VEHICLE EMISSION NOISE EVALUATION FOR ARIZONA SPECIFIC STAMINA 2.0 AND TRAFFIC NOISE MODEL (TNM)

Final Report 476

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16. Abstract

The University of Louisville Research Foundation conducted a series of Reference Energy Mean Emission Level measurements of individual vehicle operations in the state of Arizona. This study was conducted to determine if the noise emission characteristics of Arizona highway vehicles are consistent with the data contained in the Federal Highway Administration's (FHWA) Traffic Noise Model (TNM).

This study also examined the prediction accuracy of the TNM and STAMINA models. Field measurements were made at ten separate locations representative of typical Arizona topography and traffic conditions. These sites were modeled and both TNM and STAMINA were used to generate predicted sound levels at each measurement location.

The following conclusions are drawn from the results of this study:

- The Arizona TNM REMEL data is different than the FHWA/TSC national TNM REMEL at a 95% confidence level for all three vehicle types addressed in this report.
- Arizona state-specific REMEL data increases the accuracy of both STAMINA and TNM over the same models using the FHWA/TSC national REMEL data, when modeling sites in the state of Arizona.
- The most accurate prediction method for sites in Arizona at distances up to 400 ft. from the roadway is the STAMINA model using Arizona state-specific REMEL data.
- The least accurate prediction method for Arizona sites at distances up to 400 ft. from the roadway is the TNM model using national REMEL data.
- TNM significantly over-predicts sound levels whether using either FHWA/TSC or Arizona state-specific REMEL data.

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	2.54	centimeters	cm
ft	feet	0.3048	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	6.452	centimeters squared	cm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.395	hectares	ha
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		VOLUME		
fl oz	fluid ounces	29.57	millimeters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.0328	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3

Note: Volumes greater than 1000 L shall be shown in m^3.

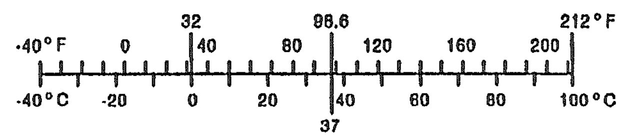
Symbol	When You Know	Multiply By	To Find	Symbol
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

These factors conform to the requirement of FHWA Order 5190.1A

*SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
yd	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
yd^2	kilometers squared	0.39	square miles	mi^2
ha	hectares (10,000 m^2)	2.53	acres	ac
		MASS (weight)		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
mL	millimeters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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I. INTRODUCTION

During the period of September 1999 through March 2000, the University of Louisville Research Foundation conducted a series of Reference Energy Mean Emission Level measurements of individual vehicle operations in the state of Arizona. This study was conducted to determine if the noise emission characteristics of Arizona highway vehicles are consistent with the data contained in the Federal Highway Administration's (FHWA) Traffic Noise Model (TNM).

Chapter II presents a description of the individual measurement sites, previously approved by the FHWA. Chapter III describes the field measurement instrumentation. Chapter IV presents the field measurement procedures. Chapter V describes the process followed in data reduction. Chapter VI presents the methodology used in the analysis of the data, Chapter VII presents the results of that analysis, and Chapter VIII presents a validation of the results of this study. Chapter IX presents a discussion of the conclusions drawn from this study, and Chapter X presents a recommended course of action for the Arizona Department of Transportation (ADOT), based on the findings of this study.

A. BACKGROUND

On March 30, 1998 FHWA released the TNM, Version 1.0.[1] TNM is the FHWA's new computer program for highway noise prediction and analysis. Along with the release of the new model, FHWA also specified a 24 month phase-in period (from the release date), after which the current highway noise analysis programs (STAMINA 2.0/OPTIMA) would be replaced by TNM. However, FHWA has identified a need for additional validation of the model and this phase-in period has been subsequently been extended until December 31, 2002.[2]

One of the primary issues regarding the required implementation of FHWA's TNM for the Arizona Department of Transportation (ADOT) is that of TNM's nationalized Reference Energy Mean Emission Level (REMEL) database. A number of states have FHWA approved state-specific REMEL data for STAMINA that have been demonstrated to be more accurate than the 1974 national emission data. These states are given authority under 23 CFR 772 to determine their own state specific REMEL database.[3] In addition, provisions are contained in the TNM model for different emission level data to be used.[4]

In 1995, the FHWA and the Volpe National Transportation Systems Center (TSC) jointly issued a report detailing the results of a national REMEL analysis.[5] To insure consistency in comparing Arizona data with the FHWA/TSC data, this study rigorously applied procedures documented in that report, as well as those in *Measurement of Highway-Related Noise*.[6] The statistical regression is developed using the acoustic energy of the measurement data, not the sound level in decibels. All measurements were made from constant-flow traffic streams, except for a number of idling automobiles required by FHWA.[5]

B. OBJECTIVES

This report contains the results of an effort to develop emission level data for three vehicle types (automobiles, medium trucks, and heavy trucks) in the state of Arizona. The procedures and analysis methodology utilized in this study will be closely modeled after the FHWA/TSC November 1995 publication, *Development of National Reference Energy Mean Emission Levels for the FHWA Traffic Noise Model (FHWA TNM), Version 1.0*.[5] The REMEL's developed in this study will be compared to the nationalized data presented in that document.

This study will also examine the prediction accuracy of the TNM model. Field measurements will be made at ten separate locations representative of typical Arizona topography and traffic conditions. These sites will be modeled and TNM used to generate predicted sound levels at each measurement location. A statistical comparison of the measured vs. predicted levels for each REMEL data set will be made.

Using the same site data, STAMINA will also be used to generate predicted sound levels at each measurement location. STAMINA will be executed using the 1974 national REMEL data and the Arizona state-specific REMELs developed in 1978.[7] The model results from both sets of REMEL data will then be statistically compared to the measurement data and the TNM predicted results.

Using the results of this analysis, a recommendation will be made to the Arizona Department of Transportation as to which emission data is most appropriate for use in the state. Also, the effects of the two different REMEL data sets will be presented as they relate to the prediction accuracy of the two models.

II. MEASUREMENT SITES

The measurement sites used to develop the Arizona REMEL data are described in this section. A discussion of general site characteristics is presented in Section II.A.; Specific site characteristics are presented in Section II.B.; the definition of specific vehicle types is contained in Section II.C.; and a discussion of the roadway pavement types found in Arizona is contained is Section II.D.

A. GENERAL SITE CHARACTERISTICS

- Each site was defined by a flat open space, free of large reflecting surfaces, such as parked vehicles, signs, buildings, or hills within 100 feet of either the vehicle path or microphone.

- Ground surfaces within the measurement area was free of snow, and was representative of acoustically hard (e.g., pavement), or acoustically soft (e.g., grass) terrain.

- Line-of-sight from the microphone to the roadway was un-obscured within an arc of 150 degrees.

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

- The predominant ambient level at each site was low enough to enable the measurement of uncontaminated vehicle pass-by sound levels. In other words, the difference between the lowest anticipated vehicle pass-by L_{AFmx} and the A-weighted ambient level (measured at the 50 ft. microphone) was at least 10 dB.

- The site was located away from other known noise sources that would potentially contaminate the measurements.

- The traffic at each site was constant speed and operating under cruise conditions at speeds between 5 and 70 mph (measurements of idling automobiles were also made in accordance with FHWA/TSC guidelines). Each site was located away from intersections, lane merges, or any other feature that would cause traffic to accelerate or decelerate.

B. SPECIFIC SITE CHARACTERISTICS

Each site, along with its location, predominant traffic speed, pavement type, and approximate ambient sound level is listed in Table 1. A photograph and brief description of each site is included in Appendix A.

C. VEHICLE TYPES

Sites were selected with traffic volumes low enough for measurement of individual vehicle pass-bys, and traffic streams diverse enough for measurement of all vehicle types of interest. Traffic was grouped into three acoustically significant types (i.e., differing vehicles within each type exhibit statistically similar acoustic characteristics). These vehicle types are defined as:

- Automobiles: All vehicles with two axles and four tires, designed primarily to carry nine or fewer passengers or light cargo. Gross vehicle weight is less than 9,900 pounds.

- Medium Trucks: All cargo vehicles with two axles and six tires. Gross weight is between 9,900 and 26,400 pounds.

- Heavy Trucks: All cargo vehicles with three or more axles. Gross weight is more than 26,400 pounds.

Table 1: Site Location and Description

Site	Location	Mph	Lanes	Median	Pavement	L_{90}, dBA
1P	SR 85 sb, 1 mi so I-10, app 30 mi w Phx.	60	2	n/a	Asphalt	45
2P	27th Str sb, 0.5 mi n Lower Buckeye Rd.	35	2	n/a	Asphalt	47
3P	US60 wb, 1.5 mi e frwy end, 15 mi e Phx.	55	4	60'	Asphalt	51
4P	51st St sb @ Winston Dr, s Baseline Rd	50	2	n/a	Asphalt	51
5P	Roeser Street eb, 0.5 mi w of 32nd Street	35	2	n/a	Asphalt	56
6P	32nd Street nb, 0.5 mi s Roeser	35	2	n/a	Asphalt	53
7P	Ecanto Dr eb, 500' w 30th Ave	25	2	n/a	Asphalt	53
8P	Pima Fwy sb, 0.5 mi s McDonald Ave	65	8	50'	Concrete	70
9T	I-19 sb, 0.75 mi s Irvington Rd	55	4	60'	Asphalt	57
10T	Country Club Ln, 0.5 mi s Valencia Rd	35	2	n/a	Asphalt	42
11T	Cntry Club Ln, 0.25 mi w Los Reales Rd	20	2	n/a	Asphalt	40
12T	22nd Street eb, 1000' e Camino Seco	35	4	0'	Asphalt	56
13T	I-10 nb, 2 mi n Cordero Road	75	4	60'	Asphalt	66
14P	I-10 nb 0.25 mi n Gila River Bridge	75	4	60'	Asphalt	60
15F	I-17 sb, mp 328 10 mi s Flagstaff	75	4	50'	Asphalt	60
16F	I-40 wb, mp 186 15 mi w Flagstaff	65	4	100'	Asphalt	51
17F	US 66 eb, mp 0, e side Flagstaff	55	2	n/a	Asphalt	50
18F	West US 66 wb @ S. Thompson Street	50	3	n/a	Asphalt	47

P = Phoenix area; T = Tucson area; F = Flagstaff area

D. PAVEMENT TYPE

Since TNM has the capability to account for different pavement types, it is important to accurately represent the various pavement types that exist within a state when investigating state-specific REMEL differences. A survey of the state of Arizona was conducted with the assistance of ADOT personnel in order to determine the type and location of various pavement surfaces. Examination of Table 1 indicates that the predominant pavement material used in the state is dense graded asphaltic concrete (DGAC). Thus, as indicated in Table 1, 94.4% of the measurement sites for this study were made on DGAC, which is representative of the pavement type distribution for the entire state.

This is compared to the FHWA study, which had the following pavement type breakdown: 79.5% of the automobile data was measured on DGAC, and 15.1% on portland cement concrete (PCC); 62.6% of the medium truck data was measured on DGAC, and 18.5% on PCC; 49.1% of the heavy truck data was measured on DGAC, and 27.5% on PCC.[5]

Given this difference in pavement type distribution between the two studies, data in this report will be compared to both the average pavement and the DGAC REMELs in the FHWA study. The average pavement condition in the FHWA study is defined as a combination of both DGAC and PCC pavements. For the automobile, medium truck, and heavy truck vehicle categories, this combination is made up of approximately 75% DGAC pavement, and 25% PCC pavement.[5] It should also be noted that at this time, FHWA policy allows use of only the average pavement type in analyzes using TNM.[4]

Because ambient air temperature might have an effect on tire/pavement noise, measurements were made in the fall and winter months, so that temperature extremes would not bias the measurement data.[5]

III. MEASUREMENT EQUIPMENT

This section identifies the field measurement equipment, including manufacturer and model number. Section III.A. describes the acoustic data acquisition system, and Section III.B. describes the measurement support equipment.

A. ACOUSTIC SYSTEM

The acoustic data acquisition system consisted of a Larson-Davis model 2560 microphone (SN 2922, factory calibrated 9/15/99, calibration certificate number 1999-22149) connected to a Larson-Davis model PRM902 preamplifier (SN 0820). The microphone/preamplifier was mounted in a nylon holder and fastened to a tripod. The microphone was positioned for grazing incidence at a height of five feet above the roadway elevation, and at a distance of 50 feet from the centerline of the nearest travel lane.

The microphone/preamplifier system was connected by a 500 ft. cable to a Larson-Davis model 824 sound level meter (SN 0457, factory calibrated 9/15/99, calibration certificate number 1999-22136), which was set to measure the maximum A-weighted sound pressure level with fast response time weighting characteristics. The sound level meter was connected by a serial cable to a Compaq model 1215 laptop computer.

The entire acoustic measurement system was calibrated using a Larson-Davis model CAL2000 calibrator (SN 0785, factory calibrated 3/23/99, calibration certificate number 1999-19234) for measurements made at all sites. This unit produces a signal of 1000 Hz at a sound pressure level of 114 dB re: 20 micro-pascal.

In addition, the electronic noise floor of the acoustic measurement system was established daily by substituting the measurement microphone with a Larson-Davis model ADP005 microphone simulator. Although no spectral data was collected, the frequency response characteristics of the acoustic measurement system was also determined on a daily basis using an Ivie model IE-20B pink noise generator (SN 4197G841).

The Larson-Davis *Data, Navigation, and Analysis* (DNA), version 2.00 software package was used to control the measurement operation and download the individual pass-by event's A-weighted maximum sound level (L_{AFmx}) from the 824's RAM memory.[8] A spreadsheet record of each event was also maintained, with the event number, L_{AFmx}, vehicle speed, vehicle type, event quality, time, ambient sound level, and any comments pertinent to a particular pass-by event. A total of fifty pass-by events were stored in the sound level meter's memory, and then downloaded to the hard drive of the laptop.

The DNA software also provided a real-time display of the time-history of each pass-by event. The time-history plots served as an on-site verification of the event quality of each event. Each acceptable event was stored on the laptop computer. Electronic copies of the time-history plots are on file at the University of Louisville.

B. MEASUREMENT SUPPORT EQUIPMENT

A CMI Magnum Speed Gun Radar (SN 59-003611) unit was set up at the observer's station, approximately 500 feet upstream of the microphone location, and was used to measure the speed of each pass-by event. The unit was positioned at a distance of no greater than 50 feet from the centerline of the near travel lane when the microphone was located 500 feet downstream of the vehicle observer. This location insured that the angle subtended by the axis of the radar antenna and the direction of travel of the sample vehicle was less than 6 degrees when the vehicle passed the microphone location. This limited the resulting uncertainty in vehicle speed readings due to angular effects on doppler accuracy, to no more than 0.35 mph over the speed range of measured vehicles in this study.[9] Calibration of the radar unit was periodically checked in the field using a calibrated tuning fork.

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

IV. MEASUREMENT PROCEDURE

A. EVENT QUALITY

Event quality was determined in the field from the electronic time-history plot and was logged for each event in the spreadsheet record of the measurements at each site. A copy of the time-history for each pass-by was also saved via the DNA software. Ideally, a rise and fall of at least 10 dB between subsequent vehicles measured at the 50 ft. microphone was desired. Rise and fall is defined as the difference between L_{AFmx} and the minimum measured level associated with either the start or end of a given event (whichever difference was smaller).

Events with a rise and fall of at least 10 dB were designated as Type 2, the highest quality event. However, if only Type 2 events were recorded, the possibility of bias would exist because noisier vehicles would be most likely to generate a 10 dB rise and fall.[5] Therefore, events with a rise and fall of between 6 and 10 dB were also included and designated as Type 1 events. Events with a rise and fall between 3 and 6 dB were designated as Type 0 events and were usually discarded. Any event with a rise and fall of less than 3 dB was discarded.

B. FIELD PROCEDURE

The measurement microphone was placed at a distance of 50 feet from the centerline of the nearest travel lane and approximately 500 feet downstream of the observer's station. Measurement instrumentation was located at the observer's station.

Prior to initial data collection and at hourly intervals thereafter, and at the end of the measurement sequence, the entire acoustic instrumentation system was calibrated. In addition, the electronic noise floor was established daily using a microphone simulator. The frequency response characteristics were also determined daily by measuring and storing 30 seconds of pink noise.

In addition, prior to data collection, at 15 minute intervals thereafter, and during any noticeable weather changes, meteorological conditions were observed and recorded. Temperature (wet and dry bulb), wind speed and direction, and cloud cover were measured. No wind speeds above 12 mph were noted. Meteorological data during each measurement sequence for each site are contained in Tables 13 through 30 in Appendix B.

Two observers (vehicle and acoustic) were used in all measurements. A potential event was identified for measurement when there were no other like vehicle types observed within a distance of 400 feet (985 ft. for different vehicle types). The technical basis for this separation distance is contained in Appendix C of the FHWA/TSC REMEL study.[5]

It is important to note that these pass-by events were truly random. In other words, the only deciding factor in selecting an event for measurement was the separation distance. Using this approach insured that extremely loud vehicles, vehicles without mufflers, or vehicles with relatively unique noise emission characteristics were not excluded from the measurement or subsequent analysis.

When the minimum separation distance criteria were met, the vehicle observer began monitoring the vehicle's speed as it passed the observer's station. Concurrently, the acoustic observer began the data logging on the 824 sound level meter, as well as observing the time-history to determine event quality. If an event met minimum acceptability criteria, the L_{AFmx} and time-history plot were stored in the memory of the 824 sound level meter.

After each acceptable event, the acoustic observer recorded the following data in a spreadsheet on the laptop computer: event number, L_{AFmx}, vehicle speed, vehicle type, event quality, time of the event, calibration data, and any other pertinent observation relating to that event. The L_{90} value, representing the ambient sound level at each site for each measurement sequence, was also recorded in this spreadsheet.

C. IDLE DATA MEASUREMENT PROCEDURE

REMEL data for idling automobiles were collected during the week of March 27-31, 2000. The idle measurement site was located at site 11t. The idle data will represent the sound level versus speed relationship for automobiles as a non-linear function down to a vehicle speed of zero.[5]

For these measurements the Larson-Davis model 2560 microphone was placed a distance of 12.5 feet from the center of the nearest travel lane where vehicles were positioned idling.[5] An L_{Aeq30s} was recorded to determine the ambient level followed by a 30 second sample of the idling vehicle.

The ground cover characteristics (drop-off rate) were determined at this site by simultaneously measuring the sound level at the 12.5 ft. microphone and at a second microphone located at 25 feet from the center of the nearest travel lane. This rate was later used to adjust the measurement at 12.5 feet to the standard reference location of 50 ft. from the center of the nearest travel lane.

V. DATA REDUCTION

Once the measurements were completed, all the data files were examined in the office and any necessary adjustments (e.g., measurements with a rise and fall of less than 10 dB) were made.

A. EVENT QUALITY

The electronic time-histories, generated and stored with the Larson-Davis DNA software, were examined and correlated with the data stored in the corresponding spreadsheets. When the rise and fall in sound level associated with an event was greater than 10 dB (Type 2 event quality), the recorded L_{AFmx} was included without adjustment. When the rise and fall in sound level associated with an event was between 6 and 10 dB, due entirely to nearby vehicles (Type 1 event quality), the L_{AFmx} was also included without adjustment. All events in this study were classified as either Type 1 or Type 2.

The primary criterion for an acceptable event was that the difference between the L_{AFmx} and the ambient level measured at the 50 ft. microphone should be at least 10 dB. However, for the low speed automobile data (less than 25 mph) this level-difference was relaxed to 6 dB at sites 2P, 7P, and 11T. For automobile data at these sites the L_{AFmx} was corrected for ambient sound levels by energy subtraction, if required, and the adjusted event included in the data base.

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

B. VEHICLE TYPES

Each vehicle was assigned an FHWA vehicle designation corresponding to one of the three types described in Section II.C. These three vehicle types are consistent with the standard vehicle types found in the FHWA TNM. The designations are as follows: Type 1 for all automobiles; Type 2 for all medium trucks; and Type 3 for all heavy trucks. These definitions are also consistent with those vehicles described in the FHWA Report Number FHWA-RD-77-108.[10]

C. IDLE DATA

As mentioned in Section IV.C., the microphone at the idle site was placed at a distance of 12.5 feet from the center of the nearest travel lane. The system was set up to measure data at 8 samples per second over a 30 second time period. The L_{Aeq30s} was then adjusted to a distance of 50 ft., using acoustic site characteristics of site number 11t. The data was then saved in a spreadsheet in a format consistent with that described in Section V.D.

D. SPREADSHEET FORMAT

The following information is contained in each spreadsheet:

- Site/event number: Site identification and sequential event number
- Measured 50' unadjusted L_{AFmx}
- Adjusted 50' L_{AFmx}, including event quality, ambient noise, and calibration adjustments, if applicable.
- Speed, in miles per hour
- Vehicle type: 1 = All automobiles
  2 = All medium trucks
  3 = All heavy trucks
- Event classification => Numerical designation for event quality:
  1 = 6 to 10 rise and fall;
  2 = greater than or equal to 10 dB rise and fall.
- Time, in 24-hour format
- L_{90}
- Numerical adjustments for 50' L_{AFmx}, including event quality, ambient noise, and calibration.
- Comments, including calibration data.

Electronic copies of all the spreadsheets are on file at the University of Louisville.

VI. DATA ANALYSIS

This section describes the methodology used for the calculating the Reference Energy Mean Emission Levels (REMELs) from the sound level measurement data. In determining the REMELs, the level-mean emission levels are first calculated by regressing the measured 50 ft. L_{AFmx} values as a function of vehicle speed. The REMELs are then calculated by adjusting the level-mean emission levels upward by a fixed value, which is a function of the relationship between the level-mean regression and the individual measured L_{AFmx} values. The regression analysis was accomplished with the SPSS for Windows (Release 8.0.0) statistical software package.

A. LEVEL-MEAN EMISSION LEVEL REGRESSION

To calculate the level-mean emission levels, the 50 ft. L_{AFmx} data were regressed as a function of speed for each vehicle type. The functional form of the regression equation is as follows:[5]

$$\begin{aligned} L(s) &= 10\log_{10}(10^{C/10} + 10^{(A\log(s)+B)/10}) \\ &= 10\log_{10}(10^{C/10} + (s^{A/10}10^{B/10})) \end{aligned} \qquad \text{(VI.1)}$$

This model has been determined to represent the speed vs. noise emission characteristics of individual vehicle pass-by events by the Volpe National Transportation Systems Center (TSC), and is assumed to be correct for the purposes of this report.[5] In the regression equation, L(s) is the logarithm to the base 10 of the coefficient C (an engine/exhaust coefficient, which is independent of vehicle speed), and the term $A\log_{10}(s) + B$ (a tire/pavement term, which increases with increasing vehicle speed).

The $A\log_{10}(s) + B$ term is consistent with that used in previous REMEL studies, as well as that used by the STAMINA program. The C coefficient was added by TSC for the purpose of predicting sound levels at low vehicle speeds.

B. ADJUSTMENT FROM LEVEL-MEAN TO ENERGY-MEAN

In previous REMEL studies, the adjustment from level mean to energy mean was calculated using an adjustment of $0.115\ s^2$, where s is the standard error of the regression. This adjustment is correct only if the level-mean data are normally distributed about the level-mean regression. However, TSC has suggested that traffic noise data tends to be scattered more widely above the mean than below.[5] Therefore, to be consistent with the methodology in the FHWA/TSC REMEL report, the following equation was used to calculate the energy-mean adjustment:[5]

$$\Delta E = 10\log_{10}\left((1/n)\sum RE_i\right) - (1/n)\sum RL_i \qquad \text{(VI.2)}$$

In this equation, RL_i represents the difference between the measured L_{AFmx} and the predicted values at the same speed from the regression equation. This is the residual determined by the regression analysis. The RE_i term represents the energy residuals, which are equivalent to $10^{(RLi/10)}$.

In accordance with the procedures outlined in the FHWA/TSC REMEL document, this adjustment was then added to both the engine/exhaust term and the tire/pavement term of the L(s) equation in the following manner:[5]

$$L_E(s) = 10\log_{10}[10^{(C+\Delta E)/10} + (s^{A/10})(10^{(B+\Delta E)/10})] \qquad \text{(VI.3)}$$

C. CONFIDENCE INTERVAL

A 95% confidence interval was next calculated for each energy-mean regression according to the following equation:[5]

$$95-percent\ CI(s) = L_E(s) \pm 1.96\varepsilon_{regr}(s) \qquad \text{(VI.4)}$$

The 95-percent confidence interval defines the upper and lower limits within which the regression equation will lie with 95% certainty. The $\varepsilon_{regr}(s)$ term represents the standard error of the regression equation as defined by the following equation:[5]

$$\begin{aligned}\varepsilon_{regr}(s) = \frac{1}{E}\{&(s^{A/10}10^{B/10})^2[(\log_{10} s)^2 \varepsilon_A{}^2 + \varepsilon_B{}^2] + (10^{C/10})^2 \varepsilon_C{}^2 \\ &+ 2(s^{A/10}10^{B/10})^2(\log_{10} s)\rho_{AB}\varepsilon_A\varepsilon_B \\ &+ 2(10^{C/10})(s^{A/10}10^{B/10})[(\log_{10} s)\rho_{AC}\varepsilon_A\varepsilon_B + \rho_{BC}\varepsilon_B\varepsilon_C] \\ &+ \frac{\sigma_{RL}{}^2\sigma_{RE}{}^2}{N(\overline{RE})^2}\}^{1/2}\end{aligned} \qquad \text{(VI.5)}$$

where: $E = 10^{C/10} + s^{A/10}10^{B/10}$; $\varepsilon_A, \varepsilon_B$, and ε_C are the standard errors of the coefficients A, B, and C, respectively; ρ_{AB}, ρ_{AC} and ρ_{BC} provide a measure of the correlation between the A, B, and C coefficients; σ_{RL} is the standard deviation of the level residuals; σ_{RE} is the standard deviation of the energy residuals; $\overline{RE}$ is the mean of the energy residuals; and N is the number of data points.

It should be noted that equation VI.5, as listed in the FHWA/TSC study, was missing a term in the second line of the equation. This error was detected while attempting to duplicate the 95 percent confidence interval for the reported FHWA/TSC data.[5] Equation VI.5, as presented here, has been corrected in accordance with instructions from TSC personnel on April 26, 2000.[11]

D. CALCULATION OF ARIZONA REMELS

The calculation of Arizona specific REMELs will be discussed in this section. The standard conditions for these calculations are:

- Pavement types consistent with Arizona state-wide use
- Level grade (1.5% or less)
- Constant vehicle speed

Pavement types in Arizona are predominantly dense graded asphaltic concrete (DGAC). Thus approximately 95% (Section I.D.) of the measurement sites for this study had DGAC pavement.

In accordance with procedures in the FHWA/TSC REMEL study, a non-linear regression model was used to determine the equation for the $L_E(s)$ function. The values of the coefficients A, B, and C were estimated using the non-linear regression method contained in the SPSS for Windows (Release 8.0.0) statistical software package.

1. Automobiles

According to the FHWA/TSC REMEL report, emission levels for automobiles are dominated by tire/pavement noise. Therefore, the transition between the tire/pavement portion of the regression and the engine/exhaust portion occurs at a very low speed.[5] Consequently, the data collected for idling automobiles formed the basis for the engine/exhaust portion of the regression. As a result, two level-mean regression equations were calculated based on the following relationships:[5]

$$L(s) = 10\log_{10}(10^{C/10}) \text{ (for speed = zero)} \qquad \text{(VI.6)}$$

$$L(s) = 10\log_{10}(s^{A/10}10^{B/10}) \text{ (for speed > zero)} \qquad \text{(VI.7)}$$

The adjustment from level-mean to energy-mean was calculated by equation VI.2. The ΔEc term was calculated from the zero speed regression and the ΔEb term was calculated from regression of the data with speeds greater than zero. These two separate regression equations were added together to form the final REMEL equation. The 95 percent confidence interval was calculated with equation VI.4; ρ_{AC} and ρ_{BC} were set to zero; σ_{RL}, σ_{RE}, $\overline{RE}$, and N were calculated with data for speeds greater than zero.

2. Medium Trucks and Heavy Trucks

The REMEL regression equations for both medium and heavy trucks were calculated according to the procedures outlined in Sections VI.A., VI.B., and VI.C.

E. COMPARISON OF AZ DATA WITH FHWA/TSC NATIONAL DATA

One of the primary goals of this study was to determine if statistically significant differences exist in the noise emission characteristics of vehicles in Arizona and the national data collected by FHWA/TSC.[5] In the FHWA/TSC report, a comparison was made between the national data and data collected by Caltrans in the state of California only. The purpose of that comparison was to determine if the national data and the California data were statistically equivalent. Therefore, the same procedure will be applied in this analysis to determine if the Arizona data and the national data are statistically the same.

The emission level equations, and all associated analysis results, for automobiles, medium trucks, and heavy trucks were first obtained for the national REMEL study.[5] The emission data collected in Arizona was then regressed (Section VI.A. and VI.B.) to obtain the corresponding emission level equations for the same vehicle types. The difference between the two regressions, and the associated standard error was calculated according to the following equations:[5]

$$L_E(s)_{DIFF} = L_E(s)_{TSC} - L_E(s)_{AZ} \qquad \text{(VI.6)}$$

$$\varepsilon_{DIFF}(s) = (\varepsilon_{TSC}(s)^2 + \varepsilon_{AZ}(s)^2)^{1/2} \qquad \text{(VI.7)}$$

The results of this comparison are fully discussed in Chapter VII.

VII. RESULTS

A. NUMBER OF SAMPLES

1. By Pavement Type

Table 2 presents a summary of the total number of measurement events. This data is presented in 5 mph speed bands by pavement type. Examination of Table 2 shows that 85.9% of the automobile data was collected on DGAC pavement, 96.6% of the medium truck data was collected on DGAC pavement, and 97.5% of the heavy truck data was collected on DGAC pavement. This distribution is consistent with pavement types found in the state of Arizona, as explained in Section I.D. of this report.

Table 2: Measurement Totals by Speed Band and Pavement Type

FWHA Veh. Type		Auto		MT		HT	
Pavement Type		DGAC	PCC	DGAC	PCC	DGAC	PCC
Speed mph	0-10	10	0	10	0	10	0
	11-15	1	0	3	0	5	0
	16-20	9	0	7	0	7	0
	21-25	7	0	8	0	11	0
	26-30	33	0	15	0	17	0
	31-35	50	0	17	0	9	0
	36-40	61	0	16	0	23	0
	41-45	56	0	41	0	41	1
	46-50	52	0	69	2	62	1
	51-55	51	31	123	5	59	3
	56-60	79	48	71	5	146	5
	61-65	48	2	47	5	76	3
	66-70	48	4	48	0	51	1
	70-75	14	1	1	0	21	0
	76-80	3	0	1	0	2	0
Subtotal		522	86	477	17	540	14
Total by Type		608		494		554	
Total		1656					

2. By Speed Band

One of the primary objectives of this study was to compare the Arizona state-specific REMEL data with the FHWA/TSC national data. It is therefore important that the relative number of samples of each vehicle type across the entire range of speeds of interest be consistent. Figures 1, 2, and 3 in Appendix C provide a comparison of the percentage of total samples, by speed band and vehicle type, of the Arizona state-specific data and the FHWA/TSC national data. Examination of these Figures demonstrates, that as a percentage of total samples, the relative number of vehicles measured in the Arizona study, by speed band and vehicle type, are very similar to the national data collected by FHWA/TSC.

B. VERIFICATION OF ADJUSTMENT METHODOLOGY

The energy-mean adjustment was calculated in accordance with equation VI.2 (Section VI.B.). In order to verify that this method provides close agreement with the actual energy-mean of the data, energy-mean values were calculated and plotted in 5 mph speed bands with the REMEL regression equation for each vehicle type. These plots, contained as Figures 4 to 6 in Appendix D, show excellent agreement between the energy-mean of the speed band data and the $L_E(s)$ calculated by the residual method.

C. ARIZONA REMEL RESULTS

The results of the Arizona regression analysis are presented in this section. Figures 7 through 9 in Appendix E present the REMEL regression line as a function of speed for all three vehicle types considered in this study.

1. Arizona Automobiles

Figure 7 in Appendix E illustrates the REMEL regression for Arizona automobiles as a function of speed. Also included is the 95 percent confidence interval (calculated by equation VI.4), and the L_{AFmx} field data points. The 95 percent CI ranges at speeds of 1, 55, and 80 mph are shown in Table 3, along with data for corresponding speeds from the FHWA/TSC REMEL study.

Because an error was found in equation VI.5 as it was stated in the FHWA/TSC REMEL study, both the reported and calculated values for the FHWA/TSC data are listed in Table 3. The equation was corrected in accordance with instructions from FHWA/TSC on April 26, 2000 (Section VI.C.).[11] The data reported in the FHWA/TSC REMEL report was then used to calculate the confidence interval for the FHWA/TSC study. Table 3 demonstrates, that for automobiles, the reported and calculated confidence intervals are the same. This provides assurance that the Arizona confidence intervals have been correctly calculated using the same methodology employed in the FHWA/TSC document.

Table 3: 95 Percent Confidence Intervals for Automobile REMEL Regression

Speed, mph	FHWA/TSC, dBA		AZ, dBA
	Reported	Calculated	
1	±1.01	±1.01	±2.37
55	±0.11	±0.11	±0.28
80	±0.21	±0.21	±0.49

Examination of Table 3 demonstrates that the range of sound levels calculated from the regression equation can be expected to agree closely with that generated by actual Arizona traffic. The Arizona data compares favorably with the FHWA/TSC REMEL study, although with a slightly greater range.

Following is a list of the regression coefficients and results of the regression analysis used to calculate the 95 percent confidence interval, and the adjustments from level-mean to energy-mean for automobiles in Arizona:

N	598				
A	24.530997	ε_A	0.981401	ρ_{AB}	-0.997000
B	29.999672	ε_B	1.655030	ρ_{AC}	0
C	42.090000	ε_C	1.280317	ρ_{BC}	0
ΔEb	1.252209	σ_{RL}	3.1053	$\overline{RL}$	$-3.03X10^{-9}$
ΔEc	1.749606	σ_{RE}	1.2716	$\overline{RE}$	1.3342

2. Arizona Medium Trucks

Figure 8 in Appendix E illustrates the REMEL regression for Arizona medium trucks as a function of speed. Also included is the 95 percent confidence interval (calculated by equation VI.4), and the L_{AFmx} field data points. The 95 percent CI ranges at speeds of 1, 55, and 80 mph are shown in Table 4, along with data for corresponding speeds from the FHWA/TSC REMEL study.

Table 4: 95 Percent Confidence Intervals for Medium Truck REMEL Regression

Speed, mph	FHWA/TSC, dBA		AZ, dBA
	Reported	Calculated	
1	±2.47	±3.18	±2.33
55	±0.22	±2.35	±1.40
80	±0.64	±1.58	±1.18

Examination of Table 4 demonstrates that the range of sound levels calculated from the Arizona medium truck regression equation can be expected to agree relatively closely with that generated by actual Arizona traffic, but the range is greater than that reported by FHWA/TSC.

However, the calculated confidence intervals for the FHWA/TSC data must also be examined. The calculated FHWA/TSC confidence interval in Table 4 were generated using equation VI.4 and the corrected equation VI.5 (discussed in Section VII.D.1.). As can be seen from Table 4, there is considerable disagreement between the calculated and reported values for the FHWA/TSC medium truck data. Since the reported and calculated confidence intervals for automobiles were the same (based on the reported data in the FHWA/TSC study, and use of corrected equation VI.5), it must be assumed that the correct confidence intervals for the FHWA/TSC medium truck data are the calculated values. Therefore, the range in expected values from the Arizona regression analysis is narrower than the FHWA/TSC results throughout the tested speed range.

Following is a list of the regression coefficients and results of the regression analysis used to calculate the 95 percent confidence interval, and the adjustments from level-mean to energy-mean for medium trucks in Arizona:

N	494				
A	23.198664	ε_A	1.947928	ρ_{AB}	-0.9986
B	37.253964	ε_B	3.406700	ρ_{AC}	0.5905
C	65.524681	ε_C	1.194062	ρ_{BC}	-0.6099
ΔEb	1.134085	σ_{RL}	3.1721	$\overline{RL}$	$-3.21X10^{-8}$
ΔEc	1.134085	σ_{RE}	1.0935	$\overline{RE}$	1.2984

3. Arizona Heavy Trucks

Figure 9 in Appendix E illustrates the REMEL regression for Arizona heavy trucks as a function of speed. Also included is the 95 percent confidence interval (calculated by equation VI.4), and the L_{AFmx} field data points. The 95 percent CI ranges at speeds of 1, 55, and 80 mph are shown in Table 5, along with data for corresponding speeds from the FHWA/TSC REMEL study.

Examination of Table 5 demonstrates that the range of sound levels calculated from the Arizona heavy truck regression equation can be expected to agree closely with that generated by actual Arizona traffic, but the range is somewhat greater than that reported by FHWA/TSC.

Table 5: 95 Percent Confidence Intervals for Heavy Truck REMEL Regression

Speed, mph	FHWA/TSC, dBA		AZ, dBA
	Reported	Calculated	
1	±0.44	±0.51	±3.70
55	±0.10	±1.11	±0.84
80	±0.30	±0.73	±0.79

However, the calculated confidence intervals for the FHWA/TSC data must also be examined. The calculated FHWA/TSC confidence interval in Table 5 were generated using equation VI.4 and the corrected equation VI.5 (discussed in Section VII.D.1.). As can be seen from Table 5, there is disagreement between the calculated and reported values for the FHWA/TSC heavy truck data. Since the reported and calculated confidence intervals for automobiles were the same (based on the reported data in the FHWA/TSC study, and use of corrected equation VI.5), it must be assumed that the correct confidence intervals for the FHWA/TSC heavy truck data are the calculated values. Therefore, the range in expected values from the Arizona regression analysis is very similar to the FHWA/TSC results at normal highway operating speeds.

Following is a list of the regression coefficients and results of the regression analysis used to calculate the 95 percent confidence interval, and the adjustments from level-mean to energy-mean for heavy trucks in Arizona:

N	554				
A	16.201656	ε_A	1.534736	ρ_{AB}	-0.9986
B	51.656114	ε_B	2.768057	ρ_{AC}	0.7968
C	67.552474	ε_C	1.995017	ρ_{BC}	-0.8154
ΔEb	0.780216	σ_{RL}	2.5046	$\overline{RL}$	$-9.52X10^{-9}$
ΔEc	0.780216	σ_{RE}	0.8491	$\overline{RE}$	1.1968

D. COMPARISON OF AZ REMEL DATA WITH NATIONAL REMEL DATA

Table 6 presents a summary comparison of REMELs calculated at a speed of 60 mph for all three vehicle types. This summary includes the following REMEL data sets: 1975 STAMINA model; 1998 Arizona STAMINA model; 1995 TNM; and 2000 Arizona TNM. It should be noted that the data collected in the 1975 and 1998 STAMINA studies were analyzed using different methods than used in the current study. However, the difference due to procedure is negligible at the highway operating speeds where most noise problems occur.[7]

Table 6: Emission Level (dBA) Comparisons at 60 mph

	Auto	MT	HT
1975 STAMINA	73.18	83.66	87.23
1998 AZ STAMINA	73.89	79.25	83.04
1995 FHWA TNM	75.37	81.13	85.19
2000 AZ TNM	74.87	79.85	81.46

Examination of Table 6 clearly demonstrates that differences do exist between the Arizona specific REMELs and national data developed by FHWA/TSC, as well as in the results generated by the two different models. These differences will be explored more fully in the following paragraphs.

Figures 10, 11, and 12 in Appendix F present a comparison of the Arizona and FHWA/TSC REMEL data as a function of speed for automobiles, medium trucks, and heavy trucks respectively. Because the dominant pavement type in Arizona is asphaltic concrete, the FHWA/TSC data for both DGAC and average pavement are presented in order to illustrate any differences in those two data sets. Examination of Figures 10, 11, and 12 indicate that at speeds above 30 mph, the DGAC curve is approximately 0.6 dBA below the average pavement curve, and for speeds less than 30 mph, the curves are virtually identical. That difference is considered insignificant for the purpose of this analysis, and all further comparisons will be made with the FHWA/TSC average pavement data.

Figure 10 illustrates that automobiles in Arizona generate more noise than the FHWA/TSC vehicles at speeds between approximately 5 and 55 mph, and are quieter below 5 and above 55 mph. Similarly, Figure 11 illustrates that Arizona medium trucks generate more noise than the FHWA/TSC vehicles between approximately 12 and 43 mph, and are quieter below 12 and above 43 mph. The most significant difference is in the heavy truck classification. Figure 12 illustrates that Arizona heavy trucks generate about the same noise as the FHWA/TSC vehicles at speeds between approximately 25 and 30 mph, but are significantly quieter at speeds over 50 mph and under 15 mph. A statistical analysis of these differences are presented in the following paragraphs.

As discussed in Section VI.E., the same statistical methodology was used to compare the FHWA/TSC and Arizona REMEL data as was used to compare the FHWA/TSC and California REMEL data. The regression results for the national REMEL data reported in the FHWA/TSC REMEL document was used to calculate $L_E(s)$ values (equation VI.3) for each vehicle type at different speeds.[5] The same report also supplied the statistical analysis results with which the standard error for each speed, s, could be calculated for each vehicle type, using equation VI.5. Section VII.C. of this report contains the corresponding information for the data collected in the Arizona REMEL study.

The difference between the two regressions and the associated difference in the standard error was calculated by equations VI.6 and VI.7, respectively. The difference in the standard errors was then used to calculate the 95 percent confidence interval around the associated $L_E(s)$ plot. Then, in accordance with procedures outlined in the FHWA/TSC REMEL document, a graphical analysis was utilized to determine if the two data sets for each vehicle type were statistically the same.[5] In this procedure, if the zero difference line lies outside the confidence interval boundaries *at any location*, then it is assumed that the difference in the two data sets are caused by something other than chance. In other words, while no conclusion can be drawn as to the actual cause of the difference, there would be clear and verifiable evidence that a statistically significant difference in the two data sets does exist. In the FHWA/TSC procedure, if the zero difference line was found to lie completely within the 95 percent confidence interval limits, then the data sets were assumed to be the statistically the same.

Figures 13, 14, and 15 in Appendix F illustrate the difference between the FHWA/TSC and Arizona regressions, and the associated 95 percent confidence interval for each vehicle type. These plots demonstrate that the two data sets, using the criteria specified by FHWA/TSC, are statistically different (i.e., the zero difference line does not lie entirely within the 95% confidence interval limits). For example, examination of Figure 13 illustrates that the Arizona and FHWA/TSC data for automobiles were similar between speeds between approximately 4 to 8 mph, and 54 to 58 mph. In all other locations, the zero difference line lies outside the 95% confidence interval limits. Therefore, since the zero difference line does not lie entirely within the 95% confidence interval limits, the Arizona and FHWA/TSC data sets for automobiles are determined to be statistically different.

E. CONCLUSIONS

Based on the results of the analysis presented in this section, several observations are apparent relative to the Arizona specific REMEL data:

- TNM will generate lower A-weighted sound levels for all vehicle types at 60 mph when using Arizona REMEL data as user-defined vehicles (see Table 6).

- STAMINA will generate lower A-weighted sound levels for medium and heavy trucks at 60 mph when using Arizona STAMINA REMEL data (see Table 6). The results for automobiles are slightly higher using AZ REMELs.

- STAMINA, with Arizona REMEL data, will generate lower A-weighted sound levels at 60 mph than TNM with either the national or Arizona REMEL data (see Table 6).

- A comparison of the Arizona TNM REMEL data with the FHWA/TSC national TNM REMEL data shows the two data sets are statistically different at a 95% confidence level for all three vehicle types addressed in this report.

The observations listed above will be discussed more fully in the conclusions found in Chapter IX.

VIII. MODEL VALIDATION

With the release of TNM version 1.0 on March 30, 1998, a memo from the FHWA Office of Environment and Planning stated that the TNM model "...has been validated and has been found to have improved accuracy over the existing FHWA prediction model.".[1] This statement was based on a limited number of field measurements at two sites, one in California and one in Maryland. Since that time, very little effort has been made by users of the model to verify its accuracy.

As a part of the research effort to compare the Arizona state-specific REMELs to the national data collected by FHWA/TSC, a set of field measurements was made to compare with the predictions of both TNM and STAMINA. The STAMINA model was included in this study to compare its predictive accuracy with that of TNM. Each of the models was executed using both national and state-specific REMEL data. The Arizona STAMINA REMEL data was collected in 1998, using a slightly different method than described in this report.[7] This Section will present the procedure, results, and analysis of the validation effort. All references to TNM will be to Version 1.0b of the model.

A. SITE SELECTION

Ten sites were chosen at which the measurements were collected. These sites were chosen to be typical of sites found in Arizona, but care was taken to insure that no unusual topographic features existed that would bias the measurement data, and thus the comparison to model predictions. Sites were chosen where electronic roadway design plans were available, so the 3-dimensional data required to set up the input files were readily available.

Each site was relatively flat and approximately the same elevation as the roadway at the receiver locations. Ground cover at each site was uniform from the roadway to the farthest receiver location. Particular attention was paid to finding sites where non-highway noise sources were absent. Sites were also chosen where traffic flow and speed would be consistent over the entire measurement period. Sites and their relevant characteristics are listed in Table 7.

B. MEASUREMENT PROCEDURE AND RESULTS

During each measurement sequence, meteorological conditions were monitored to insure consistency over the measurement sequence at each site and between sites. No measurements were made when conditions were close to or outside of those limits recommended by FHWA, nor when conditions varied significantly between measurement sequences or sites.[6]

The sound level meter (Larson-Davis model 812) was set up and calibrated in accordance with FHWA guidelines.[6] Three independent measurements were made at each site at distances of 100, 200, and 400 feet from the center of the nearest travel lane.

These distances were chosen because they represent the range of the location of sensitive receptors found in the typical highway noise study. At each distance sound levels and traffic information (volume, speed, and mix) were measured for a period of 15 minutes. This provided an accurate measurement at each location for the sample period based on the traffic flow for that period, but does not give an indication of the drop-off rate between each microphone location. The measured L_{eq} values at each site and distance are contained in Table 8.

Table 7: Measurement Sites for Validation Study

Site	Location	TNM Grnd Type	STAMINA Grnd Type
US180N	Btwn Schultz Pass Rd & Freemont	L. Soil	Soft
US180S	Btwn Schultz Pass Rd & Freemont	L. Soil	Soft
I-17	Castles and Coasters Area	H. Soil	Hard
I-19	Valencia Road Area	H. Soil	Hard
SR87N	0.2 Mi N of AZ Canal, MP 184.5	H. Soil	Hard
SR87S	1.1 Mi S of AZ Canal, MP 183.2	H. Soil	Hard
SR587E	Gila River Indian Com, S of Gila River	H. Soil	Hard
SR587W	Gila River Indian Com, S of Gila River	H. Soil	Hard
SR89AN	State Land Trust, Dirt Acc Rd, MP 361.3	H. Soil	Hard
SR89AS	Adj Blue Grey Dirt Rd, MP 358	H. Soil	Hard

Table 8: L_{eq} Field Measurements by Site

	Measured Leq (dBA) at Distance		
Site	100ft.	200ft.	400ft.
US180S	63.0	56.5	51.6
US180N	61.1	48.2	45.9
I-17	74.3	69.8	63.2
I-19	73.3	69.7	62.0
SR87N	66.8	63.3	59.5
SR87S	66.9	63.3	58.7
SR587W	61.3	58.8	46.9
SR587E	60.8	56.0	53.4
SR89AN	63.2	62.0	58.1
SR89AS	64.5	63.5	60.0

C. MODELING PROCEDURE

All data files were constructed by digitizing the roadways and receivers from a MicroStation design file. These digitized objects were then converted to STAMINA input files through a MicroStation interface developed at the University of Louisville and utilized by ADOT. The STAMINA files were constructed first because that method was simple and straightforward, and no mechanism exists to develop this data directly through TNM. The STAMINA input files were then imported into TNM.

Care was taken to insure that any additional features available to TNM were digitized at this time. For example, it is recommended that terrain lines be used to define "substantial changes in terrain elevation".[5] This feature, where needed, was digitized as a barrier for the STAMINA input file. Because of careful site selection, no other features unique to TNM were required. No ground zones, tree lines, or additional terrain lines were required because each site had consistent ground cover, was free of unusual vegetation, and was relatively flat. The term "relatively flat" implies that differences between roadway and receiver elevations were generally less than 3 feet. The primary developers of TNM recommend that no terrain lines be used if changes in terrain elevation is less than ±10 feet.[12]

D. MODELING RESULTS

Four sets of prediction results were generated at each receiver location at each site. Because independent sound level measurements and traffic counts were made at each distance at each site (Section VIII.B.), each model was executed three times at each site. Just as with the measurement data, drop-off rates are not directly obvious from the predicted results. The results of each model prediction at each site are contained in Tables 9 and 10.

Table 9: TNM Results Using National and Arizona REMELs

	FHWA TNM Predicted Leq, dBA			Arizona TNM Predicted Leq, dBA		
Site	100ft.	200ft.	400ft.	100ft.	200ft.	400ft.
US180S	62.6	56.8	51.7	61.9	56.4	51.3
US180N	61.2	55.9	50.4	61.1	55.7	50.0
I-17	79.6	77.5	73.5	78.3	76.1	72.2
I-19	75.3	73.3	69.7	72.9	70.9	67.2
SR87N	74.3	72.0	67.1	71.9	69.6	65.0
SR87S	72.6	70.0	65.8	70.3	68.6	63.7
SR587W	64.3	61.7	56.0	63.7	60.7	55.5
SR587E	64.4	61.7	56.1	63.8	60.7	55.6
SR89AN	67.6	65.1	59.0	65.9	63.1	57.4
SR89AS	66.7	63.7	60.0	65.0	62.1	58.2

A detailed discussion of the comparison between the prediction results in Tables 9 and 10, and the corresponding measurement data in Table 8 is contained in the following section (VIII.E.). The mean difference between predicted and measured values are presented in Table 11.

E. ANALYSIS OF RESULTS

The first step in this analysis was to determine if model accuracy is affected by site location. If it is demonstrated that model accuracy is not affected by different sites, then site location would not be significant to prediction accuracy. In other words, the model would predict with the same level of accuracy for all sites included in this study.

1. Effects of Site and Receiver Location

A graphical analysis was used to determine if the individual sites significantly affected the prediction accuracy of the model. In this analysis, the results contained in Tables 9 and 10 are plotted and examined for trends of the individual models at each site. Figures 16 through 19 in Appendix G illustrates the trend of each model. Examination of these figures illustrates that the prediction trend for each model is similar in shape at each site. This trend indicates that the individual site locations are not significant to the prediction accuracy of any model.

Table 10: STAMINA Results Using National and Arizona REMELs

	FHWA STAMINA Predicted Leq, dBA			Arizona STAMINA Predicted Leq, dBA		
Site	100ft.	200ft.	400ft.	100ft.	200ft.	400ft.
US180S	63.9	58.6	54.6	62.1	57.2	53.8
US180N	63.2	57.3	53.2	61.6	56.8	52.8
I-17	77.5	75.6	72.0	74.7	72.7	69.2
I-19	73.8	71.4	68.0	72.1	68.6	64.8
SR87N	73.4	71.8	66.0	70.0	68.1	62.7
SR87S	71.9	69.7	64.7	68.4	66.1	61.4
SR587W	59.8	59.0	49.0	58.9	56.8	49.7
SR587E	63.4	58.0	55.4	63.1	58.6	55.7
SR89AN	64.5	63.8	56.9	61.9	60.4	54.2
SR89AS	64.2	60.9	58.7	61.4	58.2	55.5

The next step in the analysis was to determine if receiver location relative to the roadway was significant to the prediction accuracy of the models. This was again accomplished through graphical analysis by plotting the difference between the predicted level and measured level at each receiver location. Figures 20 through 23 in Appendix G illustrate this difference for each model at each site. Examination of these figures show a variation in agreement between measured and predicted sound levels at each receiver location, indicating that receiver distance is significant to the prediction accuracy of each model. This is intuitively obvious, given the introduction of multiple other variables (e.g., meteorological factors) with increased receiver distance from the roadway. However, because these factors affect all four models in exactly the same way and magnitude, it can be concluded that the prediction accuracy of the model is not affected <u>*at the same distance*</u> from the roadway for all four models at each site.

2. Analysis of REMEL Data on Model Prediction Accuracy

Next, each site was examined individually to determine the effects of the two different sets of REMEL data on the prediction accuracy of the two models. As a preliminary analysis tool, the mean difference between predicted and measured sound levels at each receiver distance for each model/REMEL data set combination were calculated (equation VIII.1). These differences are listed in Table 11, and plotted in Figure 24 in Appendix G.

Table 11: Mean Difference Between Measured and Predicted Sound Levels

	Mean Difference, Leq (dBA)			
Model	100ft.	200ft.	400ft.	Avg.
FHWA STAMINA	2.0	3.5	3.9	3.2
AZ STAMINA	-0.1	1.2	2.1	1.1
FHWA TNM	3.3	4.7	5.0	4.3
AZ TNM	2.0	3.3	3.7	3.0

Examination of Table 11 and Figure 24 illustrates that, on average, when using the Arizona state-specific REMEL data, both STAMINA and TNM generate more accurate results than the same models using national REMEL data at each of the four distances studied. Further, the Arizona STAMINA model is more accurate, on average, than TNM with either the Arizona or national REMEL data sets, or STAMINA with the 1974 national REMEL data.

In addition, Figures 20 and 21 also demonstrate that TNM has a tendency to significantly over-predict sound levels, whether using FHWA/TSC or Arizona state-specific REMEL data. Figures 22 and 23 demonstrate that STAMINA predictions are relatively closer to the measured data at the same location than TNM, especially when utilizing the Arizona REMEL data.

It was demonstrated in Section VIII.E.1. that the selected site locations are not significant to the prediction accuracy of the models being examined. Therefore, the measured data at each site may also be statistically compared to the predicted results from each model, *at the same distance* from the roadway. The best statistical analysis method for this data is a paired two-tailed t-test. This method was chosen for obvious reasons, which include: the data represents a small sample size; the calculated and measured sound levels from each combination of prediction model and REMEL data represents samples from a single source (i.e., sound levels defined by given traffic conditions and roadway geometry); and the sample can be assumed to be normally distributed.

The sample will consist of the mean difference between the measured and predicted sound levels for each model/REMEL data combination (Table 11), for each site, and for each receiver distance independently (equation VIII.1). The mean difference is then used to calculate the standard deviation of the sample (equation VIII.2), which is in turn used to calculate a t-value (equation VIII.4). The calculated value of t is then compared to a tabulated t-value for the desired level of significance. Tabulated t-values are found in any statistics textbook.

The level of significance is defined as the probability that a given occurrence is in error. For example, a level of significance of five percent indicates that the probability of error at any given distance is five percent, which in turn implies a 95 percent confidence level in the results of the predicted data. A five percent level of significance was used in this analysis.

If the calculated t-value is greater than the tabulated t-value, then it can be stated that the difference between predicted and measured sound levels was caused by some factor other than chance. This would indicate that the difference between the predicted and measured sound level is significant. On the other hand if the calculated t-value is less than the tabulated t-value, then it can be stated that the difference between predicted and measured sound levels is not significant and can be attributed to chance.

The mean difference $\left(\bar{d}\right)$ between the measured and predicted sound level at each site and distance for each model/REMEL combination was previously calculated and the results listed in Table 11. This was accomplished by:

$$\bar{d} = \frac{\sum d}{n} \qquad \text{(VIII.1)}$$

The estimated standard deviation of each sample can then be calculated by:

$$s = \sqrt{\frac{\sum d^2 - \left(\left(\sum d\right)^2 / n\right)}{n-1}} \qquad \text{(VIII.2)}$$

The standard deviation of the mean difference of each sample is then given by:

$$s_d = \frac{s}{\sqrt{n}} \qquad \text{(VIII.3)}$$

Finally the calculated t-value is determined by comparing the mean difference to zero and dividing the result by the standard deviation of the mean difference, as follows:

$$t = \frac{\left|\bar{d} - 0\right|}{s_d} \qquad \text{(VIII.4)}$$

The calculated t-value can now be compared to the tabulated t-value to determine if a significant difference exists between the predicted and measured sound level at each receiver location, and for each model/REMEL data combination. Table 12 contains the calculated t-values for each case and Figure 25 in Appendix G presents a plot of the calculated t-values for each distance and model.

Table 12: Summary of t-values

	Calculated t-value			
Data Source	100ft.	200ft.	400ft.	Avg.
Tabulated t (5%)	2.262	2.262	2.262	2.045
FHWA STAMINA	2.647*	2.929*	3.516*	5.255*
AZ STAMINA	0.155	0.991	1.773	1.747
FHWA TNM	4.249*	4.778*	4.087*	7.489*
AZ TNM	2.984*	3.347*	3.094*	5.349*

* Statistically significant difference

The results contained in Table 12 and shown in Figure 25 presents evidence that the STAMINA model using Arizona state-specific REMEL data is the only one of the four studied that will consistently produce accurate results at a 95% confidence level at distances up to 400 feet from the roadway.

F. CONCLUSIONS

Examination of Table 11, Figure 24, Table 12, and Figure 25 leads to the following observations:

- The use of Arizona state-specific REMEL data increases the accuracy of both STAMINA and TNM over the same models using the FHWA/TSC national REMEL data, when modeling sites in the state of Arizona.

- The most accurate prediction method for sites in Arizona at distances up to 400 ft. from the roadway is the STAMINA model using Arizona state-specific REMEL data.

- The least accurate prediction method for Arizona sites at distances up to 400 ft. from the roadway is the TNM model using national REMEL data.

- TNM significantly over-predicts sound levels whether using either FHWA/TSC or Arizona state-specific REMEL data.

- The results presented in Table 12 and illustrated in Figure 25 demonstrates that at the 100, 200, and 400 ft. distances, the difference between predicted and measured levels are significant for all models except Arizona STAMINA. In other words, something other than chance affected the prediction accuracy for the other models at all three distances from the roadway.

- The results for the average difference over all 30 measurement locations presented in Table 12 demonstrate that the difference between predicted and measured levels are also significant for all models except Arizona STAMINA. In other words, something other than chance affected the prediction accuracy for the other models at all distances from the roadway as an aggregate.

- The results presented in Table 12 and illustrated in Figure 25 cannot identify the cause of the lower prediction accuracy of the TNM model and the STAMINA model using 1974 FHWA emission data. However, these results do provide clear and verifiable evidence that tangible problems do exist with the prediction accuracy of these models.

The observations listed above will be discussed more fully in the conclusions found in Chapter IX.

IX. SUMMARY AND CONCLUSIONS

This chapter presents a summary of the findings of this report and a further discussion of the conclusions presented in Chapters VII. and VIII.

A. COMPARISON OF ARIZONA WITH FHWA/TSC REMEL DATA

1. AZ REMEL Data is Statistically Different from FHWA/TSC National Data

The analysis procedure used in the FHWA/TSC REMEL study [5] was used in arriving at this conclusion, thus validating the results of the Arizona study as well as comparison of the two data sets. For example, 95% confidence intervals of the REMEL regression were calculated in accordance with FHWA/TSC guidelines. Examination of these confidence intervals in Tables 3, 4, and 5 clearly show that the statistical validity of the Arizona data is similar to the FHWA/TSC data. In addition, Figures 10, 11 and 12 in Appendix F illustrate that the Arizona state-specific REMEL data are generally quieter at normal major highway operating speeds than the FHWA/TSC national data for the same vehicle types. Finally, and most compelling, Figures 13, 14, and 15 in Appendix F illustrate the difference in the two data sets are statistically significant, when calculated and compared with procedures set forth in the FHWA/TSC study.

The conclusion that regional differences exist in REMEL data sets is also supported by the FHWA/TSC REMEL study. As a part of the national REMEL study, FHWA/TSC examined a set of measurement data developed by Caltrans. The goal of the comparison was to determine if the previously measured Caltrans data was statistically similar to the national data. If it was found to be statistically similar, then the Caltrans data would be merged with the FHWA/TSC national data. The results of the comparison demonstrated that the two data sets were not statistically similar, and the Caltrans data was not merged with the FHWA/TSC data.[5]

The FHWA/TSC REMEL study also compares data collected in individual states with the aggregate national data.[5] That report states that "...different states were targeted for different vehicle types, speeds...". This would indicate that data for a relatively large number of vehicles within a particular speed range for a given vehicle type were collected in a given state, with a corresponding smaller number of samples collected at other speeds. This data was regressed and then compared to the national data.

This comparison demonstrated that in states where large amounts of the data for a particular speed range was collected, the state-specific data was statistically similar to the national data at those speeds. However, the comparison also demonstrated that at other speeds, where relatively small amounts of data had been collected, the same data set was statistically different. The FHWA/TSC report concludes that "...not enough state-specific data were measured to determine if REMELs measured within a given state were unique across the entire speed range of interest", although there was evidence that differences did exist.

In order to insure that this issue was not a problem for the comparison of the Arizona state-specific data and the FHWA/TSC national data, care was taken to insure that a similar number of samples, by percentage, was collected across the entire speed range of interest. Figures 1, 2, and 3 in Appendix C illustrate that this goal was accomplished.

It can therefore be concluded that the results presented in Chapter VII. of this document confirms that Arizona state-specific REMEL data are statistically different from the FHWA/TSC national data.

2. AZ REMEL Data Generates Significantly Lower Leq Values on Typical AZ Highways

At normal traffic operating speeds and vehicle mixes on typical high capacity highways, TNM will produce lower A-weighted Leq sound levels when using Arizona state-specific REMELs (Table 6). At the same operating speed, STAMINA will produce lower A-weighted Leq sound levels for medium and heavy trucks when using Arizona state-specific REMELs. For example, at 60 mph, the 1998 STAMINA REMEL yields an emission level 4.4 dB lower than the 1975 FHWA data for medium trucks. The Arizona heavy truck REMEL yields an emission level 3.7 dB lower than the FHWA/TSC data at 60 mph. For automobiles, STAMINA produces slightly higher sound levels with the Arizona REMEL data. The prediction accuracy of both models on Arizona highways, with different REMEL data, will be examined in the following section.

B. VALIDATION OF PREDICTION ACCURACY

1. AZ State-Specific REMELs Are More Accurate Than National REMELs for Sites in AZ

Examination of Table 11 and Figure 24 illustrates that, on average, both TNM and STAMINA generate more accurate results when using Arizona state-specific REMEL data. Figures 20 through 23 illustrate that this increased accuracy also is realized when examining individual sites as well as all sites as an aggregate.

2. STAMINA is More Accurate Than TNM

Table 11 and Figure 24 illustrates that all four model/REMEL combinations become less accurate with increased distance from the roadway. But, the STAMINA model, using Arizona state-specific REMEL data, is the most accurate at all distances up to 400 feet. This is true at specific distances from the roadway as well as an aggregate of all the measurements made at all the sites. This study has also demonstrated that the

TNM model significantly over-predicts sound levels, whether using either the FHWA/TSC or Arizona state-specific REMEL data.

3. TNM's Prediction Inaccuracy is Likely Due to Programming Errors and Over-Complication

These findings prompt a legitimate and serious question for those agencies, such as ADOT, that will be *required* to use the TNM model effective December 31, 2002. That question is: Why does the existing noise prediction methodology (STAMINA 2.0) produce more accurate results than the newest prediction methodology (TNM)? The answer is both complicated and multi-faceted.

A complete discussion of the reason's for the prediction inaccuracies of the TNM model is beyond the scope of this study. However, these problems can be summarized under two broad headings: programming errors, and an overly complex approach to an engineering design problem.

First, the TNM model has been plagued with multiple programming and interface problems since its release on March 30, 1998. In fact, over 200 programming bugs and desired interface enhancements have been identified.[2] These programming bugs do not only cause TNM to generate inaccurate results, but also cause it to generate significantly different results at the same location with only minor modifications to the input data.[13]

Secondly, the acoustic algorithms in TNM are the result of a synthesis of research contained in the current literature and reflect much of the recent theoretical work in acoustics in this area. However, highway noise analysis and barrier design are not exercises in theoretical acoustics. The presence of numerous variables that constantly change (e.g., wind speed and direction, humidity, temperature, etc.) cannot be accommodated in TNM or any other noise model. Even the capability of TNM to model different ground cover, tree zones, and terrain features, could easily lead the user to inaccurately model (or misuse) projected geometric conditions. Experience has shown, and the results documented in this report, have demonstrated that the simplifying assumptions made in STAMINA 2.0 are adequate and accurate. More complex approaches to highway noise analysis do not, as documented in this report, lead to more accurate prediction methods.

It should be noted that this study only considered sites at which no noise barrier existed. Anecdotal evidence has suggested that the prediction accuracy for STAMINA demonstrated in this report may be diminished with the inclusion of a barrier, although with still more accurate results than TNM. There are numerous potential reasons for this degradation in prediction accuracy. Although examination of these reasons are beyond the scope of this study, two of the most likely causes may be summarized as follows:

- STAMINA utilizes only one frequency in determining the insertion loss provided by a given barrier height. Highway traffic noise is comprised of a broad band spectrum. Consideration of these other frequencies may provide more accurate determinations of insertion loss.

- STAMINA utilizes a composite source height for all three vehicle types. Consideration of actual source heights, especially for medium and heavy trucks may improve STAMINA's predicted insertion loss accuracy.

In conclusion, it can be stated that the results presented in Chapter VIII. of this document presents clear evidence that use of Arizona state-specific REMEL data increases the accuracy of both STAMINA and TNM over the same models using the FHWA/TSC national REMEL data. These results further illustrate, that for distances up to 400 feet, the STAMINA model using Arizona state-specific REMEL data is the most accurate prediction method for sites in Arizona. It was also demonstrated that TNM using the FWHA/TSC national REMEL data is the least accurate prediction method for sites in Arizona.

X. IMPLEMENTATION PLAN

Based on the results presented in this report, it recommended that ADOT:

- Request approval from FHWA of the 1998 Arizona-specific STAMINA REMEL curves for use on all ADOT projects.

- Request approval from FHWA of the Arizona-specific TNM REMEL curves developed in this study.

- Use STAMINA (with the 1998 Arizona-specific STAMINA REMEL's) on all projects until the new version of TNM (December 31, 2002) has been proven to be at least as good as STAMINA for Arizona highways.

- Continue this study to include an analysis of STAMINA and TNM performance on scenarios with noise barriers. This effort should involve a series of carefully controlled measurements (in accordance with FHWA-PD-96-046/DOT-VNTSC-FHWA-96-5, *Measurement of Highway Related Noise)* on previously built barrier projects, a careful reconstruction of the STAMINA input files and construction of TNM input files to evaluate actual barrier performance versus expected performance, and recommendations on changes (if needed) to ADOT design procedures. Approximate cost for this follow-up study would be $60,000.

- Training – A one week training course on highway noise analysis and modeling should be conducted in the Phoenix area for ADOT, city, county employees, and consultants. The purpose of this course will be to update the knowledge of the users of noise models to the current state-of-the-art, and to explain and demonstrate the strengths and weaknesses of both STAMINA and TNM. Cost of this course should be approximately $15,000, which could be partially recouped by charging private attendees a registration fee.

No additional resources will be required at this time to implement the results of this study, other than the cost for follow-up research and the training course.

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11. Telephone conversation between R.A. Harris and Cynthia, April 26, 2000.

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APPENDIX A
MEASUREMENT SITE DESCIRPTIONS

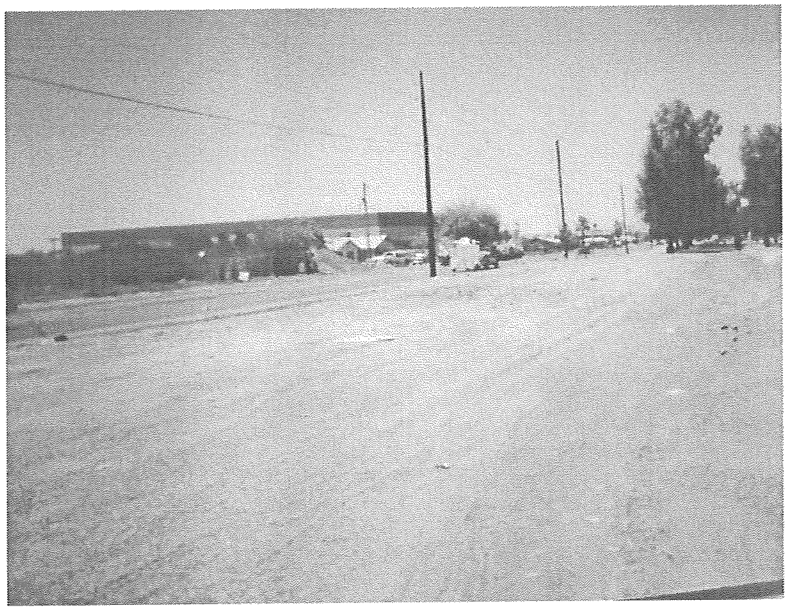
Site:	1P
Location:	SR85 SB, 1 mile south of I-10, approx. 30 miles west of Phoenix
Number of Lanes:	2
Median:	None
Pavement:	Asphalt
Speed Limit:	60 mph (prevailing)
L_{90}:	45 dBA
Comments:	Intervening ground between microphone location and traffic is dirt with a gravel shoulder

Site:	2P
Location:	27th Street SB, 1 mile south of Durango, 0.5 miles north of Lower Buckeye
Number of Lanes:	2
Median:	None
Pavement:	Concrete
Speed Limit:	35 mph
L_{90}:	47 dBA
Comments:	Intervening ground between microphone location and traffic is dirt and gravel

Site:	3P
Location:	US60 WB, approx. 15 miles east of Mesa, 1.5 miles east of the Superstition Freeway end
Number of Lanes:	4
Median:	100 ft.
Pavement:	Asphalt
Speed Limit:	55 mph
L_{90}:	51 dBA
Comments:	Intervening ground between microphone location and traffic is dirt and gravel

Site:	4P
Location:	51st Street SB at Winston Drive, 0.5 miles south of Baseline Road
Number of Lanes:	2
Median:	None
Pavement:	Asphalt
Speed Limit:	50 mph
L_{90}:	51 dBA
Comments:	Intervening ground between microphone location and traffic is dirt. Signs were outside influence zone.

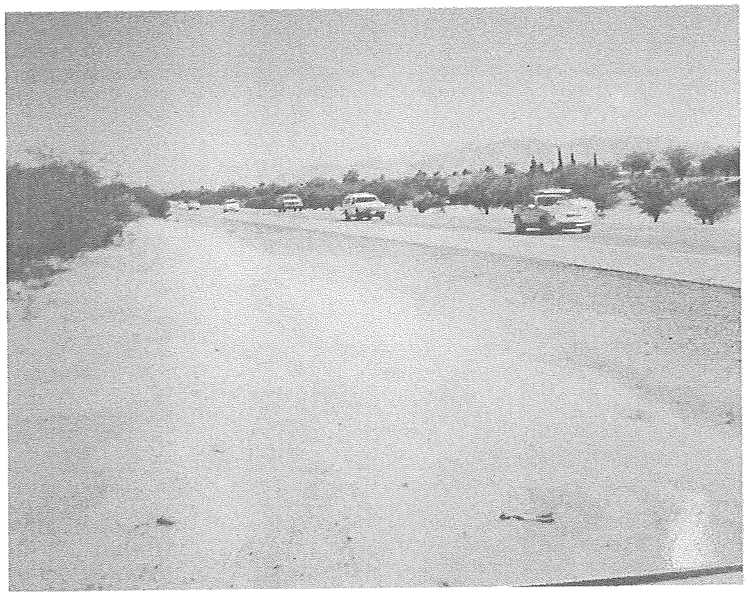
Site: 5P
Location: Roesser Street EB, 0.5 miles west of 32nd Street
Number of Lanes: 2
Median: None
Pavement: Asphalt
Speed Limit: 35 mph
L_{90}: 56 dBA
Comments: Intervening ground between microphone location and traffic is dirt and grass. Lanes are about 1 foot higher than microphone location.



Site: 6P
Location: 32nd Street NB, 0.5 miles south of Roesser
Number of Lanes: 2
Median: None
Pavement: Asphalt
Speed Limit: 35 mph
L_{90}: 53 dBA
Comments: Intervening ground between microphone location and traffic is dirt

Site:	7P
Location:	Ecanto Drive EB, 500 ft. west of 30th Avenue
Number of Lanes:	2
Median:	None
Pavement:	Asphalt
Speed Limit:	25 mph
L_{90}:	53 dBA
Comments:	Intervening ground between microphone location and traffic is dirt.Cross Street (30th Avenue) has little traffic

Site:	8P
Location:	Pima Freeway SB, 0.5 miles north of McDowell
Number of Lanes:	8
Median:	50 ft.
Pavement:	Concrete
Speed Limit:	65 mph
L_{90}:	69 dBA
Comments:	Intervening ground between microphone location and traffic is dirt and scrub. Lanes are level with microphone location.



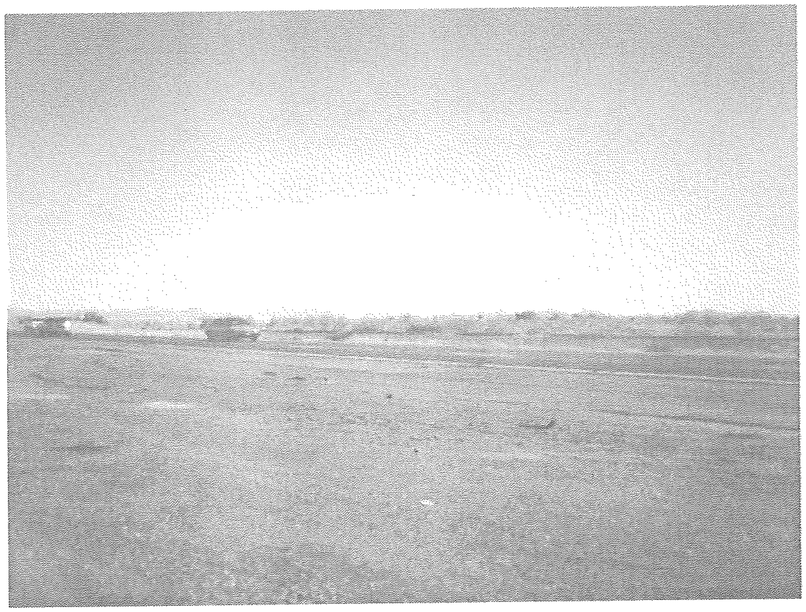
Site:	9T
Location:	I-19 SB, 0.9 miles south of Irvington Road
Number of Lanes:	4
Median:	60 ft.
Pavement:	Asphalt
Speed Limit:	55 mph
L_{90}:	57 dBA
Comments:	Intervening ground between microphone location and traffic is dirt and gravel. Lanes are within one ft. of level with microphone location.

Site:	10T
Location:	Country Club Lane, 0.5 miles south of Valencia Road
Number of Lanes:	2
Median:	None
Pavement:	Asphalt
Speed Limit:	35 mph
L_{90}:	42 dBA
Comments:	Intervening ground between microphone location and traffic is gravel.

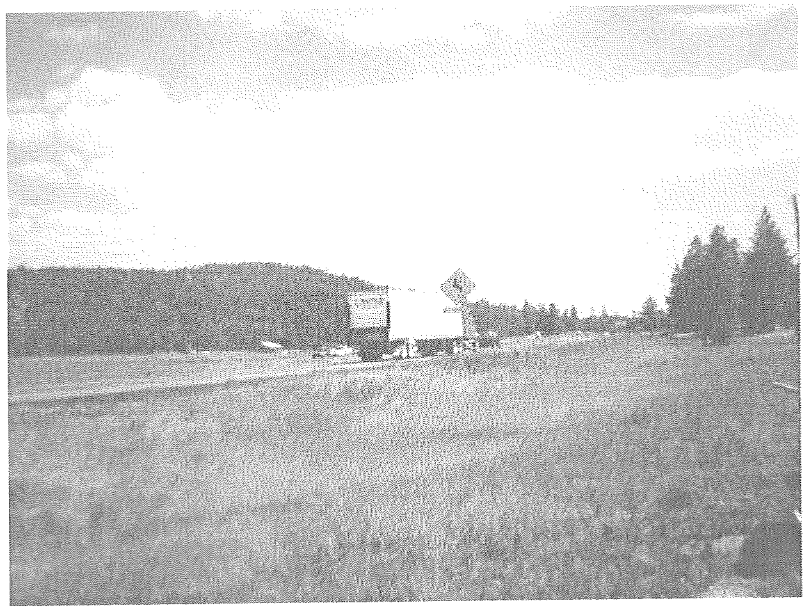
Site:	11T
Location:	Country Club Lane, 0.25 miles west of Los Reales Road
Number of Lanes:	2
Median:	None
Pavement:	Asphalt
Speed Limit:	20 mph
L_{90}:	40 dBA
Comments:	Intervening ground between microphone location and traffic is dirt, gravel, and scrub.

Site: 12T
Location: 22nd Street EB, 1000 ft. east of Camino Seco
Number of Lanes: 4
Median: None
Pavement: Asphalt
Speed Limit: 35 mph
L_{90}: 56 dBA
Comments: Intervening ground between microphone location and traffic is dirt

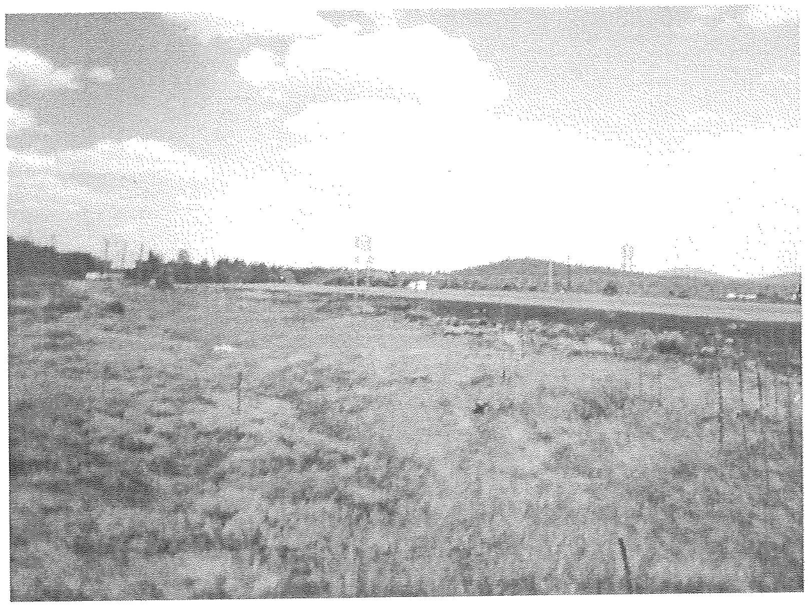
Site:	13T
Location:	I-10 NB, 2 miles north of Cordero Road (exit 246)
Number of Lanes:	4
Median:	60 ft.
Pavement:	Asphalt
Speed Limit:	75 mph
L_{90}:	66 dBA
Comments:	Intervening ground between microphone location and traffic is dirt and gravel. Lanes are about 1-2 ft. higher than microphone location.



Site:	14P
Location:	I-10 NB, 0.25 miles north of the Gila River bridge
Number of Lanes:	4
Median:	60 ft.
Pavement:	Asphalt
Speed Limit:	75 mph
L_{90}:	60 dBA
Comments:	Intervening ground between microphone location and traffic is gravel.



Site:	15F
Location:	I-17 SB (mp 328), approx. 10 miles south of Flagstaff
Number of Lanes:	4
Median:	50 ft.
Pavement:	Asphalt
Speed Limit:	75 mph
L_{90}:	60 dBA
Comments:	Intervening ground between microphone location and traffic is grass. Lanes are equal in elevation with the microphone location, although the terrain rolls some within the area.



Site:	16F
Location:	I-40 WB (mp 186), approx. 15 miles west of Flagstaff
Number of Lanes:	4
Median:	100 ft.
Pavement:	Asphalt
Speed Limit:	65 mph
L_{90}:	51 dBA
Comments:	Intervening ground between microphone location and traffic is gravel and grass. Lanes are about the same elevation as the microphone location.

Site:	17F
Location:	US66 EB (mp 0), east of Flagstaff
Number of Lanes:	2
Median:	None
Pavement:	Asphalt
Speed Limit:	55 mph
L_{90}:	50 dBA
Comments:	Intervening ground between microphone location and traffic is gravel. Lanes are about 1 ft. higher than microphone location.

Site:	18F
Location:	West US66 WB, 500 ft. west of South Thompson Street
Number of Lanes:	3
Median:	None
Pavement:	Asphalt
Speed Limit:	50 mph
L_{90}:	47 dBA
Comments:	Intervening ground between microphone location and traffic is gravel and grass.

APPENDIX B
METEOROLOGICAL OBSERVATIONS

Table 13: Site 1P Meteorological Data

Date	Time	Ambient Temp (deg F.)	Relative Humidity (%)	Wind Speed (mph)	Wind Dir.	Cloud Cover
11/5/1999	0745	65	58	2	NE	3
	0800	65	51	1	NE	3
	0815	66	46	3	NE	3
	0830	66	44	4	NE	3
	0845	69	48	3	N	3
	0900	71	38	3	N	3
	0915	72	34	5	N	3
	0930	72	39	7	NE	3
	0945	74	32	5	N	3
	1000	75	36	8	N	3
	1015	77	29	6	NE	3
	1030	78	27	7	N	3
	1045	78	27	9	NE	3
	1100	80	28	5	N	3
	1115	83	24	3	NE	3
	1130	86	29	6	NE	3
	1145	87	24	7	N	3
1/18/2000	0840	61	56	4	SW	3
	0855	61	55	4	SW	3
	0910	63	53	3	SW	3
	0925	64	58	5	SW	3
	0940	64	48	2	SW	3
	0955	66	48	2	SW	3
	1010	67	49	4	SW	3
	1035	68	44	6	SW	3
	1050	70	40	5	SW	3
	1105	71	37	5	SW	3
	1120	73	38	5	SW	3
	1135	76	32	6	SW	3
	1150	76	30	6	SW	3
1/21/2000	1145	78	38	5	S	3
	1200	78	37	1	S	3
	1215	78	40	4	SE	3
	1230	78	32	4	S	3
	1245	79	29	4	S	3
	1300	79	29	4	S	3
	1315	79	28	4	S	3
	1330	79	29	4	S	3
	1345	80	29	4	SE	3
	1400	80	27	3	S	3

Table 14: Site 2P Meteorological Data

Date	Time	Ambient Temp (deg F.)	Relative Humidity (%)	Wind Speed (mph)	Wind Dir.	Cloud Cover
11/4/1999	0700	65	39	1	NE	3
	0715	68	42	1	NE	3
	0730	68	42	1	NE	3
	0745	68	38	2	NE	3
	0800	70	31	1	NE	3
	0815	72	36	3	NE	3
	0830	72	29	1	NE	3
	0845	73	28	1	N	3

Table 15: Site 4P Meteorological Data

Date	Time	Ambient Temp (deg F.)	Relative Humidity (%)	Wind Speed (mph)	Wind Dir.	Cloud Cover
11/4/1999	1045	83	29	1	S	3
	1100	84	29	2	S	3
	1115	84	32	1	S	3
	1130	84	26	1	S	3
	1145	84	28	0	-	3
	1200	84	26	0	-	3
1/20/2000	1230	80	28	0	-	3
	1245	80	27	0	-	3
	1300	81	28	0	-	3
	1315	82	28	1	SW	3
	1330	82	26	0	-	3
	1345	82	26	0	-	3
	1400	82	26	2	S	3
	1415	82	26	0	-	3
	1430	82	26	0	-	3
1/21/2000	0900	63	50	3	N	3
	0915	63	48	1	NE	3
	0930	65	49	2	NE	3
	0945	67	47	1	N	3
	1000	68	49	1	N	3
	1015	70	48	1	N	3
	1030	72	45	0	-	3
3/27/2000	1245	79	10	3	N	3
	1300	81	10	3	N	3
	1315	83	10	2	N	3
	1330	84	11	2	N	3
	1345	85	11	2	NE	3
	1400	84	10	2	N	3
	1415	82	11	1	NW	3
	1430	82	10	2	N	3
	1445	83	11	1	N	3
	1500	82	11	2	N	3
	1515	83	10	3	N	3
	1530	81	11	1	N	3
	1545	80	11	2	NE	3

Table 16: Site 4P Meteorological Data

Date	Time	Ambient Temp (deg F.)	Relative Humidity (%)	Wind Speed (mph)	Wind Dir.	Cloud Cover
3/29/2000	0800	60	9	0	-	3
	0815	63	9	0	-	3
	0845	67	9	0	-	3
	0900	69	9	0	-	3
	0915	71	10	0	-	3
	0930	70	11	0	-	3
	0945	73	12	0	-	3
	1000	73	11	0	-	3
	1015	74	10	0	-	3
	1030	74	12	0	-	3
	1200	77	10	2	E	3
	1215	79	9	1	E	3
	1230	78	8	1	SE	3
	1245	79	9	1	E	3
	1300	80	11	1	S	3
	1315	80	10	2	SE	3
	1330	81	11	1	E	3
	1345	82	10	1	E	3
	1400	82	10	2	E	3
	1415	82	11	1	SE	3
3/30/2000	0730	69	9	0	-	3
	0745	71	8	0	-	3
	0800	75	9	0	-	3
	0815	74	9	0	-	3
	0830	75	10	1	W	3
	0845	76	11	1	SW	3
	0900	76	10	0	-	3
	0915	75	10	2	SW	3
	0930	76	11	3	W	3
	0945	76	11	1	SW	3
	1000	77	10	1	SW	3
	1015	77	10	2	SW	3
	1030	77	10	2	S	3

Table 17: Site 5P Meteorological Data

Date	Time	Ambient Temp (deg F.)	Relative Humidity (%)	Wind Speed (mph)	Wind Dir.	Cloud Cover
10/22/99	1355	95	23	2	SE	3
	1410	93	20	0	-	3
	1425	94	16	0	-	3
	1440	93	15	2	SE	3
	1455	93	14	0	-	3
	1510	93	17	0	-	3
	1525	93	14	1	SE	3
	1540	92	15	0	-	3
	1555	92	17	0	-	3
	1610	93	16	0	-	3
	1625	87	24	0	-	3
	1640	87	22	0	-	3
	1655	86	24	0	-	3
1/20/2000	0935	61	46	1	S	3
	0950	63	48	1	S	3
	1005	66	46	1	S	3
	1020	68	40	1	S	3

Table 18: Site 6P Meteorological Data

Date	Time	Ambient Temp (deg F.)	Relative Humidity (%)	Wind Speed (mph)	Wind Dir.	Cloud Cover
10/22/99	0845	77	25	1	E	3
	0900	82	26	0	-	3
	0915	82	27	1	E	3
	0930	82	27	1	E	3
	0945	81	27	2	E	3
	1000	82	25	0	-	3
	1015	83	23	0	-	3
	1030	84	21	2	E	3
	1045	84	24	2	E	3
	1100	87	23	3	NE	3
	1115	86	21	1	E	3
	1130	87	24	2	E	3
	1145	87	22	2	E	3
	1200	89	23	2	E	3

Table 19: Site 7P Meteorological Data

Date	Time	Ambient Temp (deg F.)	Relative Humidity (%)	Wind Speed (mph)	Wind Dir.	Cloud Cover
11/4/1999	1345	92	15	3	NE	3
	1400	88	13	1	N	3
	1415	90	17	0	-	3
	1430	90	13	2	N	3
	1445	88	20	1	N	3
	1500	88	31	0	-	3
	1515	88	18	2	NE	3
	1530	87	24	1	NE	3
	1545	87	20	1	NE	3
	1600	86	25	0	-	3

Table 20: Site 8P Meteorological Data

Date	Time	Ambient Temp (deg F.)	Relative Humidity (%)	Wind Speed (mph)	Wind Dir.	Cloud Cover
1/18/2000	0430	65	46	0	-	3
	0445	63	40	0	-	3
	0500	62	51	0	-	3
	0515	62	45	0	-	3
	0530	62	40	0	-	3
	0545	62	40	4	SW	3
1/19/2000	0030	58	49	2	SW	3
	0045	58	51	1	S	3
	0100	58	50	1	SW	3
	0115	57	49	0	-	3
	0130	58	47	1	S	3
	0145	57	51	2	S	3
	0200	56	48	0	-	3
	0215	55	45	0	-	3
	0230	55	46	0	-	3

Table 21: Site 9T Meteorological Data

Date	Time	Ambient Temp (deg F.)	Relative Humidity (%)	Wind Speed (mph)	Wind Dir.	Cloud Cover
11/2/1999	1500	83	46	5	W	3
	1515	87	43	3	NW	3
	1530	85	43	4	NW	3
	1545	85	40	3	NW	3
	1600	84	42	2	NW	3
	1615	84	42	3	NW	3
	1630	84	43	3	W	3

Table 22: Site 10T Meteorological Data

Date	Time	Ambient Temp (deg F.)	Relative Humidity (%)	Wind Speed (mph)	Wind Dir.	Cloud Cover
11/1/1999	1615	85	15	0	-	3
	1630	85	12	0	-	3
	1645	86	11	0	-	3
	1700	86	16	0	-	3
	1715	83	13	1	SW	3
	1730	78	17	0	-	3

Table 23: Site 11T Meteorological Data

Date	Time	Ambient Temp (deg F.)	Relative Humidity (%)	Wind Speed (mph)	Wind Dir.	Cloud Cover
11/1/1999	1345	88	13	3	NE	3
	1400	88	11	1	NE	3
	1415	90	13	1	NE	3
	1430	89	10	2	NE	3
	1445	88	11	2	NE	3
	1500	88	11	3	NE	3
	1515	86	9	2	NE	3
	1530	86	10	2	NE	3
11/3/1999	0730	68	42	1	NE	3
	0745	64	28	1	NE	3
	0800	68	31	2	NE	3
	0815	72	21	2	NE	3
	0830	71	30	3	NE	3
	0845	72	28	3	NE	3
	0900	73	22	2	NE	3
	0915	75	21	1	NE	3
	0930	75	27	1	NE	3
	0945	76	28	2	NE	3
	1000	79	25	1	NE	3
	1015	83	21	2	NE	3
	1030	81	20	3	NE	3
	1045	82	22	2	NE	3
	1100	84	24	3	NE	3
	1115	86	28	2	NE	3
	1130	86	16	1	NE	3
3/28/2000	0800	62	9	1	N	3
	0815	64	8	1	NE	3
	0830	64	9	3	N	3
	0845	65	9	2	N	3
	0900	65	11	3	E	3
	0915	67	10	4	NE	3
	0930	66	10	3	N	3
	0945	67	9	4	N	3
	1000	68	10	3	NE	3
	1015	69	10	3	NE	3
	1030	69	10	4	NE	3
	1045	68	10	4	E	3
	1100	70	10	5	NE	3
	1115	69	9	4	NE	3
	1130	69	10	4	NE	3

Table 24: Site 12T Meteorological Data

Date	Time	Ambient Temp (deg F.)	Relative Humidity (%)	Wind Speed (mph)	Wind Dir.	Cloud Cover
11/2/1999	1230	88	12	2	N	3
	1245	90	11	1	N	3
	1300	89	10	1	N	3
	1315	90	13	0	-	3
	1330	90	10	0	-	3

Table 25: Site 13T Meteorological Data

Date	Time	Ambient Temp (deg F.)	Relative Humidity (%)	Wind Speed (mph)	Wind Dir.	Cloud Cover
11/2/1999	0800	71	21	1	W	3
	0815	70	21	1	W	3
	0830	72	21	1	W	3
	0845	70	22	1	W	3
	0900	74	23	1	W	3
	0915	73	19	1	W	3
	0930	75	21	1	W	3
	0945	74	30	0	-	3
	1000	79	25	0	-	3
	1015	80	18	0	-	3
	1030	83	18	0	-	3

Table 26: Site 14P Meteorological Data

Date	Time	Ambient Temp (deg F.)	Relative Humidity (%)	Wind Speed (mph)	Wind Dir.	Cloud Cover
1/18/2000	2245	65	28	1	SW	3
	2300	65	24	0	-	3
	2315	64	29	0	-	3
1/19/2000	1500	79	20	3	S	3
	1515	77	19	1	S	3
	1530	80	15	1	S	3
	1545	79	24	2	S	3
	1600	79	20	1	S	3
	1615	78	22	0	-	3
	1630	77	25	1	S	3
	1645	77	19	0	-	3
	1700	78	21	0	-	3

Table 27: Site 15F Meteorological Data

Date	Time	Ambient Temp (deg F.)	Relative Humidity (%)	Wind Speed (mph)	Wind Dir.	Cloud Cover
10/20/99	1610	71	24	1	E	3
	1625	70	15	2	E	3
	1640	69	18	2	E	3
	1655	66	17	2	E	3

Table 28: Site 16F Meteorological Data

Date	Time	Ambient Temp (deg F.)	Relative Humidity (%)	Wind Speed (mph)	Wind Dir.	Cloud Cover
10/20/99	1340	78	24	1	NE	3
	1355	78	24	3	NE	3
	1410	78	24	1	NE	3
	1425	75	21	2	NE	3

Table 29: Site 17F Meteorological Data

Date	Time	Ambient Temp (deg F.)	Relative Humidity (%)	Wind Speed (mph)	Wind Dir.	Cloud Cover
10/20/99	0930	60	21	2	SE	3
	0945	69	21	2	SE	3
	1000	70	19	2	SE	3
	1015	77	24	1	SE	3
	1030	78	24	2	SE	3
	1045	70	15	2	SE	3
	1100	72	18	3	SE	3
	1115	74	20	3	SE	3
	1130	75	20	2	SE	3
	1145	72	18	4	SE	3
	1200	71	15	2	SE	3

Table 30: Site 18F Meteorological Data

Date	Time	Ambient Temp (deg F.)	Relative Humidity (%)	Wind Speed (mph)	Wind Dir.	Cloud Cover
10/21/99	0905	63	29	0	n/a	3
	0920	65	24	0	n/a	3
	0935	66	21	0	n/a	3
	0950	67	22	1	NW	3
	1005	69	24	1	NW	3
	1020	73	22	1	NW	3
	1035	72	18	2	NW	3

APPENDIX C
COMPARISON OF PERCENTAGE OF SAMPLES BY SPEED BAND

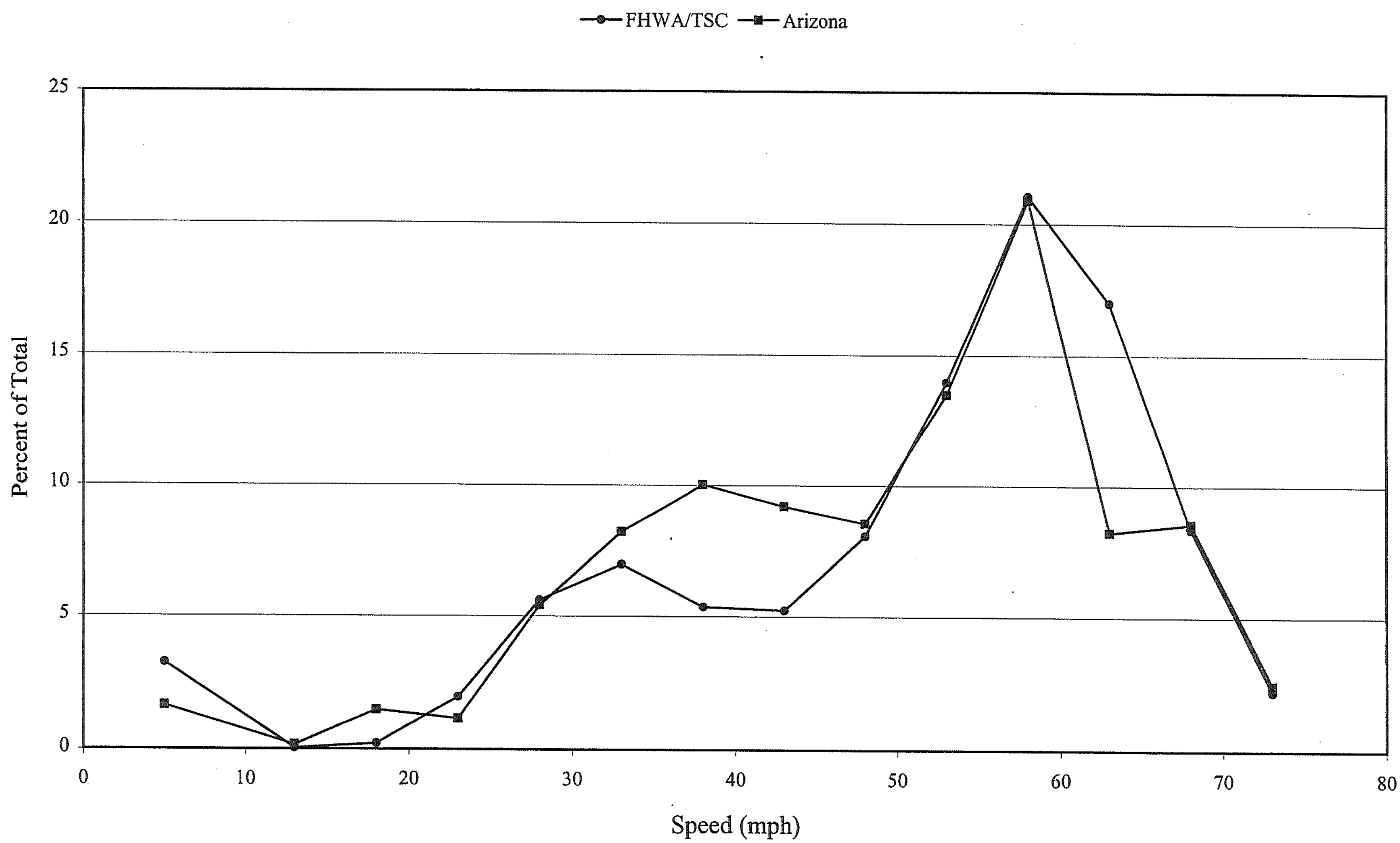


Figure 1: Number of Samples by Percentage, Automobiles

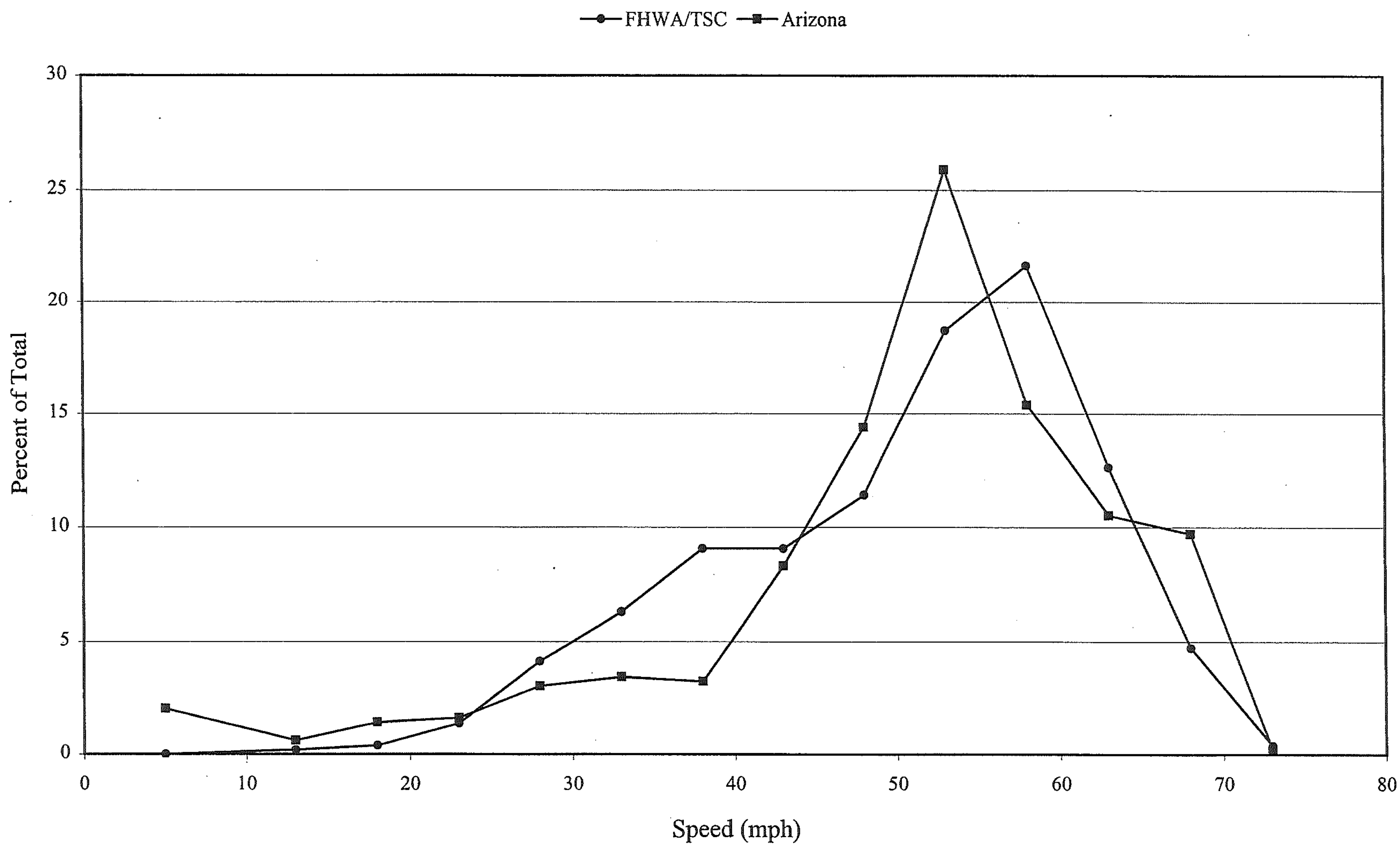


Figure 2: Number of Samples by Percentage, Medium Trucks

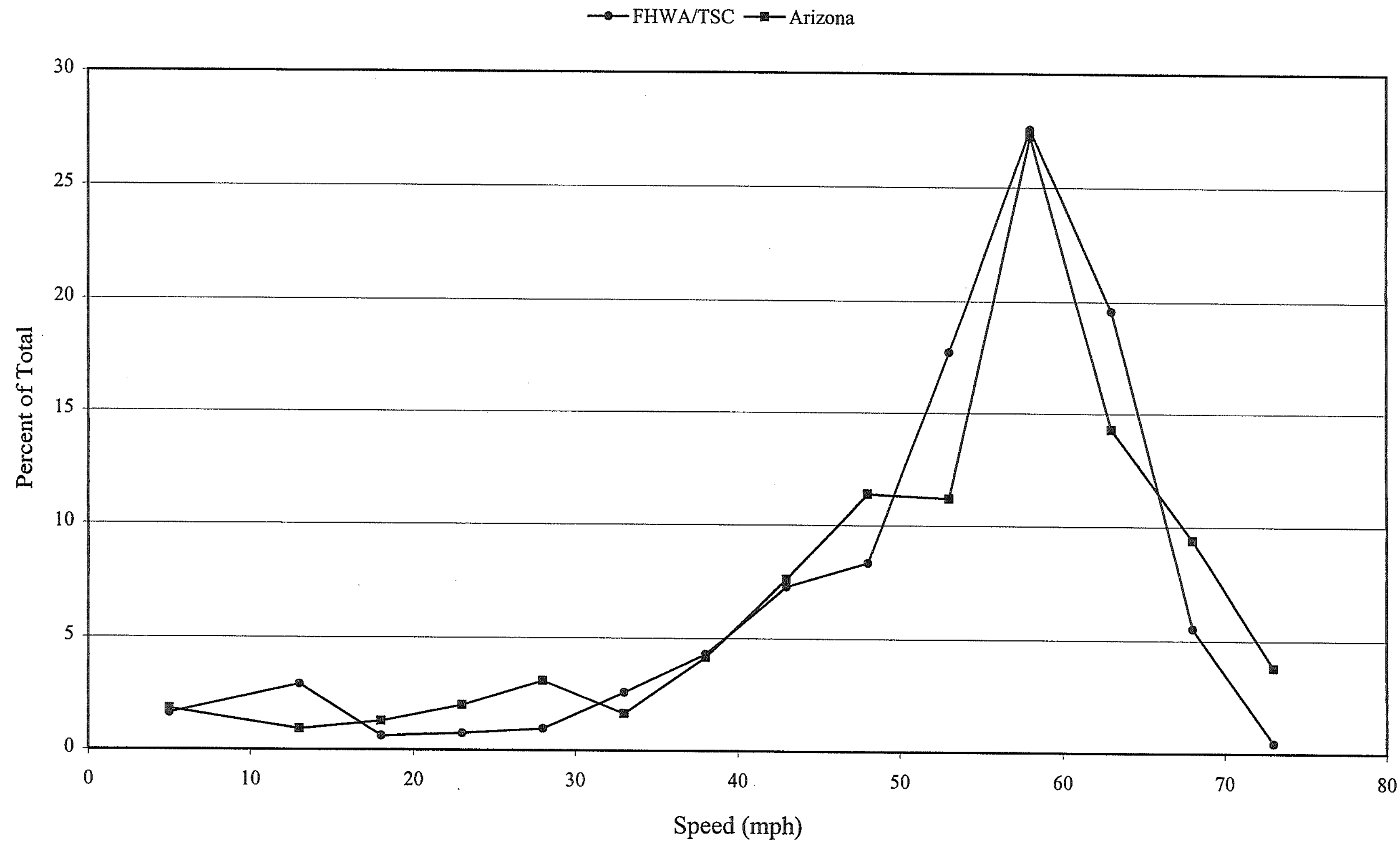


Figure 3: Number of Samples by Percentage, Heavy Trucks

APPENDIX D
ENERGY MEAN vs. REMEL REGRESSION by SPEED BAND

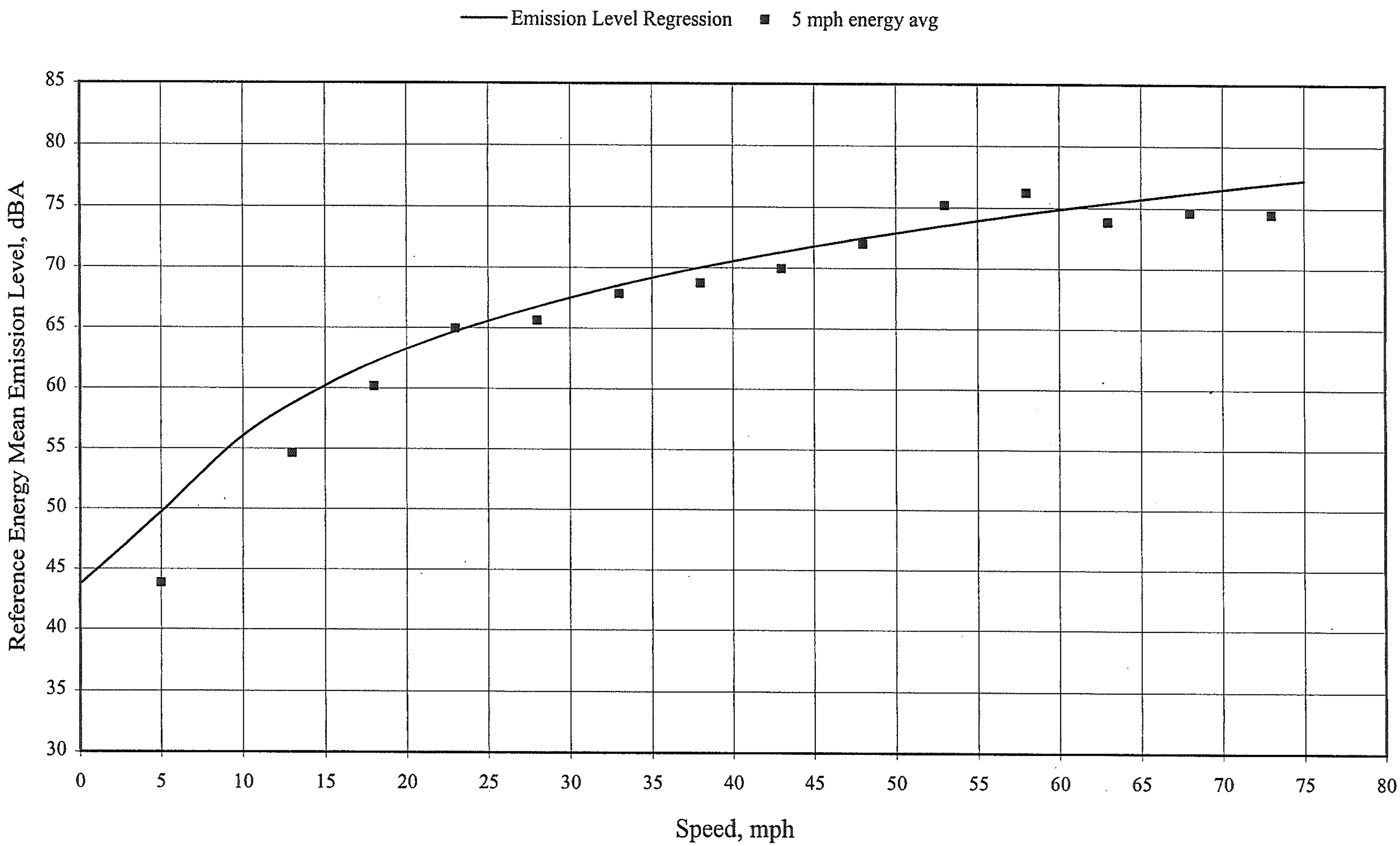


Figure 4: AZ REMEL Regression vs. Energy Mean, Automobiles

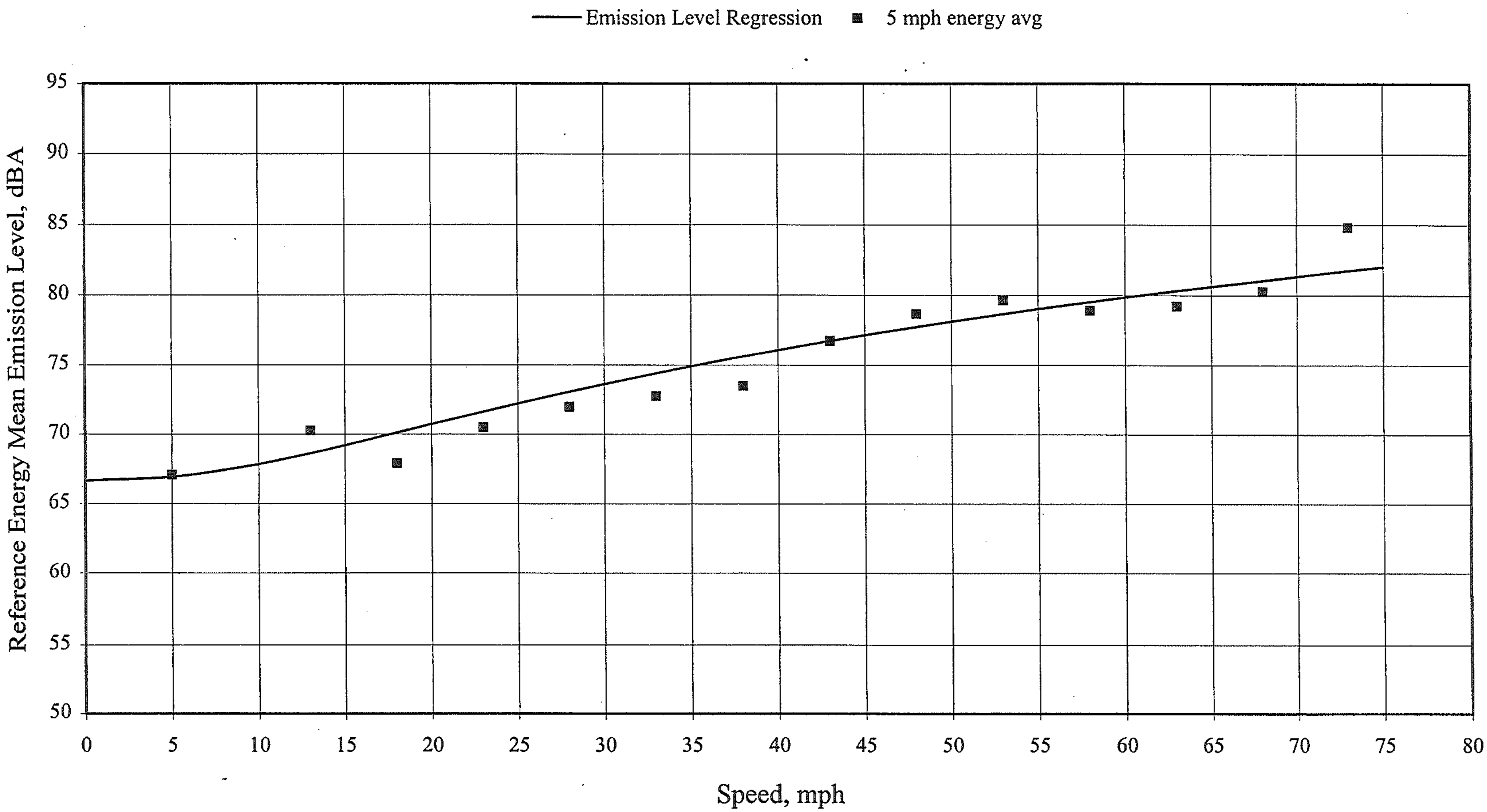


Figure 5: AZ REMEL Regression vs. Energy Mean, Medium Trucks

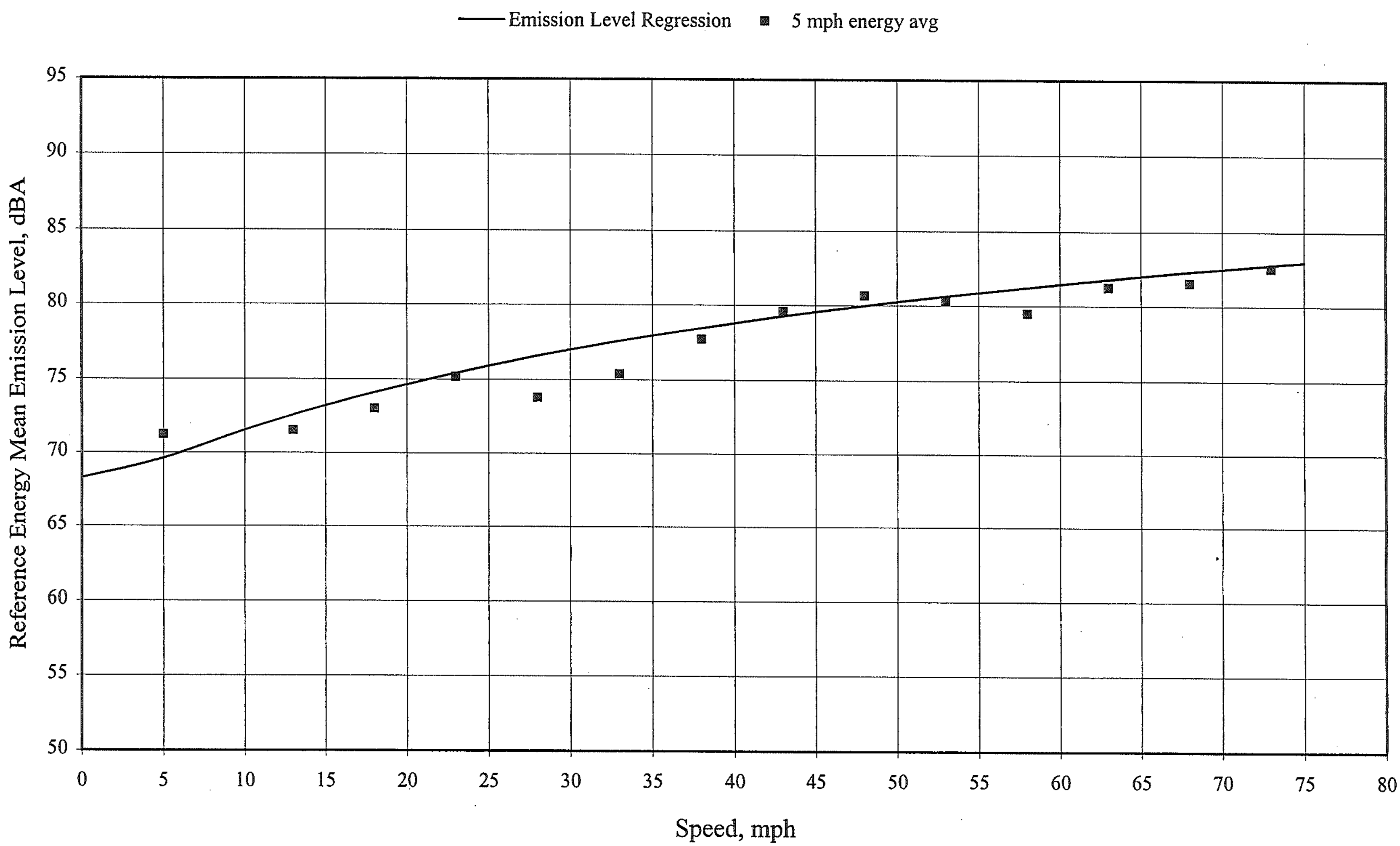


Figure 6: AZ REMEL Regression vs. Energy Mean, Heavy Trucks

APPENDIX E
EMISSION LEVEL REGRESSION PLOTS

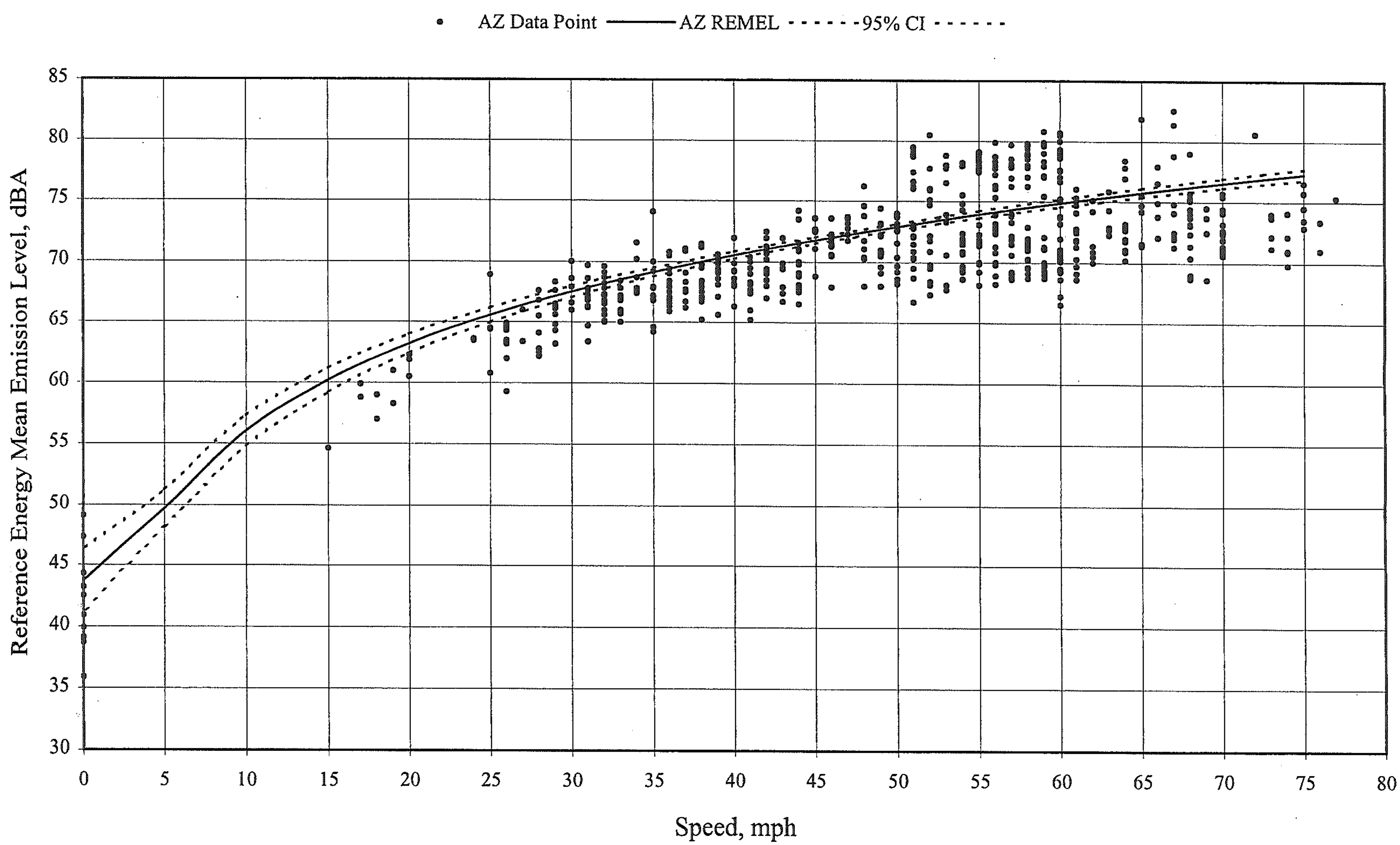


Figure 7: AZ Automobiles Emission Level Regression

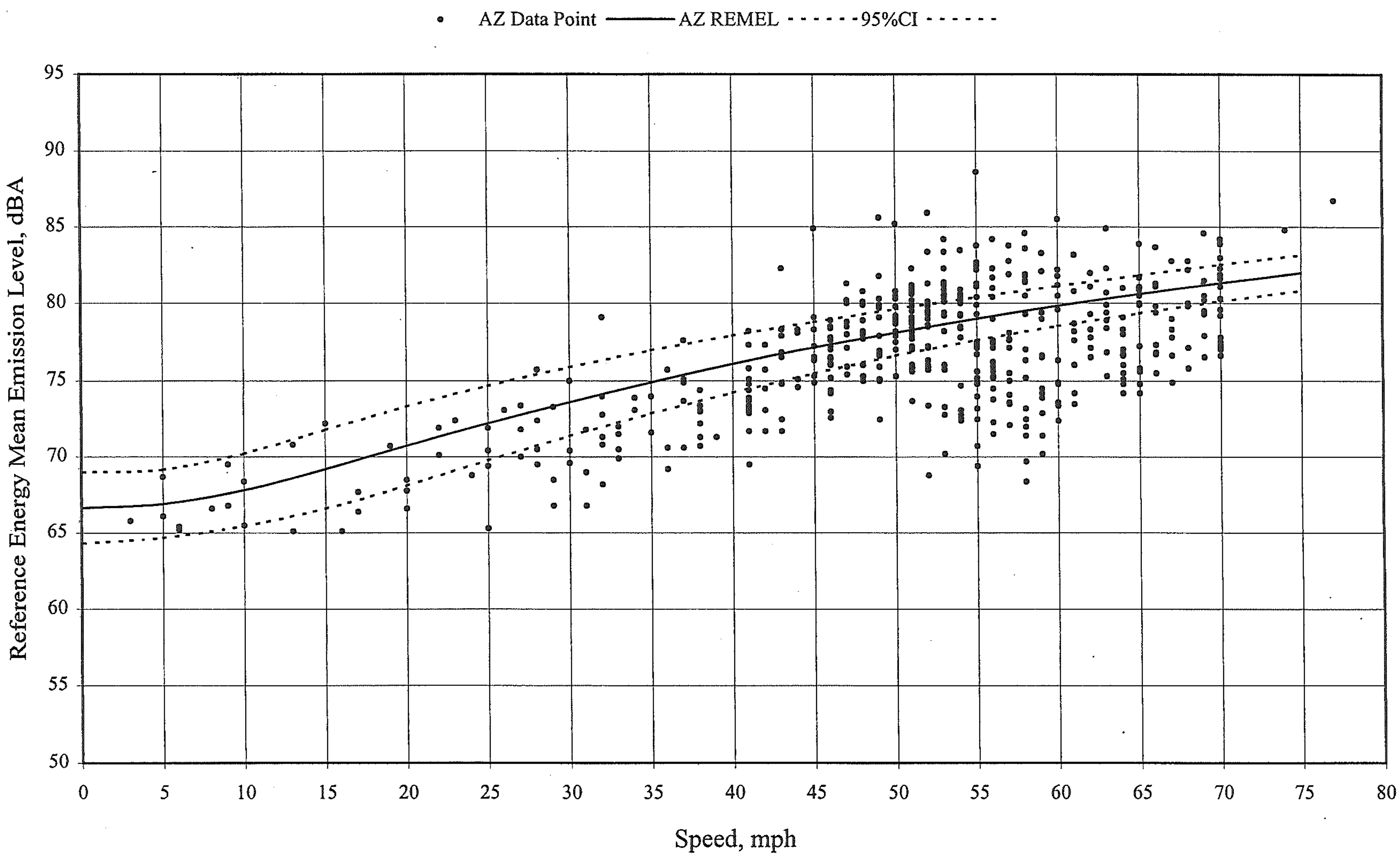


Figure 8: AZ Medium Trucks Emission Level Regression

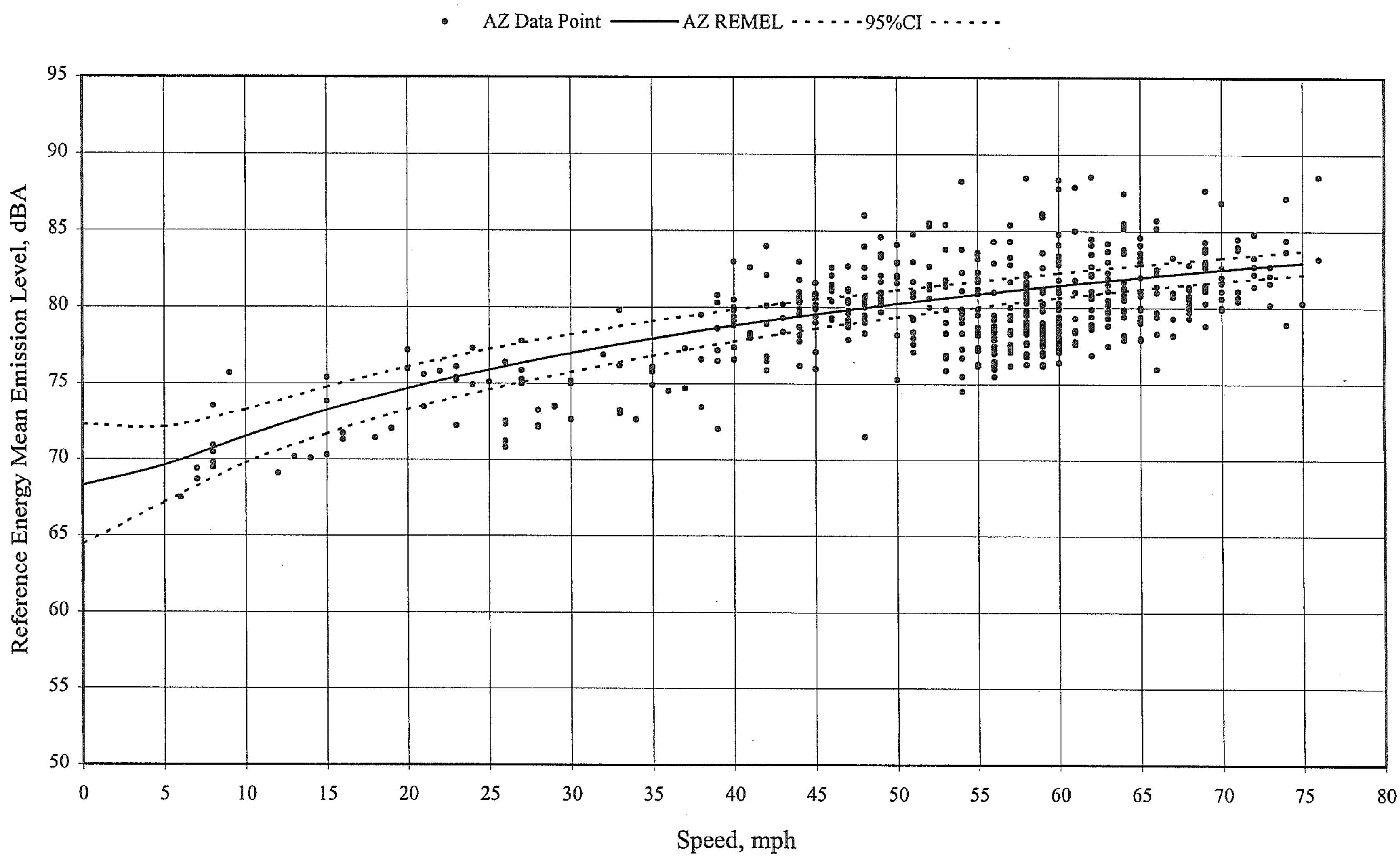


Figure 9: AZ Heavy Trucks Emission Level Regression

APPENDIX F
COMPARISON OF TSC and ARIZONA REMEL DATA

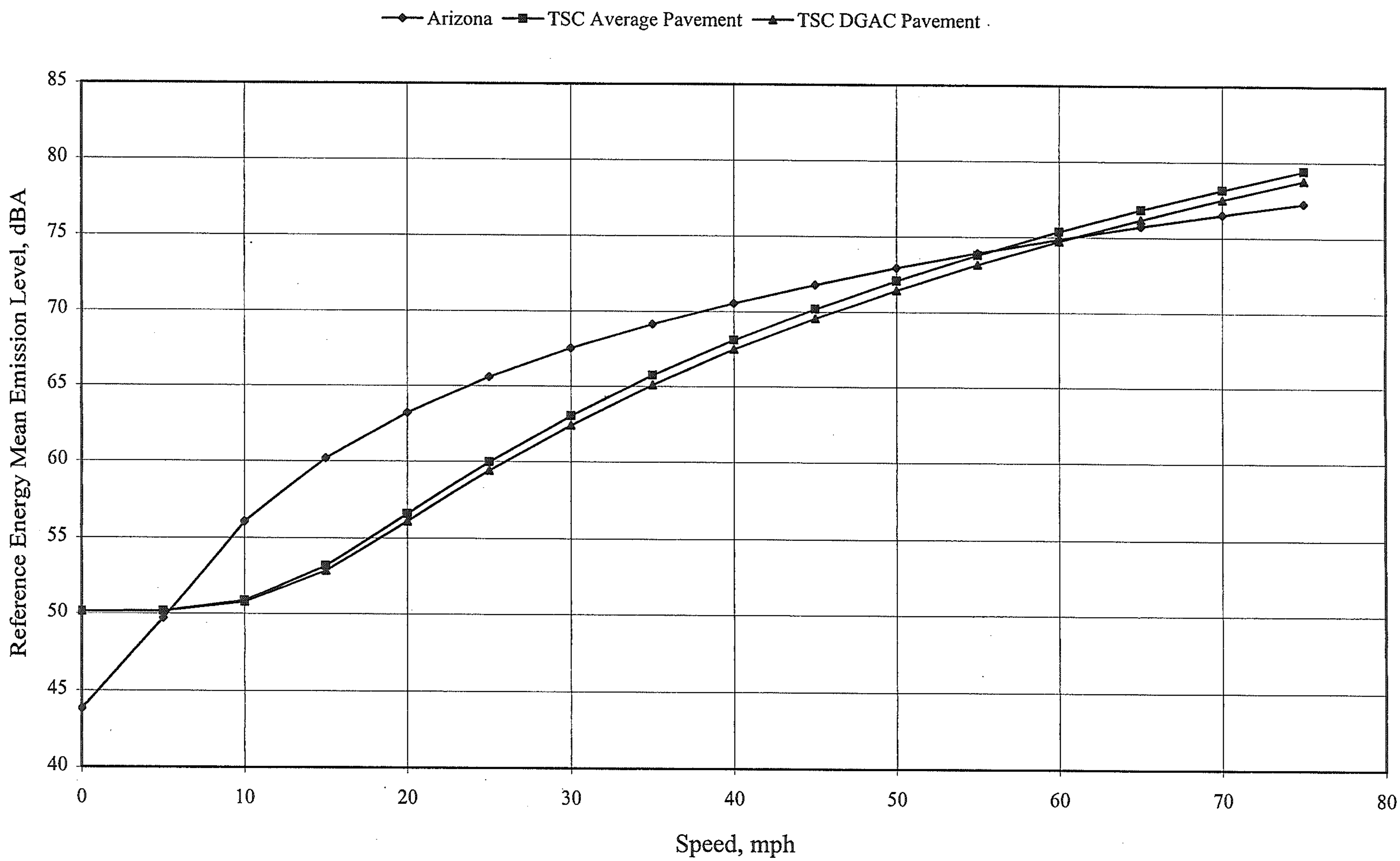


Figure 10: AZ vs. FHWA/TSC Emission Levels, Automobiles

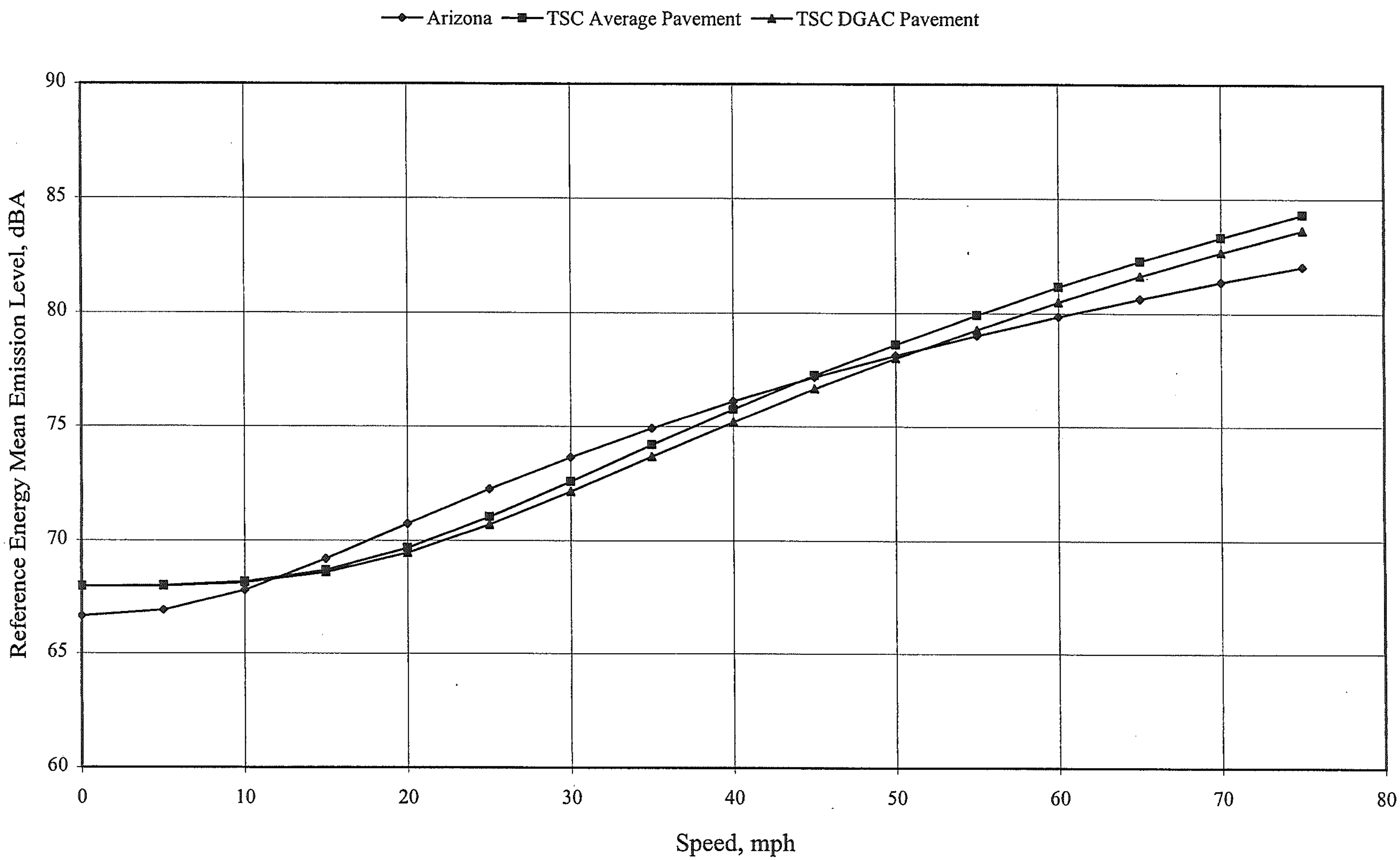


Figure 11: AZ vs. FHWA/TSC Emission Levels, Medium Trucks

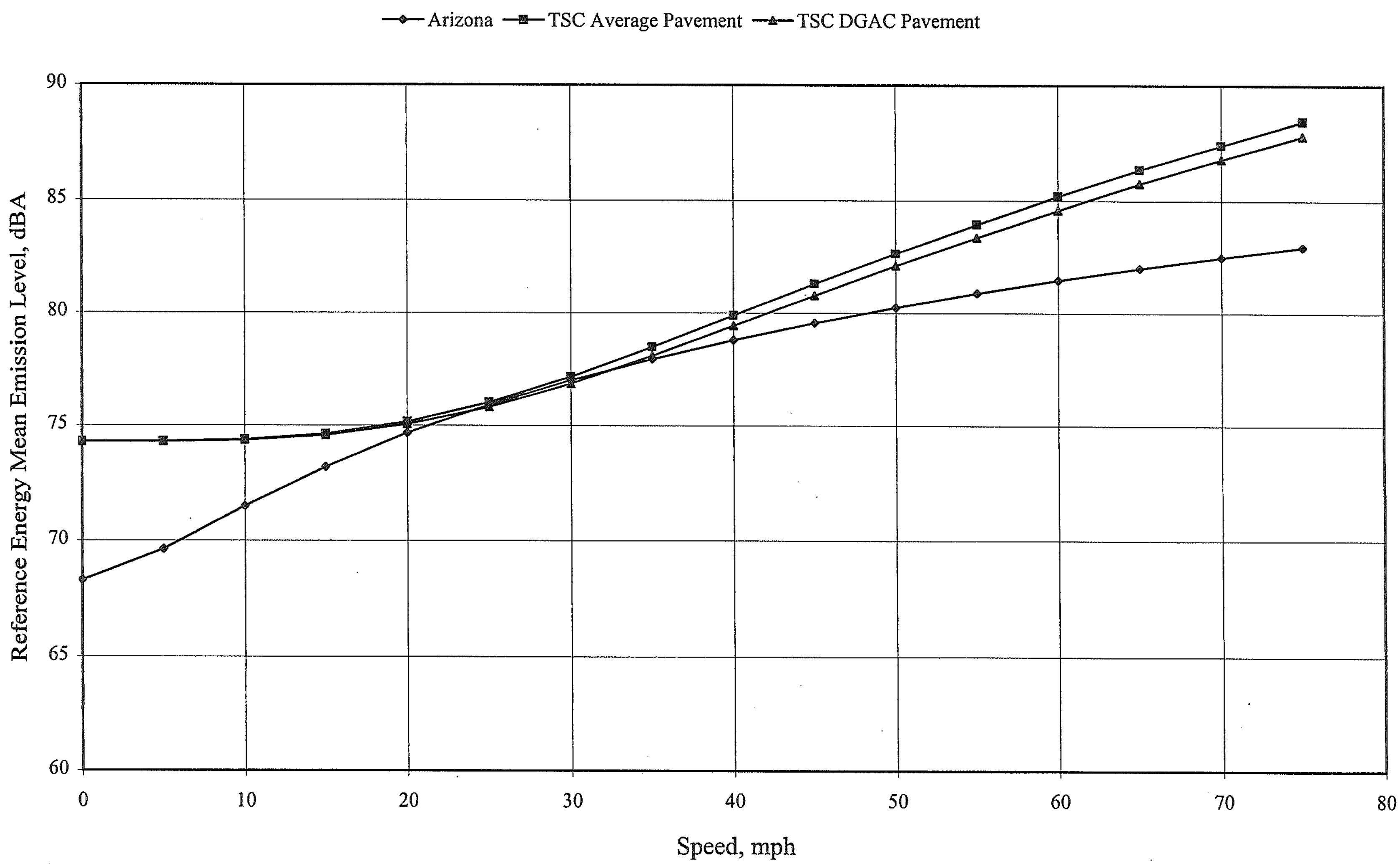


Figure 12: AZ vs. FHWA/TSC Emission Levels, Heavy Trucks

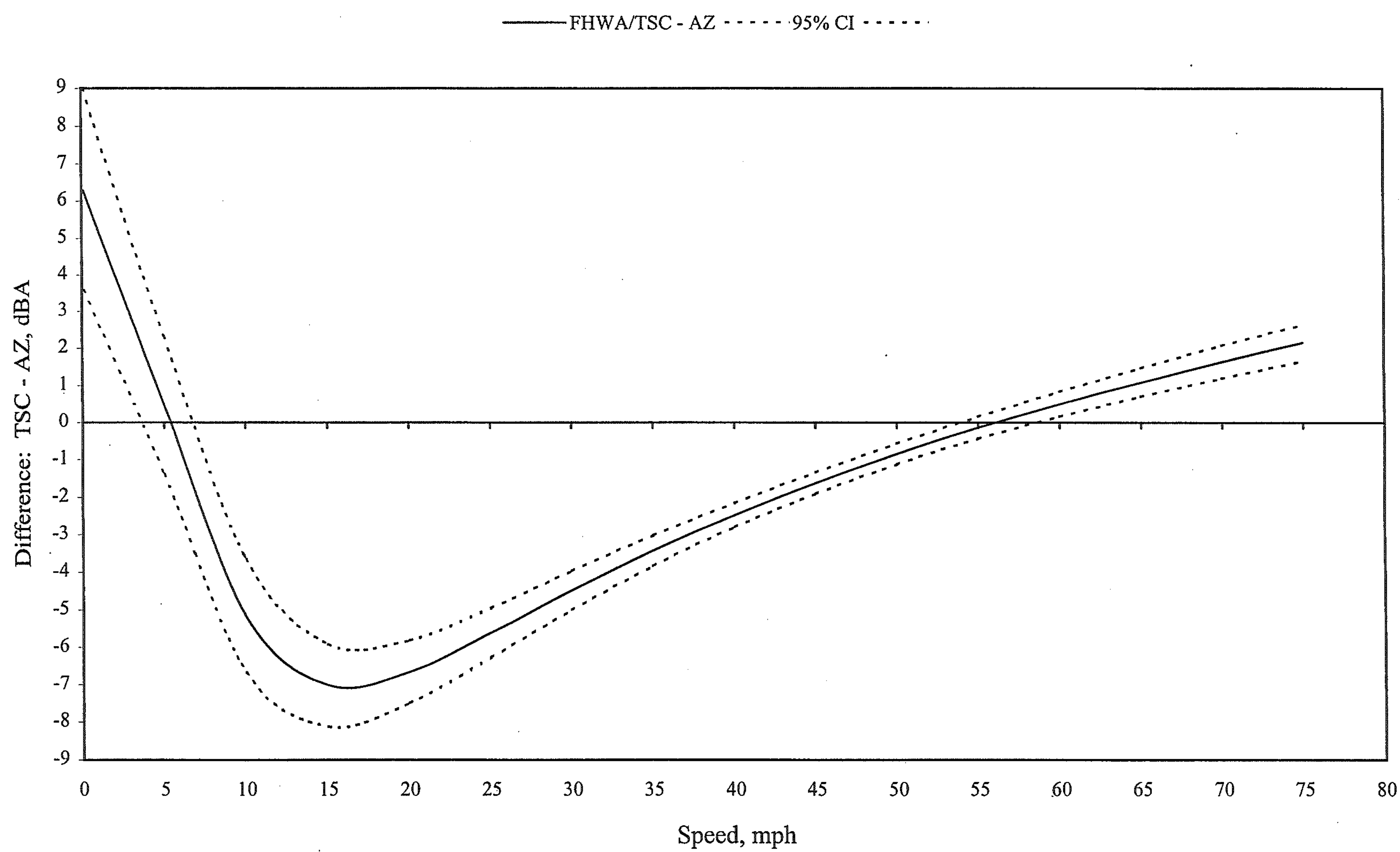


Figure 13: Comparison of AZ and FHWA/TSC Data, Automobiles

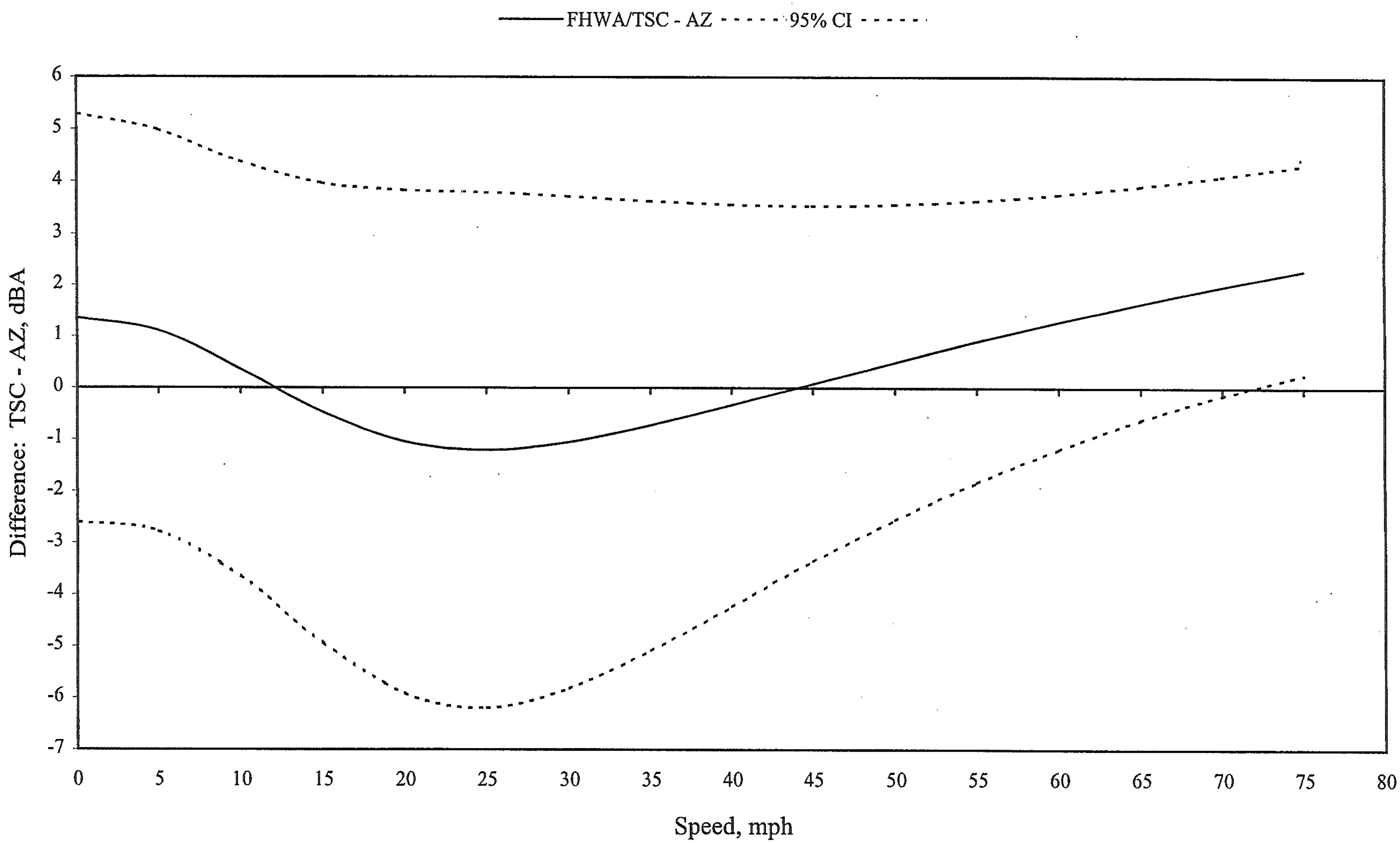


Figure 14: Comparison of AZ and FHWA/TSC Data, Medium Trucks

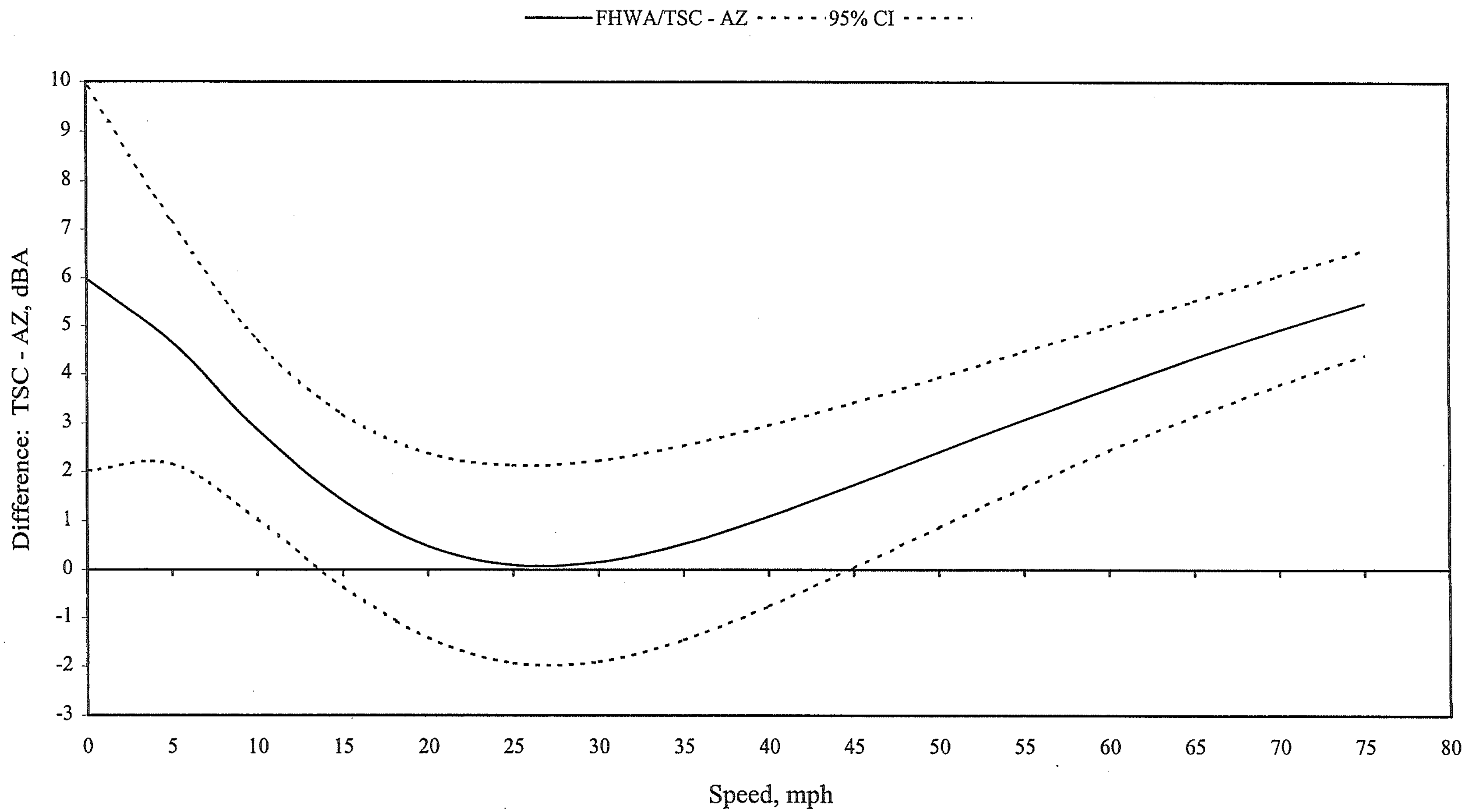


Figure 15: Comparison of AZ and FHWA/TSC Data, Heavy Trucks

APPENDIX G
MODEL VALIDATION

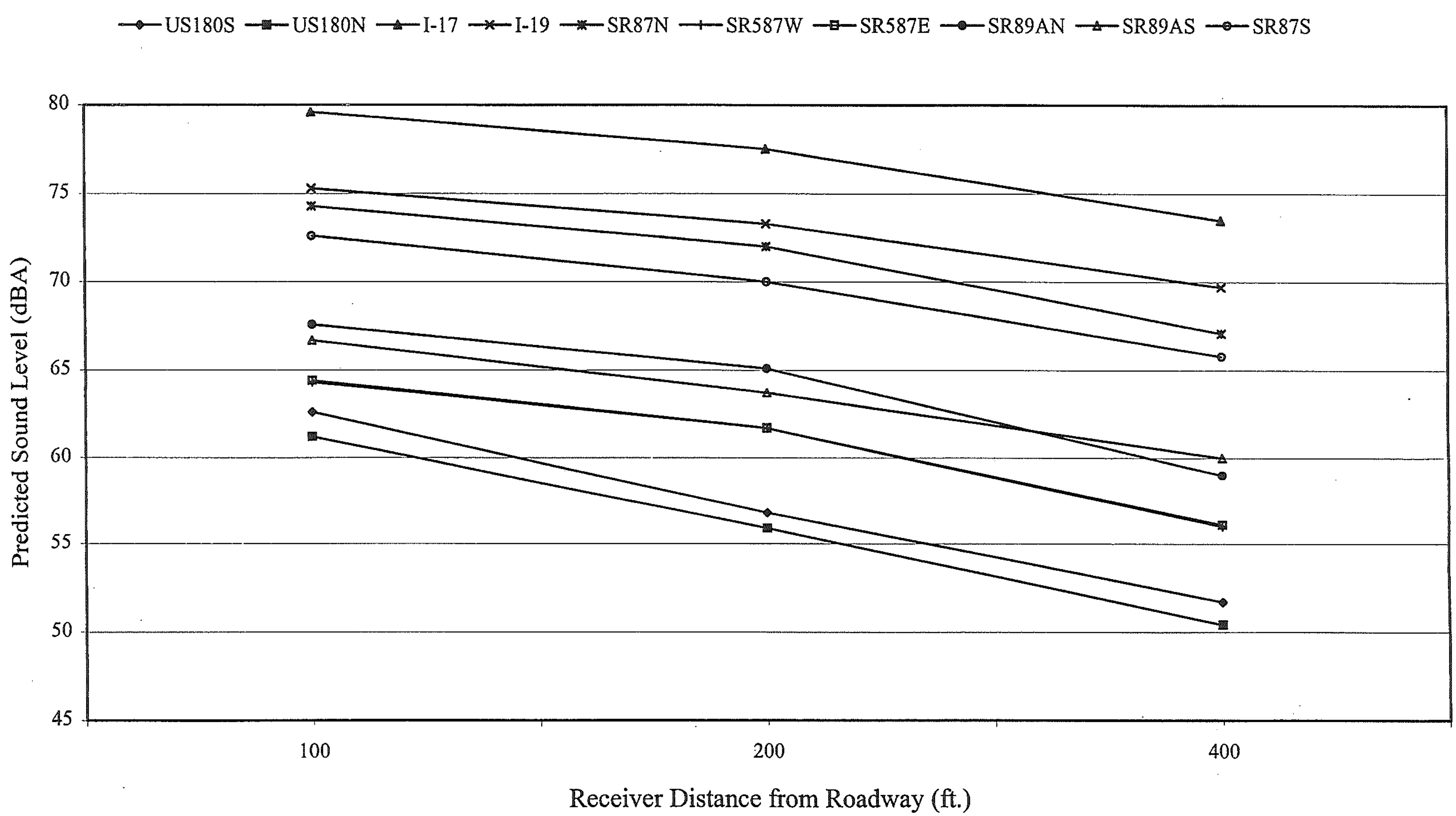


Figure 16: TNM Predictions with FHWA REMELs

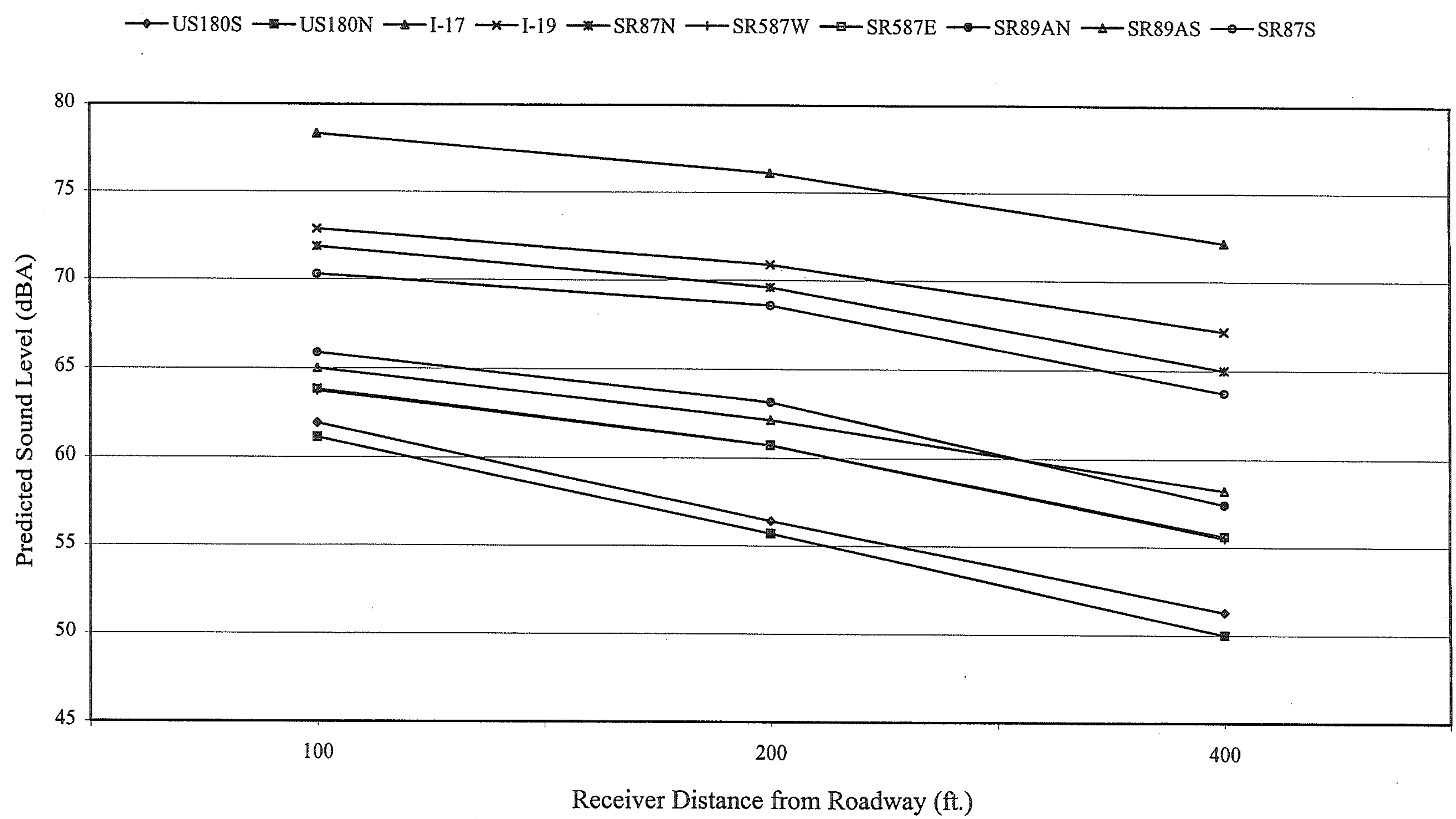


Figure 17: TNM Predictions with Arizona REMELs

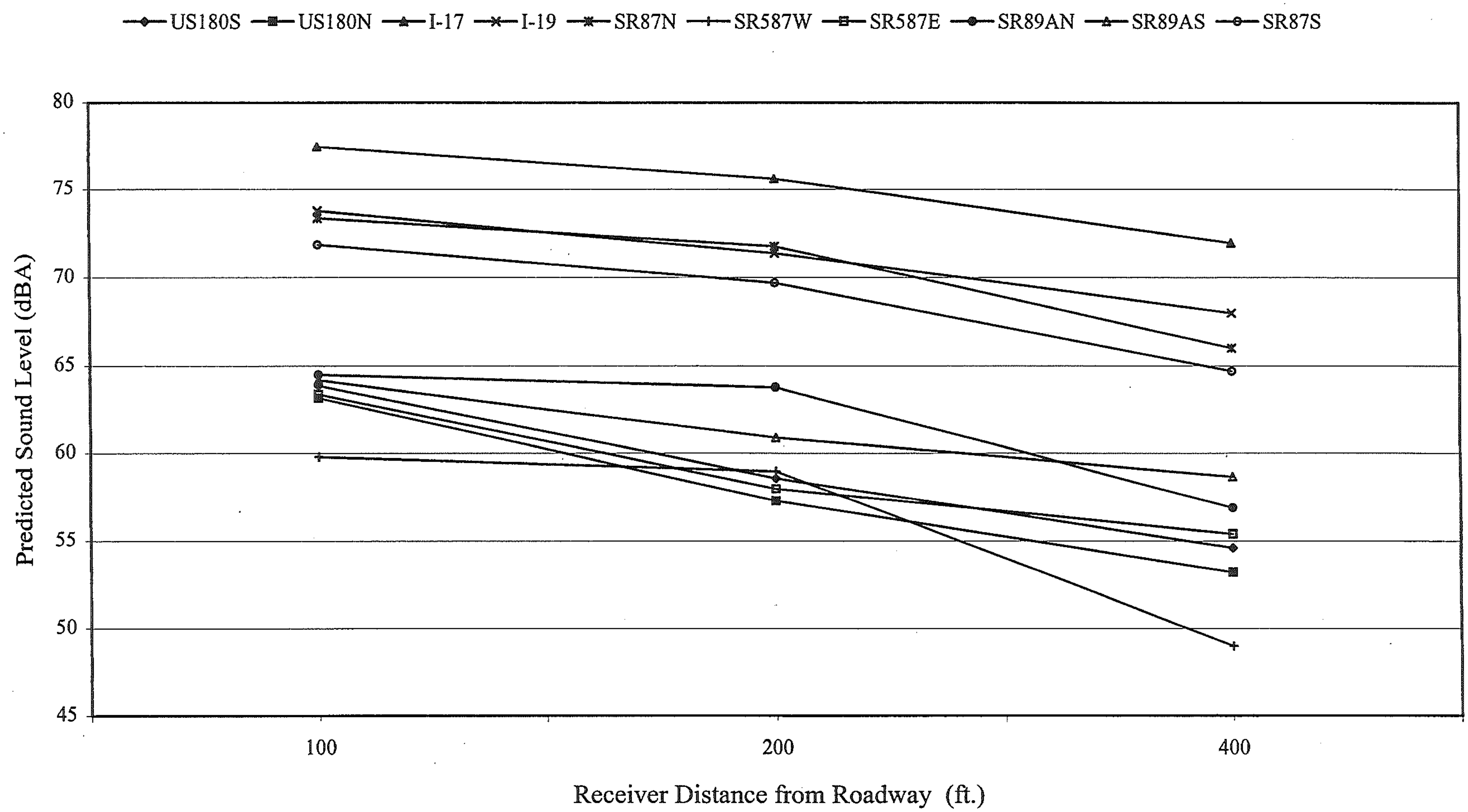


Figure 18: STAMINA Predictions with FHWA REMELs

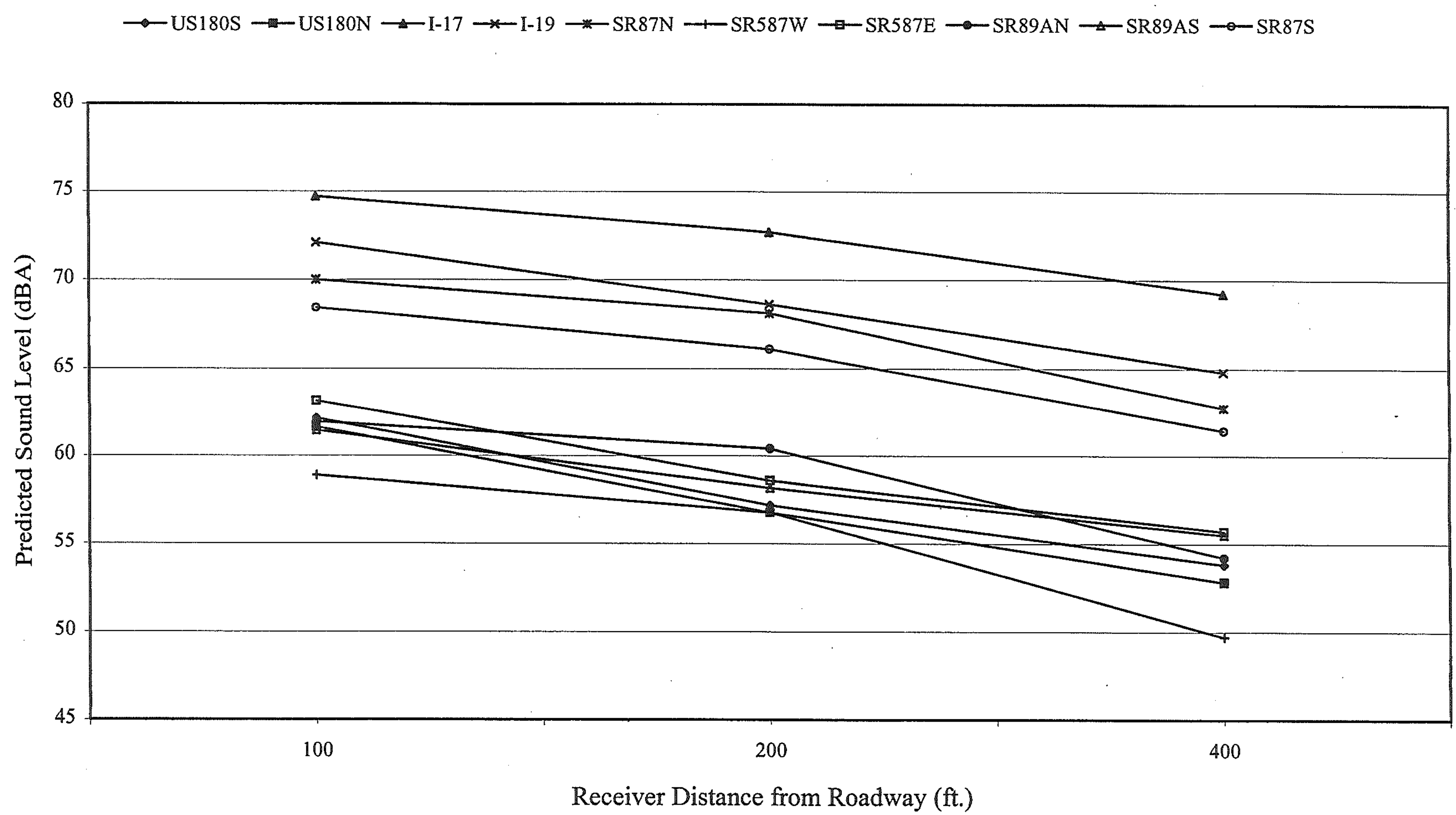


Figure 19: STAMINA Predictions with Arizona REMELs

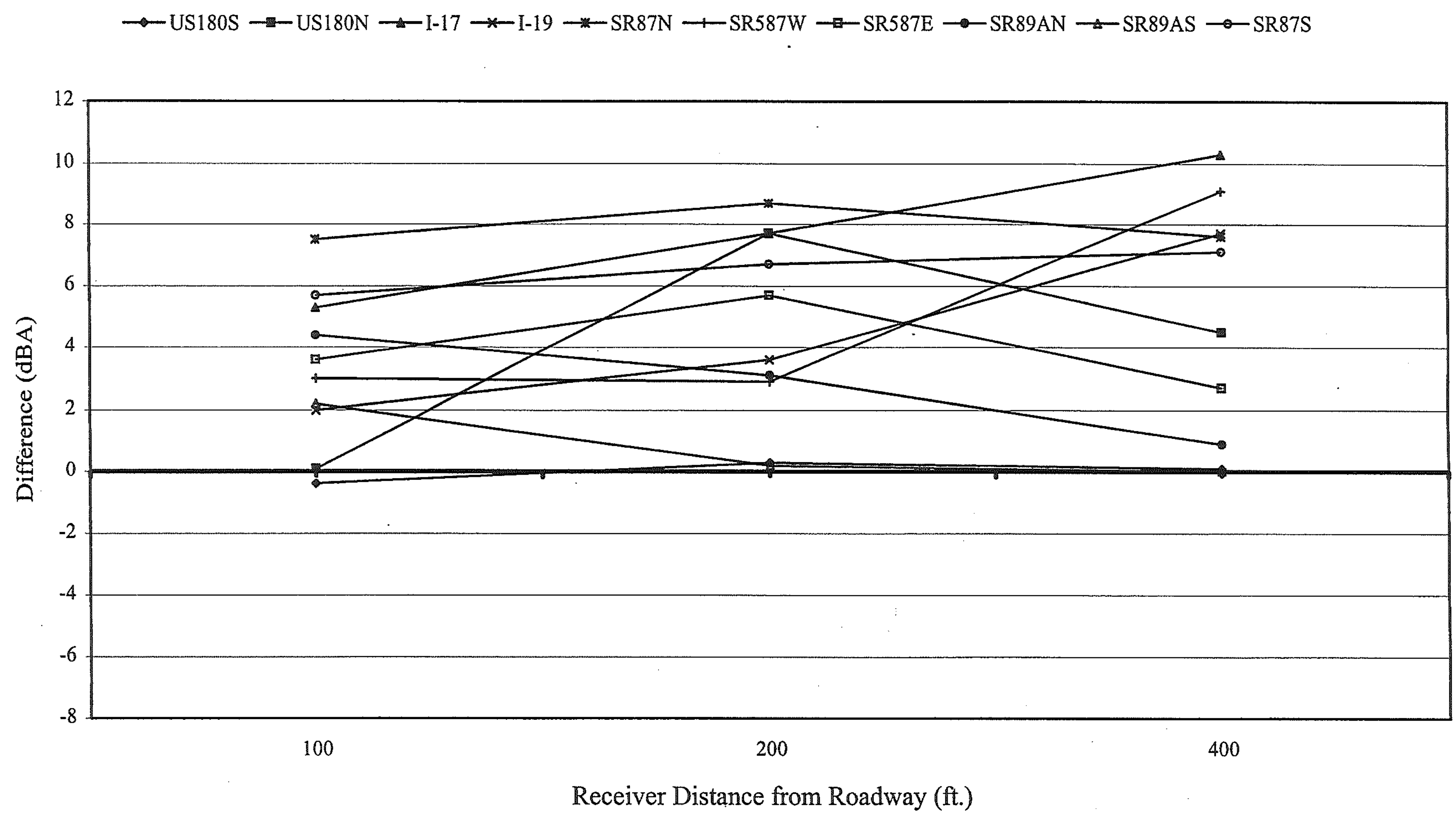


Figure 20: TNM Predictions vs. Measurements (FHWA REMELs)

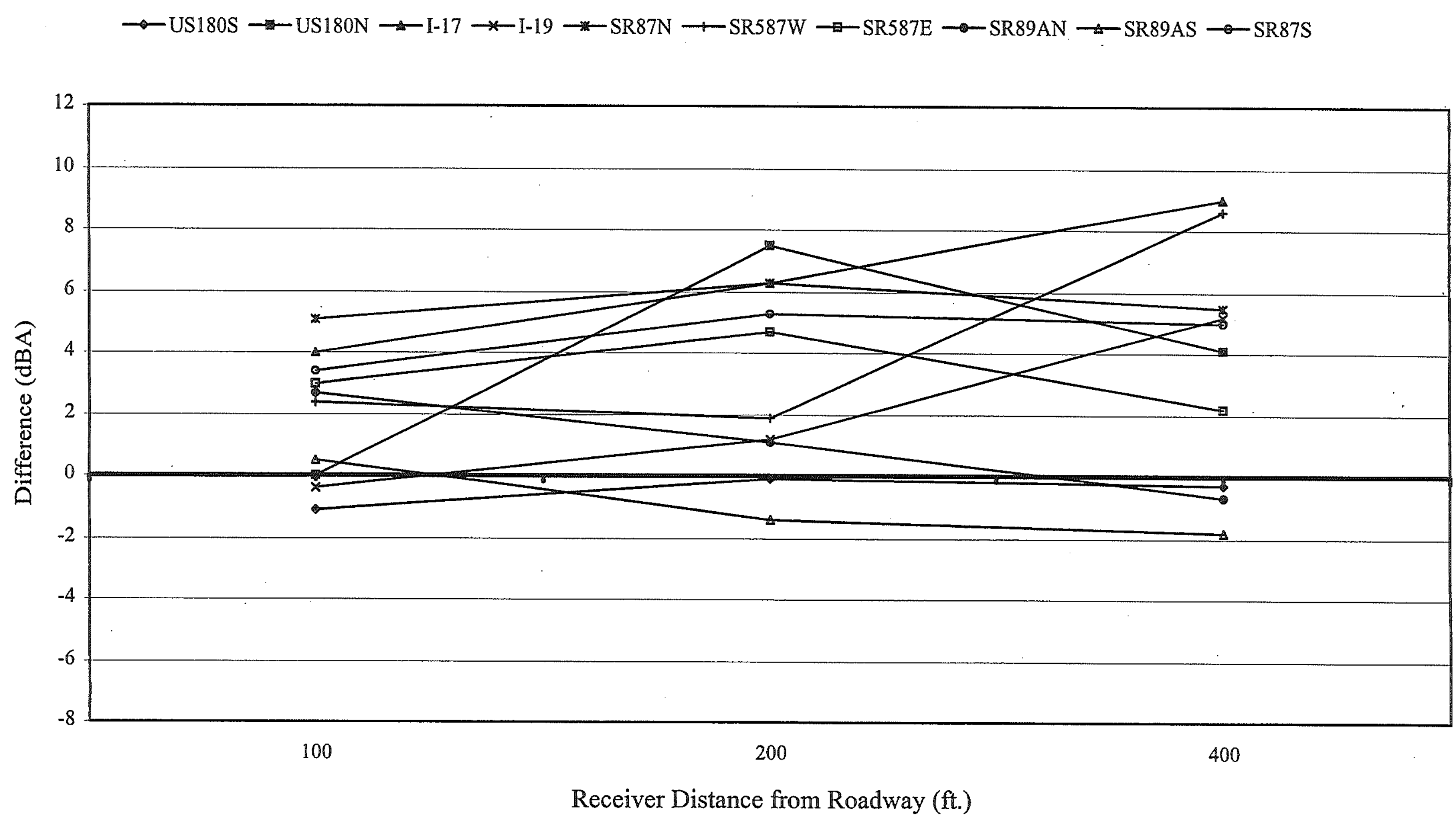


Figure 21: TNM Predictions vs. Measurements (Arizona REMELs)

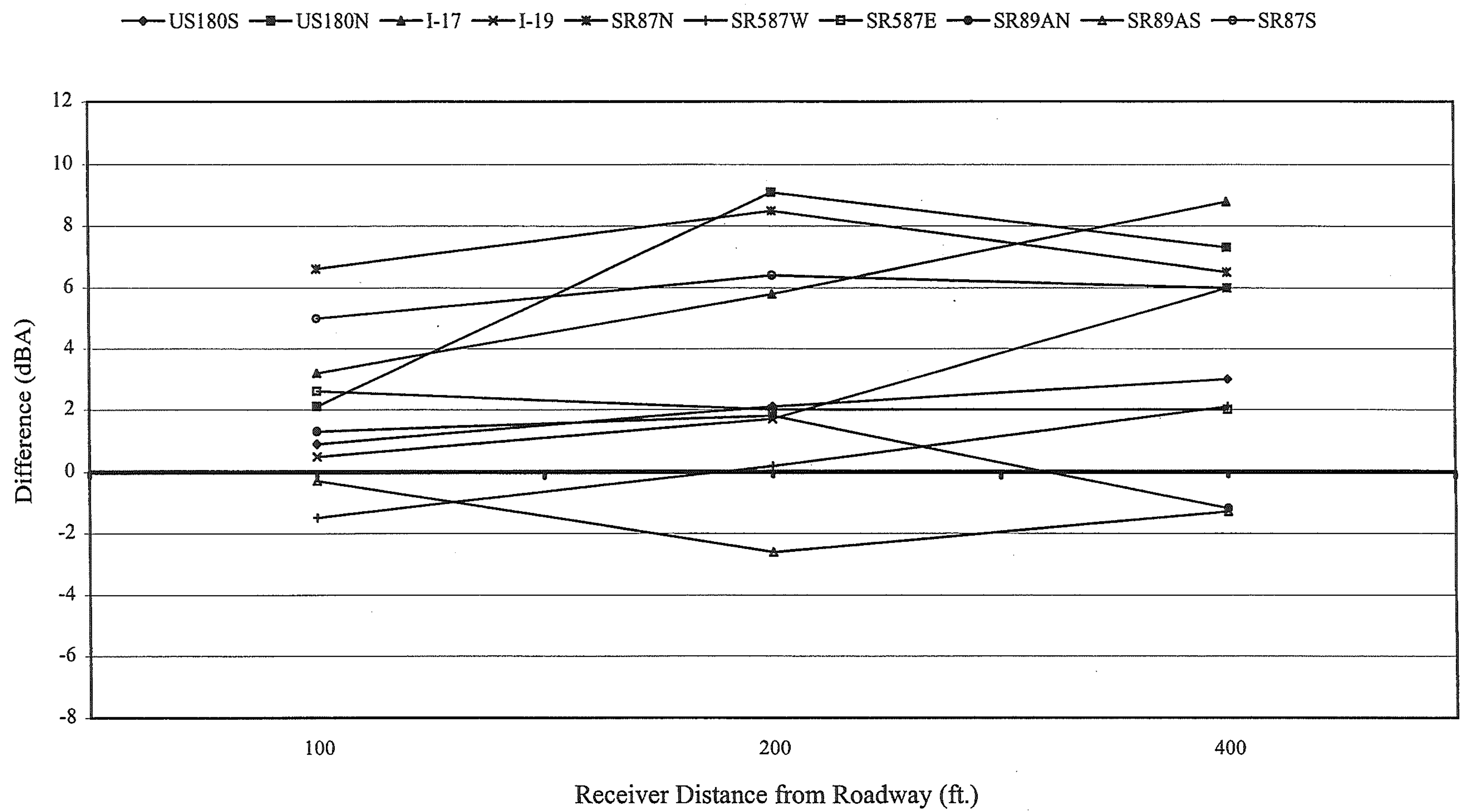


Figure 22: STAMINA Predictions vs. Measurements (FHWA REMELs)

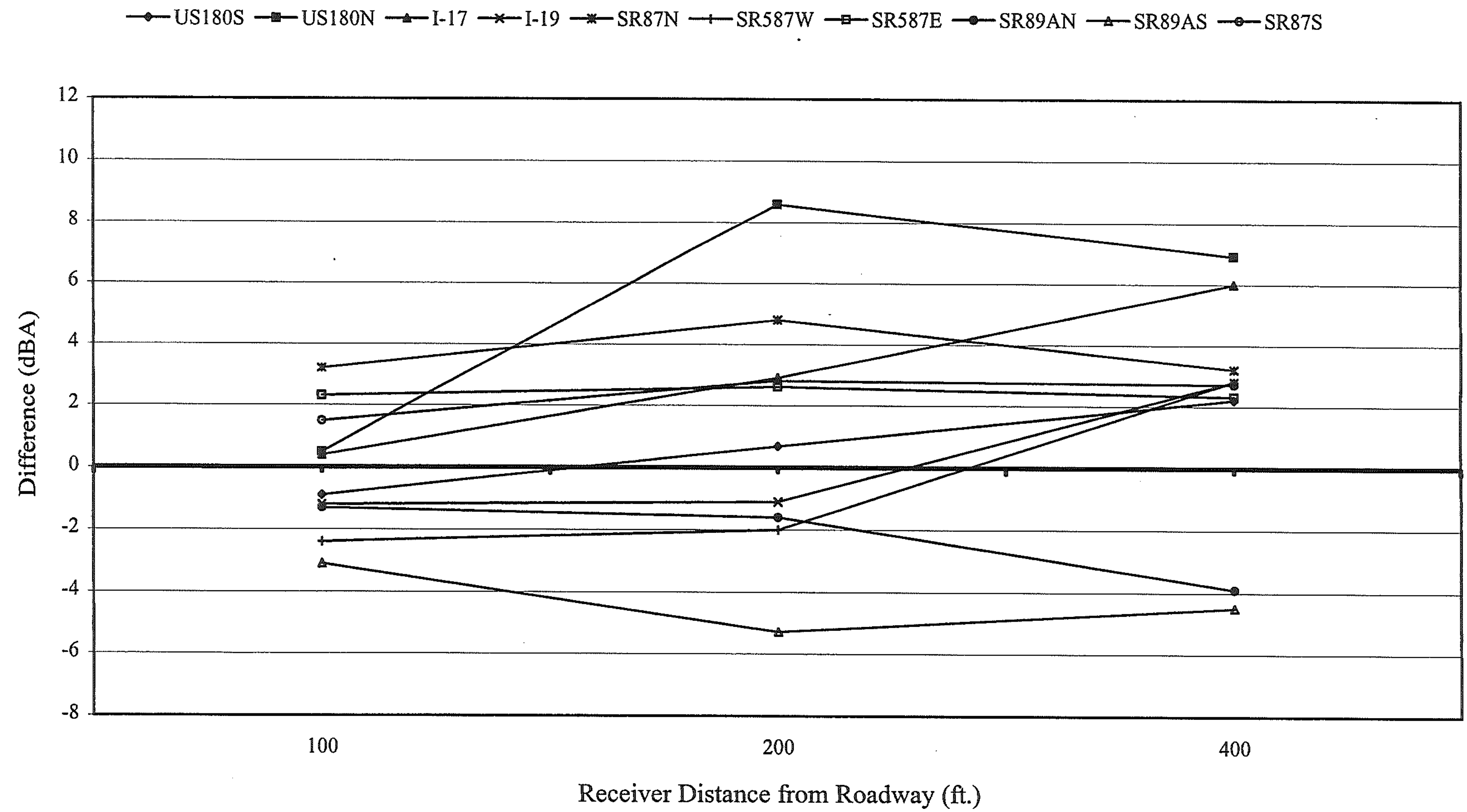


Figure 23: STAMINA Predictions vs. Measurements (Arizona REMELs)

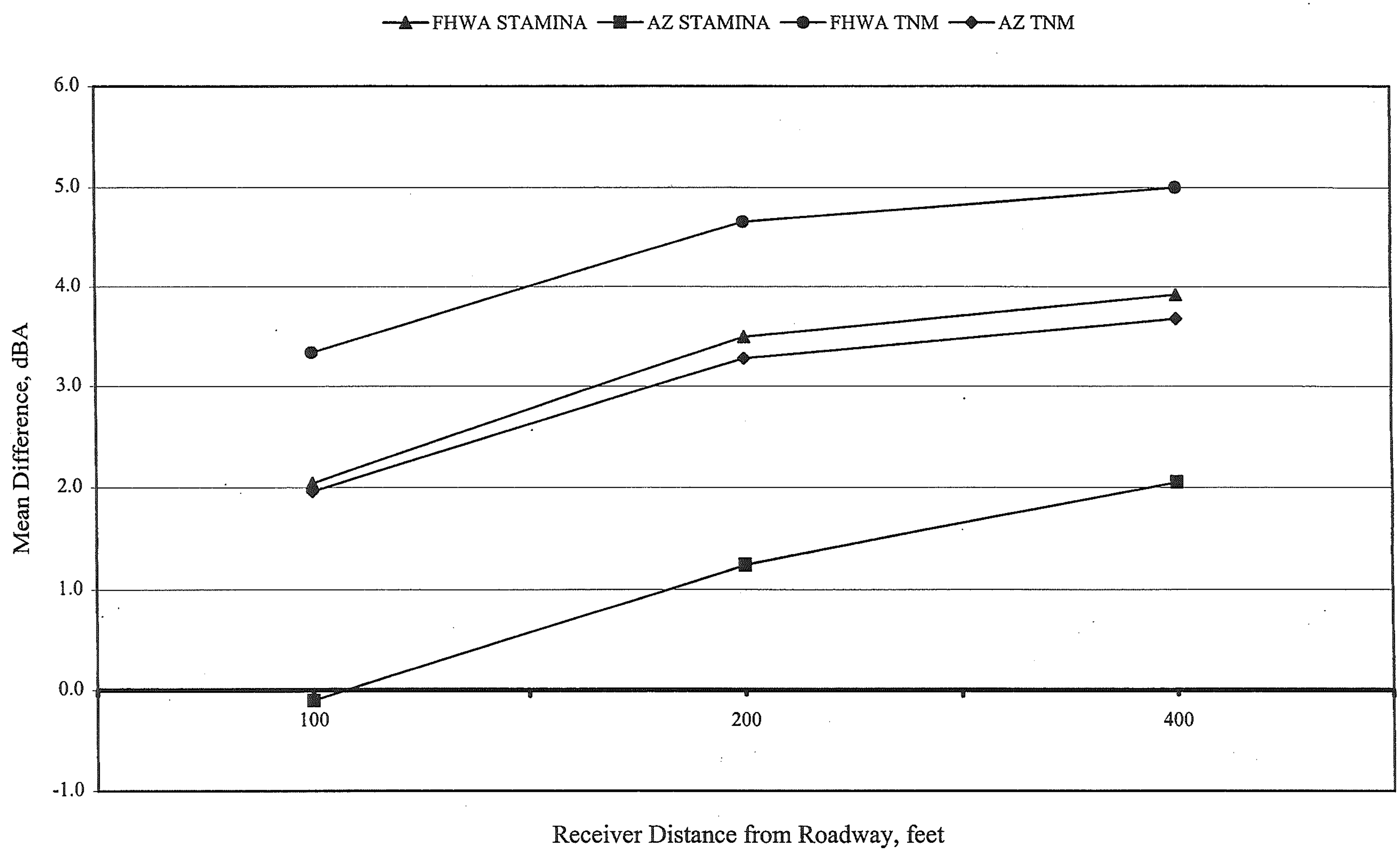


Figure 24: Mean Difference, Predicted minus Measured, by Model

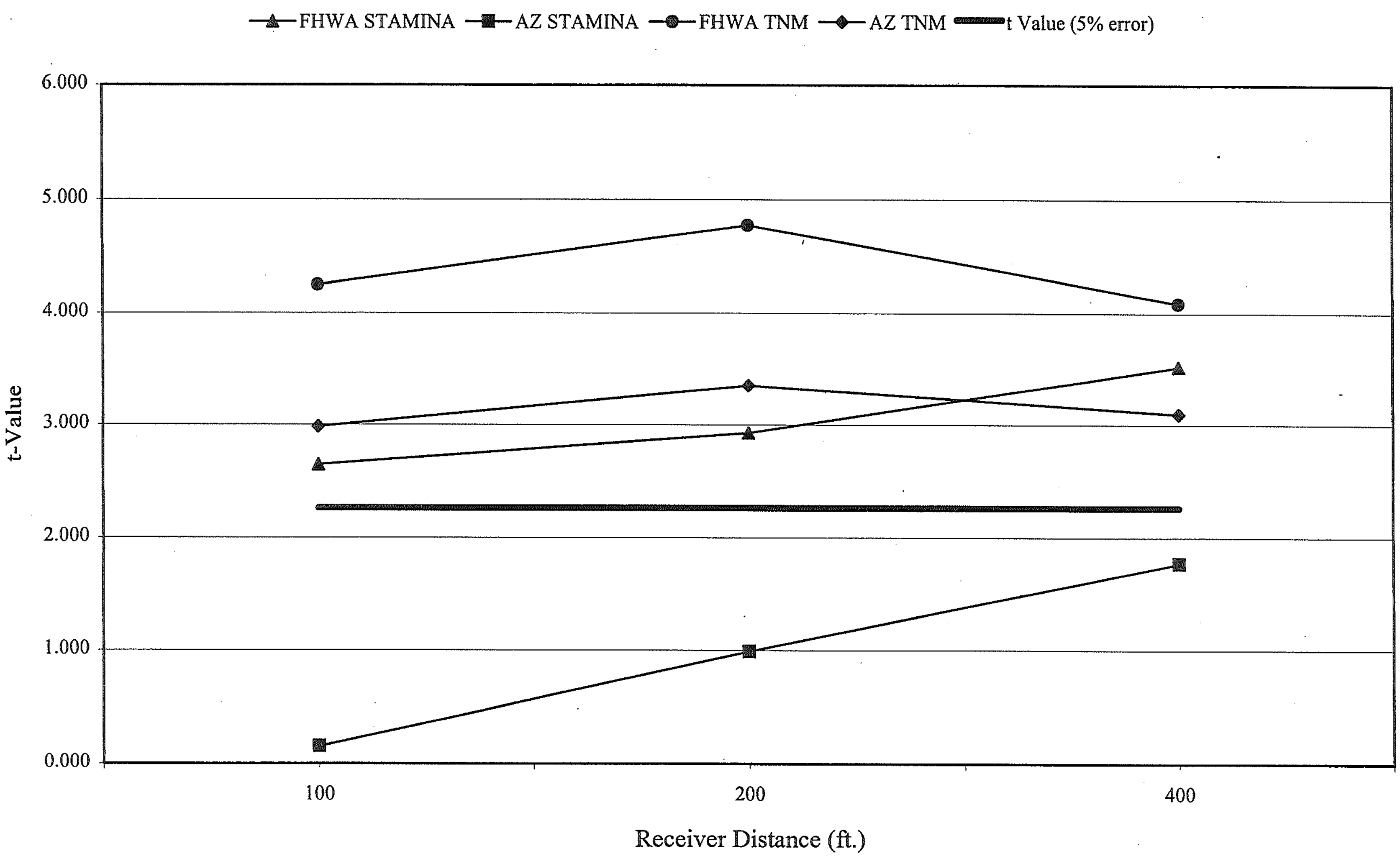


Figure 25: Comparison of t-Values, by Model