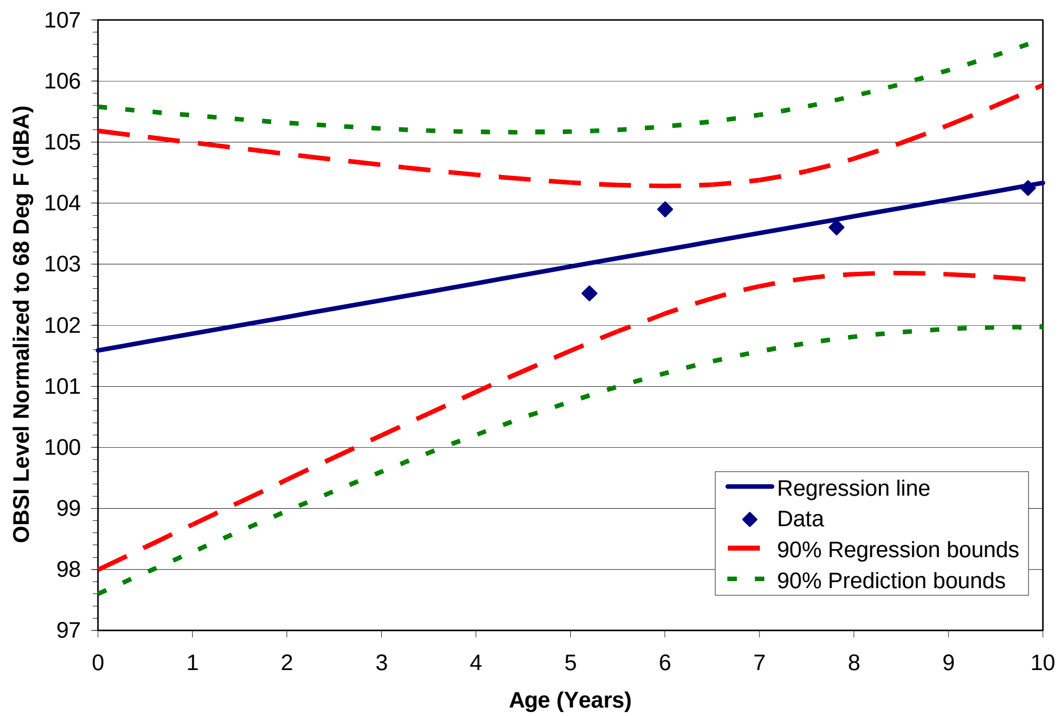

Figure 11. Linear regression analysis results for Site 16, PCC (carpet drag) with the 90% confidence regression and prediction bounds.

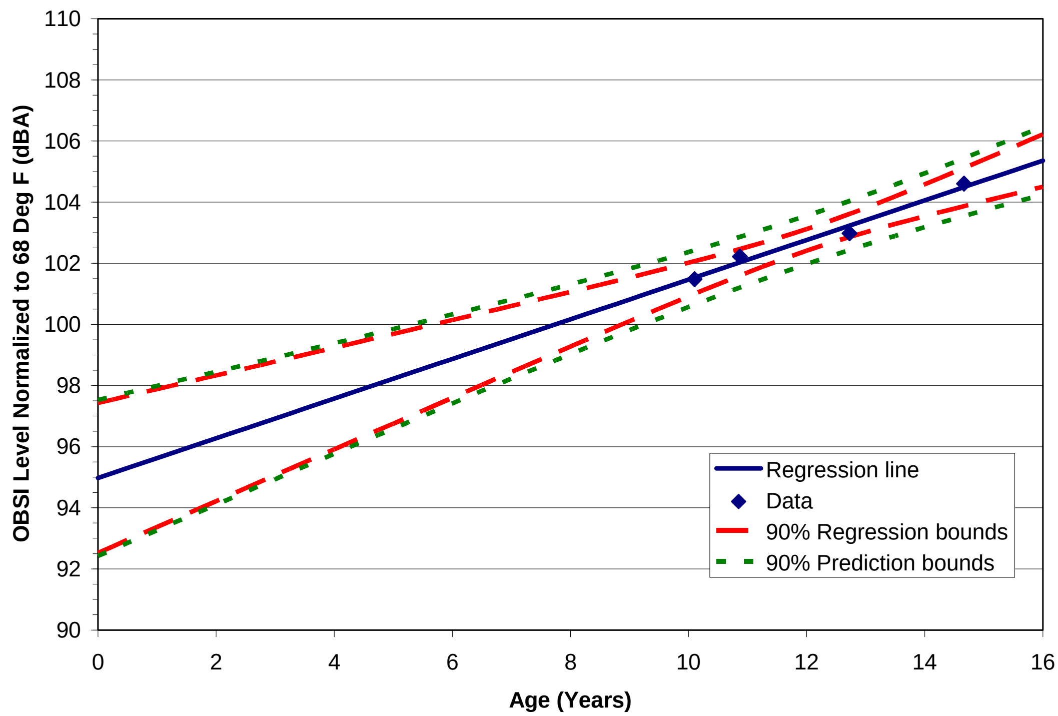

Figure 12. Linear regression analysis results for Site 26, PCC (longitudinal tining) with the 90% confidence regression and prediction bounds.

Frequency Trends with Age

By examining changes in the spectra of tire-pavement noise with age, it is possible to assess how the quality or perception of the noise changes with age. Figure 13 and Figure 14 show the average 1/3-octave band spectra for the three major pavement types (SMA, HMA, and PCC) from the first and last measurement periods, respectively. Thus, the data in the two figures are separated by five years of aging (2006 to 2011). From the figures, the average noise levels of the PCC pavement relative to SMA and HMA is consistently smaller at low frequencies and greater at high frequencies. Comparing the two asphalt pavements (SMA and HMA), in the first measurement period (Figure 13) the average SMA and HMA levels are nearly the same at low frequencies, while at higher frequencies, the SMA levels are less than HMA. However, after aging (Figure 14), the average high frequency levels of the SMA pavement have increased to nearly the same as HMA. For all three pavement types, the two bands with the greatest levels (800 to 1000 Hz) have all increased from the first to last measurement period.

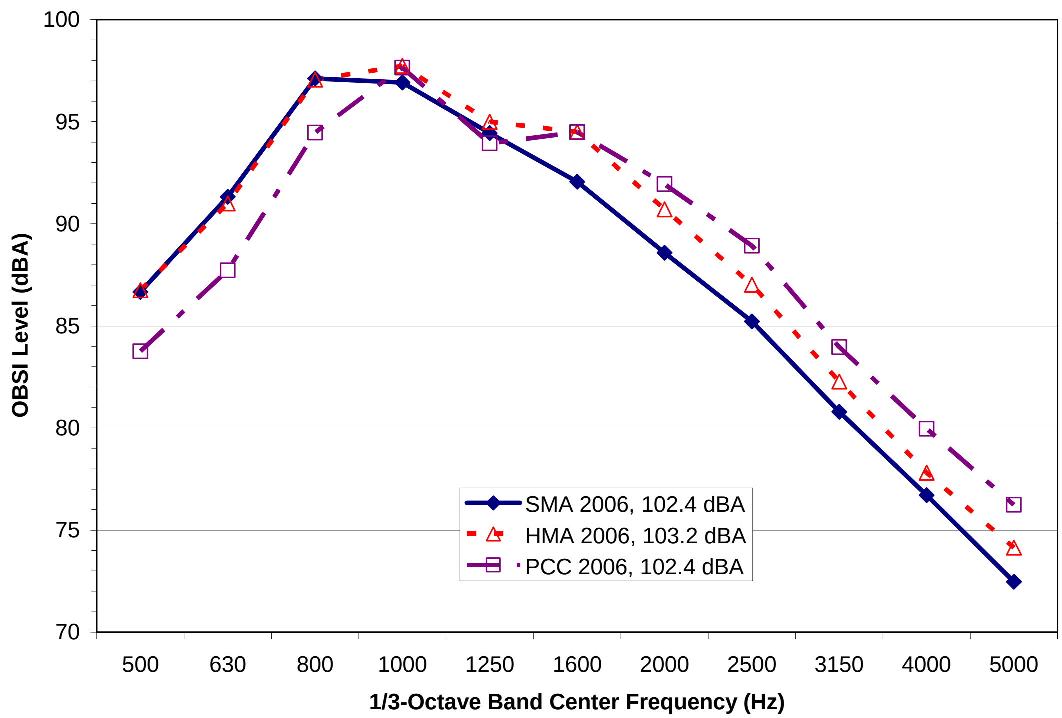

Figure 13. Average tire-pavement noise spectra for each pavement type from the 2006 measurement period.

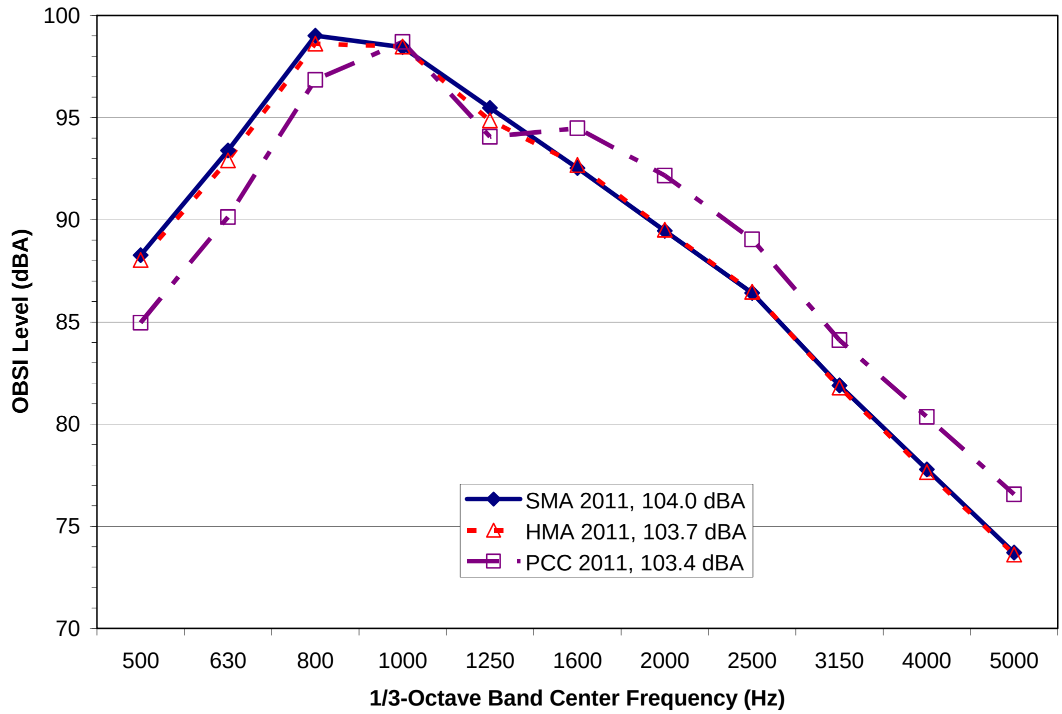

Figure 14. Average tire-pavement noise spectra for each pavement type from the 2011 measurement period.

Figure 15 shows the difference in average spectra for the two measurement periods for each pavement type. More precisely, the figure shows the average SMA spectrum shown in Figure 14 for the 2011 measurement period minus the average SMA spectrum shown in Figure 13 for the 2006 measurement period, and similarly for HMA and PCC. From Figure 15, on average, the noise level increase of SMA pavement occurred broadly, across the spectrum at both low and high frequencies. The HMA pavement increases with age primarily at low frequencies and (on average) the high frequency bands reduced in level. Finally, the noise level of PCC pavements increased at low frequency and remained relatively constant at high frequencies.

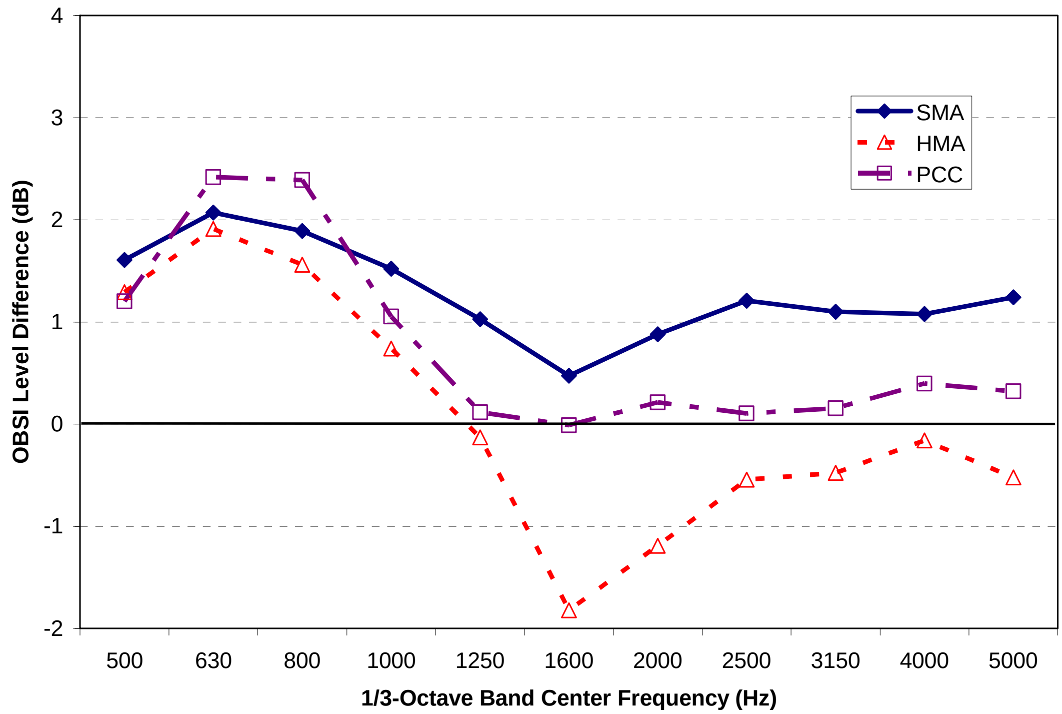

Figure 15. Difference of the 2011 and 2006 average spectral levels (positive indicates level increase over time).

From the perspective of sound quality and human perception, the tire-pavement noise from PCC pavements will have a slightly higher pitch than the asphalt pavements. The SMA pavements may initially sound quieter than the HMA pavement, with less high frequency content. But after aging, the two asphalt pavements sound nearly the same. It should be noted, however, that this assessment is based on average spectra from the first and last measurement periods. Any individual test section may behave slightly different. Also, noise from jointed PCC pavement may have transient characteristics (for example, joint slap noise). This and the noise resulting from pavement distresses such as cracking and faulting will not be adequately characterized through a frequency analysis alone.

Relationship between Environmental Tests

In 2009 and 2011, statistical pass-by and time-averaged testing was conducted with additional microphone positions. This is in support of two methods that have recently been standardized by the AASHTO as TP 98 and 99 for SIP and CTIM, respectively. Both of these test methods describe additional microphone positions beyond the conventional 50 ft. offset / 5 ft. height that had been used since the beginning of this study. So that CDOT is prepared for possible adoption of these new methods, two additional microphone positions were used on most of the sites, namely a 50 ft. horizontal offset with a 12 ft. height, and a 25 ft. horizontal offset with a 4 ft. height. Table 15 and Table 17 show the difference in sound level at these microphone positions relative to CDOT's standard 50×5 position.

As can be seen from these tables, the levels measured at the new "high" microphone position at the 50 ft. offset are approximately 0.5 to 1.6 dBA greater than the existing standard height of 5 ft. Furthermore, the closer microphone at 25 ft. measures 6.7 to 7.0 dBA greater for the SPB measurements, and 3.9 to 4.2 dBA greater for the time-averaged measurements, with the difference largely attributed to the idealized source type (point source with SPB versus line source with TA).

Table 15. Difference in A-weighted sound pressure level (dBA) between microphone positions from SPB measurements.

	2009 SPL Differences (dBA)				**2011 SPL Differences (dBA)**			
	(25×4) – (50×5)		**(50×12) – (50×5)**		**(25×4) – (50×5)**		**(50×12) – (50×5)**	
Site	**Car**	**Hvy. Trk.**	**Car**	**Hvy. Trk.**	**Car**	**Hvy. Trk.**	**Car**	**Hvy. Trk.**
4	7.9	8.2			7.4	7.2		
6	6.2	6.1	0.7	0.4	6.1	5.9	0.2	0.3
10	6.6	6.5	1.0	1.2	7.5	7.3	1.6	1.6
19	6.4	6.7						
20	7.7	7.8	1.1	1.8	6.4	6.6	0.0	0.5
22	6.5	6.6	0.3	0.6	6.2		0.2	
Avg	6.9	7.0	0.8	1.0	6.7	6.7	0.5	0.8

Table 16. Difference in A-weighted sound pressure level (dBA) between microphone positions from TA measurements.

Site	2009 SPL Differences (dBA)		2011 SPL Differences (SPL)	
	(25×4) – (50×5)	**(50×12) – (50×5)**	**(25×4) – (50×5)**	**(50×12) – (50×5)**
1			3.4	1.1
2		-0.1		0.3
7	3.6	0.7	3.4	0.9
9	4.1		3.8	
12	4.9	2.2	4.5	1.6
13	3.5	0.8	3.7	0.5
16	4.7	2.0		5.4
17	5.0	1.4	5.2	2.1
21	3.9	0.7	3.5	0.5
30	3.7	1.6	3.6	1.6
Avg	4.2	1.2	3.9	1.6

Car versus Heavy Truck Noise Levels

The SPB measurement process analyzes sound levels as a function of vehicle classification: car and heavy truck. The car classification is technically a "light vehicle" classification and encompasses 2-axle, 4-wheel vehicles including cars and pickup trucks. Because of the separation in classification, SPB results can be used to study the difference in sound levels from cars (light vehicles) versus heavy trucks. These differences for each year and microphone position are shown in Table 17. The difference is fairly consistent year-to-year and between microphone locations. On average, truck sound levels are 8.0 dBA greater than car sound levels at 25 to 50 feet to the wayside.

Table 17. Difference between light vehicle (car) and heavy truck A-weighted sound levels (dBA) from SPB measurements.

Site	2006 Levels (dBA)	2007 Levels (dBA)	2009 Levels (dBA)			2011 Levels (dBA)		
	50×5	50×5	50×5	25×4	50×12	50×5	25×4	50×12
4	6.7	5.5	6.5	6.8		7.5	7.3	
6	8.6	7.2	8.4	8.3	8.1	7.5	7.3	7.6
7[1]	9.0	8.9						
10	8.9		8.2	8.1	8.4	9.5	9.3	9.5
19[2]	7.0	5.7	6.5	6.8				
20	9.0		8.7	8.8	9.4	8.7	8.8	9.2
22[3]	7.4	7.8	7.4	7.5	7.7			
Avg,	8.1	7.0	7.6	7.7	8.4	8.3	8.2	8.8

Notes: [1] SPB conducted in 2006 and 2007. TA conducted in 2009 and 2011.
[2] SPB not conducted in 2011 due to site resurfacing.
[3] Not enough truck traffic in 2011 for valid results.

Environmental Wayside (SPBI+) Results

In the vicinity of Site 21, there was an opportunity to conduct SPBI+ testing in 2009 and 2011. At this location, three 5-ft. high microphone positions were used with horizontal offsets of 50, 100, and 200 ft. Table 18 shows the results of these tests for 2011, with calculated time-averaged sound pressure levels and the differences between each position.

Table 18. 2011 SPB+ test summary A-weighted SPL (dB ref 20 µPa).

Mic Position (ft) Distance × Height	**SPL (dBA)**
50×5	74.1
100 × 5	70.4
200 × 5	66.1
Differences in Level	**SPL Difference**
(100×5) – (50×5)	-3.7
(200×5) – (100×5)	-4.3
(200×5) – (50×5)	-7.9

Figure 16 illustrates calculated SPBI+ levels as a function of distance, with the level at 25 ft estimated based on the level differences for Site 21 reported in Table 17. From this figure, an average level change of -3.8 dBA per doubling of distance (DD) is calculated. This value is to be expected considering that a theoretical point source (e.g., an idealized single vehicle pass by) would have a change of -6 dBA/DD and a theoretical line source (e.g., an idealized traffic lane with dense traffic) would have a change of -3 dBA/DD. The traffic flow on this section during measurement was somewhere in between these theoretical extremes, with approximately 1150 vehicles per hour (total for 4 lanes, including both directions) and an average speed of 67 mph. Figure 17 plots the SPBI+ level as a function of distance for the results from years 2009 and 2011. The plot illustrates the consistency of results between 2009 and 2011. When the data from both years is considered, the average level change is -4.0 dBA/DD.

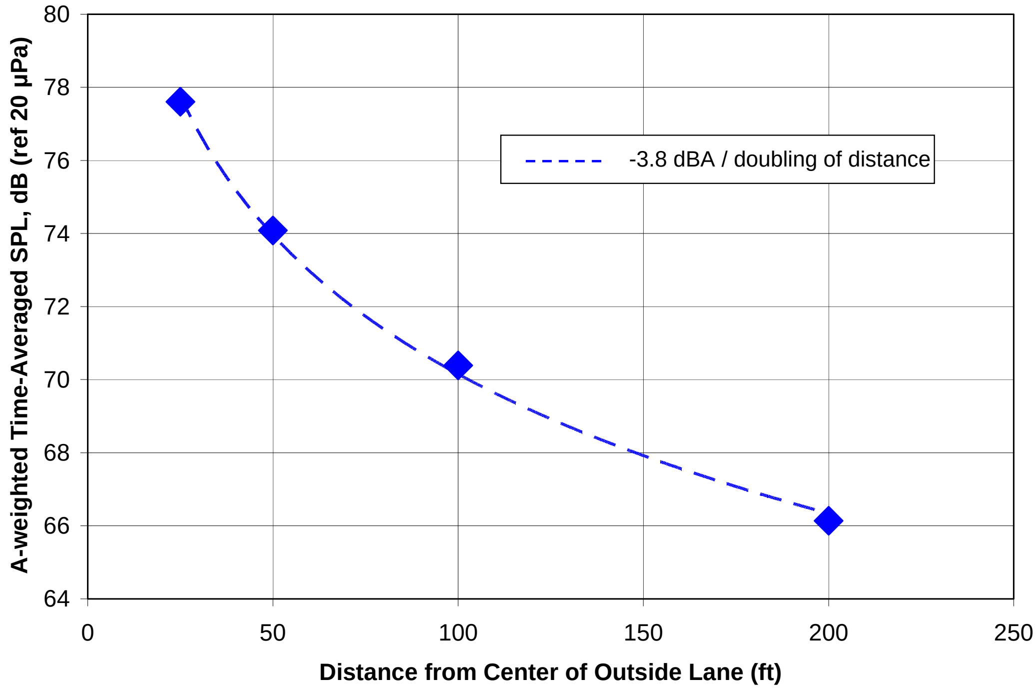

Figure 16. 2011 Relationship of time-averaged SPL and distance for SPB+ site.

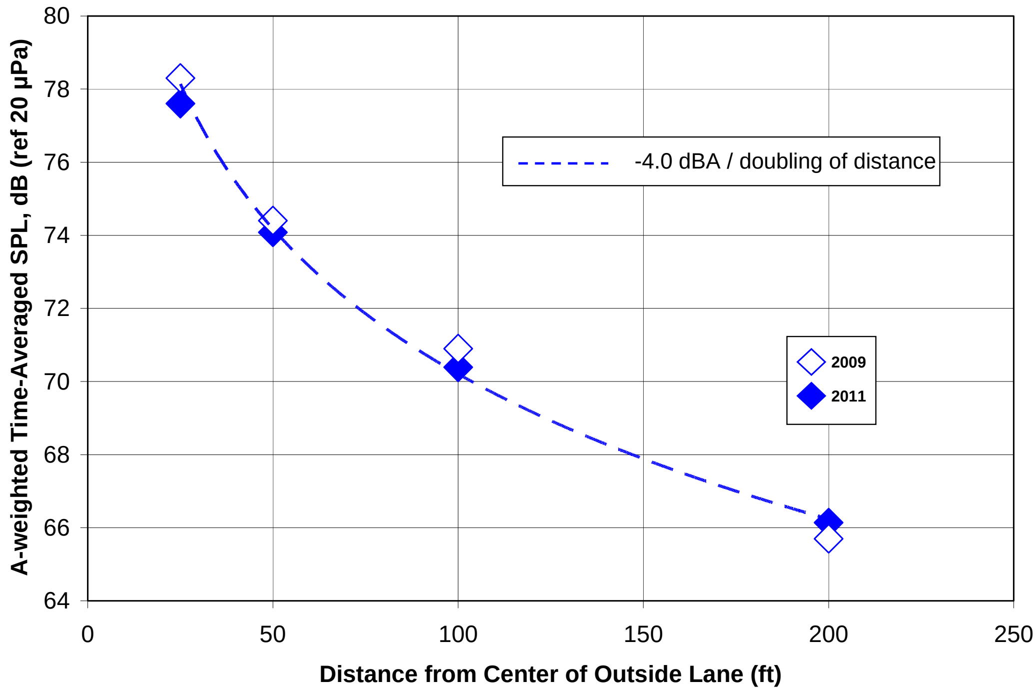

Figure 17. Relationship of time-averaged SPL and distance for results from 2009 and 2011.

Frequency Trends with Distance

Frequency analysis of the SPB+ data collected at Site 21 can be used to assess how the perception of the traffic noise may change as a function of distance from the roadway. Figure 18 shows the third-octave spectra of a sample of the traffic noise at the three microphones from the 2011 measurement period. Some observations from the spectra:

1. The spectra at each microphone have the same general shape.
2. The 1000 Hz band has the highest level for all three microphone distances.
3. The traffic noise is predominantly in the range covered by the 250 to 4000 Hz third-octave bands. The levels in bands below 250 and above 4000 Hz are more than 10 dB lower than the maximum level of the 1000 Hz band.
4. Some of the high frequency bands (5000, 6300, and 10000 Hz) have levels elevated relative to the neighboring bands. Through data inspection and listening, this is attributed to insect chirping noise.

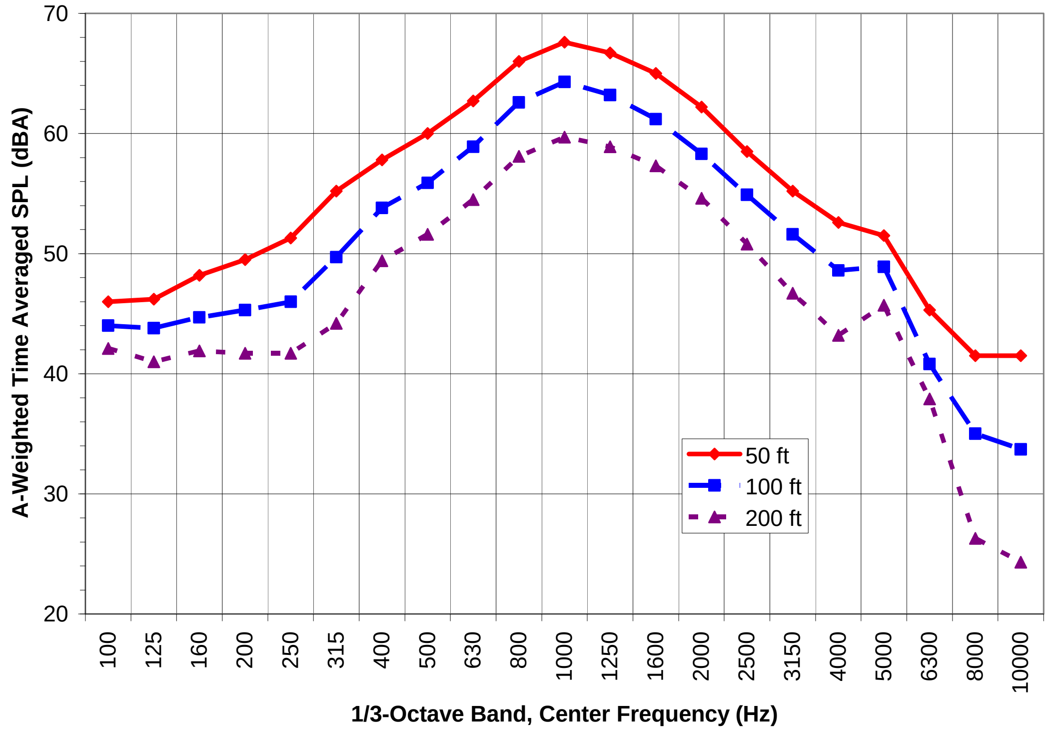

Figure 18. Traffic noise spectra for the three microphone positions at Site 21. The band levels are A-weighted and based on a time average over a representative 10 minute interval.

Figure 19 shows the traffic noise spectra with some of the high frequency band levels estimated with insect noise removed. Finally, Figure 20 shows a plot of the difference in traffic noise spectra from one microphone to the next.

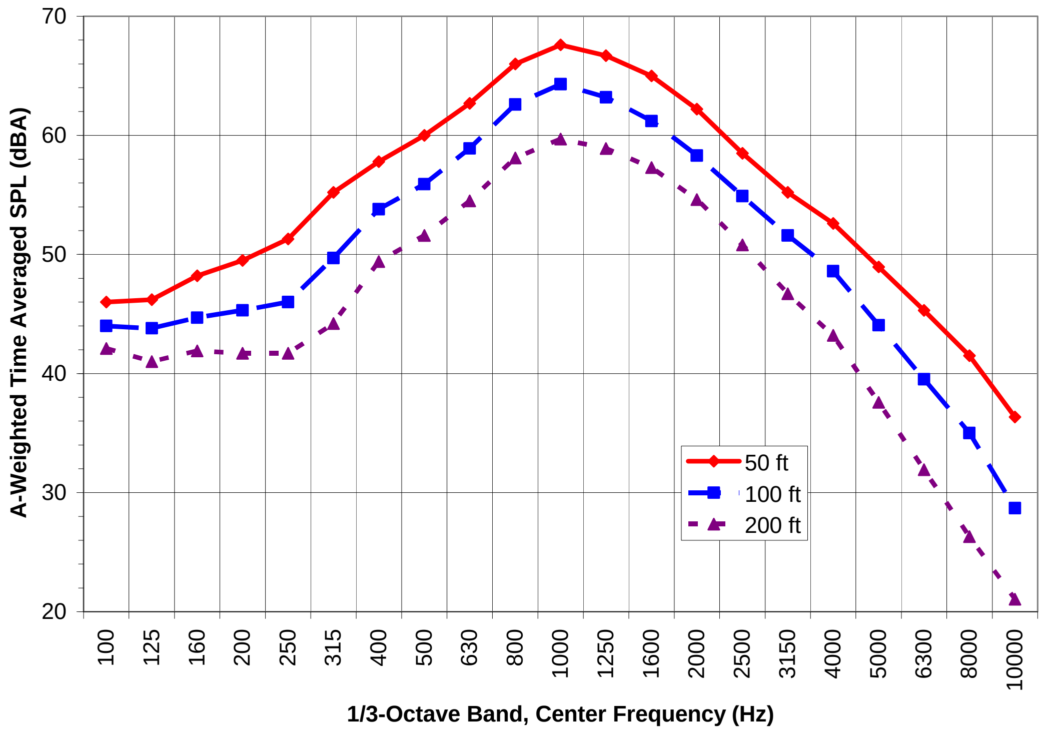

Figure 19. Traffic noise spectra from Figure 18 with the levels of some of the high frequency bands adjusted to remove insect noise

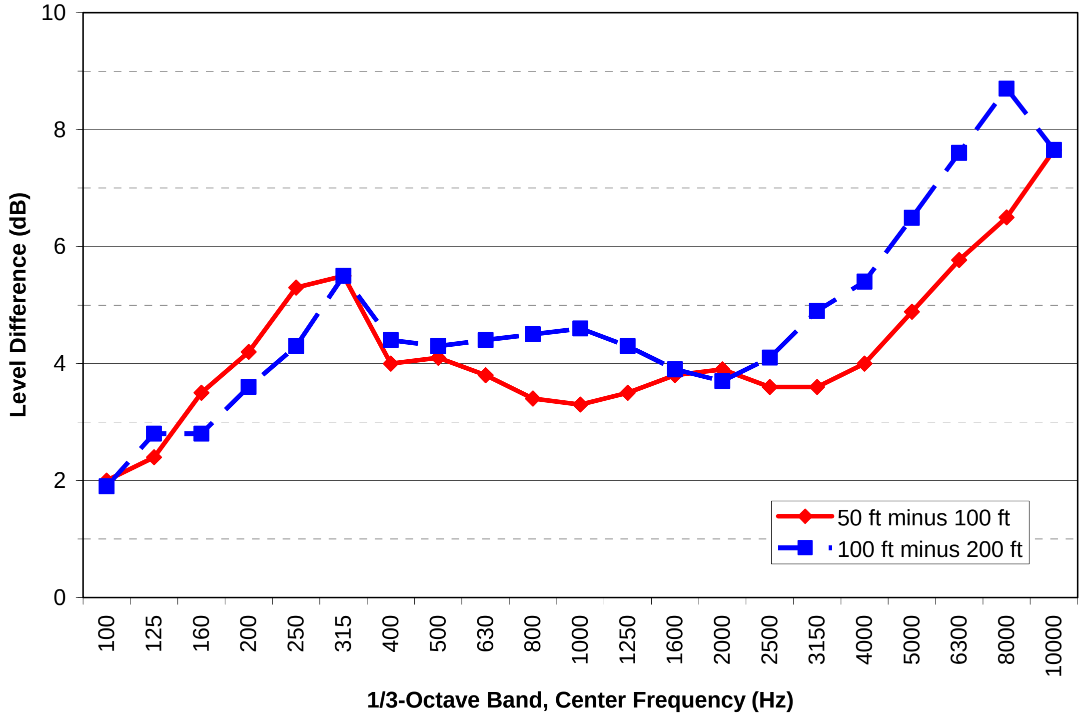

Figure 20. Traffic noise level differences between microphones (with insect noise removed).

Examining Figure 20, in the frequency range where the traffic noise is dominant (250 to 4000 Hz), the sound level reduction from one microphone to the next is 4 ±1 dB. This is consistent with the reduction in the overall level with doubling of distance shown in Figure 16 and Figure 17. Therefore, the dominant traffic noise sound will be perceived as getting quieter with distance.

At frequencies above 4000 Hz, the sound level reduces at a rate greater than 4 dB, with doubling of distance attenuation of up to 8 dB at 10000 Hz. This is expected because the absorption of sound by the air is greater at higher frequencies. Noise in this high frequency range is sometimes described as the "sh" sound at the end of the word "swish". Therefore, as perceived by human hearing, the traffic noise loses its "swishing" characteristic as distance from the roadway increases. At distances of 200 ft and beyond, the high frequency noise levels are reduced enough so that the traffic noise level is below that of the insect chirping noises.

CONCLUSIONS AND RECOMMENDATIONS

The following sections highlight some of the key outcomes of this research.

Which Pavement Is Quietest?

From the measurement results, it cannot be concluded that a single pavement type is quietest among all of the alternatives used by CDOT. Each pavement type has a demonstrated range of noise levels, and these ranges largely overlap (see Figure 1 and Figure 4.) One notable anomaly are the asphalt pavements along US 34 (Sites 32, 33, and 34), which were constructed as part of the crumb-rubber asphalt experiment. While these sections were measured to be among the quieter pavements, they were also newly constructed, and have since construction had the largest rate of change in acoustic performance (dBA/year). In the most current set of measurements, these pavements are now in the same range as the other pavements in this study.

Acoustic Durability

Table 19 summarizes the average acoustic durability of the three major pavement types. As can be seen, these values are approximately the same, and thus no single pavement type can be singled out as having an advantage in this regard. That said, it should be noted that these calculations are based on a change in noise over time, and do not include the effects of accumulated traffic and its associated wear.

Table 19. Average acoustic durability for various pavement types.

Pavement Type	Average Acoustic Durability (dBA/yr)
Concrete	0.23
Dense-graded HMA	0.19
SMA	0.25

Sound Propagation

At Site 21, a special study was conducted to evaluate the change in sound level as a function of distance from the pavement (source). On this site, with a relatively continuous traffic stream, the sound level was found to decrease 4.0 dBA per doubling of distance from the outside lane. This calculation was based on distances ranging from 25 to 200 feet from the center of the outside lane of pavement, and is in the range that is to be expected based on the principles of acoustics.

Correlation between Source and Wayside Measurements

Based on the data collected in this study, there is good correlation between tire-pavement noise levels measured at the source (using the OBSI method) and sound pressure levels at the wayside. The wayside sound level measured at 50 ft is offset from the OBSI level by an average of 28.2 dBA:

Wayside Average Sound Pressure Level at 50 ft (dBA) = Overall OBSI level (dBA) – 28.2

An important consideration from this finding is that OBSI levels can be used as a reasonable predictor for roadside measurements. This finding (including the calculated offset) has been confirmed by independent research conducted under NCHRP 1-44.

Car versus Heavy Truck Noise Levels

Based on the data collected using the SPB measurement method, average truck sound levels are 8.0 dBA greater than car sound levels at 25 to 50 feet to the wayside. To facilitate a lay perspective on this difference, this difference in level can be viewed as an average truck being approximately as loud as 6 to 7 cars.

Wayside Microphone Positions

Based on the data collected using the statistical pass-by and time-averaged measurement methods at various microphone positions, good correlation is demonstrated between the CDOT wayside microphone position (50×5 ft) and the now standardized AASHTO wayside positions (25×4 ft and 50×12 ft). When compared to the 50×12 ft microphone position, the CDOT microphone position measures 0.5 to 1.6 dBA greater. Sound levels at the AASHTO close-in microphone position (25×4 ft) are significantly greater than the CDOT microphone position, with the level offset dependent on the traffic stream. For relatively continuous traffic, the close-in microphone position is about 4.0 dBA greater. For traffic with more sparse traffic, the close-in microphone is about 6.8 dBA greater. This is to be expected given the difference level differences expected between a point and a line source.

TNM

The TNM application continues to evolve, with the latest version scheduled for beta testing in 2012, and plans for the development and delivery of newer versions in the coming years. A Pavements Effects Implementation (PEI) study has also been sponsored in recent years, conducted by the Volpe Center. As a result of the PEI study, it appears that there will be the potential to include specific pavement types within the TNM prediction in the future, so as long as adequate measures are taken to ensure the accuracy and relevance of the data that is used as the basis of the prediction. While it is beyond the scope of this project to develop the requisite corrections, the data that was collected has been entered into a national database that is being used by the PEI researchers. As a result, CDOT will be well represented in the final recommendations that emerge from that study.

Future Research

As a result of this study, various research activities are possible. The most relevant and fruitful will include a more detailed investigation of specific variants of asphalt mixtures and concrete textures that result in quieter surfaces. Before embarking on this work, CDOT should build off of work that is already underway. Some of this work is already underway by CDOT, and others are the result of national-level efforts. Some of these include:

- CDOT Study No. 21.80: Assessment of Alternate PCCP Texturing Methodologies in Colorado
- Pooled Fund TPF-5(158) (CDOT Study 34.22): FHWA Traffic Noise Model: Version 3.0 Software Development
- Pooled Fund TPF-5(135): Tire-Pavement Noise Research Consortium
- Pooled Fund TPF-5(139): PCC Surface Characteristics: Tire -Pavement Noise Program Part 3 - Innovative Solutions /Current Practices

Overall Conclusions

This study is part of a culmination of nearly a decade of research in traffic and tire-pavement noise, sponsored by the Colorado Department of Transportation. Over the years, a lot of advancements have been made in the technology necessary to design, construct, maintain, and measure quieter pavements. With the data collected under this study, it can be concluded that tire-pavement noise can be considered without necessarily affecting the other tenets of prudent pavement engineering; namely, safety, durability, and cost-effectiveness, among others.

The use of quieter pavements can become a routine aspect of the CDOT's pavement specifications. This can be accomplished by exploring the common aspects of those pavements that have demonstrated the best acoustical durability. For example, it appears that asphalt and SMA mixtures using smaller nominal maximum aggregate sizes can provide improved acoustical performance, as can concrete textures with fine textures including drag surfaces and diamond grinding.

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APPENDIX A – PHOTOGRAPHS

Figure A.1. OBSI measurement bracket configuration.

Figure A.2. Test tires – ASTM F 2493 SRTT and Goodyear Aquatred III.

Figure A.3. Wayside measurement configuration.

APPENDIX B – DETAILED SITE DATA

Site: 01
General Information

Highway: US Highway 83, Northbound
Location: Between CR-14 & Hess Rd., Parker (80134)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 39.4883 / 104.7591 / 5960

Nominal Surface: SMA (3/4") **Construction Accepted:** 2004

OBSI?: Yes **Pass-by?:** Yes
Total Section Length: 1558 ft.
Distance from Begin to Wayside Microphone: n/a

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 01
Time-Averaged Wayside Test Information

Sampling Periods: 1

Sample Period 1 – 6 Blocks @ 15 min ea. = 90 min. (10:30 am to 12:00 pm MDT, 6/9/11)

Traffic Volumes and Speeds during Sample Period

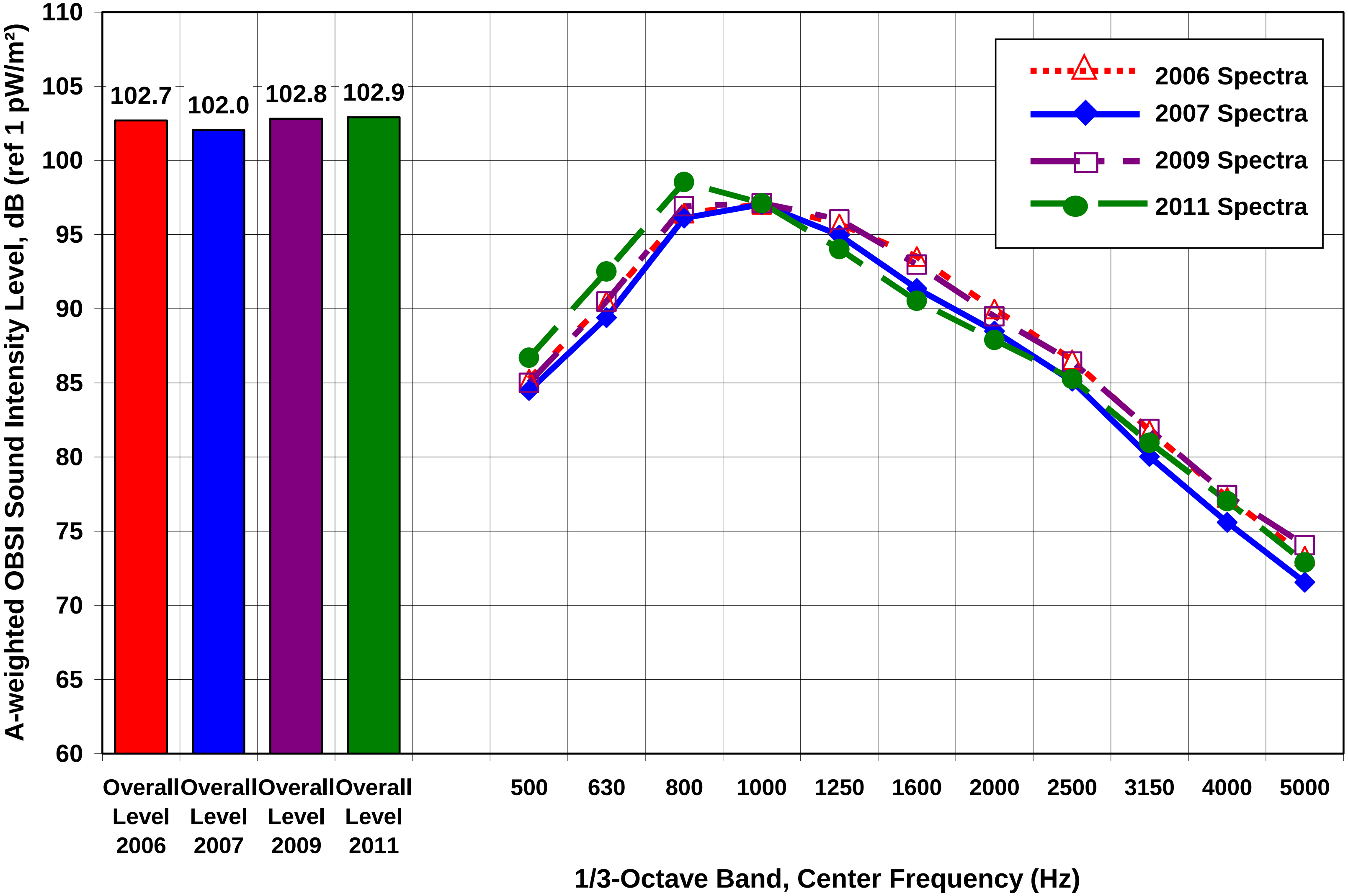
	NB Lane 3 (Outside)	NB Lane 2	NB Lane 1 (Inside)	SB Lane 1 (Inside)	SB Lane 2	SB Lane 3 (Outside)
Distance from Mic (ft.)*	50	62	74	121	133	145
Average Speed (mph)		55			56	
Automobile	388	526	652	456	447	475
Heavy Truck	9	11	4	4	9	11
Medium Truck	8	17	3	13	14	11
Bus	0	0	2	0	0	0
Motorcycle	1	2	3	2	2	4
Auto + 1-Axle Trlr.	6	2	4	6	2	4
Auto + 2-Axle Trlr.	2	4	4	2	0	3
M. Trk. + 1-Axle Trlr.	0	0	1	1	1	0
M. Trk. + 2-Axle Trlr.	0	1	1	2	0	2

** Note: for 50 ft mic positions*

A-Weighted Time Averaged Sound Pressure Levels during Sample Period (dB ref 20 µPa)

Mic Position (ft) Distance × Height	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6	Average
50×5	71.2	71.2	71.1	71.4	70.6	71.1	**71.1**
25×4	74.7	74.5	74.4	74.7	74.2	74.6	**74.5**
50×12	72.4	72.2	72.2	72.4	72.0	72.2	**72.2**

Site: 01
OBSI (SRTT) Test Information



Site: 02

General Information

Highway: Interstate 70, Eastbound

Location: Between Evergreen Pkwy. & CR-65, Golden (80439)

Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 39.7084 / 105.3511 / 7490

Nominal Surface: SMA (3/4") **Construction Accepted:** 1/2004

OBSI?: Yes **Pass-by?:** Yes

Total Section Length: 5308 ft.

Distance from Begin to Wayside Microphone: 4116 ft.

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 02
Time-Averaged Wayside Test Information

Sampling Periods: 1

Sample Period 1 – 6 Blocks @ 15 min ea. = 90 min. (1:40 pm to 3:10 pm MDT, 6/22/11)

Traffic Volumes and Speeds during Sample Period

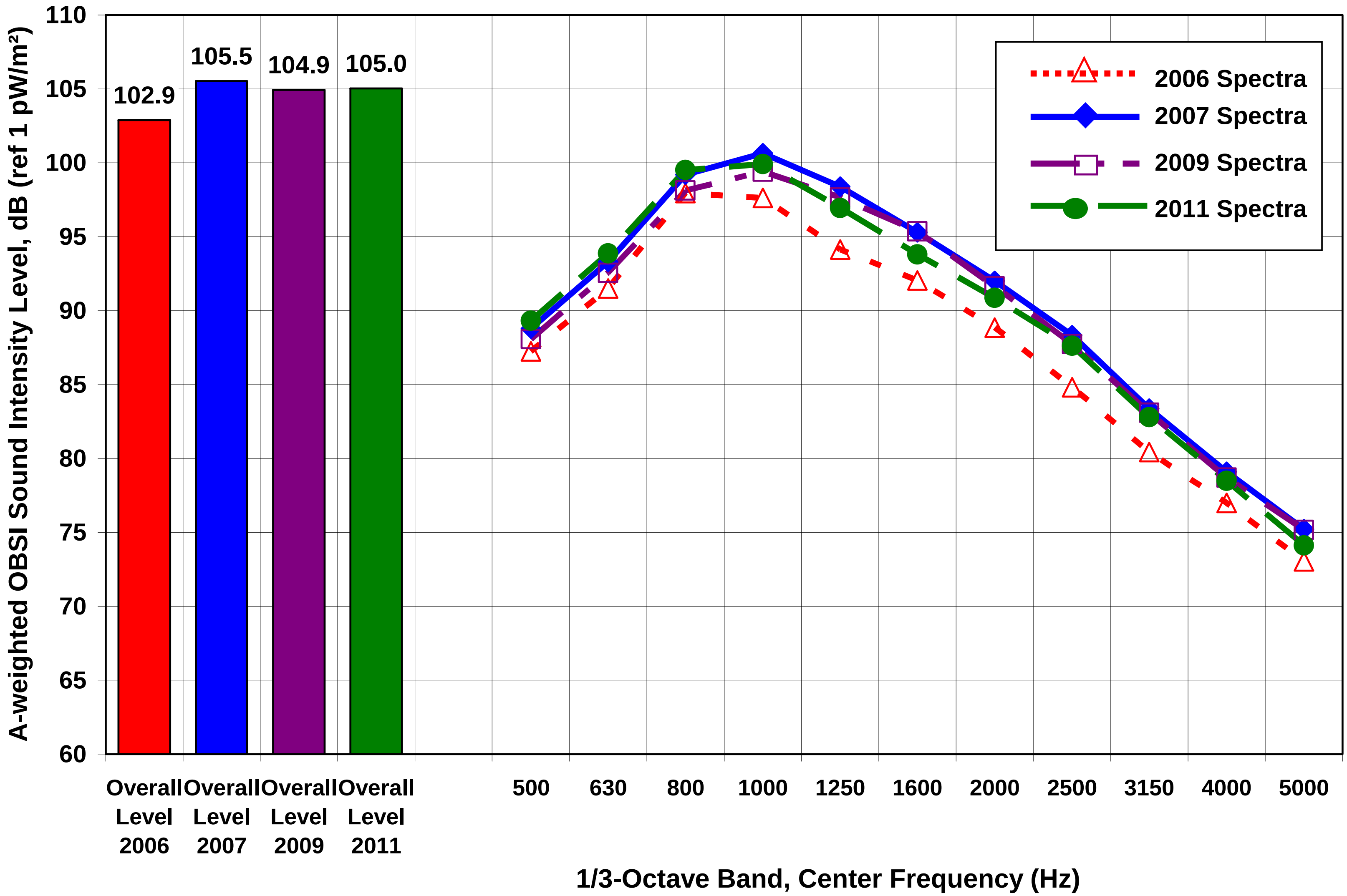
	EB Lane 3 (Outside)	**EB Lane 2**	**EB Lane 1 (Inside)**	**WB Lane 1 (Inside)**	**WB Lane 2**	**WB Lane 3 (Outside)**
Distance from Mic (ft.)*	50	62	74	131	143	155
Average Speed (mph)		67			67	
Automobile	369	938	428	555	1009	356
Heavy Truck	144	39	4	1	33	75
Medium Truck	95	21	4	1	17	21
Bus	4	1	1	0	0	1
Motorcycle	6	25	6	3	6	13
Auto + 1-Axle Trlr.	13	11	1	1	15	14
Auto + 2-Axle Trlr.	15	14	0	2	13	12
M. Trk. + 1-Axle Trlr.	2	0	0	0	1	1
M. Trk. + 2-Axle Trlr.	10	3	1	0	5	9

** Note: for 50 ft mic positions*

A-Weighted Time Averaged Sound Pressure Levels during Sample Period (dB ref 20 μPa)

Mic Position (ft) Distance × Height	**Block 1**	**Block 2**	**Block 3**	**Block 4**	**Block 5**	**Block 6**	**Average**
50×5	77.8	78.7	77.8	78.0	78.8	78.3	**78.2**
50×12	78.1	79.0	78.2	78.3	79.2	78.6	**78.6**

Site: 02
OBSI (SRTT) Test Information

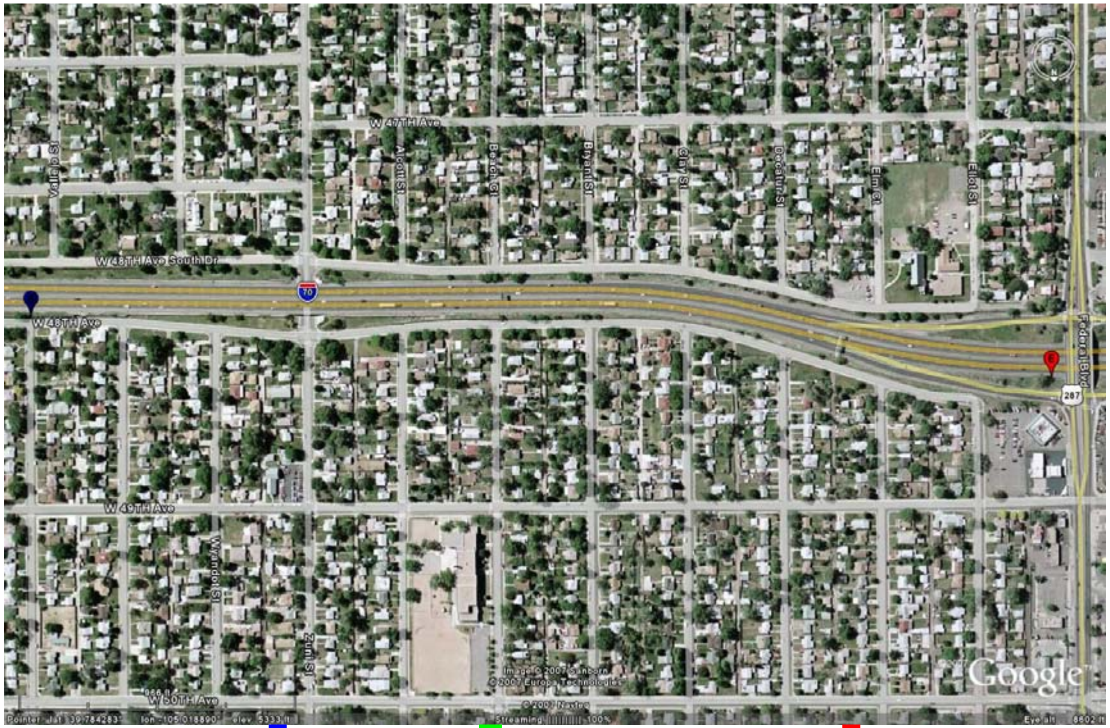


Site: 03
General Information

Highway: Interstate 70, Westbound
Location: Between Federal Blvd. & Pecos St., Denver (80221)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 39.7841 / 105.0186 / 5330

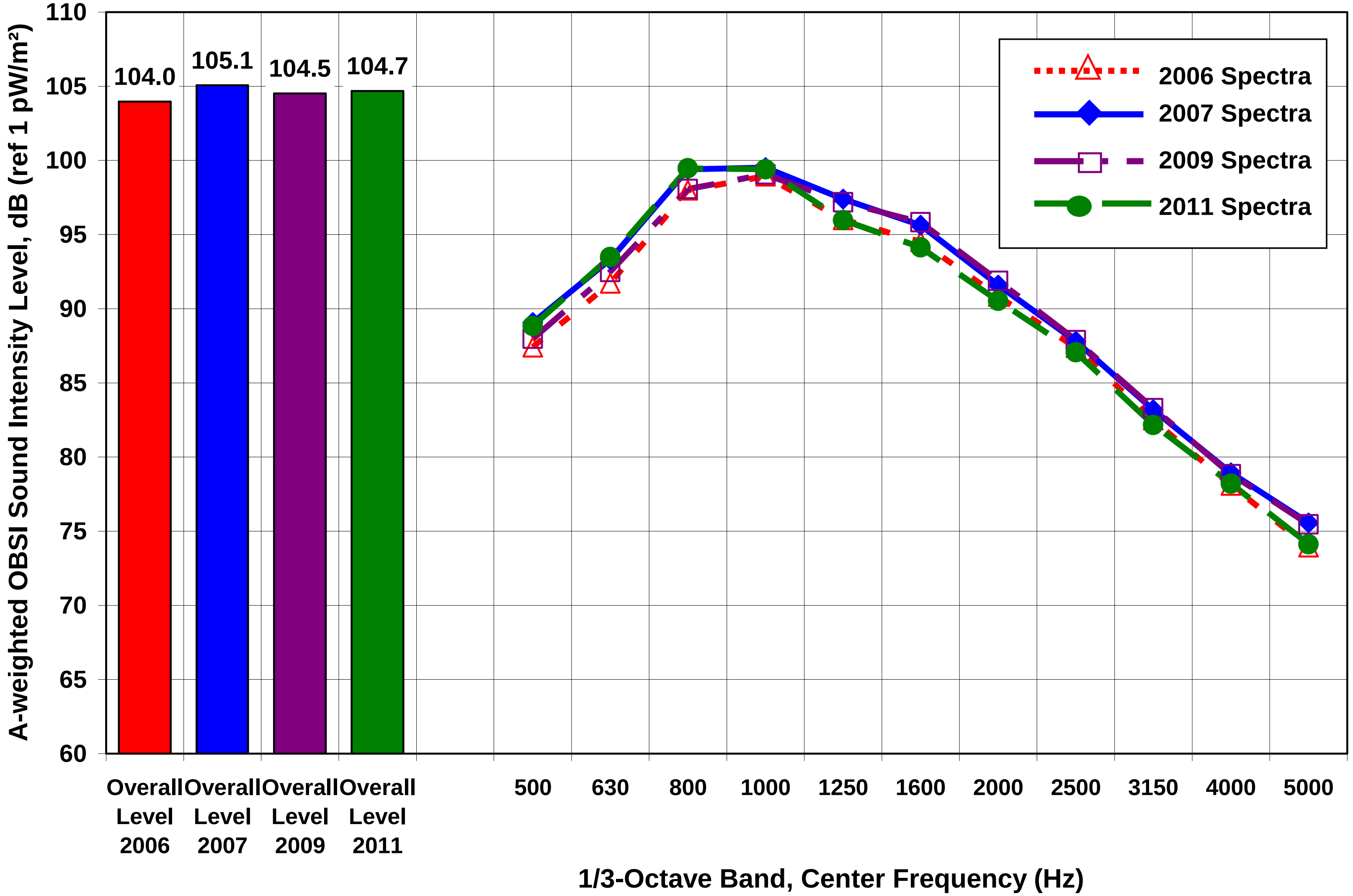
Nominal Surface: SMA (3/4") **Construction Accepted:** 10/2003

OBSI?: Yes **Pass-by?:** No
Total Section Length: 3575 ft.
Distance from Begin to Wayside Microphone: n/a



Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 03
OBSI (SRTT) Test Information



Site: 04
General Information

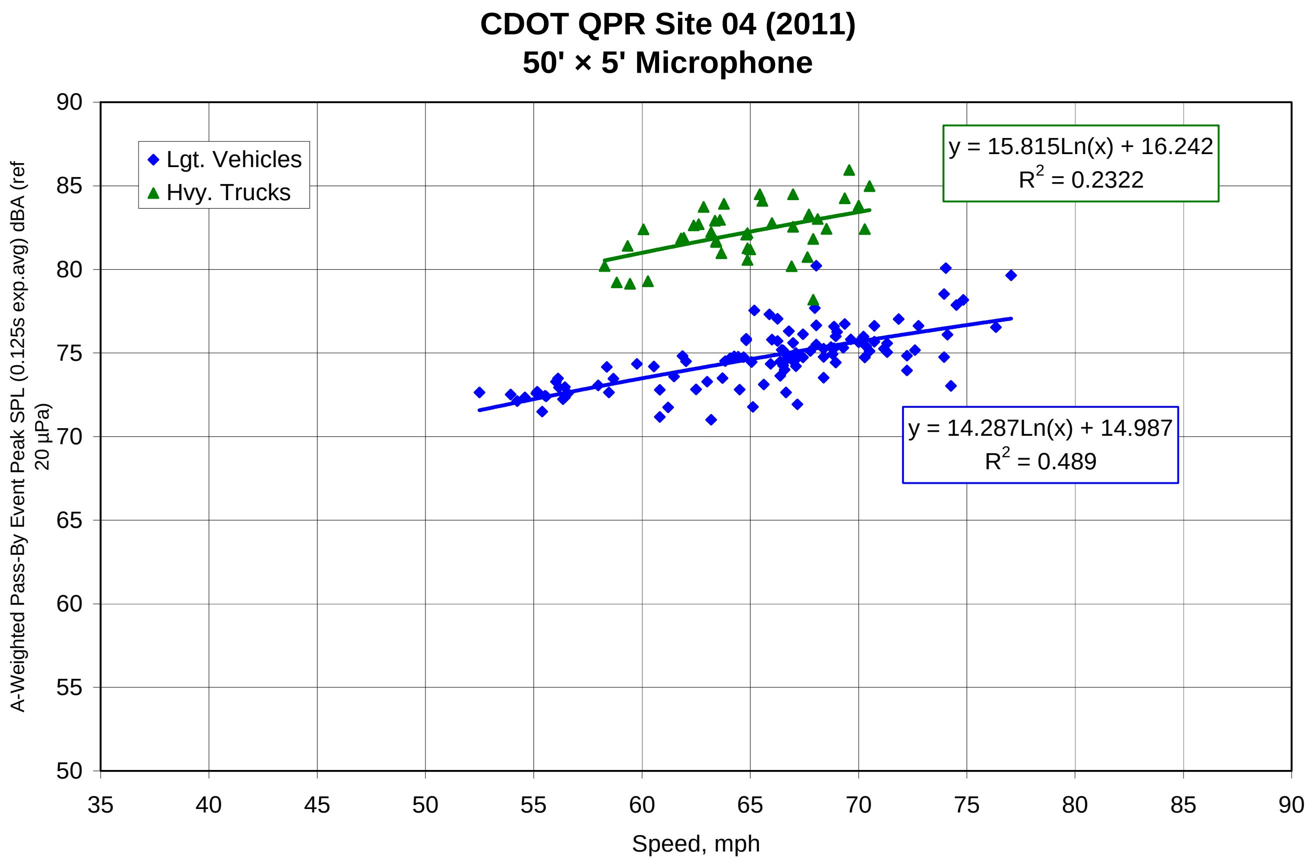
Highway: US Highway 50, Westbound
Location: Between 35 6/10 Rd. & Bridgeport Rd., Grand Junction (81527)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 38.8721 / 108.3385 / 5110

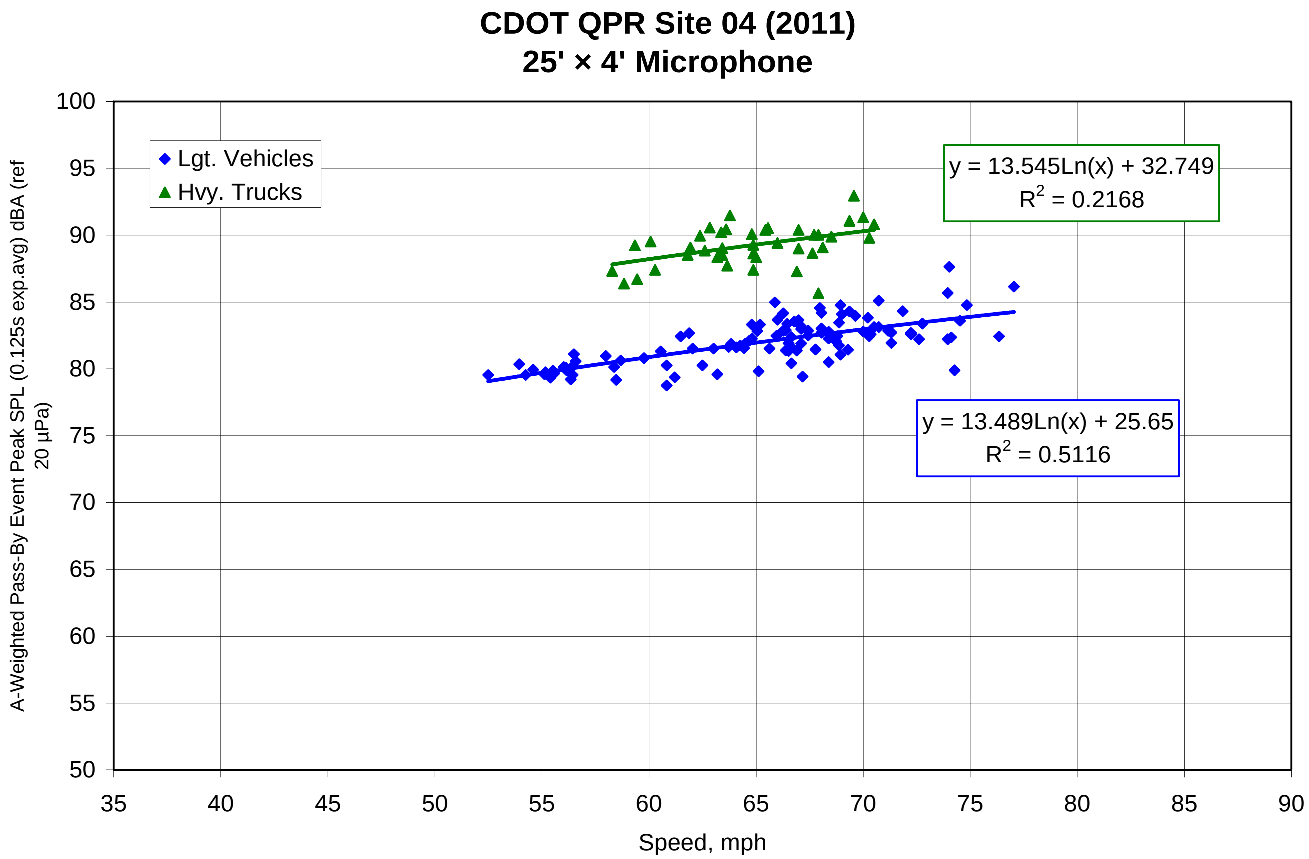
Nominal Surface: SMA (1/2") **Construction Accepted:** 8/2002

OBSI?: Yes **Pass-by?:** Yes
Total Section Length: 4847 ft.
Distance from Begin to Wayside Microphone: 1422 ft.

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 04
SPB Wayside Test Information

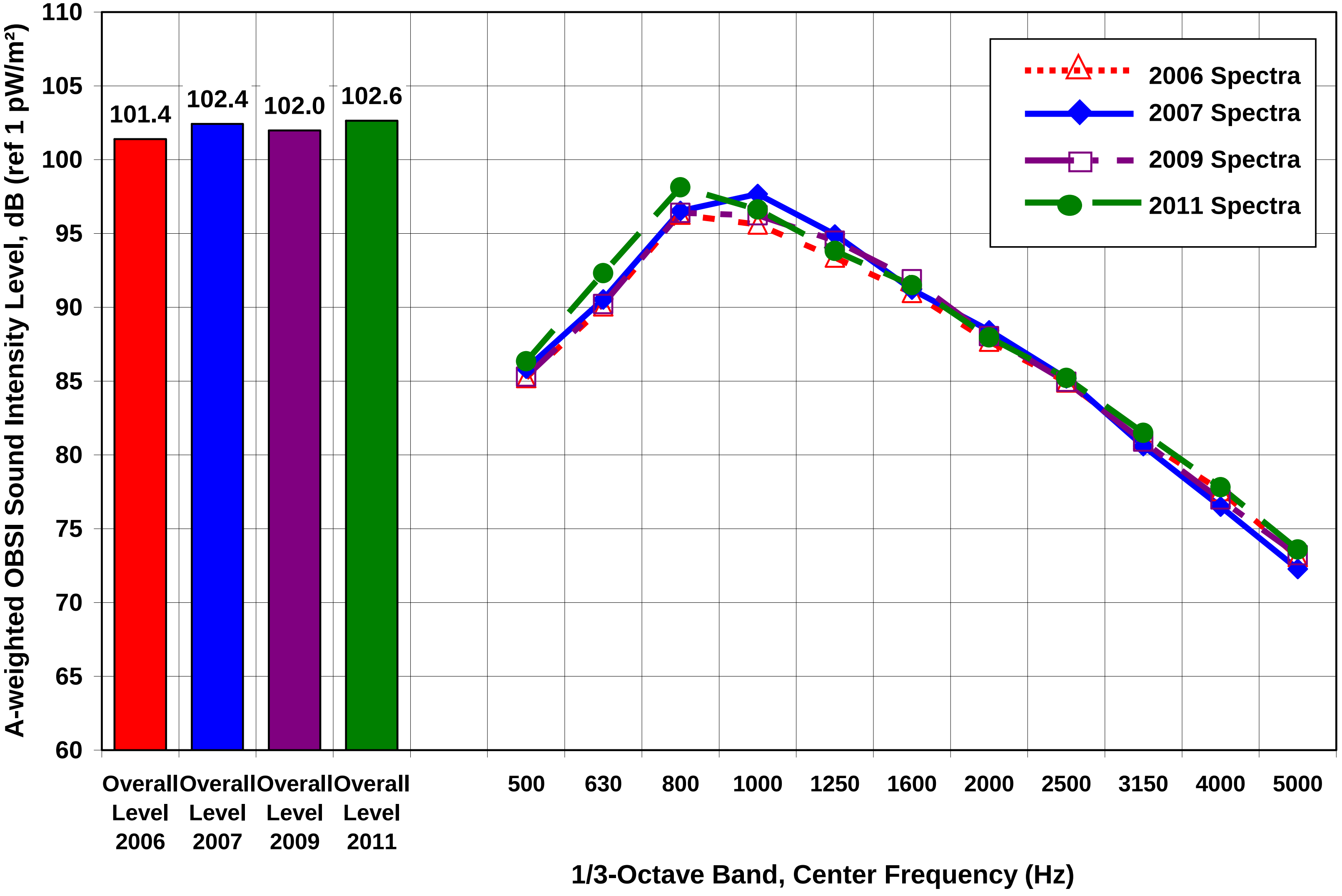




Average A-weighted SPB Level at 60 mph (dB ref 20 µPa), SPBI

Vehicle	50×5 microphone	25×4 microphone
Lgt. Vehicle (Car)	**73.5**	**80.9**
Hvy. Truck	**79.6**	**88.2**

Site: 04
OBSI (SRTT) Test Information



Site: 05
General Information

Highway: State Highway 74, Eastbound
Location: Between Bergen Pkwy. & Lewis Ridge Rd., Evergreen (80439)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 39.6702 / 105.3599 / 7680

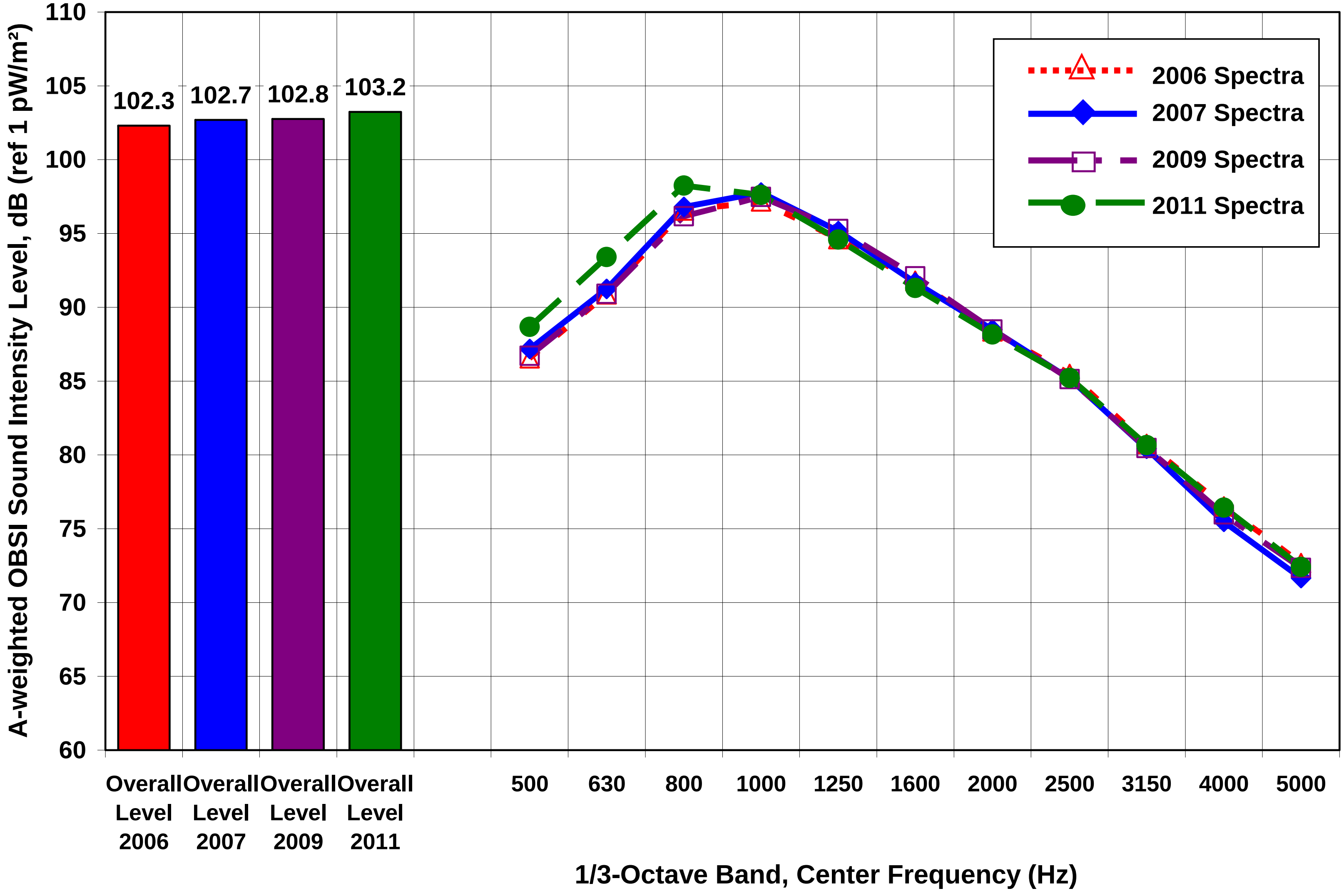
Nominal Surface: SMA (3/8") **Construction Accepted:** 7/2004

OBSI?: Yes **Pass-by?:** No
Total Section Length: 3488 ft.
Distance from Begin to Wayside Microphone: n/a

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 05

OBSI (SRTT) Test Information

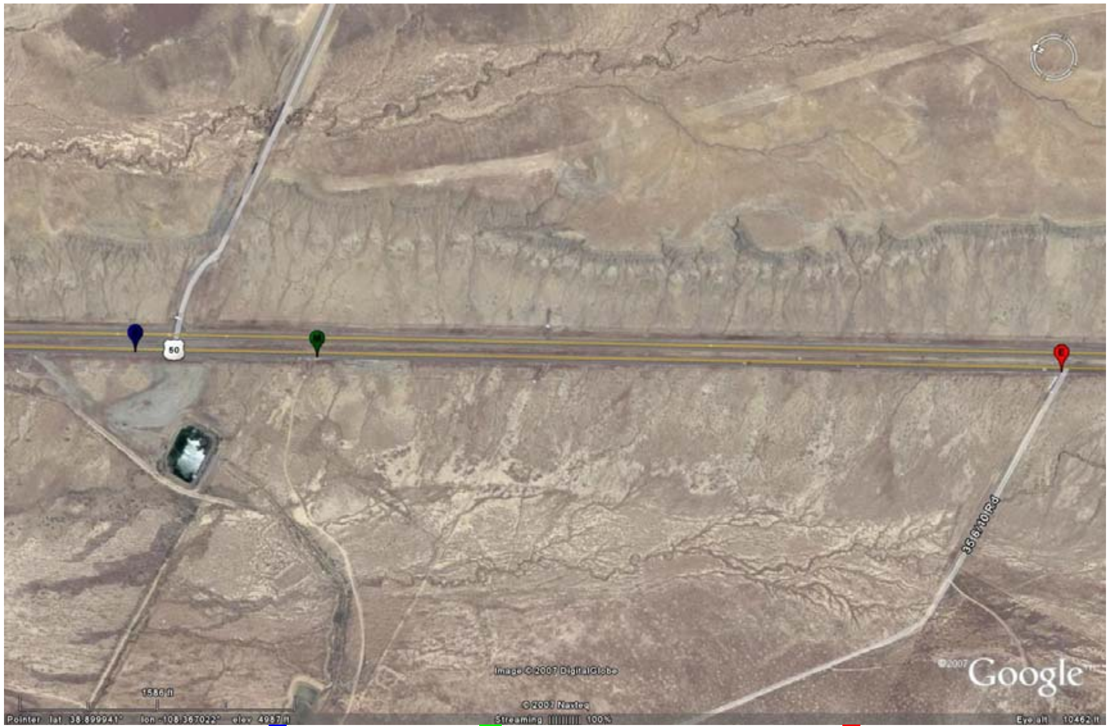


Site: 06
General Information

Highway: US Highway 50, Eastbound
Location: Between 35 6/10 Rd. & Bridgeport Rd., Grand Junction (81527)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 38.8994 / 108.3666 / 5010

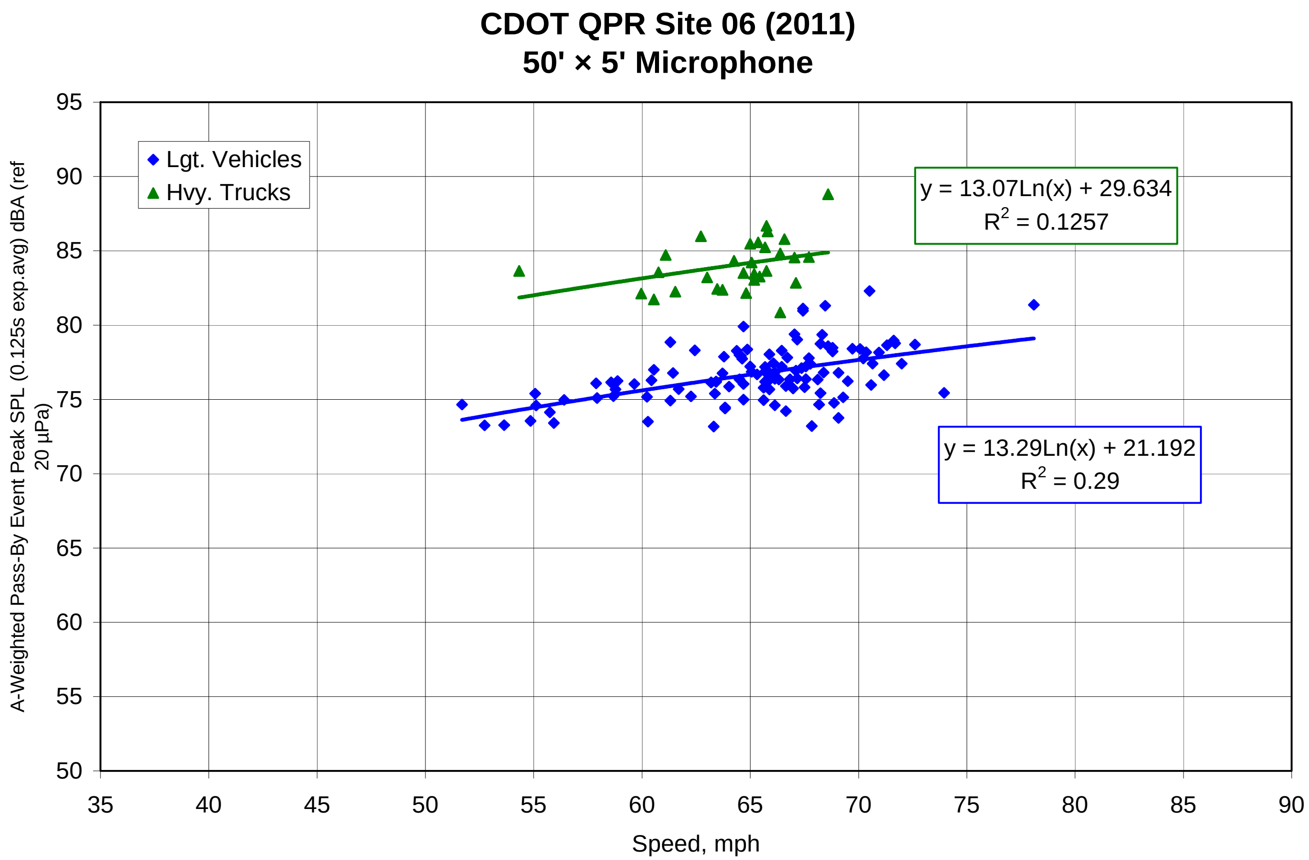
Nominal Surface: Asphalt (SX, 1/2") **Construction Accepted:** 8/2002

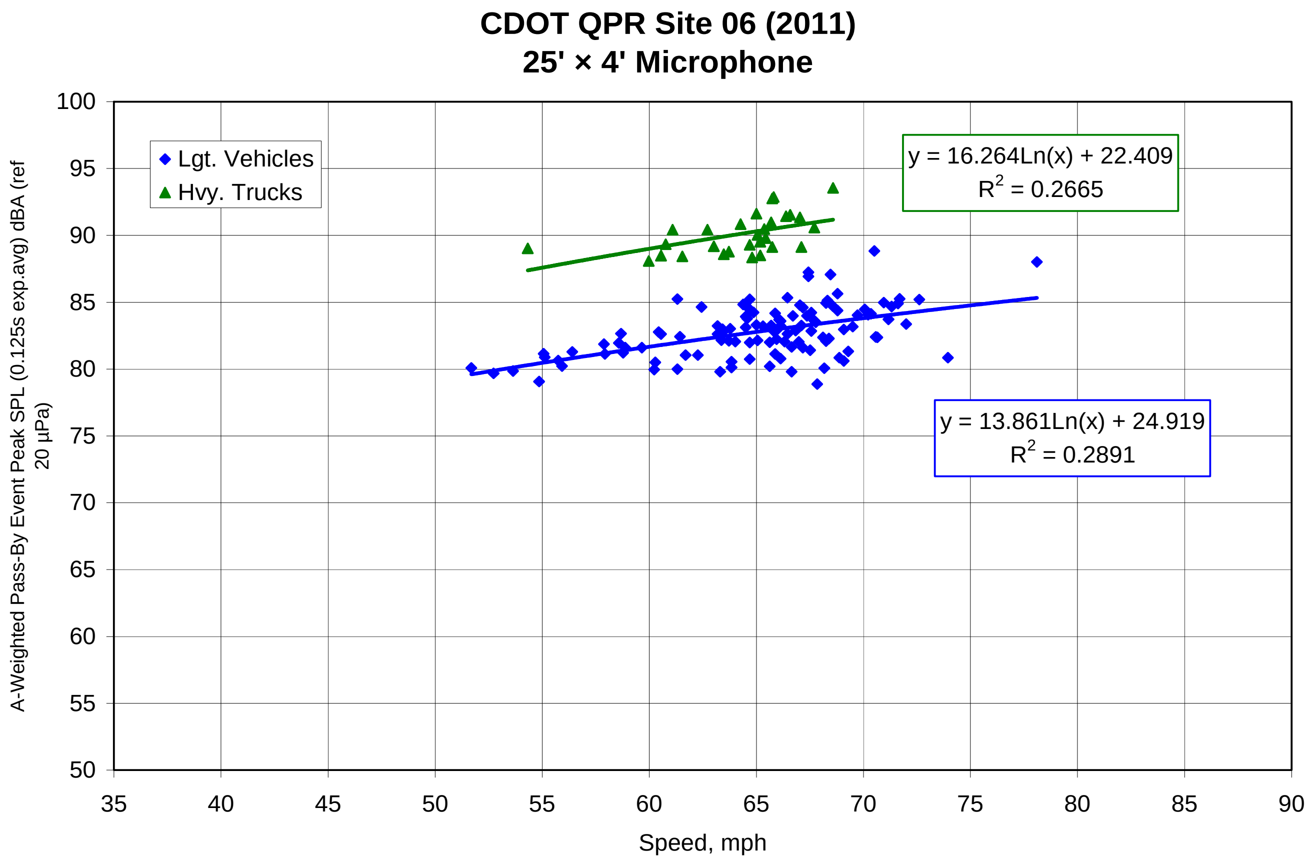
OBSI?: Yes **Pass-by?:** Yes
Total Section Length: 5333 ft.
Distance from Begin to Wayside Microphone: 1048 ft.



Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 06
SPB Wayside Test Information




CDOT QPR Site 06 (2011)
25' × 4' Microphone
A-Weighted Pass-By Event Peak SPL (0.125s exp.avg) dBA (ref 20 µPa)
Speed, mph
Lgt. Vehicles
Hvy. Trucks
y = 16.264Ln(x) + 22.409
R2 = 0.2665
y = 13.861Ln(x) + 24.919
R2 = 0.2891
100
95
90
85
80
75
70
65
60
55
50
35
40
45
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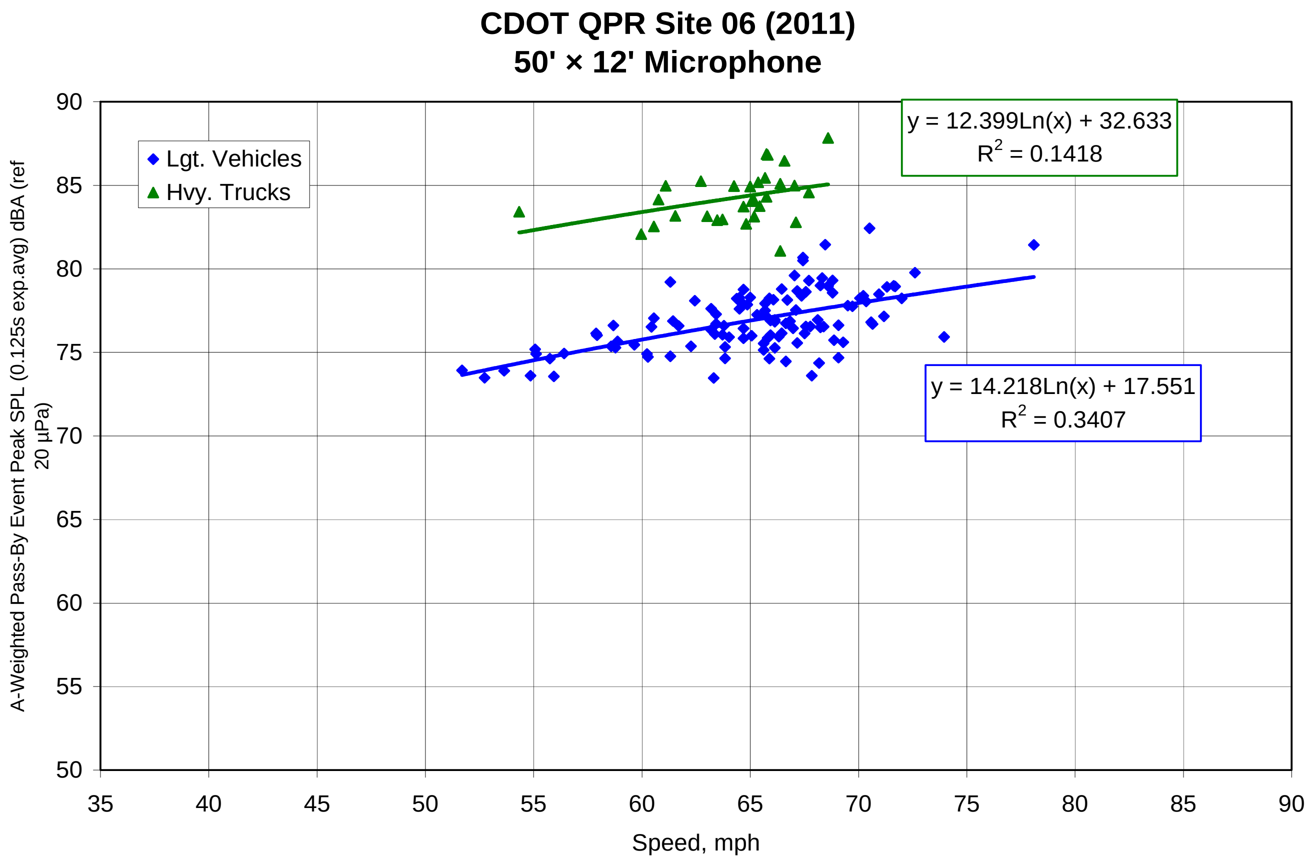
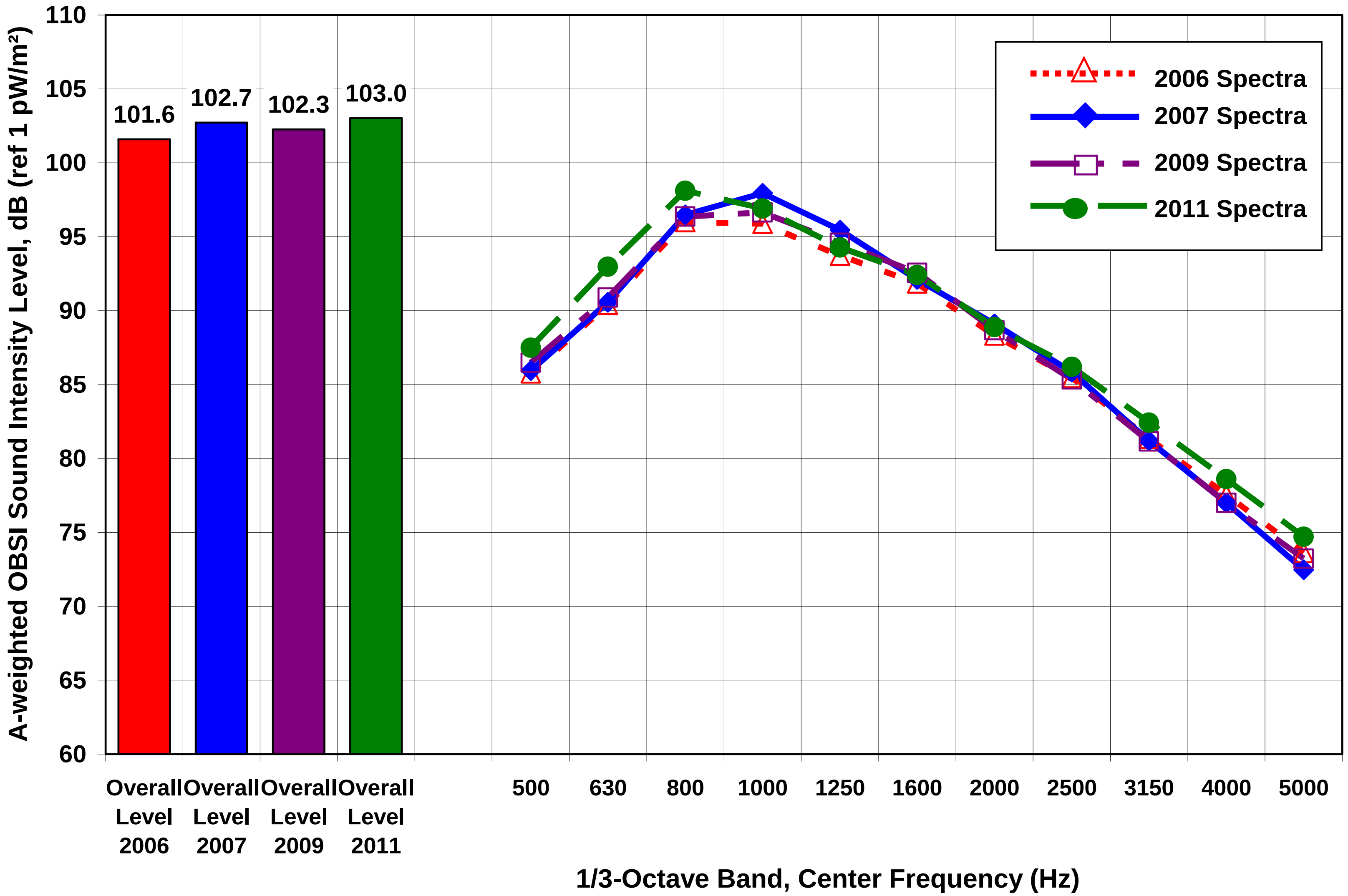
55
60
65
70
75
80
85
90



Average A-weighted SPB Level at 60 mph (dB ref 20 μPa), SPBI

Vehicle	50×5 microphone	25×4 microphone	50×12 microphone
Lgt. Vehicle (Car)	**75.6**	**81.7**	**75.8**
Hvy. Truck	**83.1**	**89.0**	**83.4**

Site: 06
OBSI (SRTT) Test Information



Site: 07
General Information

Highway: US Highway 85, Southbound
Location: Between Daniels Park Rd. & Happy Canyon Rd., Sedalia (80135)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 39.4288 / 104.9111 / 6000

Nominal Surface: Asphalt (SX, 1/2") **Construction Accepted:** 2006

OBSI?: Yes **Pass-by?:** Yes
Total Section Length: 2686 ft.
Distance from Begin to Wayside Microphone: 1864 ft.

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 07
Time-Averaged Wayside Test Information

Sampling Periods: 1

Sample Period 1 – 5 Blocks @ 15 min ea. = 75 min. (9:45 am to 11:15 am MDT, 6/21/11)

Traffic Volumes and Speeds during Sample Period

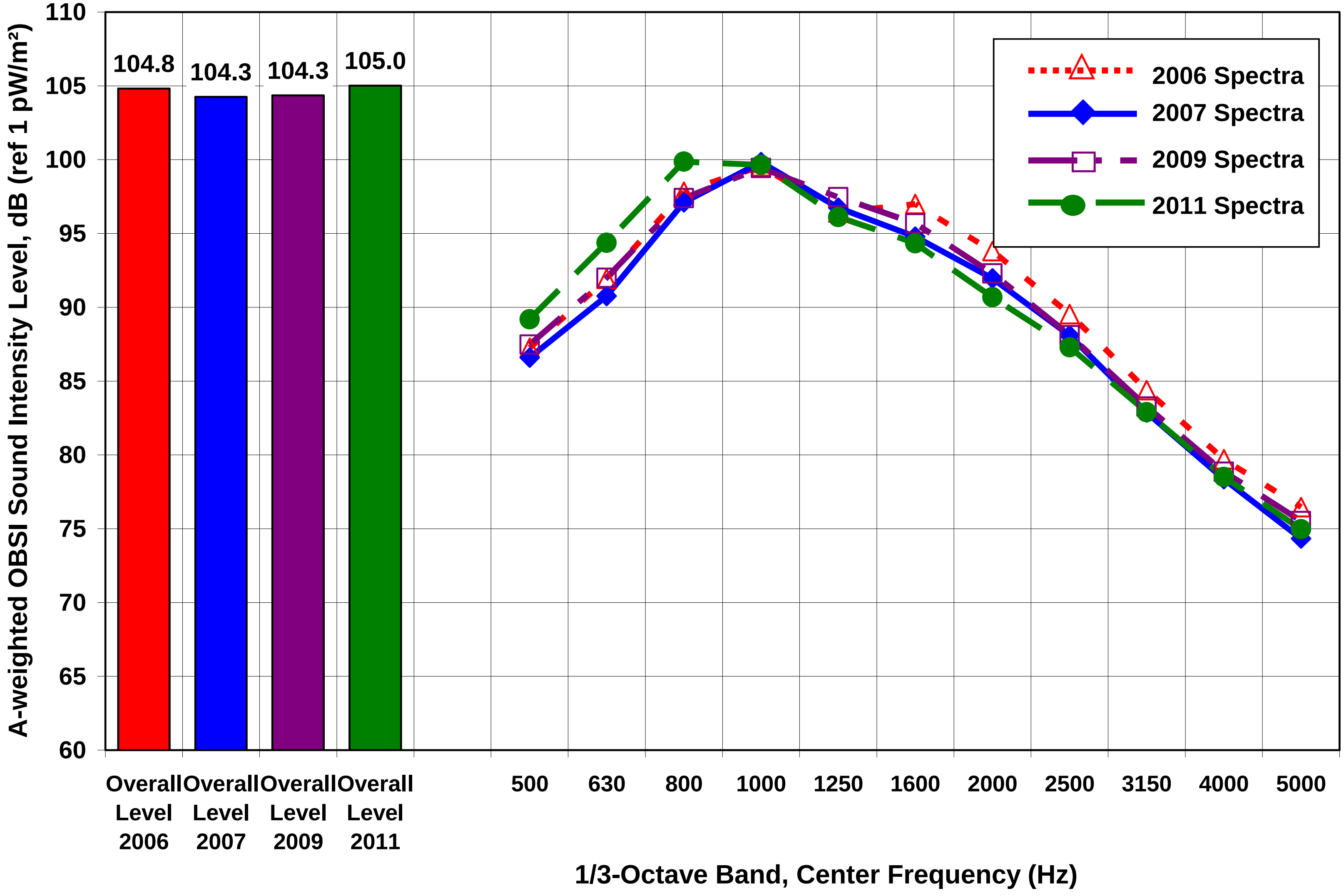
	SB Lane 1	**NB Lane 1**
Distance from Mic (ft.)*	50	62
Average Speed (mph)	54	53
Automobile	397	437
Heavy Truck	30	22
Medium Truck	14	18
Bus	1	1
Motorcycle	4	11
Auto + 1-Axle Trlr.	3	6
Auto + 2-Axle Trlr.	6	10
M. Trk. + 1-Axle Trlr.	0	0
M. Trk. + 2-Axle Trlr.	2	7

** Note: for 50 ft mic positions*

A-Weighted Time Averaged Sound Pressure Levels during Sample Period (dB ref 20 μPa)

Mic Position (ft) Distance × Height	**Block 1**	**Block 2**	**Block 3**	**Block 4**	**Block 5**	**Average**
50×5	73.3	71.2	70.7	71.4	71.3	**71.6**
25×4	75.2	74.9	74.4	75.2	75.1	**75.0**
50×12	74.0	72.1	71.7	72.4	72.3	**72.5**

Site: 07
OBSI (SRTT) Test Information



Site: 08
General Information

Highway: Interstate 70, Eastbound
Location: Between US 6 & Herman Gulch Rd., Bakerville (E of Dillon) (80444)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 39.6976 / 105.8703 / 10470

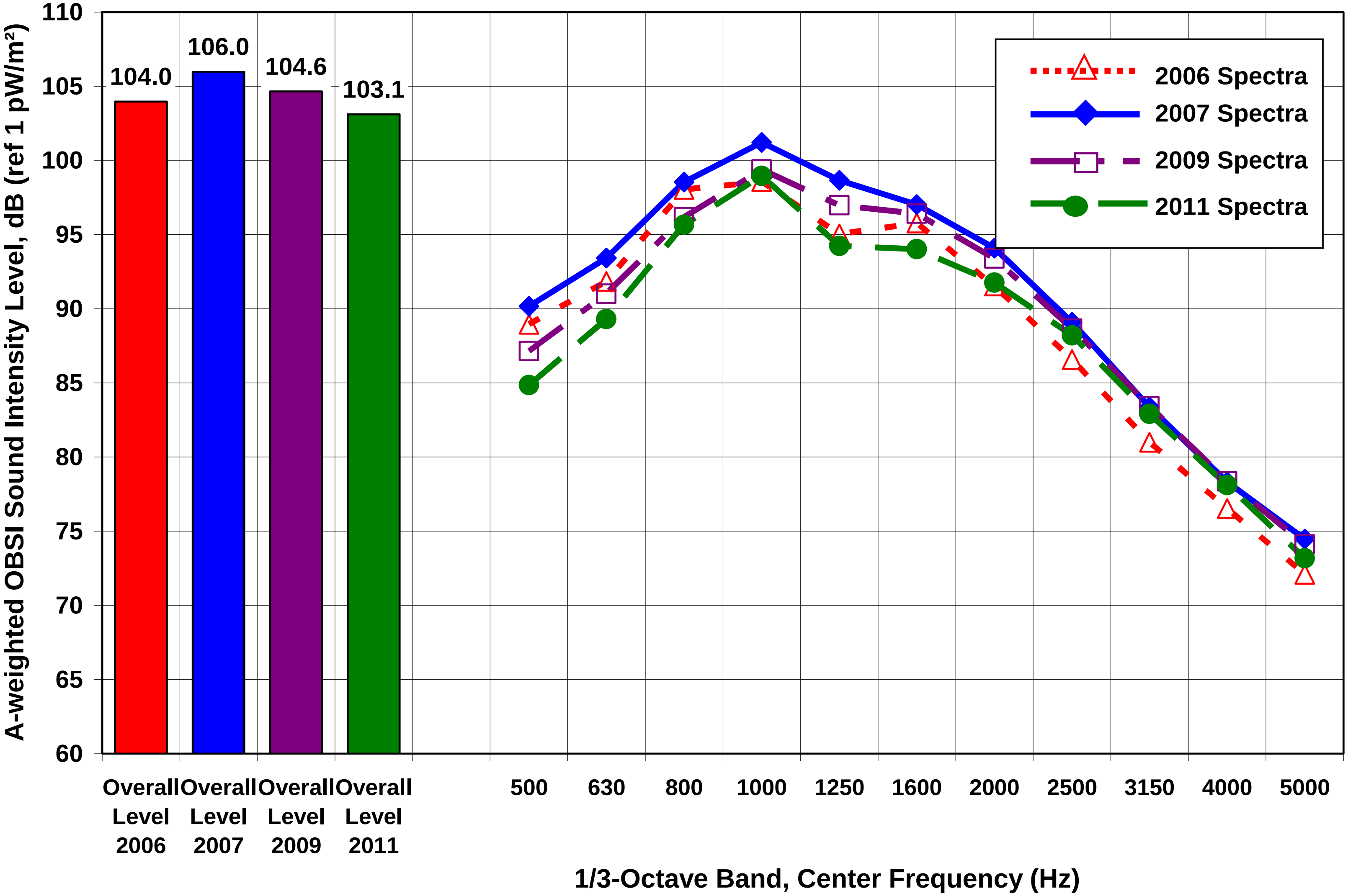
Nominal Surface: Asphalt (SX, 1/2") **Construction Accepted:** 2005

OBSI?: Yes **Pass-by?:** No
Total Section Length: 3535 ft.
Distance from Begin to Wayside Microphone: n/a

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 08

OBSI (SRTT) Test Information



Site: 09
General Information

Highway: Highway C-470, Westbound (Northbound)
Location: Between US 285 & Morrison Rd., Morrison (80465)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 39.641 / 105.1723 / 5760

Nominal Surface: SMA (1/2") **Construction Accepted:** 6/2006

OBSI?: Yes **Pass-by?:** Yes
Total Section Length: 3033 ft.
Distance from Begin to Wayside Microphone: 2460 ft.

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 09
Time-Averaged Wayside Test Information

Sampling Periods: 2

Sample Period 1 – 2 Blocks @ 15 min ea. = 30 min. (3:15 pm to 4:15 pm MDT, 5/31/11)
Sample Period 2 – 2 Blocks @ 15 min ea. = 30 min. (10:00 am to 11:00 am MDT, 6/3/11)

Traffic Volumes and Speeds during Sample Periods

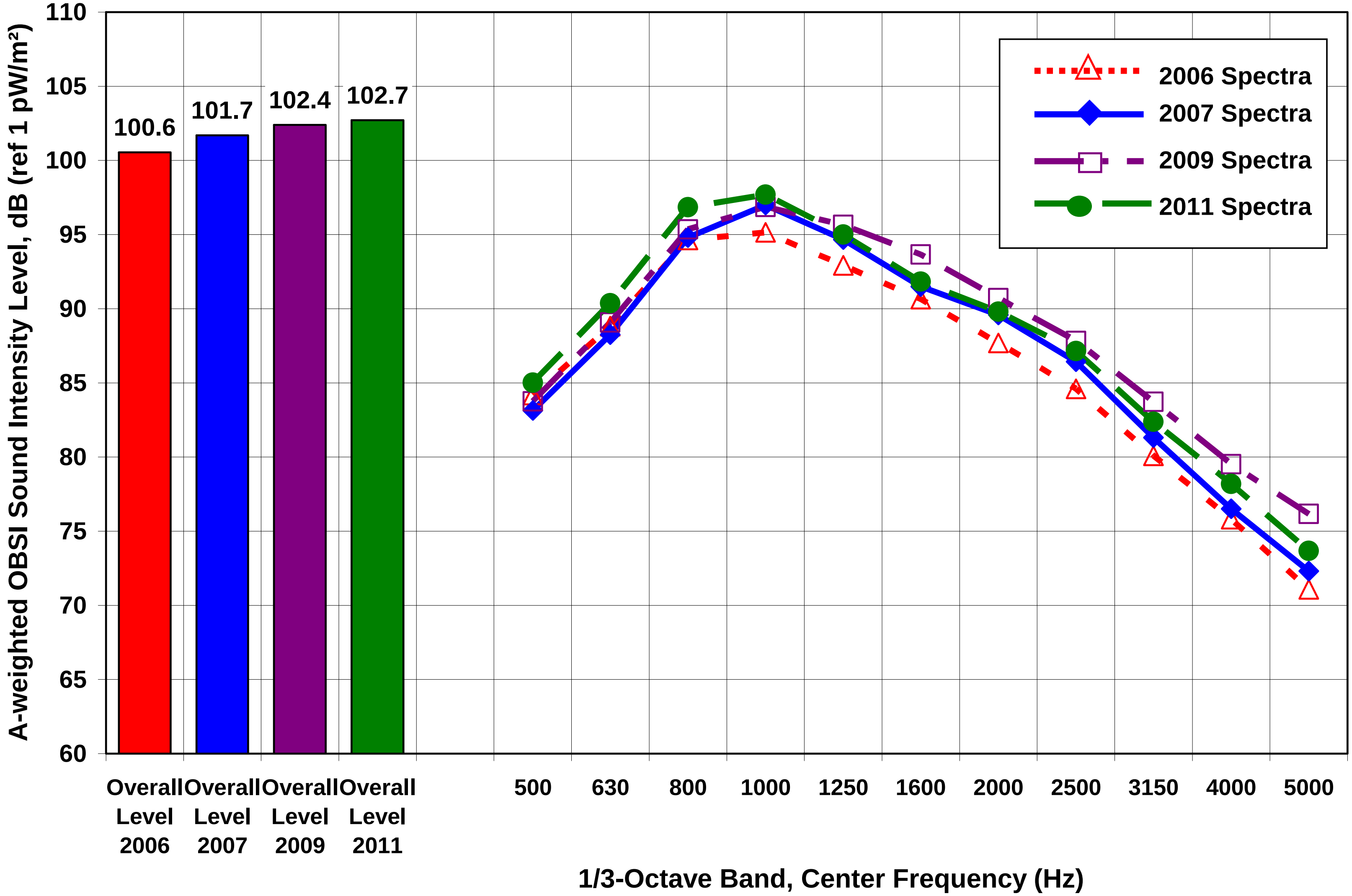
	WB Lane 3 (Outside)	WB Lane 2	WB Lane 1 (Inside)	EB Lane 1 (Inside)	EB Lane 2	EB Lane 3 (Outside)
Distance from Mic (ft.)	50	62	74	121	133	145
Average Speed (mph)		66			64	
Automobile	1139	1142	343	318	1131	1003
Heavy Truck	11	65	7	12	36	6
Medium Truck	19	41	8	9	32	7
Bus	4	2	2	0	1	0
Motorcycle	9	13	1	4	14	6
Auto + 1-Axle Trlr.	10	14	1	7	11	2
Auto + 2-Axle Trlr.	5	17	1	5	11	2
M. Trk. + 1-Axle Trlr.	0	1	0	0	0	0
M. Trk. + 2-Axle Trlr.	1	7	0	2	3	0

** Note: for 50 ft mic positions*

A-Weighted Time Averaged Sound Pressure Levels during Sample Periods (dB ref 20 µPa)

Mic Position (ft) Distance × Height	Block 1	Block 2	Block 3	Block 4	Average
50×5	75.9	76.4	76.6	76.4	**76.3**
25×4	80.2	80.3	80.1	79.9	**80.1**

Site: 09
OBSI (SRTT) Test Information

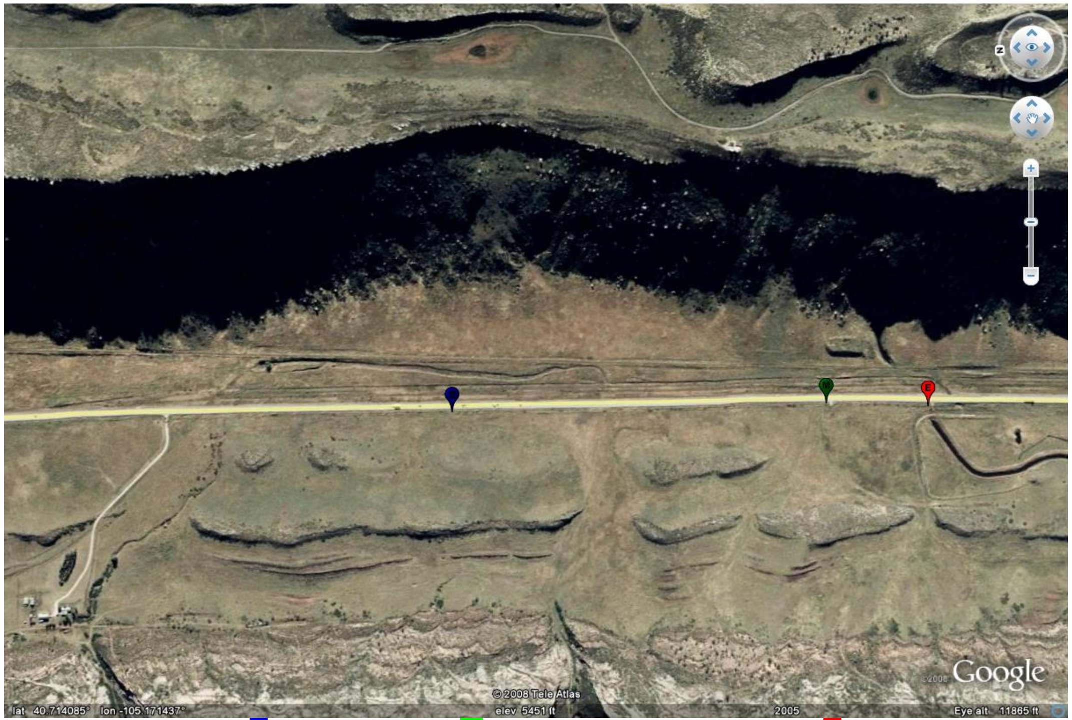


Site: 10
General Information

Highway: US Highway 287, Southbound
Location: Between Bonner Spring Ranch Rd. & SH 14, Laporte (80535)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 40.7113 / 105.173 / 5470

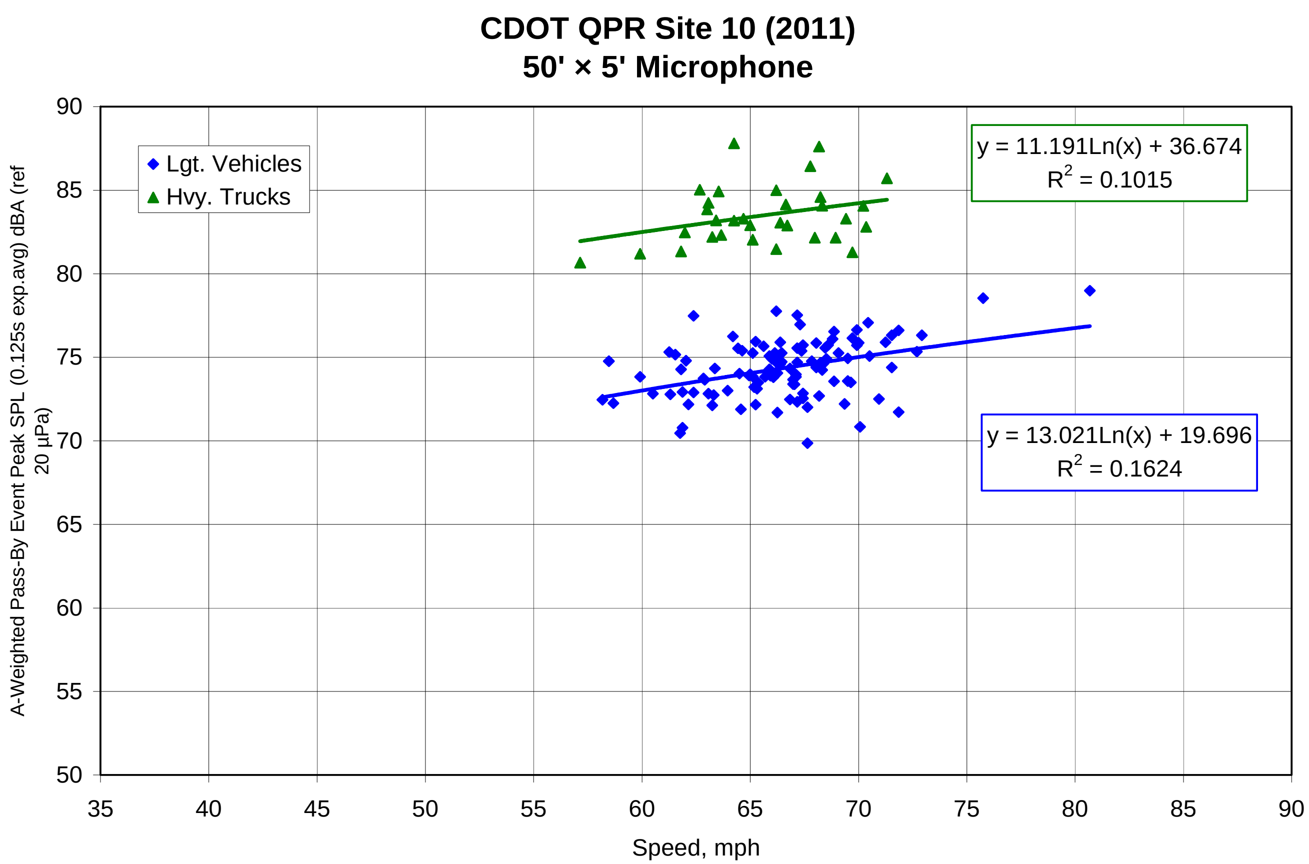
Nominal Surface: Asphalt (S, 3/4") **Construction Accepted:** 10/2003

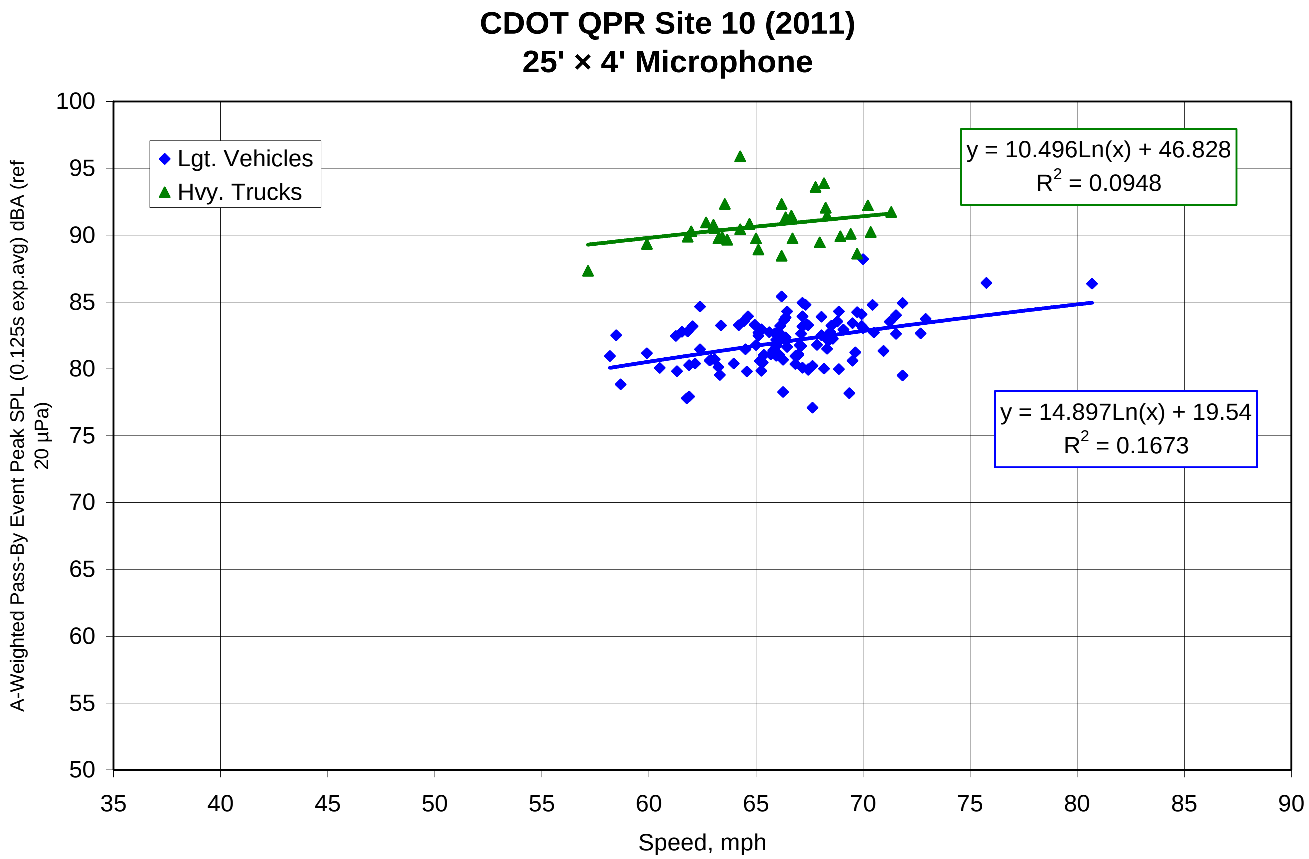
OBSI?: Yes **Pass-by?:** Yes
Total Section Length: 3380 ft.
Distance from Begin to Wayside Microphone: 2649 ft.

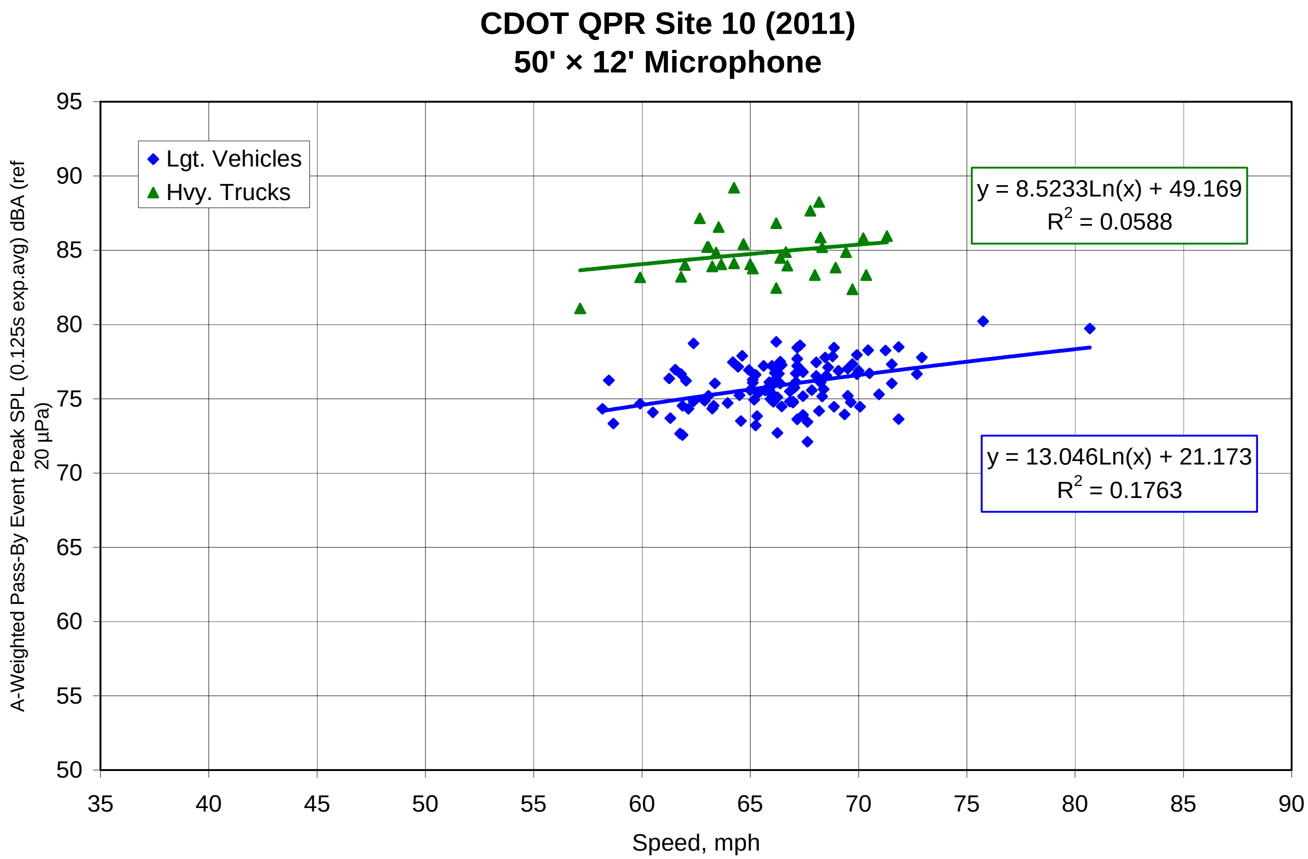


Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 10
SPB Wayside Test Information



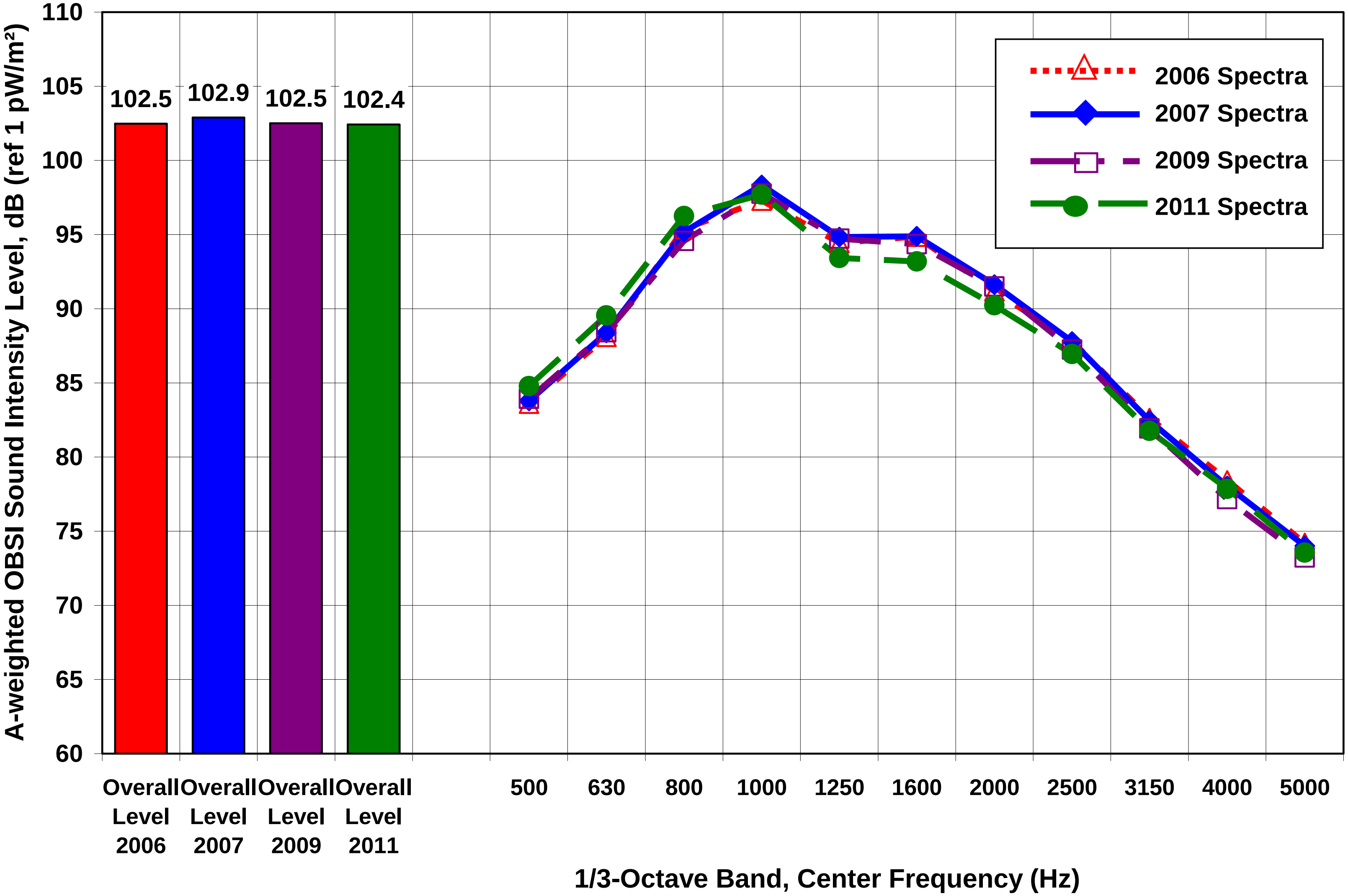

CDOT QPR Site 10 (2011)
25' × 4' Microphone
Lgt. Vehicles
Hvy. Trucks
y = 10.496Ln(x) + 46.828
R2 = 0.0948
y = 14.897Ln(x) + 19.54
R2 = 0.1673
A-Weighted Pass-By Event Peak SPL (0.125s exp.avg) dBA (ref 20 µPa)
Speed, mph
100
95
90
85
80
75
70
65
60
55
50
35
40
45
50
55
60
65
70
75
80
85
90



Average A-weighted SPB Level at 60 mph (dB ref 20 µPa), SPBI

Vehicle	50×5 microphone	25×4 microphone	50×12 microphone
Lgt. Vehicle (Car)	**73.0**	**80.5**	**74.6**
Hvy. Truck	**82.5**	**89.8**	**84.1**

Site: 10
OBSI (SRTT) Test Information



Site: 11
General Information

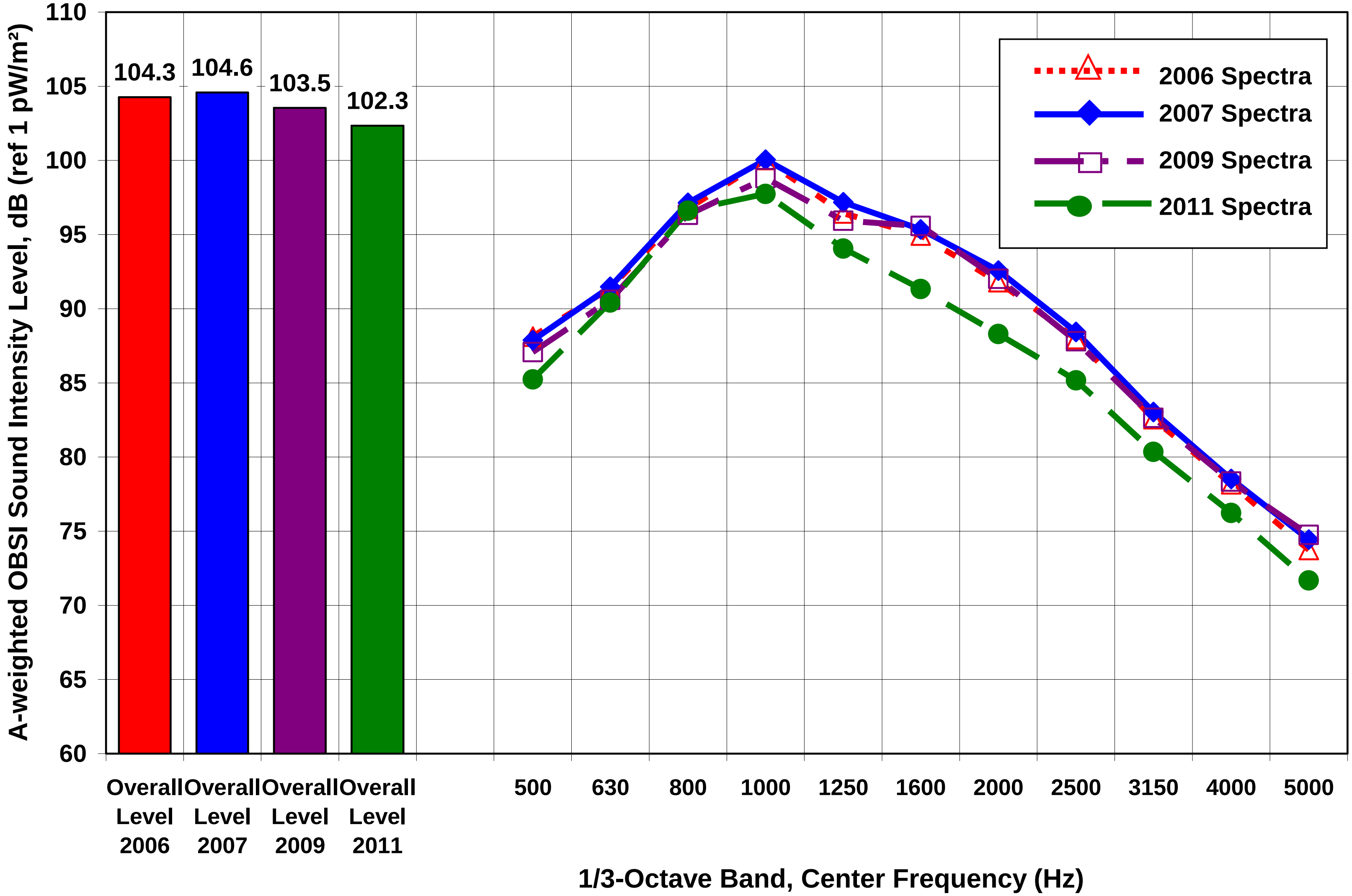
Highway: State Highway 82, Eastbound
Location: Between Hunter Logan & Lower River Rd., Basalt (81654)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 39.3389 / 106.9989 / 6880

Nominal Surface: NovaChip **Construction Accepted:** 10/2000

OBSI?: Yes **Pass-by?:** No
Total Section Length: 3228 ft.
Distance from Begin to Wayside Microphone: n/a

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 11
OBSI (SRTT) Test Information

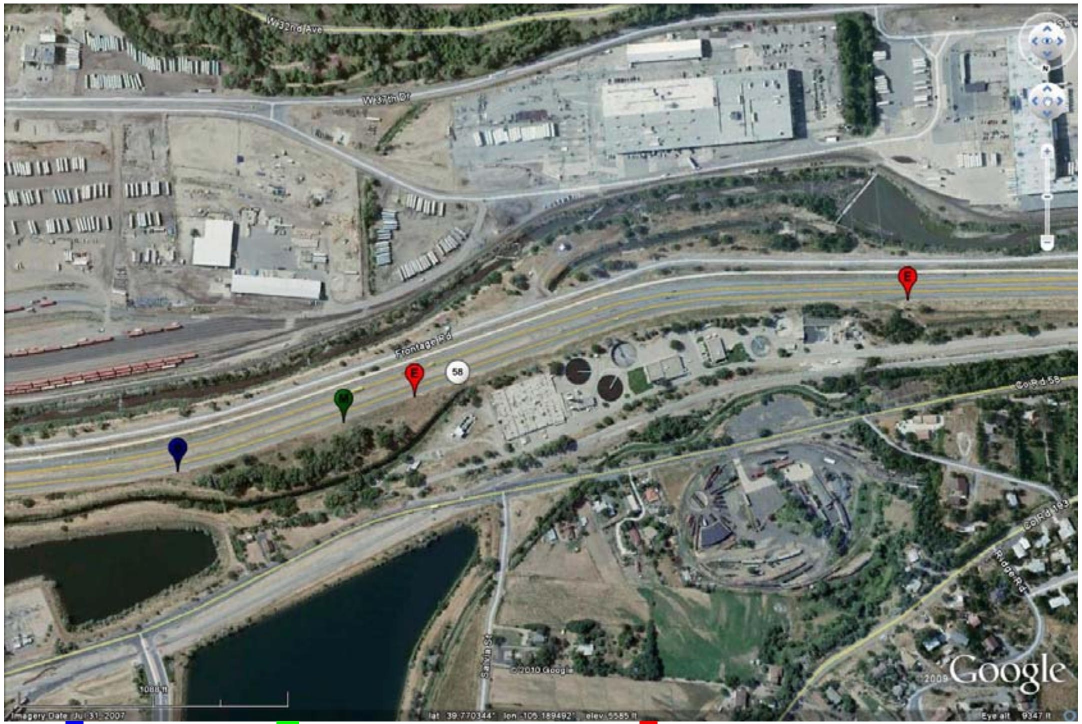


Site: 12
General Information

Highway: State Highway 58, Westbound
Location: Between McIntyre St. & 44th Ave., Golden (80403)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 39.7706 / 105.1904 / 5600

Nominal Surface: NovaChip **Construction Accepted:** 6/2003

OBSI?: Yes **Pass-by?:** Yes
Total Section Length: 1010 ft. (same point of begin as previous 3082 ft. section)
Distance from Begin to Wayside Microphone: 653 ft.



Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section (shorter section from 2009 and on)

Site: 12
Time-Averaged Wayside Test Information

Sampling Periods: 1

Sample Period 1 – 4 Blocks @ 15 min ea. = 60 min. (9:30 am to 11:00 am MDT, 6/23/11)

Traffic Volumes and Speeds during Sample Period

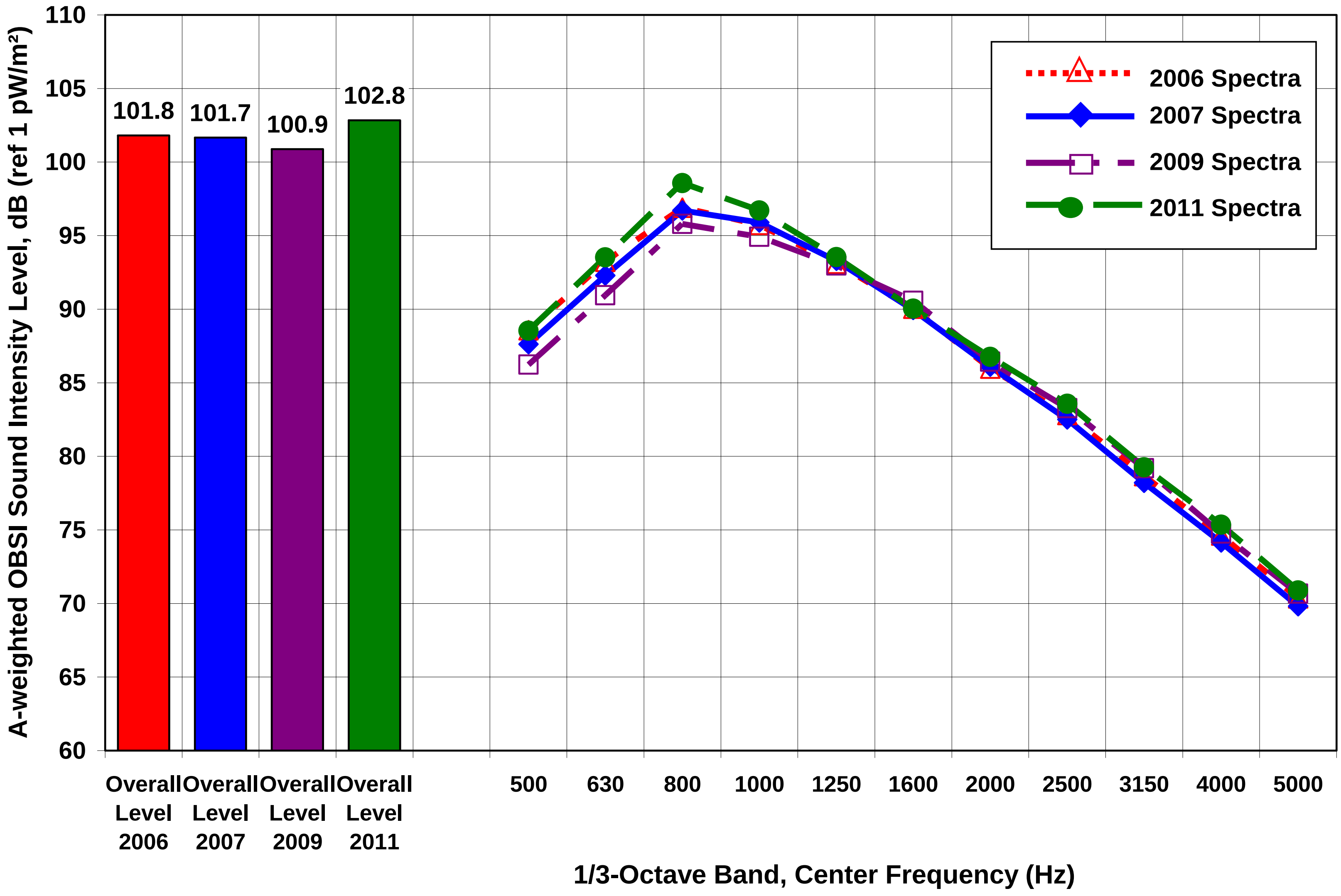
	WB Lane 2 (Outside)	WB Lane 1 (Inside)	EB Lane 1 (Inside)	EB Lane 2 (Outside)
Distance from Mic (ft.)	50	62	111	123
Average Speed (mph)	65		66	
Automobile	408	155	145	301
Heavy Truck	13	1	10	16
Medium Truck	6	0	0	15
Bus	2	1	0	1
Motorcycle	7	3	1	5
Auto + 1-Axle Trlr.	2	0	0	3
Auto + 2-Axle Trlr.	5	1	0	3
M. Trk. + 1-Axle Trlr.	0	0	0	0
M. Trk. + 2-Axle Trlr.	2	0	1	1

** Note: for 50 ft mic positions*

A-Weighted Time Averaged Sound Pressure Levels during Sample Period (dB ref 20 µPa)

Mic Position (ft) Distance × Height	Block 1	Block 2	Block 3	Block 4	Average
50×5	73.0	69.8	70.0	70.6	**70.8**
25×4	76.3	74.7	74.8	75.4	**75.3**
50×12	74.3	71.5	71.8	72.3	**72.5**

Site: 12
OBSI (SRTT) Test Information



Site: 13
General Information

Highway: Interstate 25, Southbound
Location: Between CR-12 & CR-10, Erie (80516)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 40.0667 / 104.9809 / 5060

Nominal Surface: Concrete (Long. Tining) **Construction Accepted:** 10/2005

OBSI?: Yes **Pass-by?:** Yes
Total Section Length: 3389 ft.
Distance from Begin to Wayside Microphone: 1054 ft.

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 13
Time-Averaged Wayside Test Information

Sampling Periods: 1

Sample Period 1 – 4 Blocks @ 15 min ea. = 60 min. (9:45 am to 11:30 am MDT, 6/8/11)

Traffic Volumes and Speeds during Sample Period

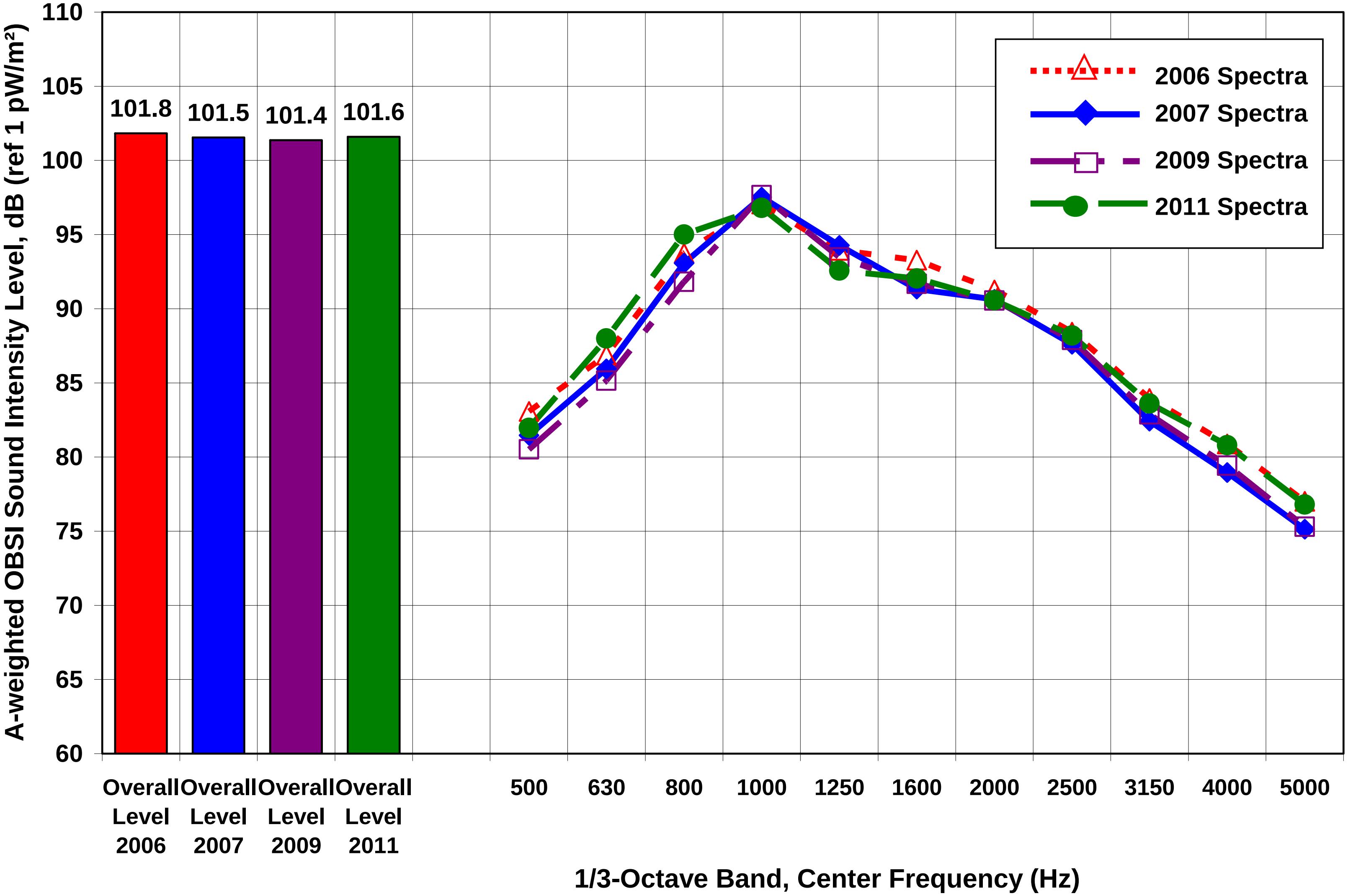
	SB Lane 3 (Outside)	SB Lane 2	SB Lane 1 (Inside)	NB Lane 1 (Inside)	NB Lane 2	NB Lane 3 (Outside)
Distance from Mic (ft.)	50	62	74	145	157	169
Average Speed (mph)		73			71	
Automobile	320	914	949	877	940	317
Heavy Truck	140	94	10	11	102	160
Medium Truck	51	41	8	10	51	38
Bus	2	1	0	1	0	7
Motorcycle	2	5	5	0	5	11
Auto + 1-Axle Trlr.	7	8	2	1	9	8
Auto + 2-Axle Trlr.	13	12	2	5	14	11
M. Trk. + 1-Axle Trlr.	1	2	0	0	0	4
M. Trk. + 2-Axle Trlr.	12	3	1	0	6	2

** Note: for 50 ft mic positions*

A-Weighted Time Averaged Sound Pressure Levels during Sample Period (dB ref 20 µPa)

Mic Position (ft) Distance × Height	Block 1	Block 2	Block 3	Block 4	Average
50×5	79.5	79.5	79.6	79.6	**79.5**
25×4	83.2	83.2	83.2	83.2	**83.2**
50×12	80.0	80.0	80.1	80.1	**80.0**

Site: 13
OBSI (SRTT) Test Information



Site: 14
General Information

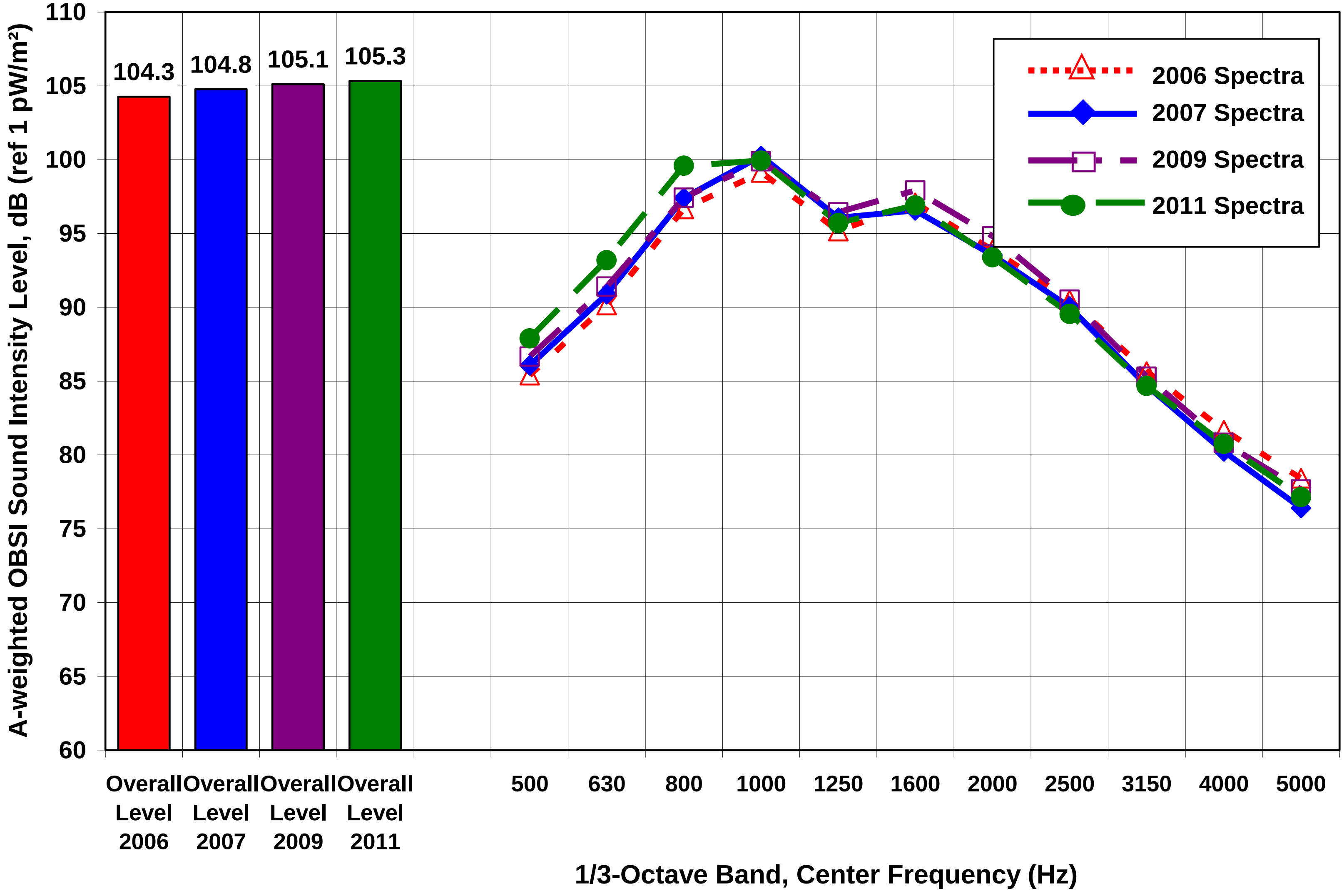
Highway: US Highway 285, Northbound
Location: Between Surrey Dr. & Goddard Ranch Ct., Indian Hills (80465)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 39.5838 / 105.2258 / 7130

Nominal Surface: Concrete (Long. Tining) **Construction Accepted:** 10/1999

OBSI?: Yes **Pass-by?:** No
Total Section Length: 1613 ft.
Distance from Begin to Wayside Microphone: n/a

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 14
OBSI (SRTT) Test Information



Site: 15

General Information

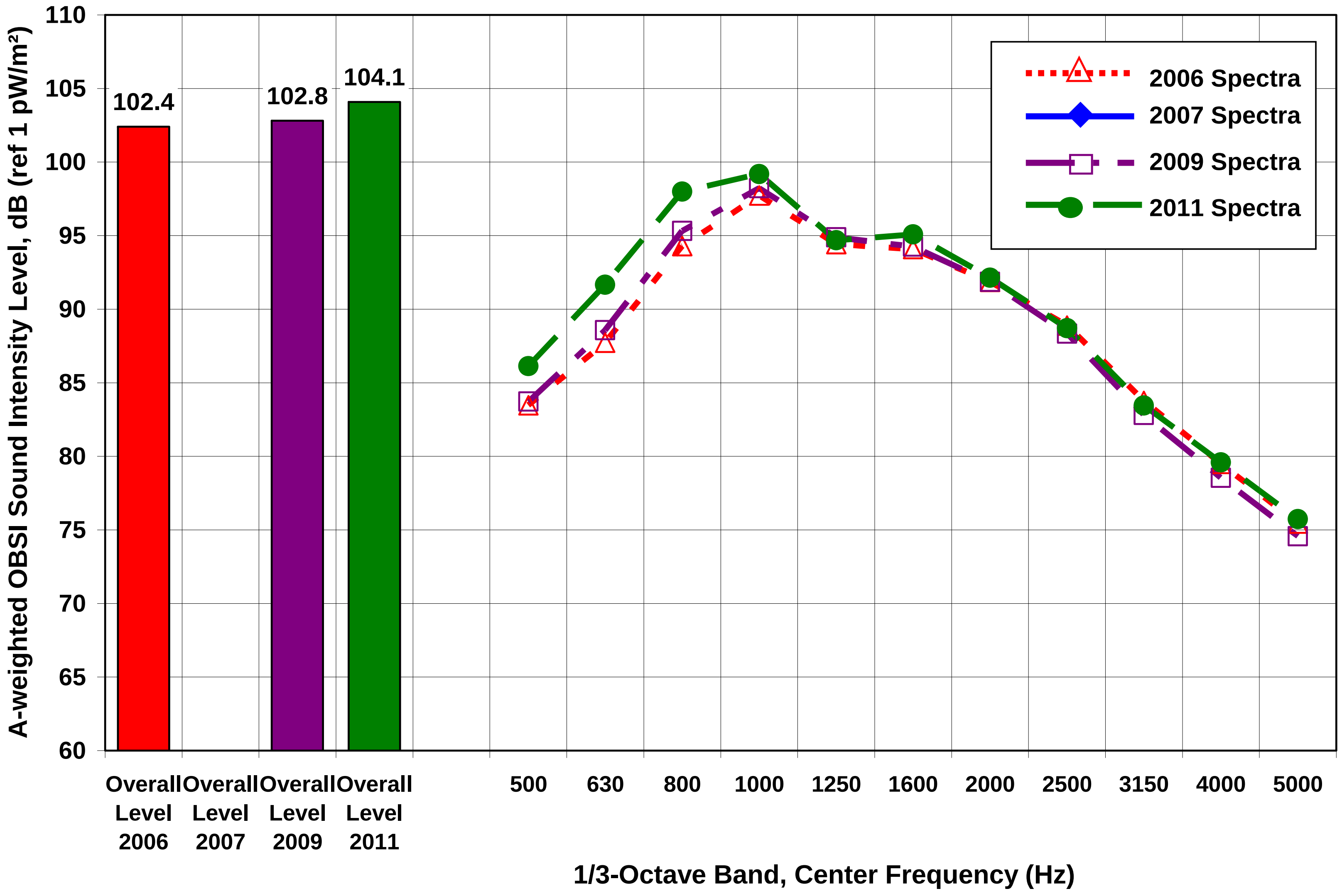
Highway: Interstate 25, Northbound
Location: Between Fontanero St. & Fillmore St., Colorado Springs (80907)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 38.8672 / 104.834 / 6130

Nominal Surface: Concrete (Long. Grooving) **Construction Accepted:** 11/2001

OBSI?: Yes **Pass-by?:** No
Total Section Length: 4485 ft.
Distance from Begin to Wayside Microphone: n/a

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 15
OBSI (SRTT) Test Information



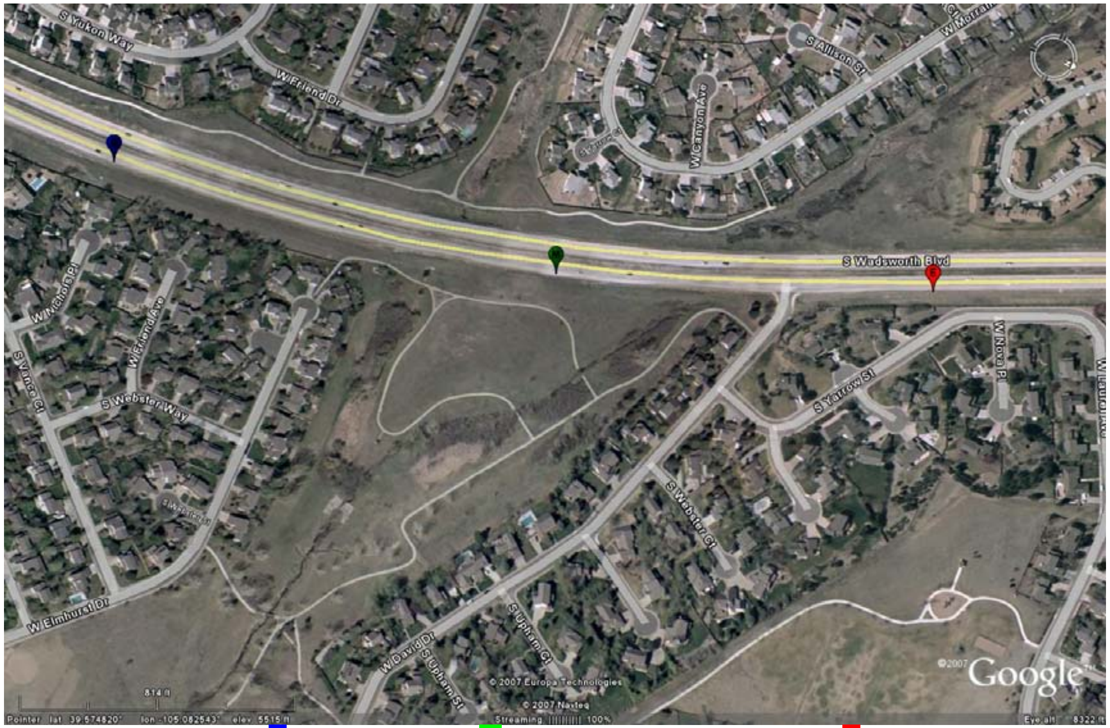
Site: 16

General Information

Highway: State Highway 121, Northbound
Location: Between Chatfield Ave. & Ken Caryl Ave., Littleton (80128)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 39.5741 / 105.0837 / 5580

Nominal Surface: Concrete (Carpet Drag) **Construction Accepted:** 8/2001

OBSI?: Yes **Pass-by?:** Yes
Total Section Length: 2422 ft.
Distance from Begin to Wayside Microphone: 1323 ft.



Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 16
Time-Averaged Wayside Test Information

Sampling Periods: 1

Sample Period 1 – 4 Blocks @ 15 min ea. = 60 min. (10:00 am to 11:15 am MDT, 5/31/11)

Traffic Volumes and Speeds during Sample Period

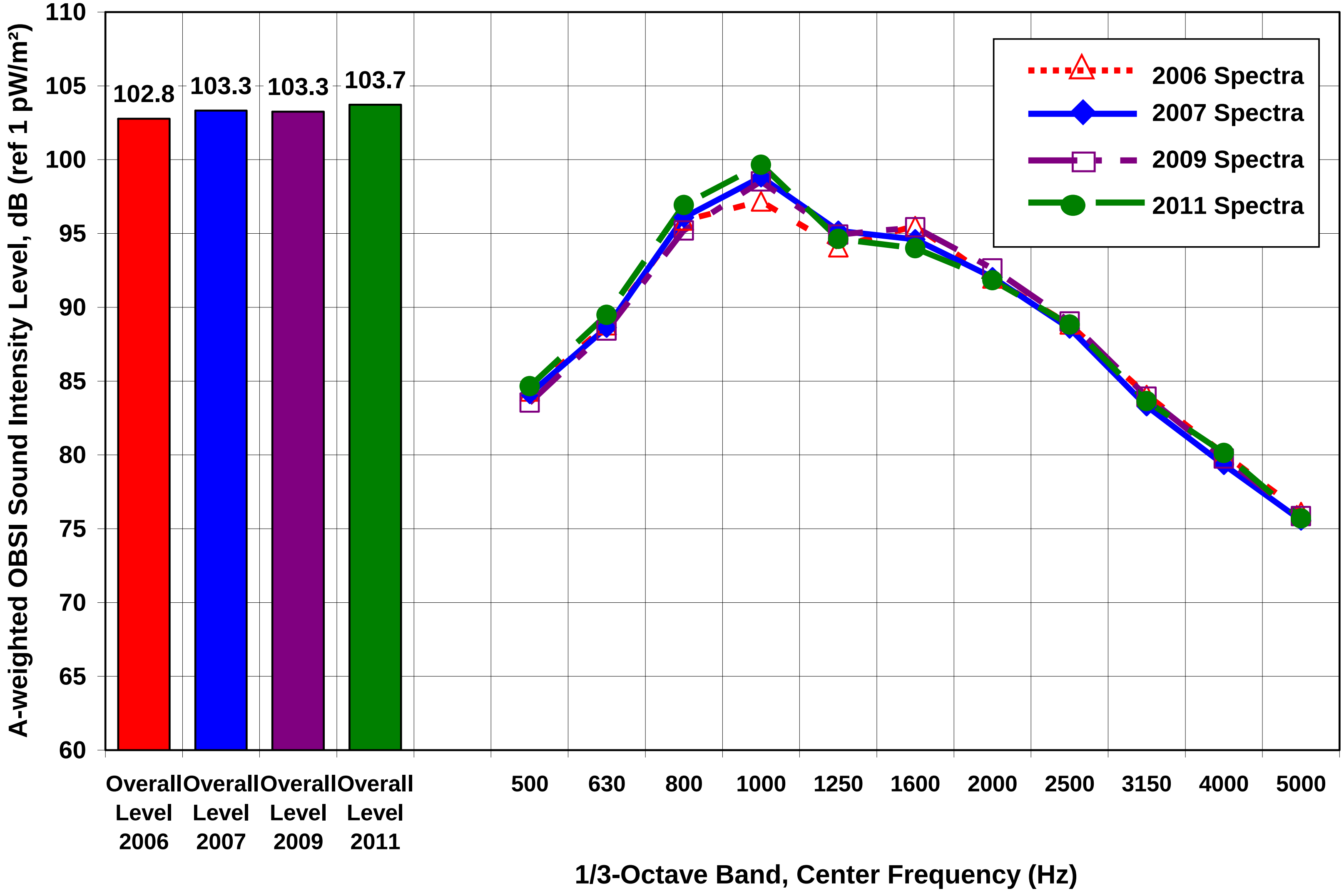
	NB Lane 2 (Outside)	**NB Lane 1 (Inside)**	**SB Lane 1 (Inside)**	**SB Lane 2 (Outside)**
Distance from Mic (ft.)	50	62	104	116
Average Speed (mph)	59		61	
Automobile	329	288	354	241
Heavy Truck	4	1	1	8
Medium Truck	52	1	3	5
Bus	0	0	0	0
Motorcycle	4	1	4	2
Auto + 1-Axle Trlr.	1	2	4	3
Auto + 2-Axle Trlr.	4	1	2	5
M. Trk. + 1-Axle Trlr.	0	0	0	1
M. Trk. + 2-Axle Trlr.	0	0	0	0

** Note: for 50 ft mic positions*

A-Weighted Time Averaged Sound Pressure Levels during Sample Period (dB ref 20 µPa)

Mic Position (ft) Distance × Height	**Block 1**	**Block 2**	**Block 3**	**Block 4**	**Average**
50×5	66.5	65.3	65.0	64.9	**65.4**
25×4	74.0	73.0	72.8	73.1	**73.2**
50×12	71.4	70.7	70.5	70.7	**70.8**

Site: 16
OBSI (SRTT) Test Information



Site: 17
General Information

Highway: Interstate 70, Westbound
Location: Between SH 13 & US 6/24, Rifle (81650)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 39.5205 / 107.8229 / 5290

Nominal Surface: Concrete (Diamond Grinding) **Construction Accepted:** 11/2005

OBSI?: Yes **Pass-by?:** Yes
Total Section Length: 6368 ft.
Distance from Begin to Wayside Microphone: 1177 ft.

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 17
Time-Averaged Wayside Test Information

Sampling Periods: 1

Sample Period 1 – 4 Blocks @ 15 min ea. = 60 min. (11:45 am to 1:15 pm MDT, 6/27/11)

Traffic Volumes and Speeds during Sample Period

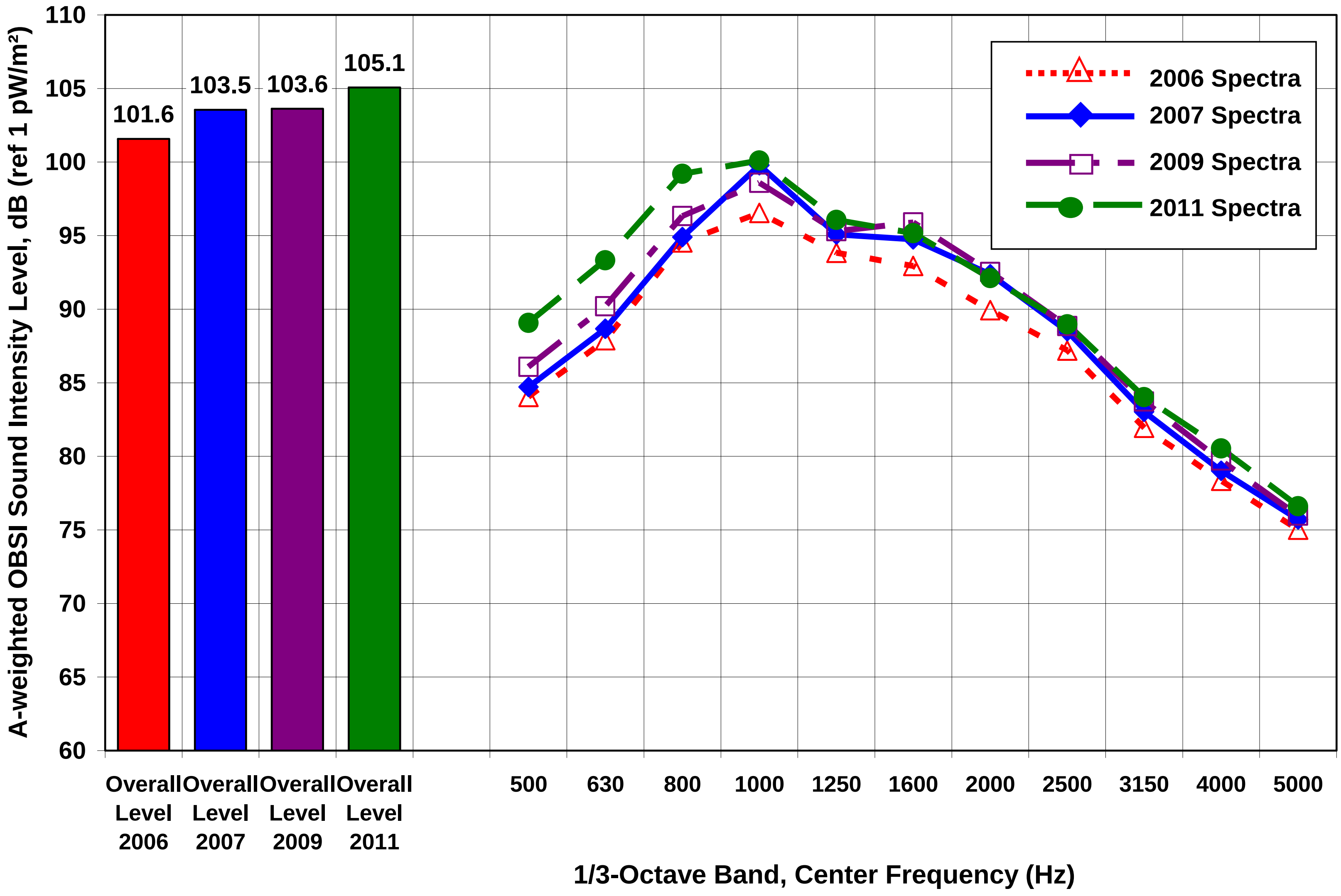
	WB Lane 2 (Outside)	**WB Lane 1 (Inside)**	**EB Lane 1 (Inside)**	**EB Lane2 (Outside)**
Distance from Mic (ft.)	50	62	174	186
Average Speed (mph)	74		78	
Automobile	311	181	212	321
Heavy Truck	72	15	12	52
Medium Truck	16	0	4	27
Bus	1	0	0	0
Motorcycle	6	2	5	5
Auto + 1-Axle Trlr.	7	2	7	21
Auto + 2-Axle Trlr.	10	2	53	33
M. Trk. + 1-Axle Trlr.	0	0	0	0
M. Trk. + 2-Axle Trlr.	4	1	0	6

** Note: for 50 ft mic positions*

A-Weighted Time Averaged Sound Pressure Levels during Sample Period (dB ref 20 μPa)

Mic Position (ft) Distance × Height	**Block 1**	**Block 2**	**Block 3**	**Block 4**	**Average**
50×5	74.5	74.6	74.8	75.7	**74.9**
25×4	79.8	80.0	80.1	80.8	**80.2**
50×12	76.6	76.9	76.9	77.5	**77.0**

Site: 17
OBSI (SRTT) Test Information



Site: 18
General Information

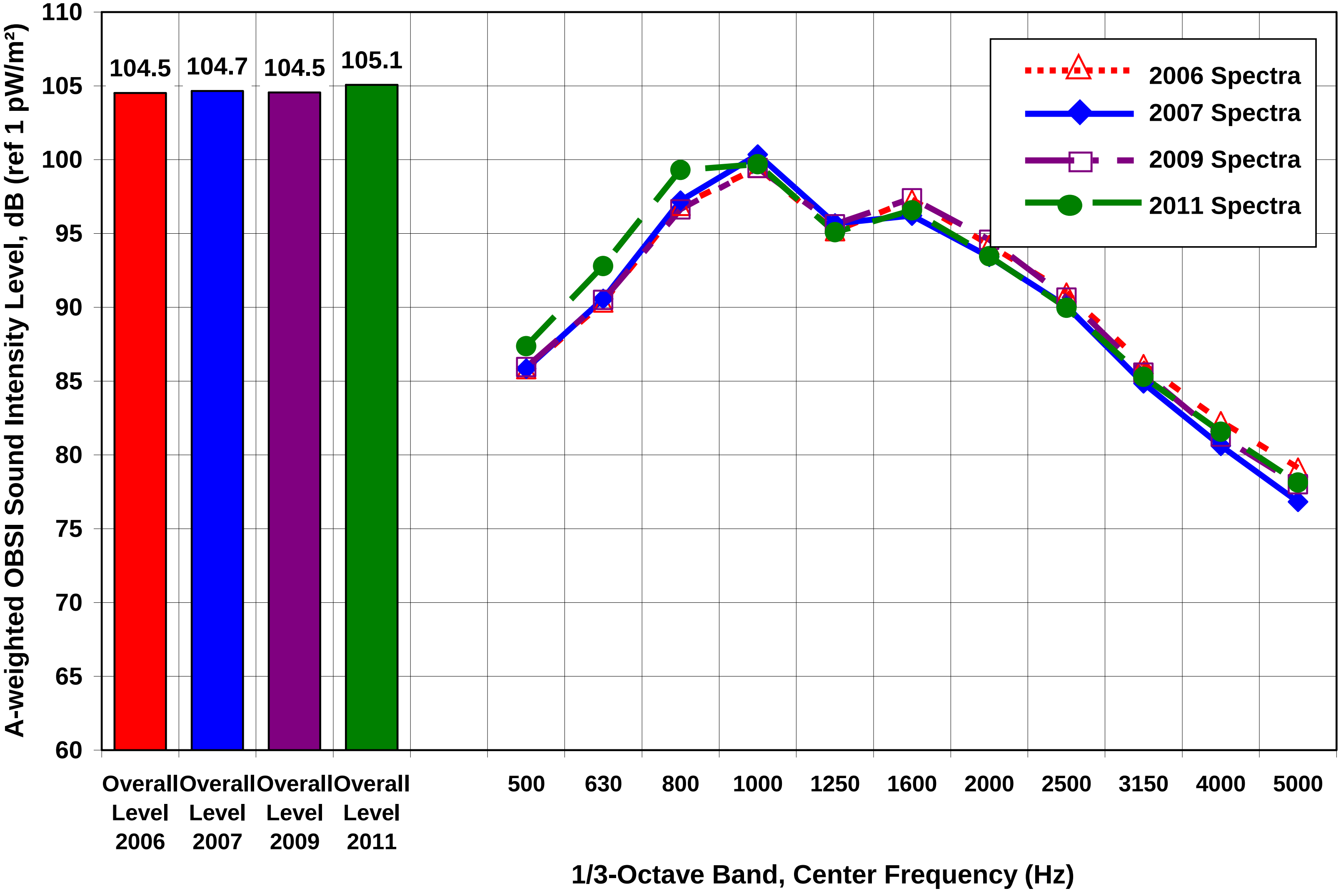
Highway: US Highway 285, Northbound
Location: Between Turkey Creek Rd. & Chamberlain Rd., Indian Hills (80465)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 39.598 / 105.2255 / 7050

Nominal Surface: Concrete (Diamond Grinding) **Construction Accepted:** 10/1999

OBSI?: Yes **Pass-by?:** No
Total Section Length: 2069 ft.
Distance from Begin to Wayside Microphone: n/a

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 18
OBSI (SRTT) Test Information



Site: 19
General Information

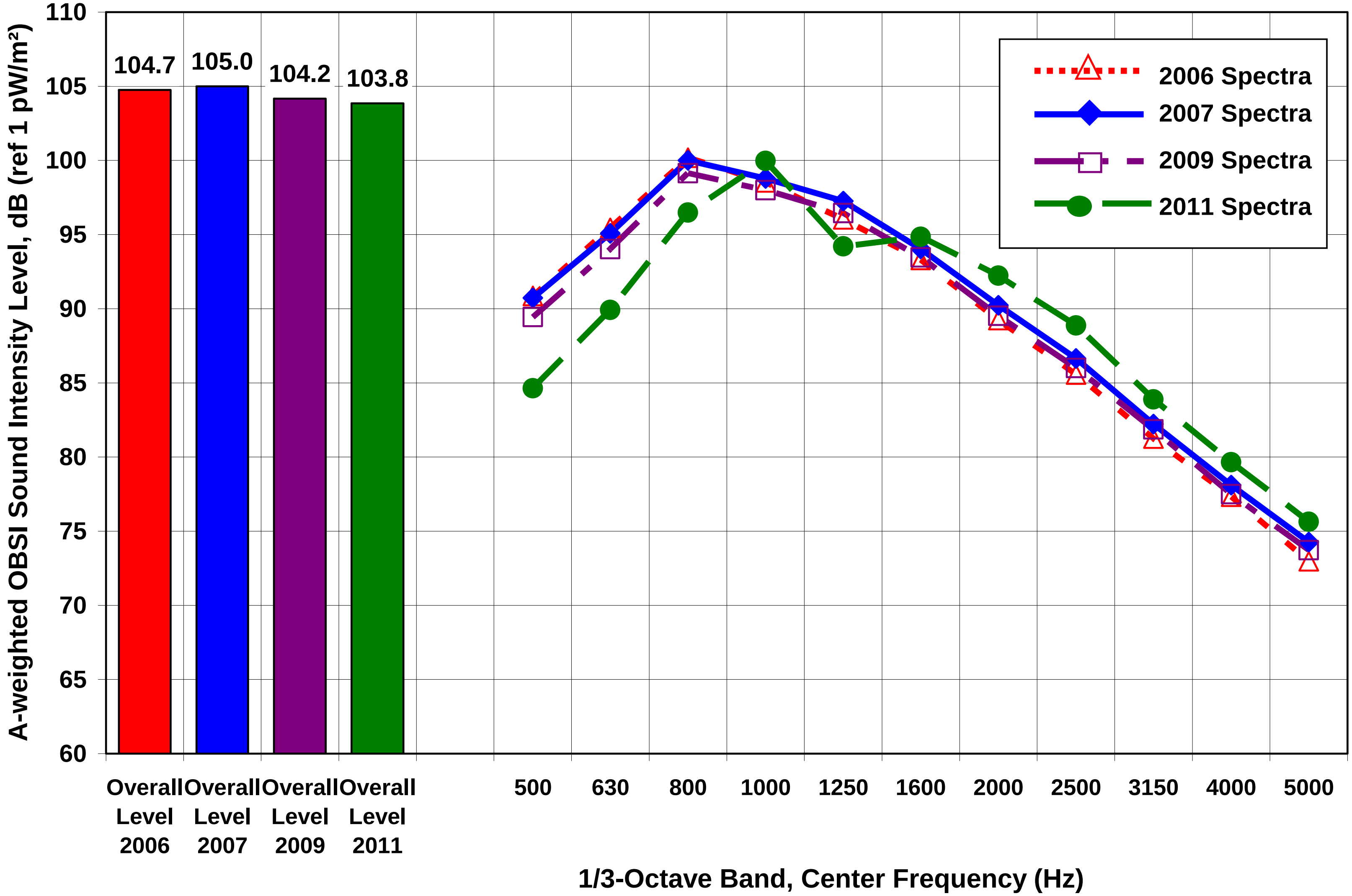
Highway: Interstate 70, Westbound
Location: Between Camino Dorado Rd. & Trail Gulch Rd., Gypsum (81637)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 39.6528 / 106.8823 / 6630

Nominal Surface: SMA **Construction Accepted:** 8/1996

OBSI?: Yes **Pass-by?:** No
Total Section Length: 3122 ft.
Distance from Begin to Wayside Microphone: 443 ft.

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 19
OBSI (SRTT) Test Information



Site: 20
General Information

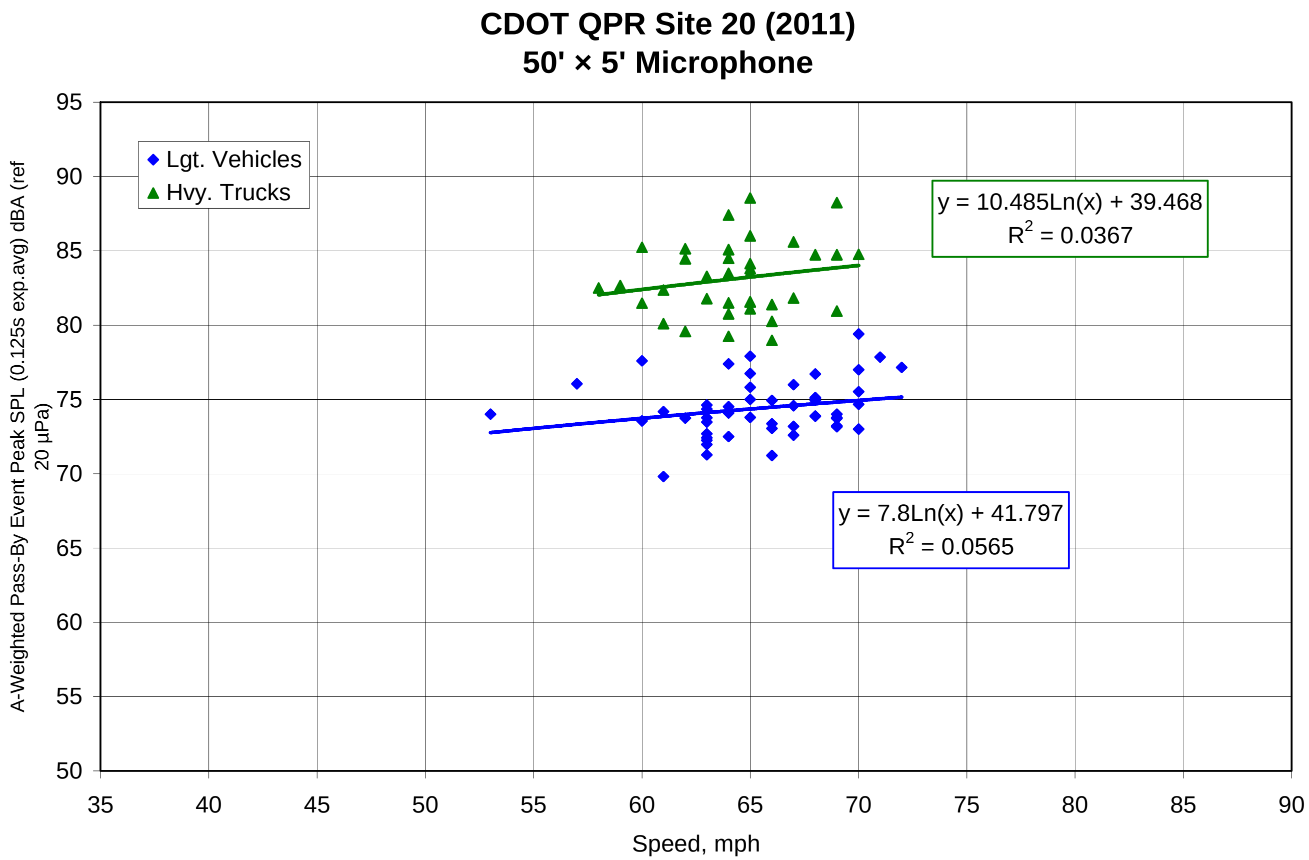
Highway: US Highway 40, Westbound
Location: Between CR-8 & SH 94, Kit Carson (80862)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 38.8328 / 103.054 / 4520

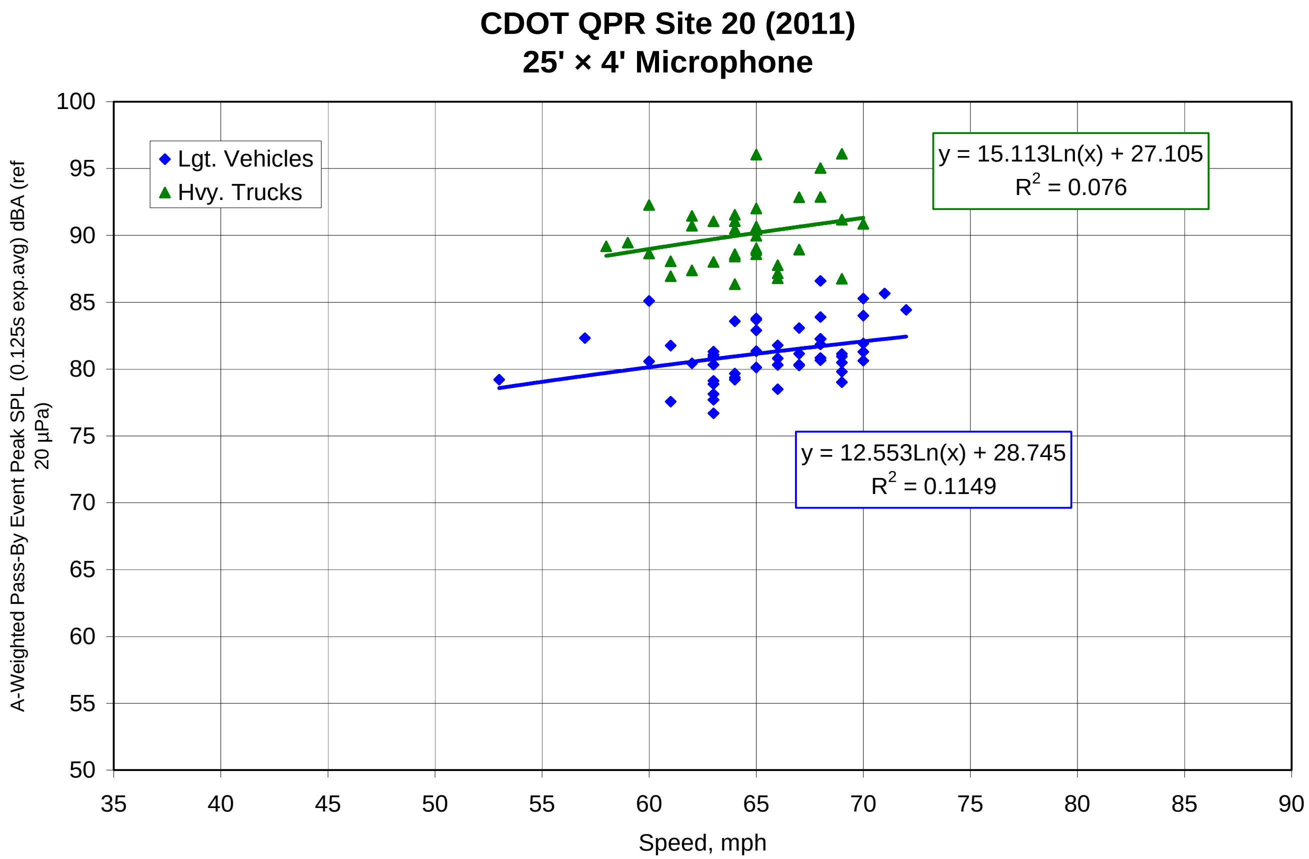
Nominal Surface: Concrete **Construction Accepted:** 4/2002

OBSI?: Yes **Pass-by?:** Yes
Total Section Length: 5241 ft.
Distance from Begin to Wayside Microphone: 2668 ft.

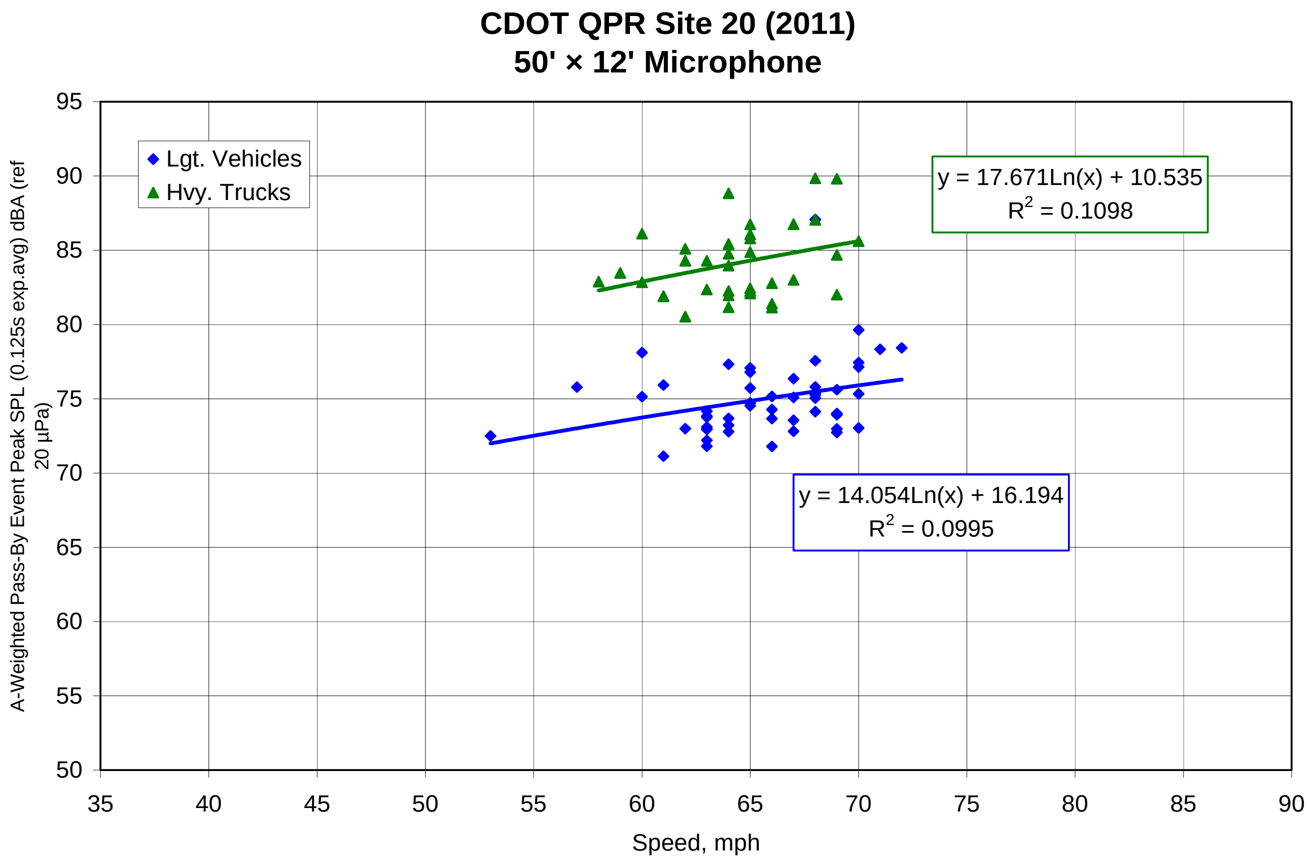
Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 20
SPB Wayside Test Information





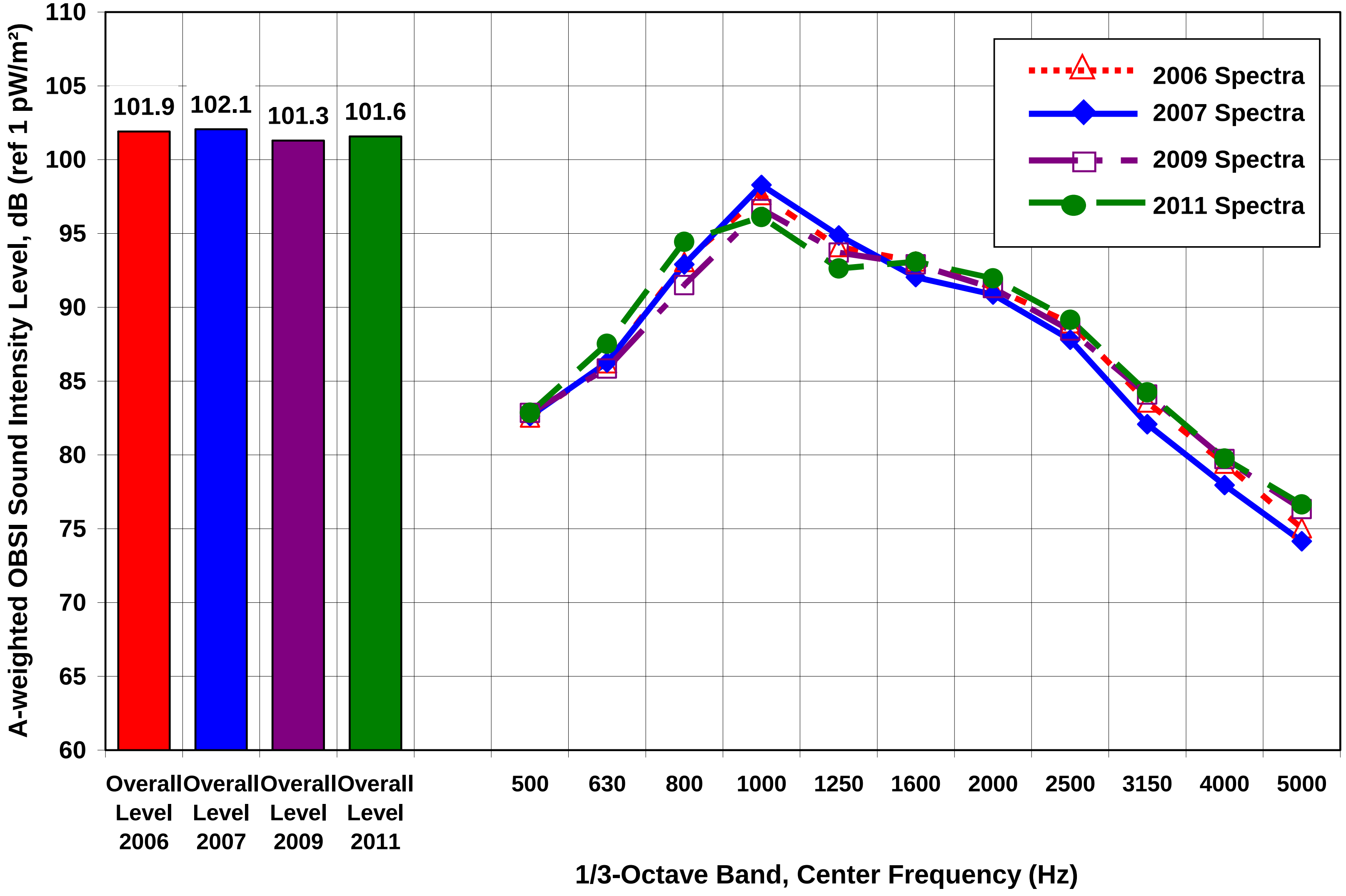
CDOT QPR Site 20 (2011)
25' × 4' Microphone
Lgt. Vehicles
Hvy. Trucks
y = 15.113Ln(x) + 27.105
R2 = 0.076
y = 12.553Ln(x) + 28.745
R2 = 0.1149
A-Weighted Pass-By Event Peak SPL (0.125s exp.avg) dBA (ref 20 µPa)
Speed, mph
100
95
90
85
80
75
70
65
60
55
50
35
40
45
50
55
60
65
70
75
80
85
90



Average A-weighted SPB Level at 60 mph (dB ref 20 µPa), SPBI

Vehicle	50×5 microphone	25×4 microphone	50×12 microphone
Lgt. Vehicle (Car)	**73.7**	**80.1**	**73.7**
Hvy. Truck	**82.4**	**89.0**	**82.9**

Site: 20
OBSI (SRTT) Test Information



Site: 21
General Information

Highway: US Highway 285, Southbound
Location: Between Kipling Pkwy. & C-470, Morrison (80227)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 39.6438 / 105.1318 / 5700

Nominal Surface: Asphalt (S, 3/4") **Construction Accepted:** 11/2003

OBSI?: Yes **Pass-by?:** Yes
Total Section Length: 3599 ft.
Distance from Begin to Wayside Microphone: 1451 ft.

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 21
Time-Averaged Wayside Test Information

Sampling Periods: 2 (TA and SPB+)

Sample Period 1 – 4 Blocks @ 15 min ea. = 60 min. (1:30 pm to 3:00 pm, 6/1/11)

Traffic Volumes and Speeds during Sample Period 1

	EB Lane 2 (Outside)	EB Lane 1 (Inside)	WB Lane 1 (Inside)	WB Lane2 (Outside)
Distance from Mic (ft.)	50	62	110	122
Average Speed (mph)	66		67	
Automobile	366	151	212	465
Heavy Truck	20	2	2	19
Medium Truck	13	2	3	10
Bus	0	0	0	3
Motorcycle	8	1	0	3
Auto + 1-Axle Trlr.	7	1	1	4
Auto + 2-Axle Trlr.	5	1	0	2
M. Trk. + 1-Axle Trlr.	0	0	0	1
M. Trk. + 2-Axle Trlr.	1	0	0	1

** Note: for 50 ft mic positions*

A-Weighted Time Averaged Sound Pressure Levels during Sample Period 1 (dB ref 20 μPa)

Mic Position (ft) Distance × Height	Block 1	Block 2	Block 3	Block 4	Average
50×5	74.3	75.0	75.7	74.6	**74.9**
25×4	78.1	78.4	79.1	78.0	**78.4**
50×12	75.1	75.4	76.0	75.2	**75.4**

Sample Period 2 (SPB +) – 4 Blocks @ 15 min ea. = 60 min. (10:15 am to 12:00 pm MDT, 6/1/11)

Traffic Volumes and Speeds during Sample Period 2

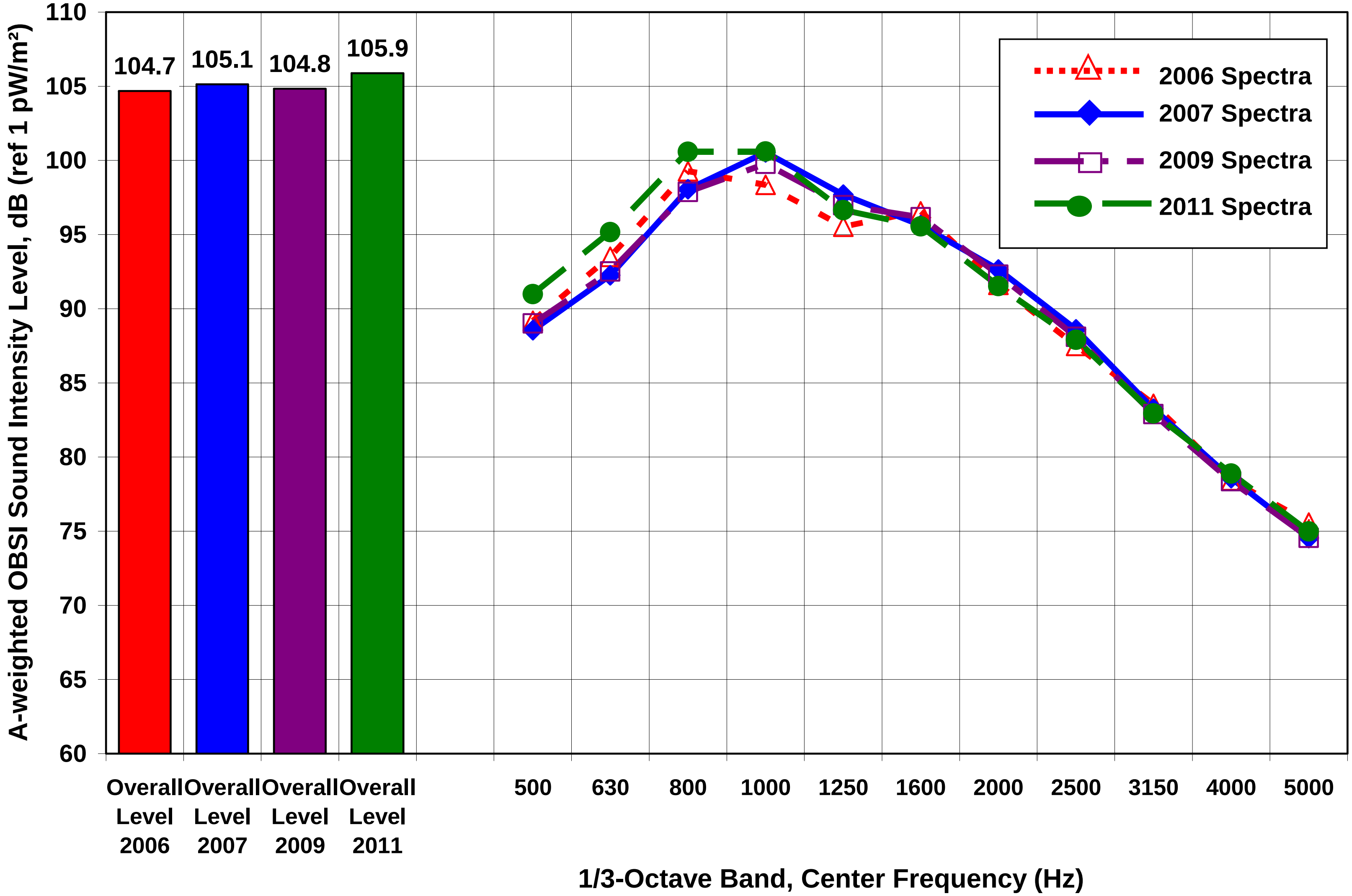
	EB Lane 2 (Outside)	**EB Lane 1 (Inside)**	**WB Lane 1 (Inside)**	**WB Lane2 (Outside)**
Distance from Mic (ft.)	50	62	110	122
Average Speed (mph)	67		67	
Automobile	336	146	170	430
Heavy Truck	21	3	5	20
Medium Truck	11	0	2	12
Bus	0	0	0	0
Motorcycle	4	2	1	9
Auto + 1-Axle Trlr.	3	1	0	4
Auto + 2-Axle Trlr.	1	1	0	6
M. Trk. + 1-Axle Trlr.	0	0	0	0
M. Trk. + 2-Axle Trlr.	1	0	1	1

** Note: for 50 ft mic positions*

A-Weighted Time Averaged Sound Pressure Levels during Sample Period 2 (dB ref 20 µPa)

Mic Position (ft) Distance × Height	**Block 1**	**Block 2**	**Block 3**	**Block 4**	**Average**
50×5	74.3	74.0	73.8	74.2	**74.1**
100 × 5	70.6	70.3	70.1	70.5	**70.4**
200 × 5	66.0	66.6	65.8	66.2	**66.1**

Site: 21
OBSI (SRTT) Test Information



Site: 22
General Information

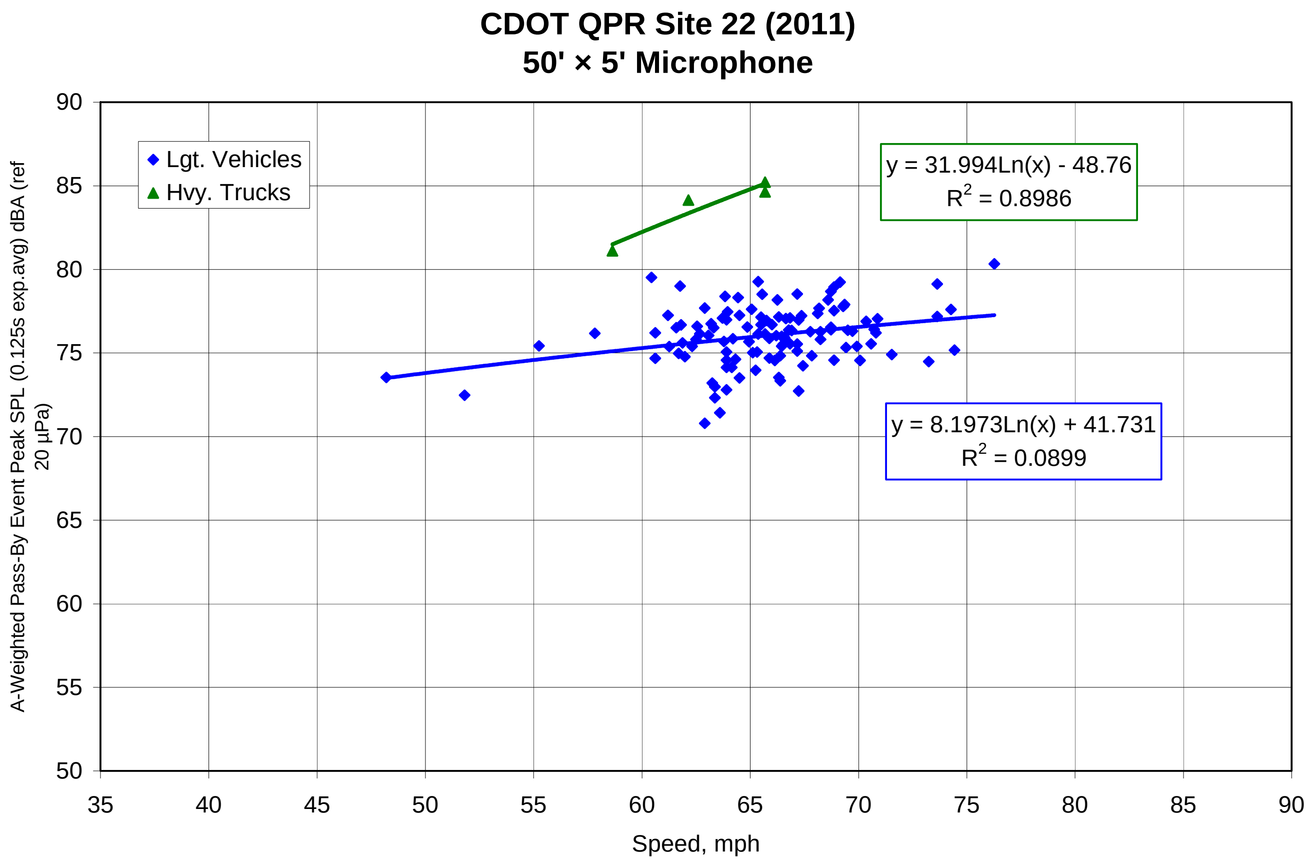
Highway: US Highway 160, Westbound
Location: Between CR-103 & Threemile Rd., Alamosa (81101)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 37.5177 / 105.9948 / 7610

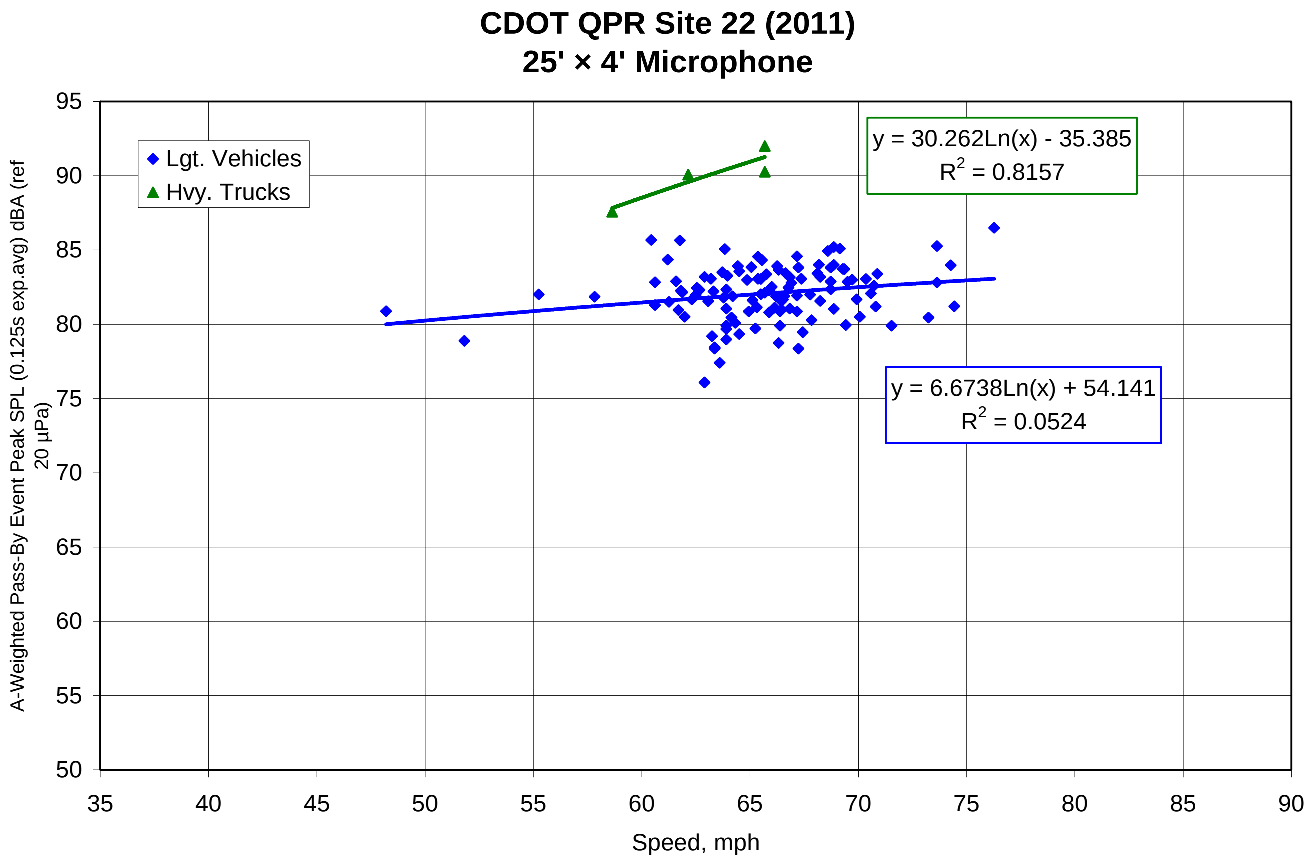
Nominal Surface: Asphalt **Construction Accepted:** 10/1999

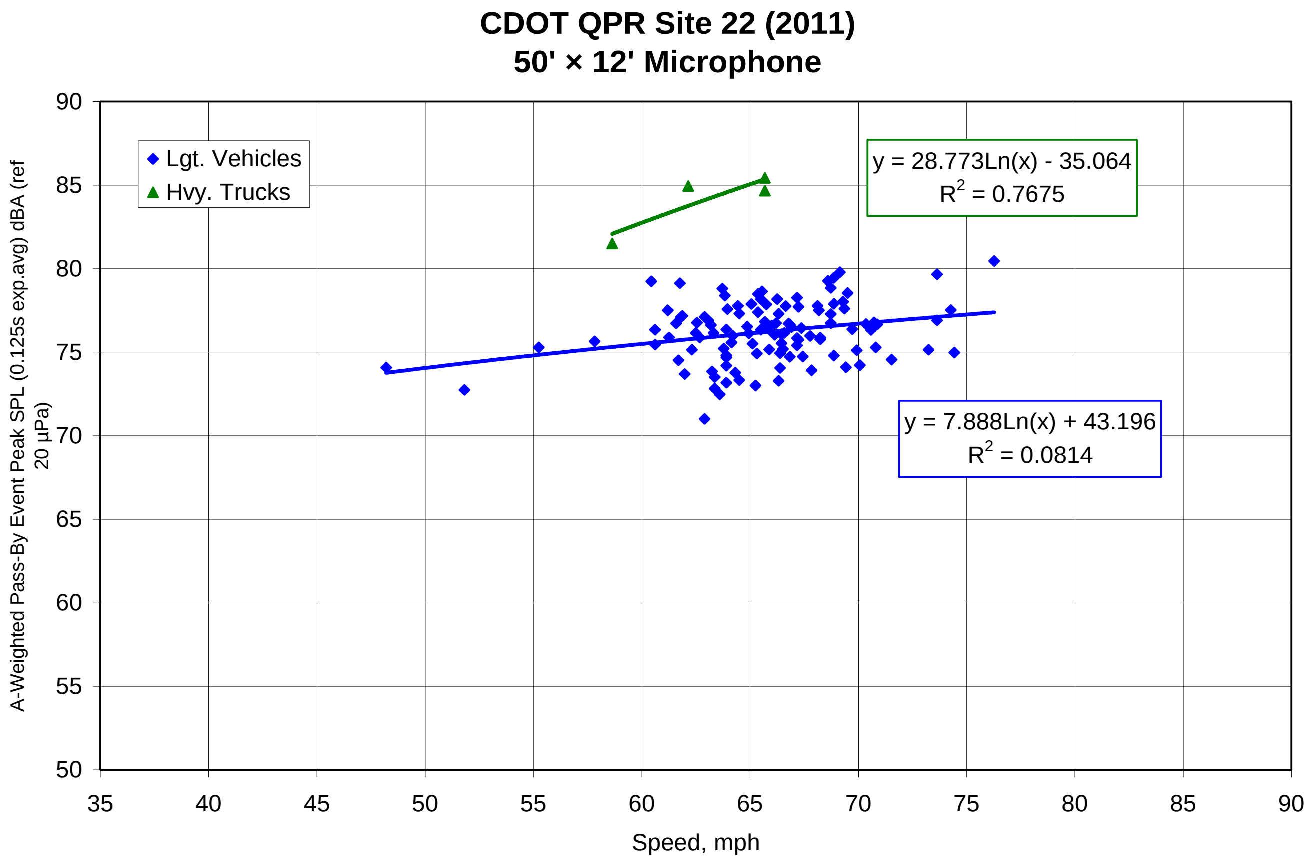
OBSI?: Yes **Pass-by?:** Yes
Total Section Length: 2930 ft.
Distance from Begin to Wayside Microphone: 796 ft.

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 22
SPB Wayside Test Information




CDOT QPR Site 22 (2011)
25' × 4' Microphone
Lgt. Vehicles
Hvy. Trucks
y = 30.262Ln(x) - 35.385
R2 = 0.8157
y = 6.6738Ln(x) + 54.141
R2 = 0.0524
A-Weighted Pass-By Event Peak SPL (0.125s exp.avg) dBA (ref 20 µPa)
Speed, mph
95
90
85
80
75
70
65
60
55
50
35
40
45
50
55
60
65
70
75
80
85
90

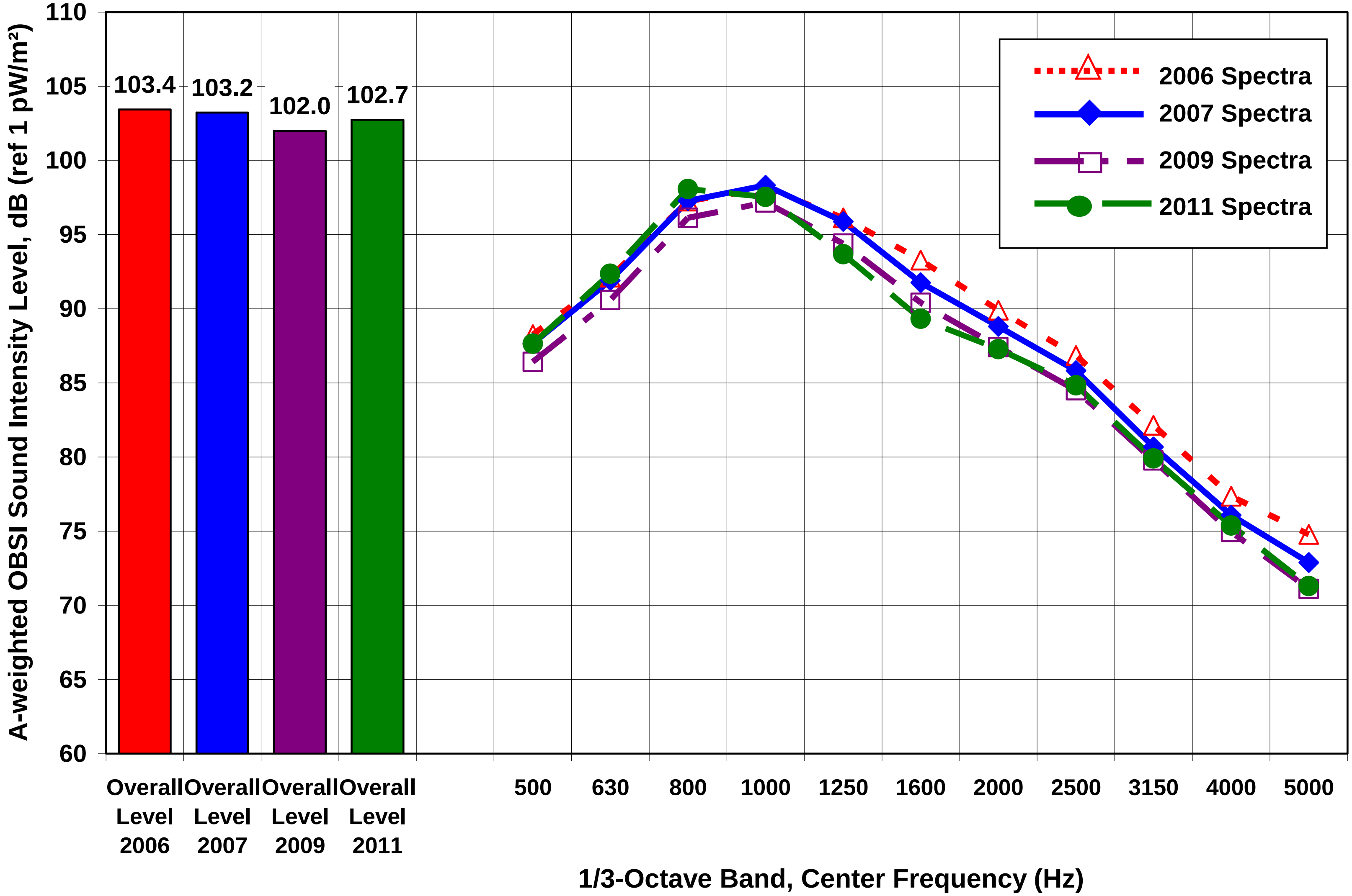


Average A-weighted SPB Level at 60 mph (dB ref 20 μPa), SPBI

Vehicle	50×5 microphone	25×4 microphone	50×12 microphone
Lgt. Vehicle (Car)	**75.3**	**81.5**	**75.5**
Hvy. Truck	Note 1	Note 1	Note 1

Notes: (1) Insufficient number of vehicles.

Site: 22
OBSI (SRTT) Test Information



Site: 23

General Information

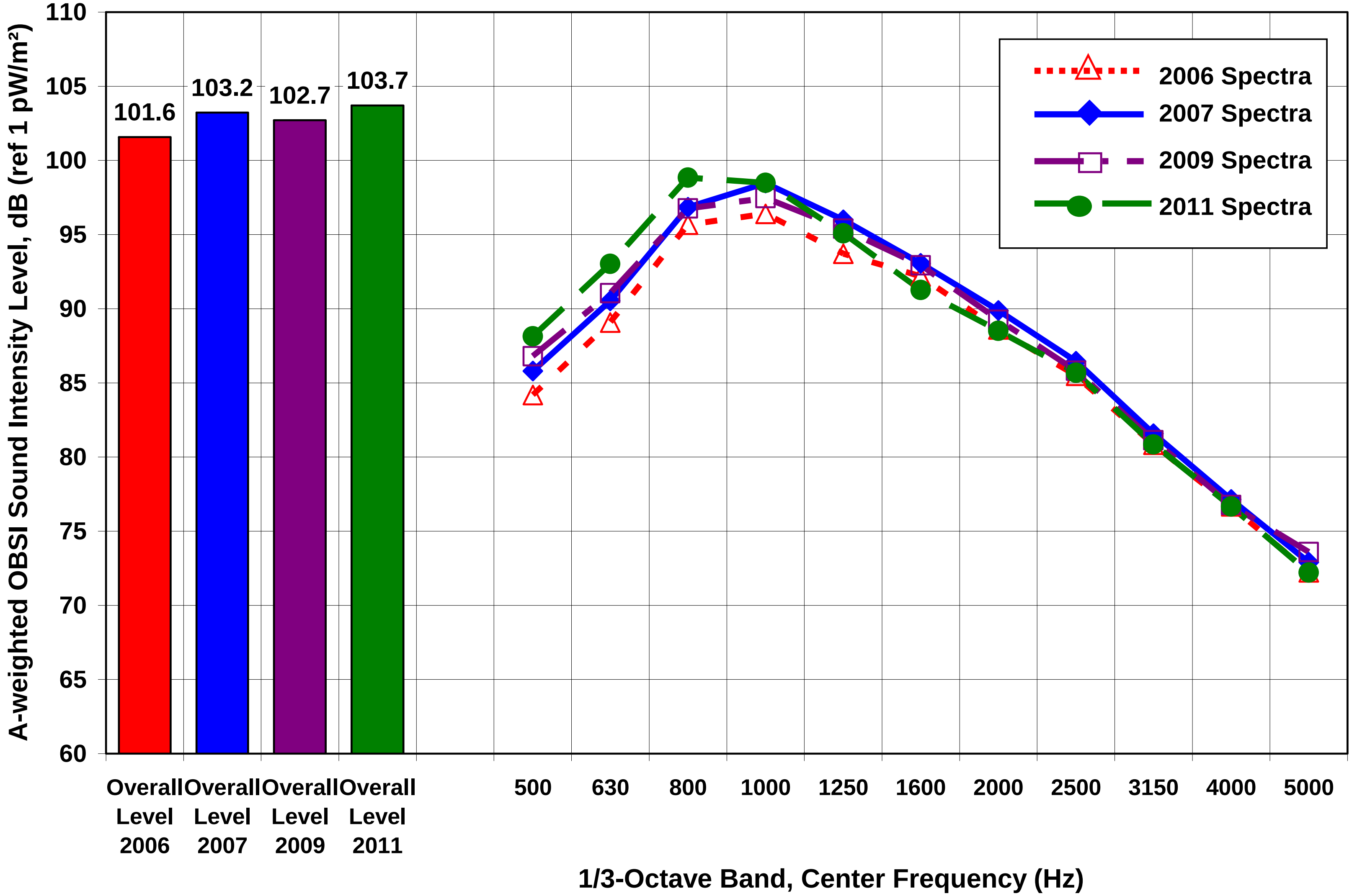
Highway: Interstate 70, Eastbound
Location: Between 23 Rd. & 24 Rd., Grand Junction (81505)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 39.1138 / 108.6193 / 4560

Nominal Surface: Asphalt **Construction Accepted:** 10/2004

OBSI?: Yes **Pass-by?:** No
Total Section Length: 3623 ft.
Distance from Begin to Wayside Microphone: n/a

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 23
OBSI (SRTT) Test Information



Site: 24
General Information

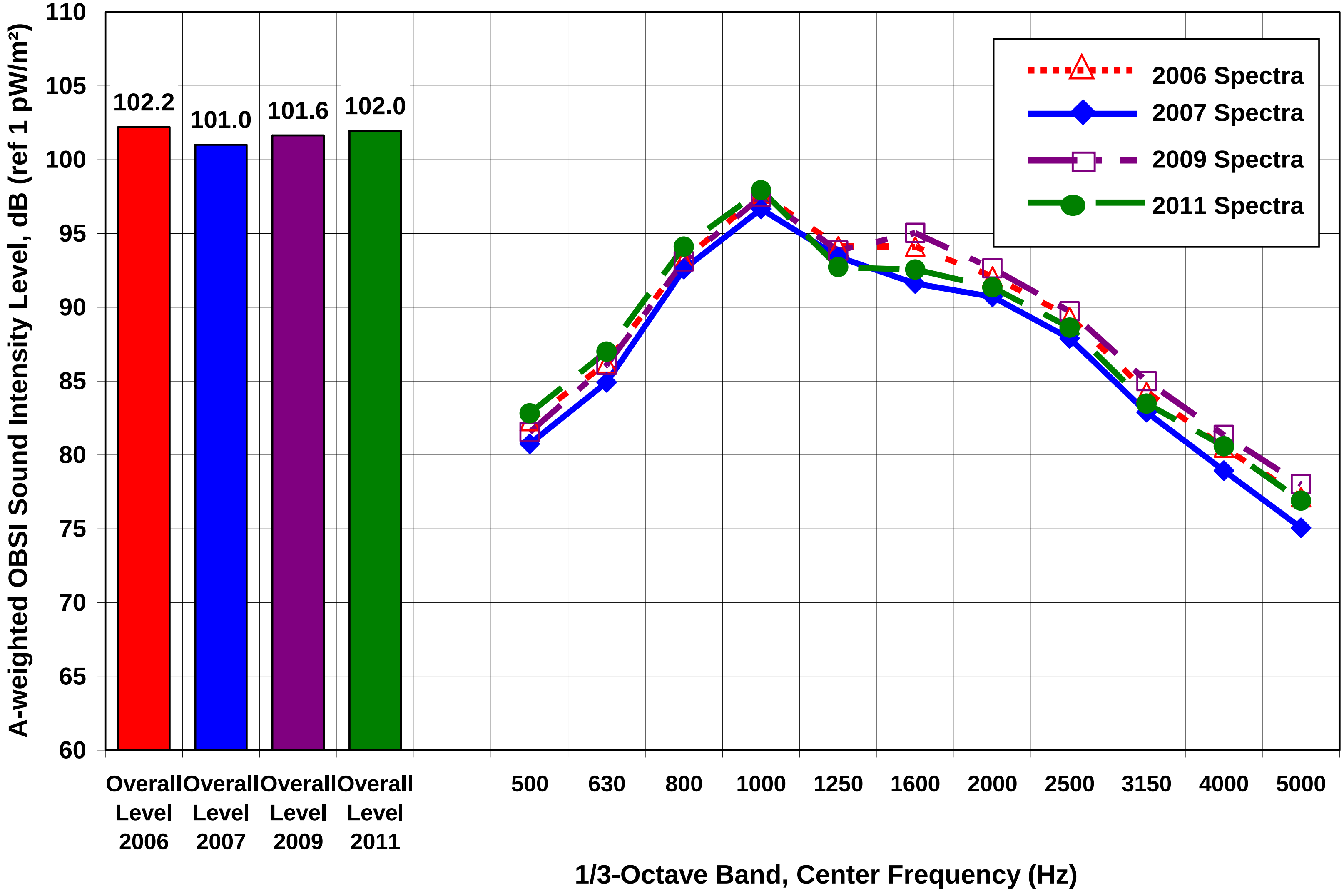
Highway: Interstate 76, Westbound
Location: Between CR-49 & SH 52, Hudson (80642)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 40.0942 / 104.6143 / 4940

Nominal Surface: Concrete **Construction Accepted:** 3/2001

OBSI?: Yes **Pass-by?:** No
Total Section Length: 3345 ft.
Distance from Begin to Wayside Microphone: n/a

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 24
OBSI (SRTT) Test Information



Site: 25
General Information

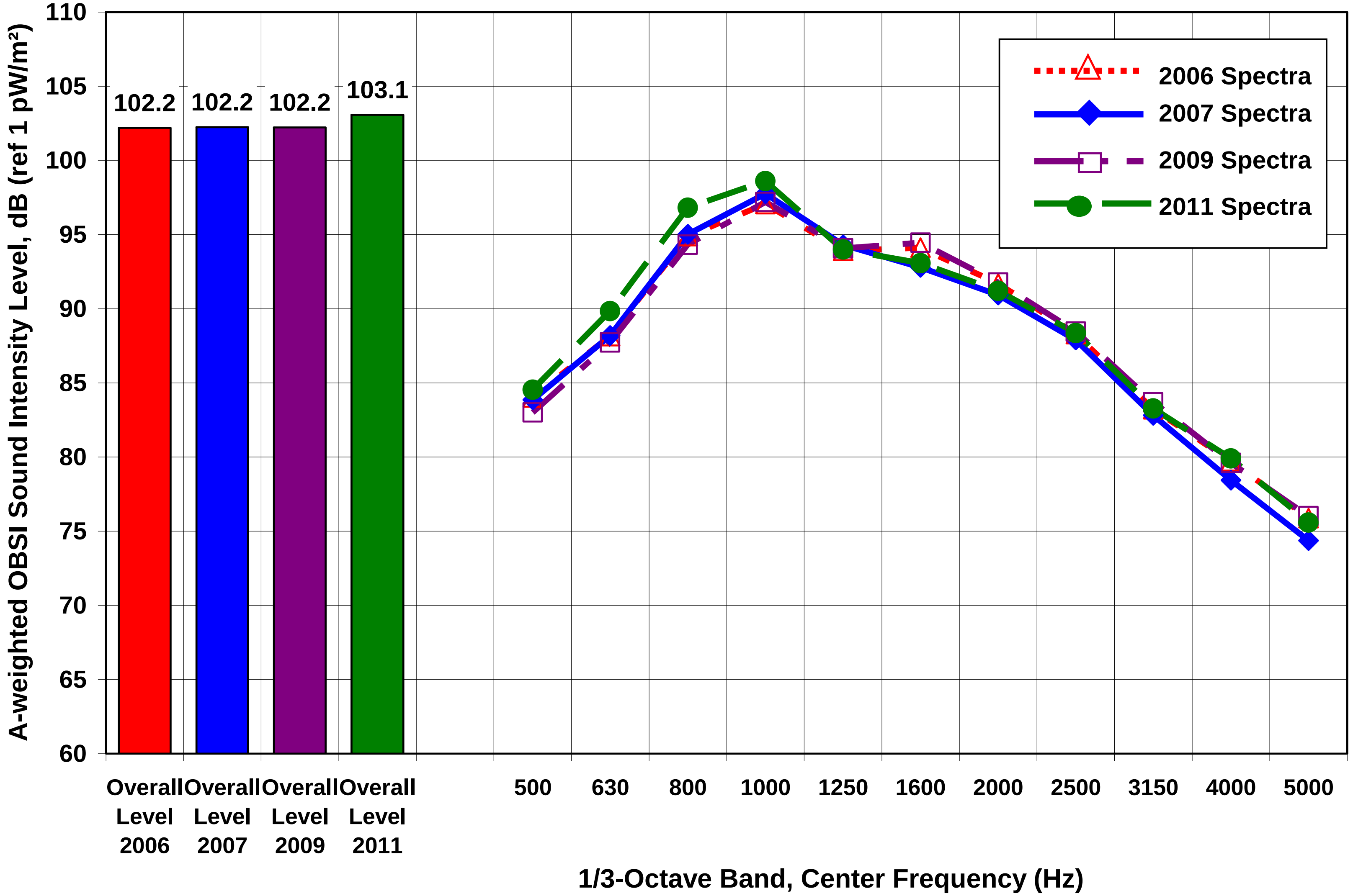
Highway: Interstate 76, Eastbound
Location: Between 88th Ave. & 96th Ave., Henderson (80640)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 39.8655 / 104.9059 / 5120

Nominal Surface: Concrete **Construction Accepted:** 11/2002

OBSI?: Yes **SPB Pass-by?:** No
Total Section Length: 2495 ft.
Distance from Begin to Wayside Microphone: n/a

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 25
OBSI (SRTT) Test Information



Site: 26
General Information

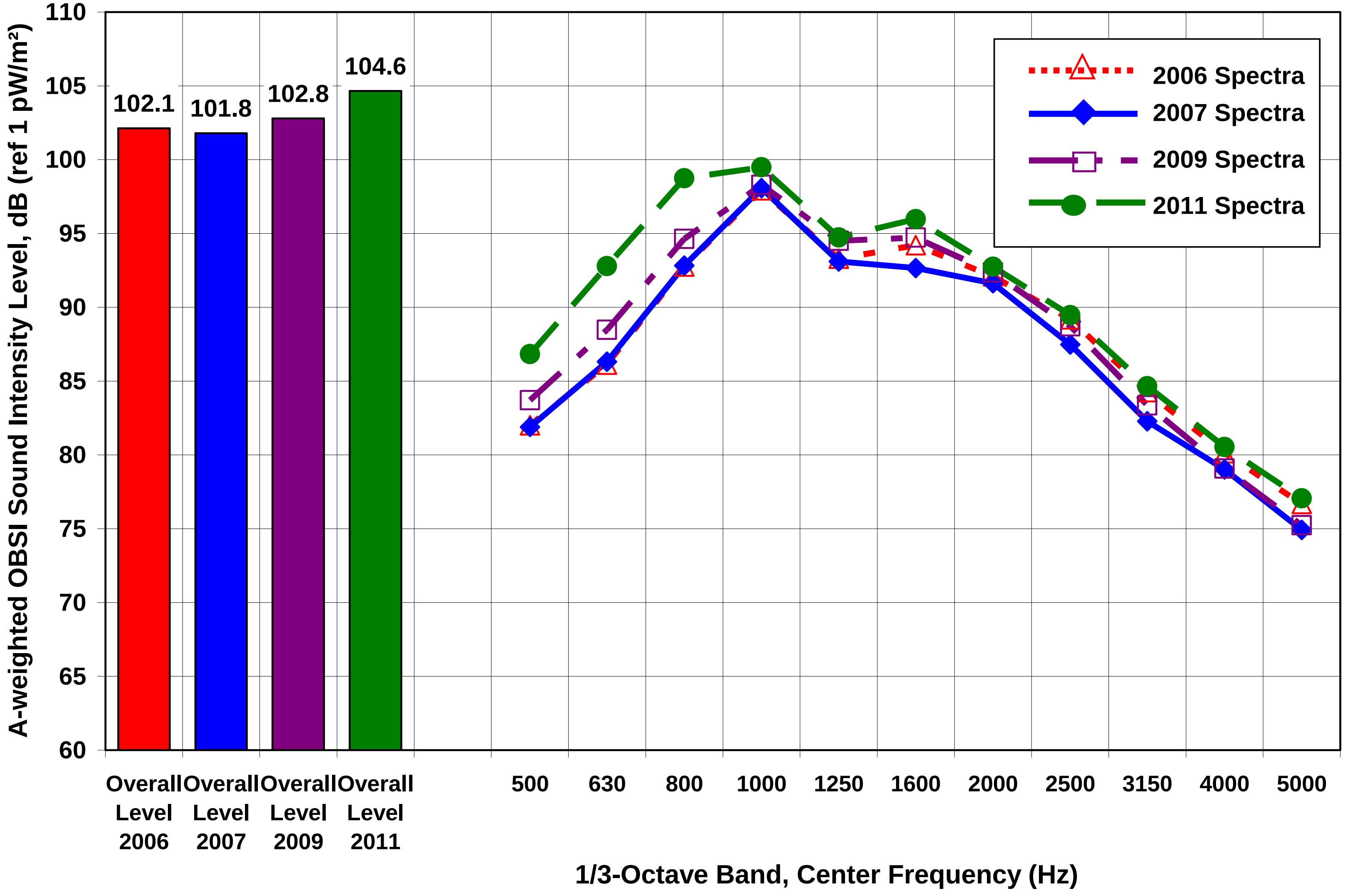
Highway: Interstate 25, Southbound
Location: Between SH 105 & Higby Rd., Monument (80132)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 39.0862 / 104.8614 / 7010

Nominal Surface: Concrete **Construction Accepted:** 10/1996

OBSI?: Yes **Pass-by?:** No
Total Section Length: 1493 ft.
Distance from Begin to Wayside Microphone: n/a

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 26
OBSI (SRTT) Test Information



Site: 27
General Information

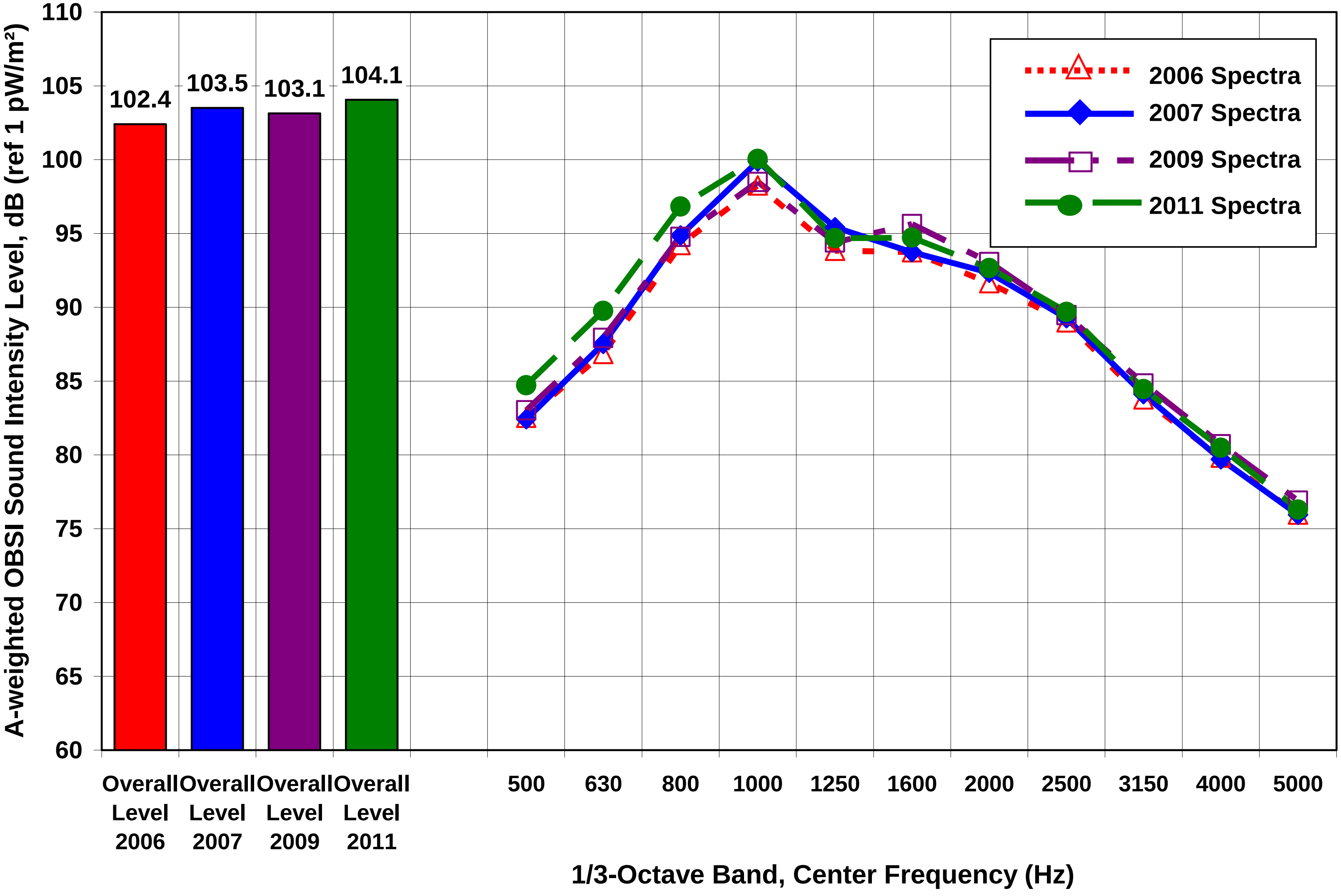
Highway: Highway C-470, Westbound (Northbound)
Location: Between Morrison Rd. & Alameda Pkwy., Morrison (80228)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 39.6759 / 105.1869 / 5890

Nominal Surface: Concrete **Construction Accepted:** 1/2001

OBSI?: Yes **Pass-by?:** No
Total Section Length: 7873 ft.
Distance from Begin to Wayside Microphone: n/a

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 27
OBSI (SRTT) Test Information

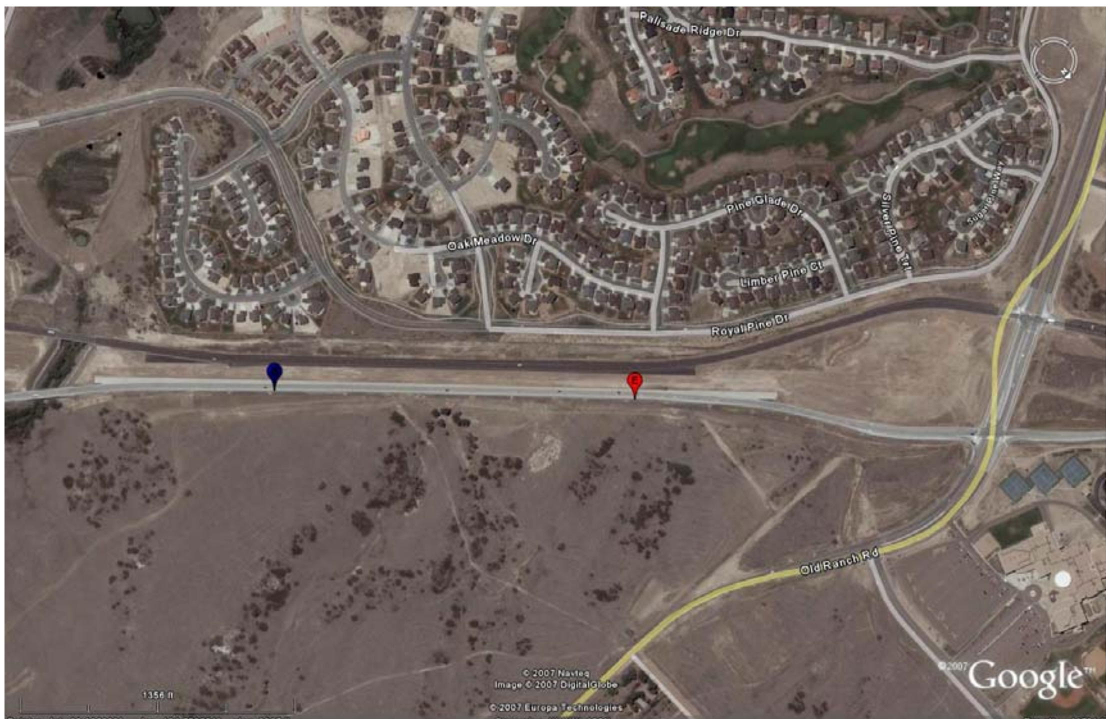


Site: 28
General Information

Highway: Powers Blvd., Northbound (Westbound)
Location: Between Union Blvd. & Old Ranch Rd., Colorado Springs (80908)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 38.9796 / 104.7574 / 7030

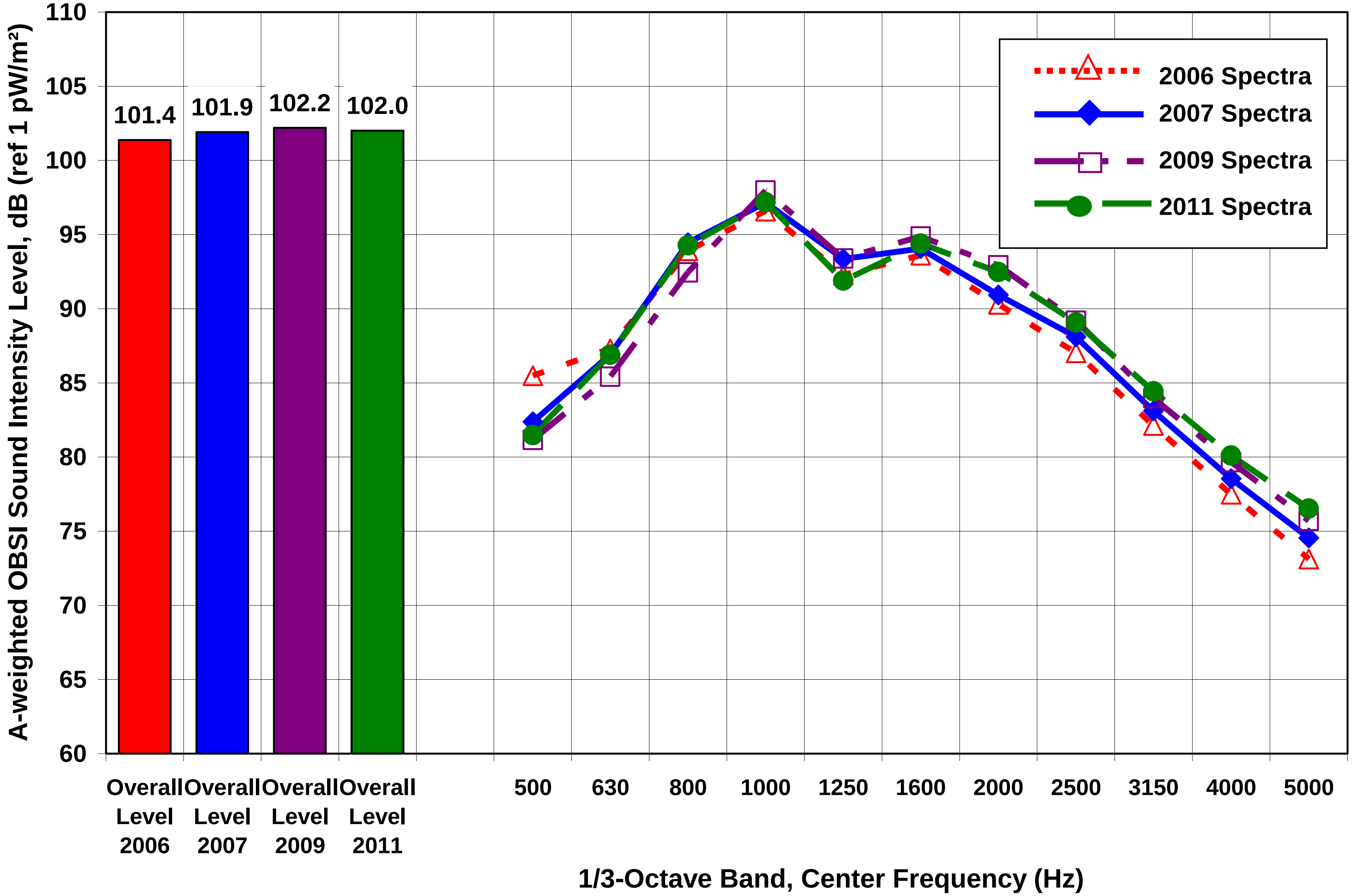
Nominal Surface: Concrete (Drag) **Construction Accepted:** 12/2004

OBSI?: Yes **Pass-by?:** No
Total Section Length: 1804 ft.
Distance from Begin to Wayside Microphone: n/a



Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 28
OBSI (SRTT) Test Information



Site: 29
General Information

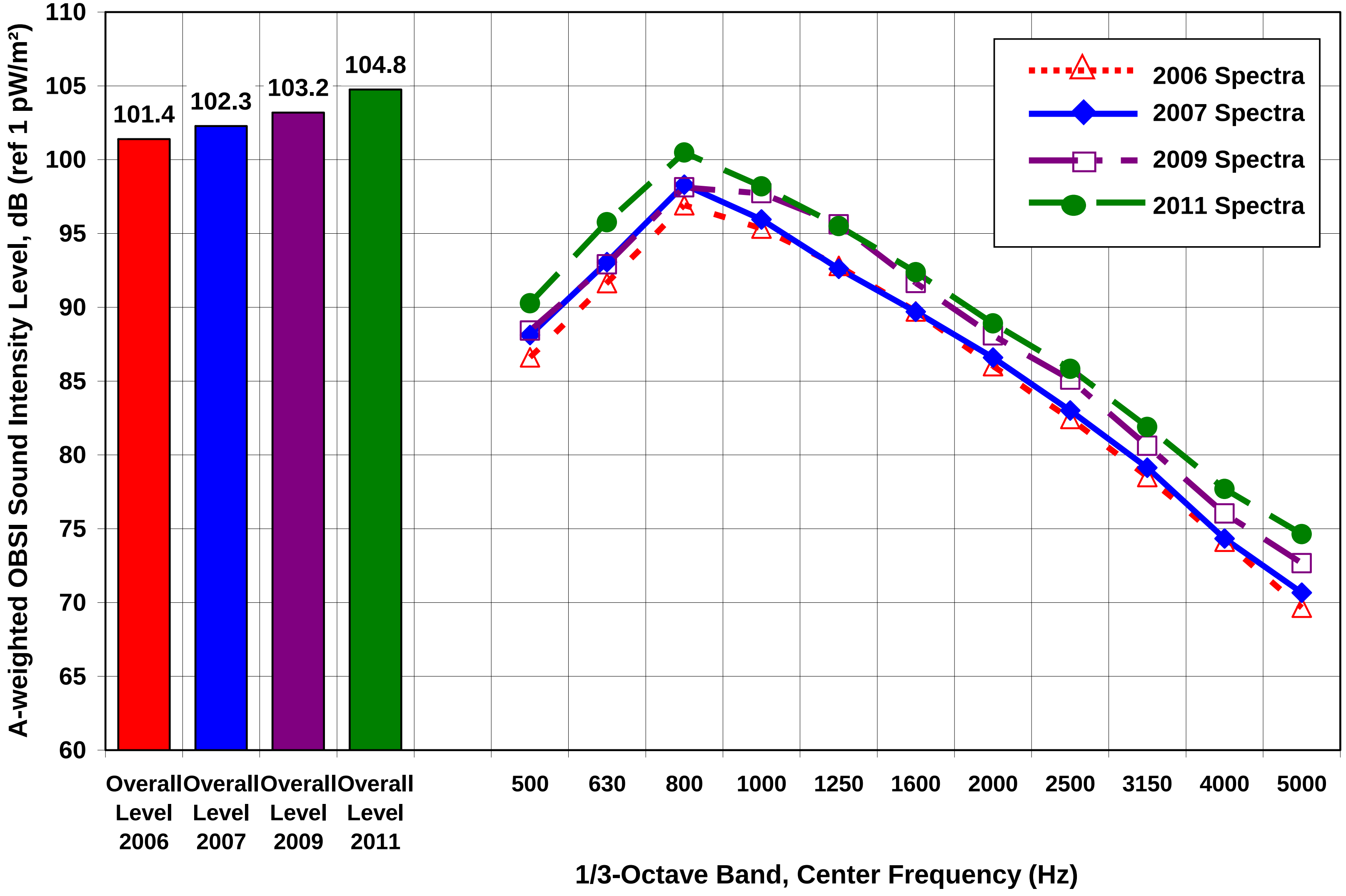
Highway: Powers Blvd., Southbound (Eastbound)
Location: Between Old Ranch Rd. & Union Blvd., Colorado Springs (80920)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 38.979 / 104.7575 / 6990

Nominal Surface: SMA **Construction Accepted:** 9/2005

OBSI?: Yes **Pass-by?:** No
Total Section Length: 1724 ft.
Distance from Begin to Wayside Microphone: n/a

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 29
OBSI (SRTT) Test Information



Site: 30
General Information

Highway: US Highway 85, Northbound
Location: Between Daniels Park Rd. & SH 67, Sedalia (80135)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 39.4365 / 104.9514 / 5870

Nominal Surface: Concrete (Burlap Drag) **Construction Accepted:** 2003

OBSI?: Yes **Pass-by?:** Yes
Total Section Length: 3019 ft.
Distance from Begin to Wayside Microphone: 2657

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 30
Time-Averaged Wayside Test Information

Sampling Periods: 1

Sample Period 1 – 4 Blocks @ 15 min ea. = 60 min. (9:15 am to 11:00 am MDT, 6/22/11)

Traffic Volumes and Speeds during Sample Period

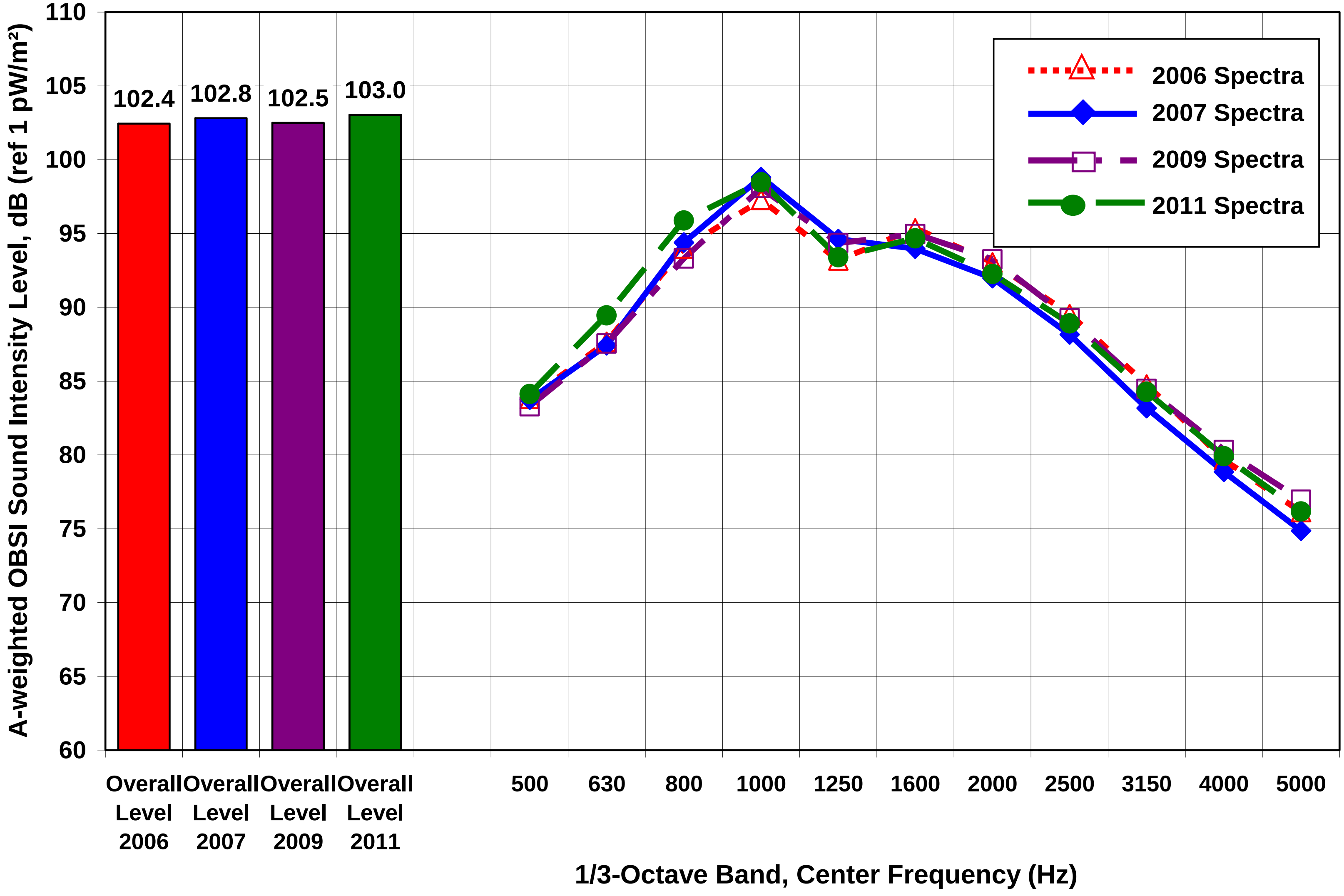
	NB Lane 2 (Outside)	**NB Lane 1 (Inside)**	**SB Lane 1 (Inside)**	**SB Lane2 (Outside)**
Distance from Mic (ft.)	50	62	90	102
Average Speed (mph)	55		57	
Automobile	187	183	167	240
Heavy Truck	14	4	3	16
Medium Truck	9	11	1	10
Bus	0	0	0	0
Motorcycle	2	4	0	2
Auto + 1-Axle Trlr.	2	1	1	6
Auto + 2-Axle Trlr.	5	1	1	9
M. Trk. + 1-Axle Trlr.	2	0	0	0
M. Trk. + 2-Axle Trlr.	1	1	0	1

** Note: for 50 ft mic positions*

A-Weighted Time Averaged Sound Pressure Levels during Sample Period (dB ref 20 µPa)

Mic Position (ft) Distance × Height	**Block 1**	**Block 2**	**Block 3**	**Block 4**	**Average**
50×5	67.8	67.6	67.7	67.6	**67.7**
25×4	71.2	71.3	71.5	71.1	**71.8**
50×12	69.4	69.2	69.3	69.1	**69.7**

Site: 30
OBSI (SRTT) Test Information



Site: 31
General Information

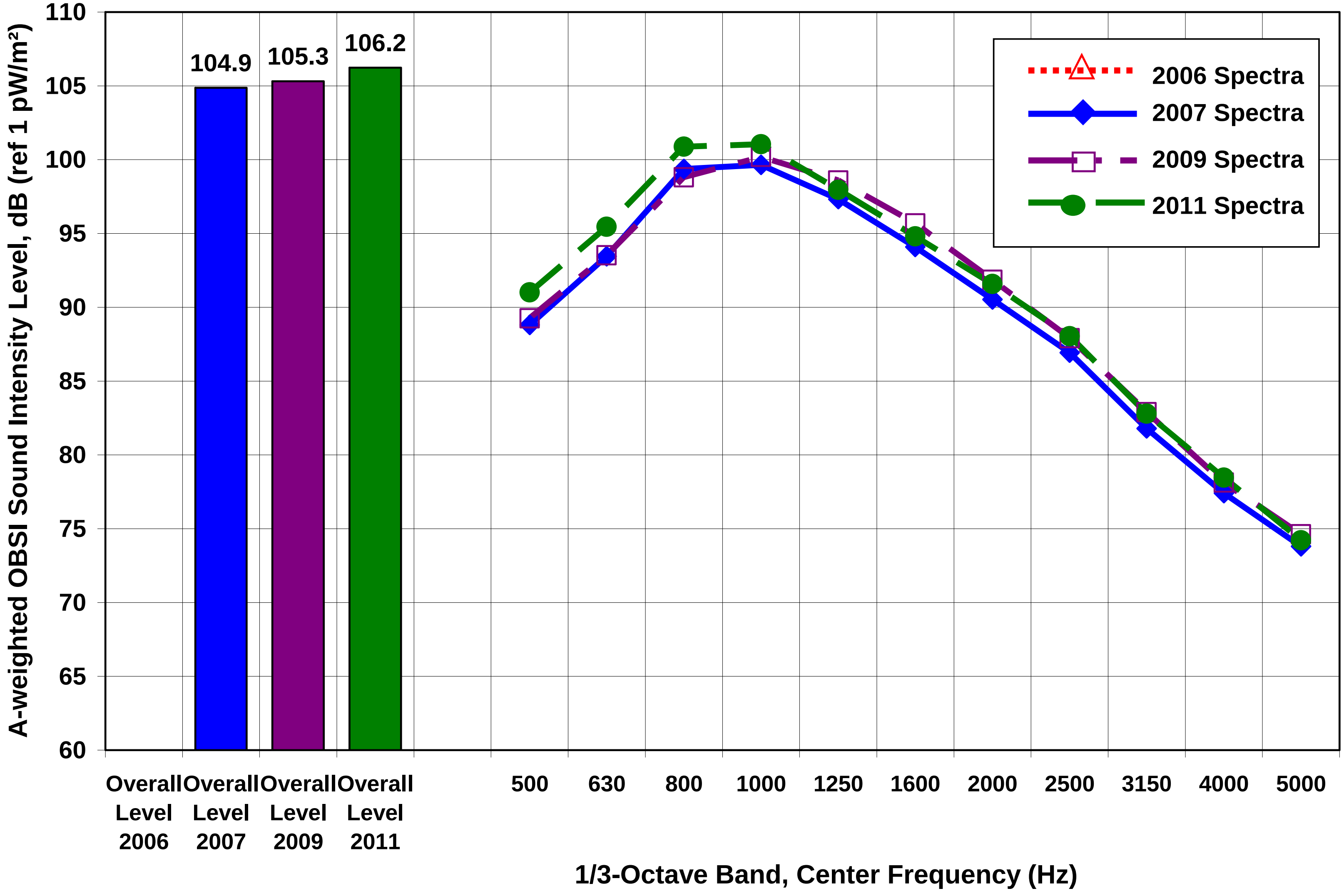
Highway: Interstate 70, Eastbound
Location: Between 15th St. & US 40, Georgetown (80444)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 39.7286 / 105.6919 / 8560

Nominal Surface: SMA (3/4") **Construction Accepted:** 10/2006

OBSI?: Yes **Pass-by?:** No
Total Section Length: 5529 ft.
Distance from Begin to Wayside Microphone: n/a

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 31
OBSI (SRTT) Test Information



Site: 32
General Information

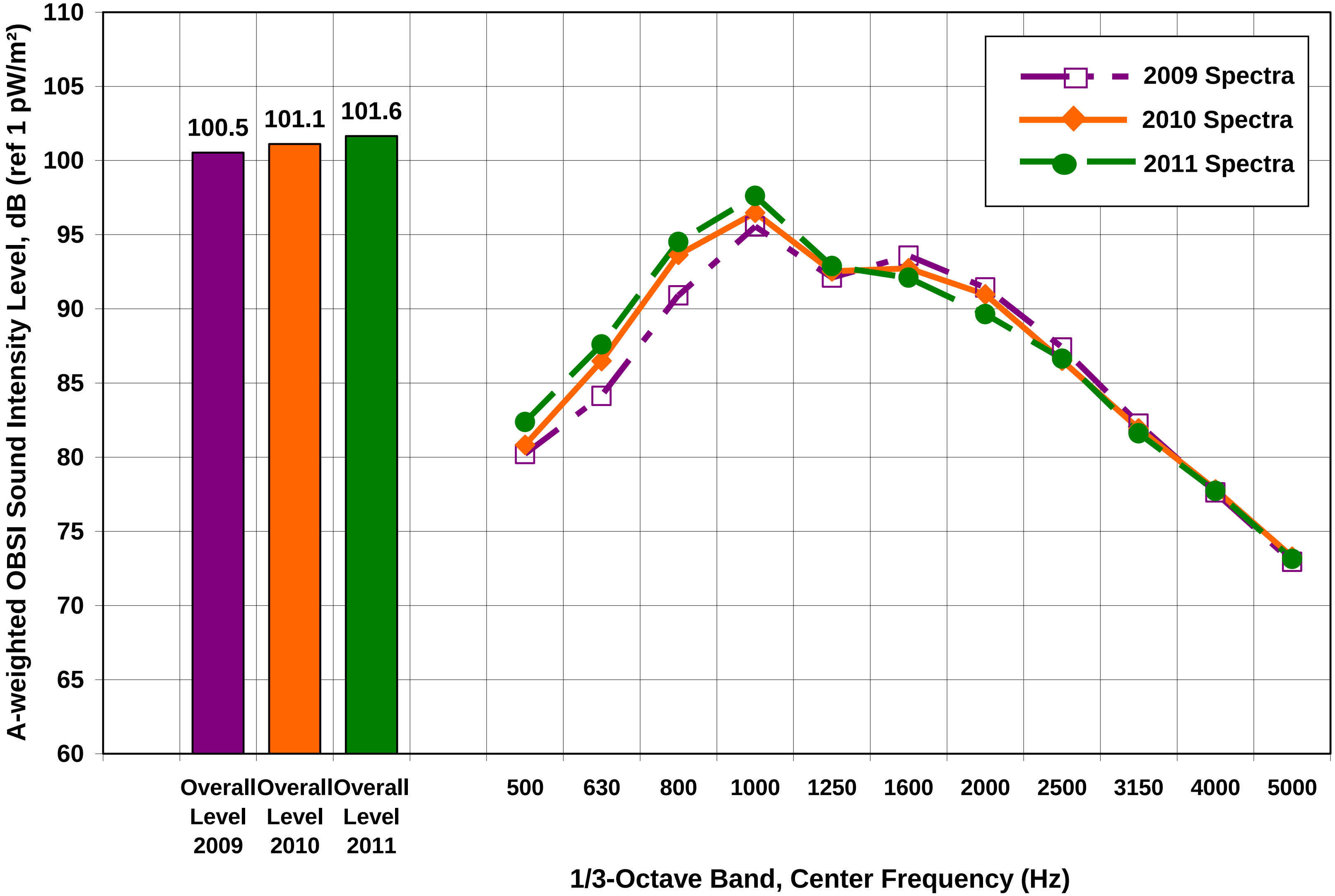
Highway: US Highway 34, Eastbound
Location: Between 71st Ave. & 65th Ave., Greeley (80634)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 40.3920 / 104.7896 / 4900

Nominal Surface: Asphalt (PG 64-28) **Construction Accepted:** 8/2009

OBSI?: Yes **Pass-by?:** No
Total Section Length: 440 ft.
Distance from Begin to Wayside Microphone: n/a

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 32
OBSI (SRTT) Test Information



Site: 33

General Information

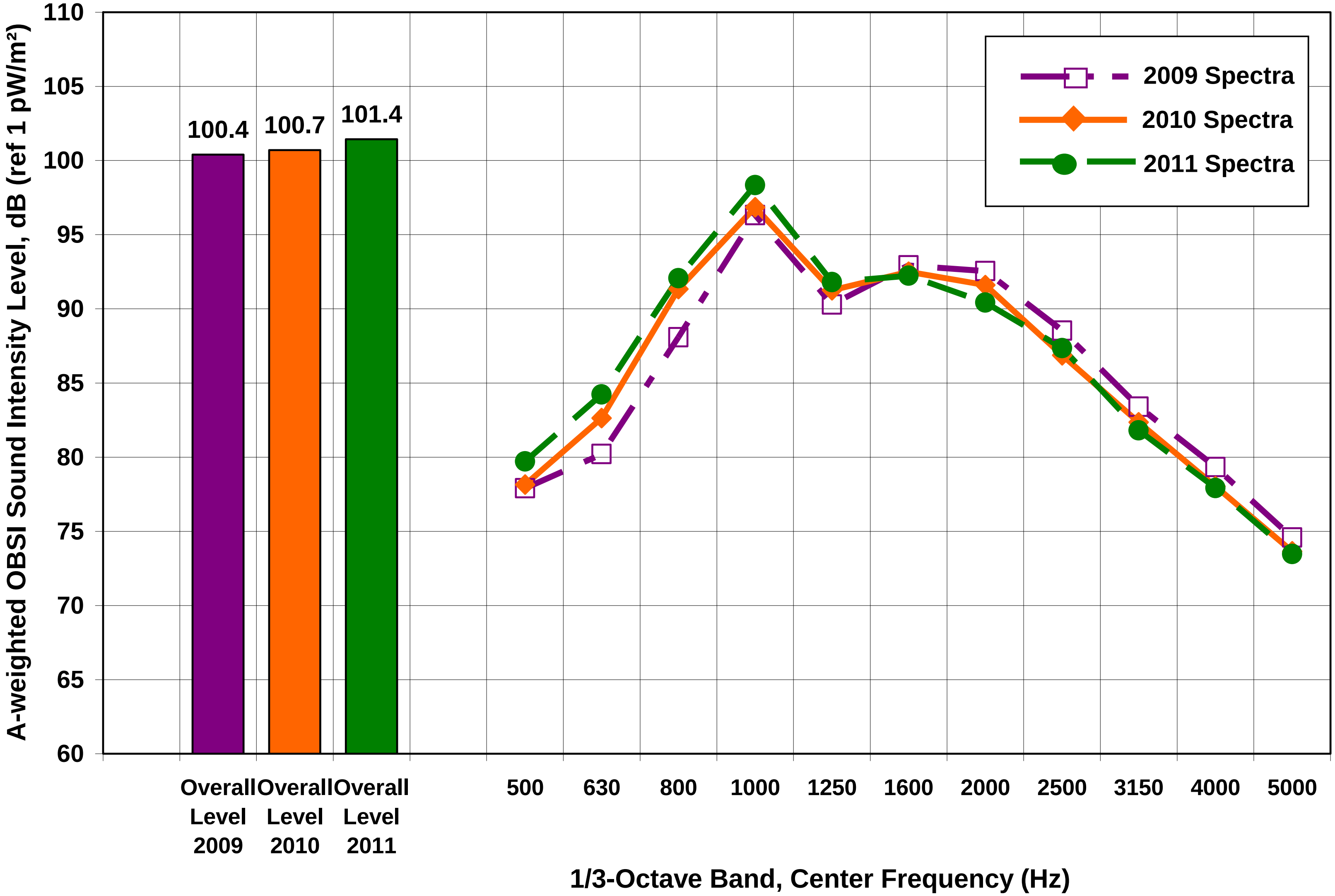
Highway: US Highway 34, Eastbound
Location: Between 65th Ave. & 59th Ave., Greeley (80634)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 40.3920 / 104.7764 / 4890

Nominal Surface: Asphalt (CRM, Wet Proc) **Construction Accepted:** 8/2009

OBSI?: Yes **Pass-by?:** No
Total Section Length: 440 ft.
Distance from Begin to Wayside Microphone: n/a

Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 33
OBSI (SRTT) Test Information



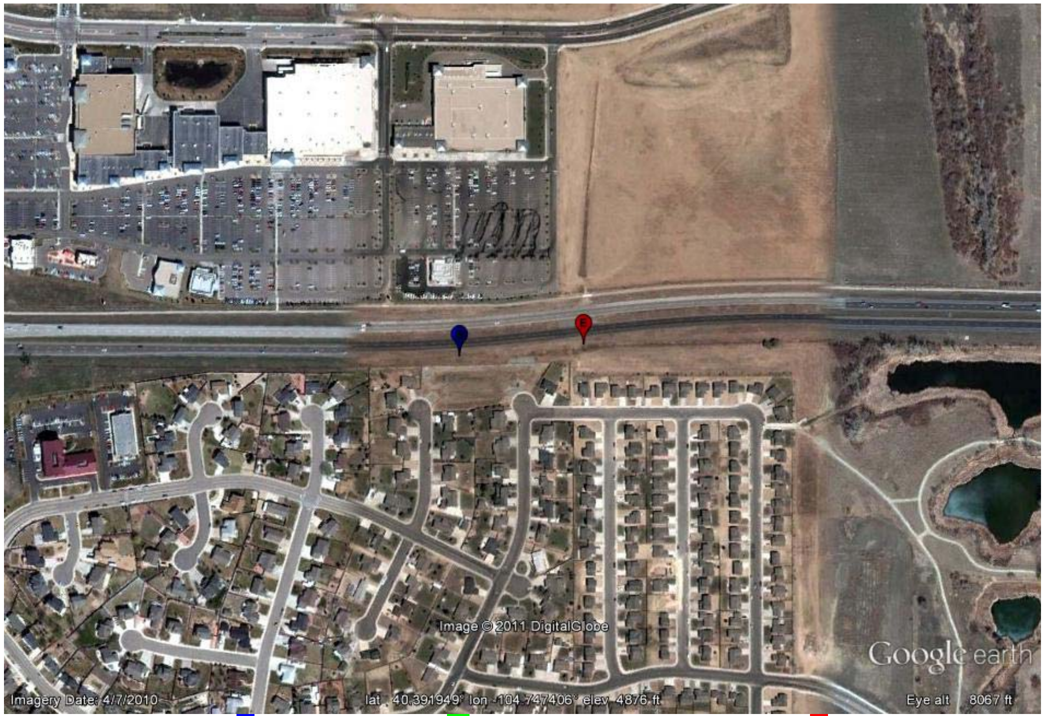
Site: 34

General Information

Highway: US Highway 34, Eastbound
Location: Between 47th Ave. & 35th Ave., Greeley (80634)
Approx. Latitude (°N) / Longitude (°W) / Elevation (ft.): 40.3920 / 104.7474 / 4870

Nominal Surface: Asphalt (CRM Term. Blend) **Construction Accepted:** 8/2009

OBSI?: Yes **Pass-by?:** No
Total Section Length: 440 ft.
Distance from Begin to Wayside Microphone: n/a



Placemark Key: B = Begin Section; M = Mid Section (Wayside Mic); E = End Section

Site: 34
OBSI (SRTT) Test Information