Updated Tier 2 Ambient Ratio Method (ARM) for 1-hr NO_2 NAAQS Analyses

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EPA's March 2011 1-hr NO_2 NAAQS Modeling Guidance

"Given the stringency of the 1-hour NO_2 standard relative to the annual standard, many more permit applicants may find it necessary to use the less conservative Tier 2 or Tier 3 approaches."

EPA has "not indicated any preference of one option over the other."

Current ARM Guidance for 1-hr NO_2 Analyses

* ARM was originally developed for annual NO_2 modeling, using annual ambient NO_2/NOx ratios for all monitoring sites in 1987-1989.
* EPA has cited two recent studies to support the current recommendation of a fixed ARM ratio of 0.80 for 1-hr analyses.
* However, both of these studies, as well as other monitoring data evaluations, demonstrate that variable ratios are observed as a function of distance/time from the source. This indicates that the current fixed-value ARM method may be overly conservative for 1-hr NO_2 analyses, especially when nearby "fenceline" concentrations are the controlling impact.

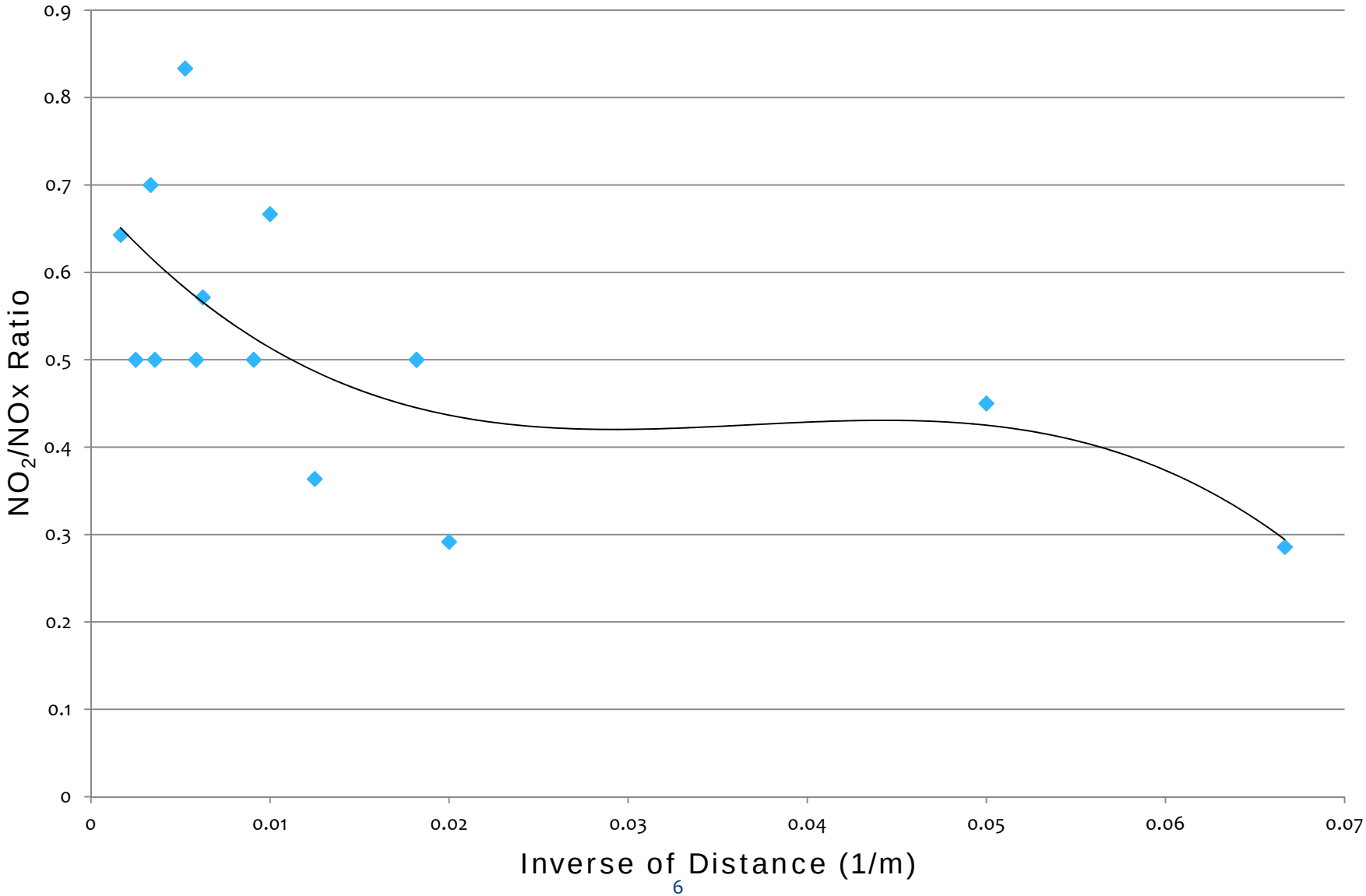
Wang Study of NOx near Roadways

* Wang reports on four short-term monitoring tests near roadways.
* Background NOx and ozone concentrations were low; 1 to 6 ppb NOx, and ozone ~ 25 ppb.
* Maximum measured roadway 1-hr NO2 impacts were also low at < 10ppb NO_2 (ambient ozone concentration is not limiting conversion).
* This study is based on such low NOx and NO_2 measured impacts that it may not be indicative of the higher impacts that can occur from stationary point sources (with less mixing and ozone entrainment than roadway emissions, and more likely to be "ozone limited").

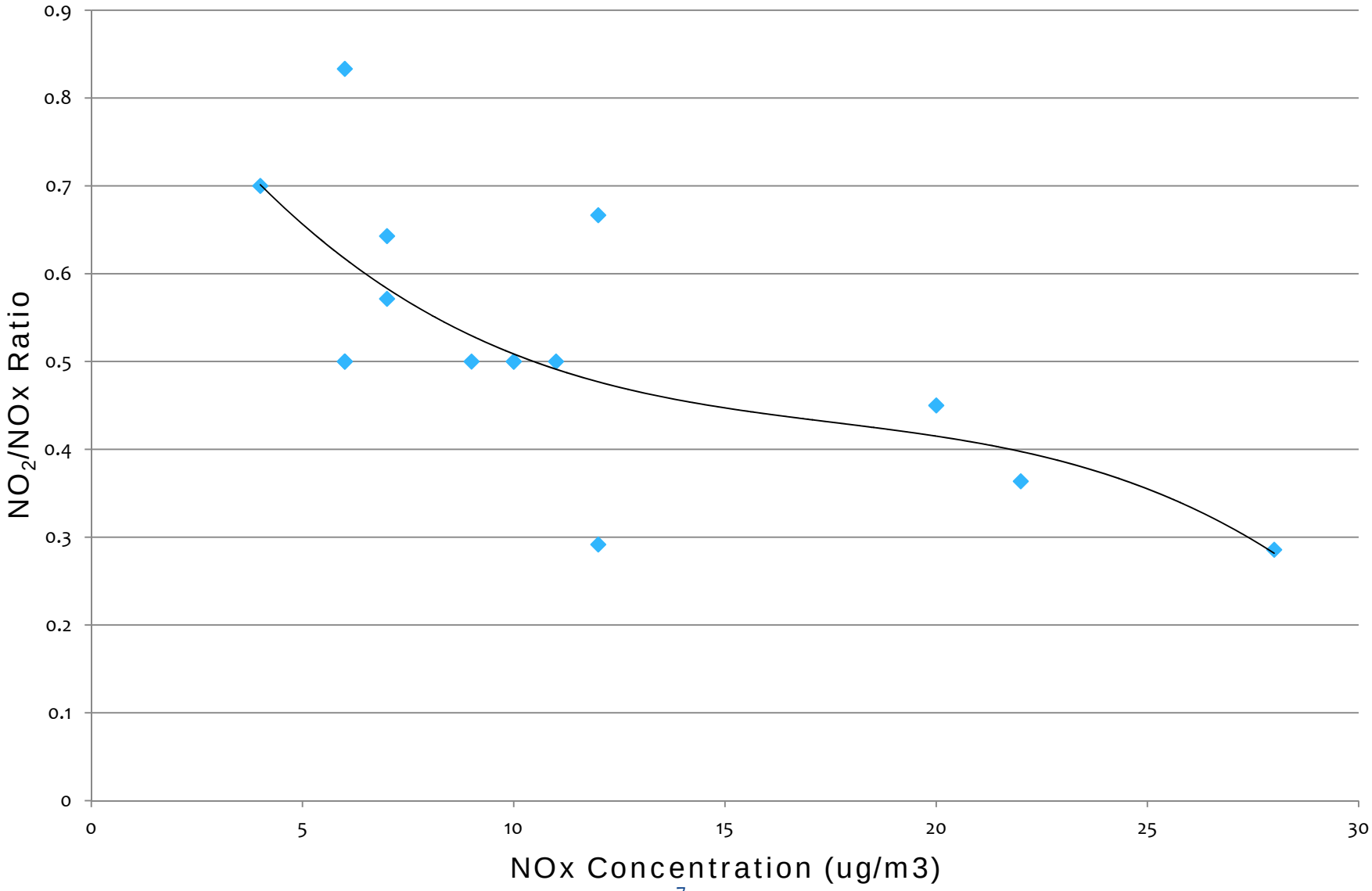
Wang Study Results

* The measured NO_2/NOx ambient ratios were variable – min is 0.3, max is 0.8, average is 0.5.
* Use of a fixed ratio of 0.8 is conservative, but would overestimate most NO_2 concentrations.
* The following two graphs plot the measured NO_2/NOx ambient ratios as a function of distance and of NOx concentration. These graphs illustrate that plotting ratios as a function of NOx concentration can be a surrogate for using distance on the X-axis.

Wang Study - Plot of Measured NO_2/NOx Ambient Ratio as a Function of Inverse of Distance



Wang Study - Plot of Measured NO_2/NOx Ambient Ratio as a Function of NOx Concentration



Can ARM be refined to perform better for 1-hr analyses?

* A variable ratio ARM method ("ARM2") could be less conservative than current fixed 0.8 ARM guidance, yet more conservative than refined Tier 3 methods.

* Current fixed ratio ARM is not very useful for 1-hr modeling; ARM2 could fill a gap in Tier 2 and 3 techniques.

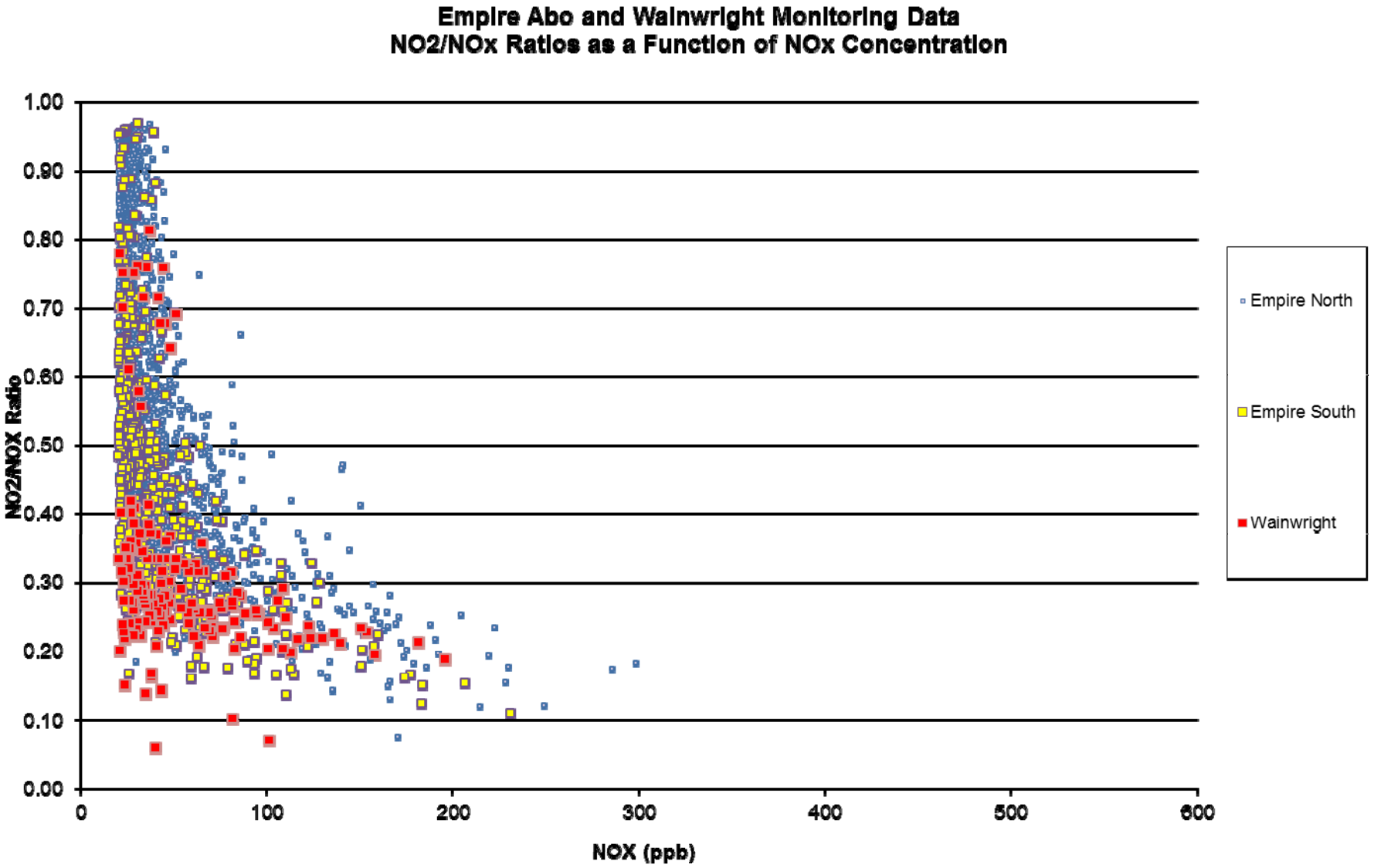
* If a variable ratio 1-hr ARM2 is based on a large enough data set of 1-hr ambient monitoring data, it would implicitly address the range of entrainment, mixing, and conversion processes that are occurring over a wide range of total NOx concentrations

What are the benefits of updating ARM for 1-hr NO_2 analyses?

* ARM is a simplified screening approach that is easy to implement
* ARM does not need detailed in stack NO_2/NOx ratio data for all modeled sources
* ARM does not require representative ozone data (also, ozone scavenging by local NOx sources is a potentially important issue for ozone data sets that has not been fully evaluated)
* ARM would not introduce complex "offsetting errors" between dispersion and conversion that could mask poor model performance
* Use of ARM would reduce agency resources required for review

Analysis of Ambient NO_2 and NOx Data to Develop 1-hr "ARM2"

* Numerous 1-hr NO_2 and NOx monitoring data sets have been reviewed (AQS data base of all NOx sites reported to EPA in the US, as well as various AQS subsets by land use and geographical areas, also Empire Abo, Wainwright, NMED, and Canadian Oil Sands data bases)
* Data has been summarized by plotting observed NO_2/NOx ambient ratios as a function of observed NOx concentration (again, NOx concentration represents the distance/time that has occurred for dilution, entrainment, and conversion process - for example, high NOx concentrations would imply less dilution, entrainment, and conversion).
* ALL ambient data sets reviewed show similar relationships, as illustrated in the following set of slides


Empire Abo and Wainwright Monitoring Data
NO2/NOx Ratios as a Function of NOx Concentration
NO2/NOX Ratio
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
100
200
300
400
500
600
NOX (ppb)
Empire North
Empire South
Wainwright

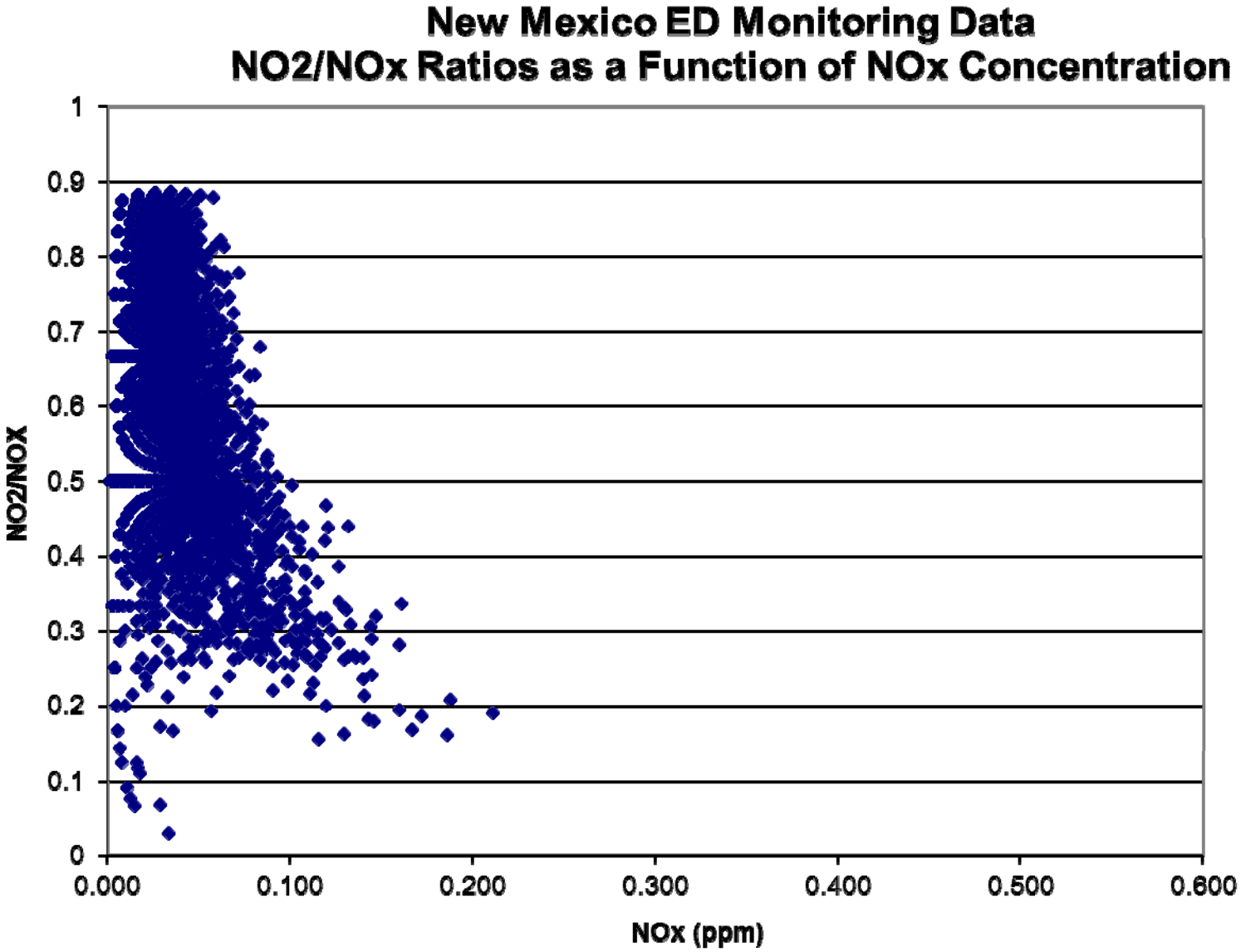
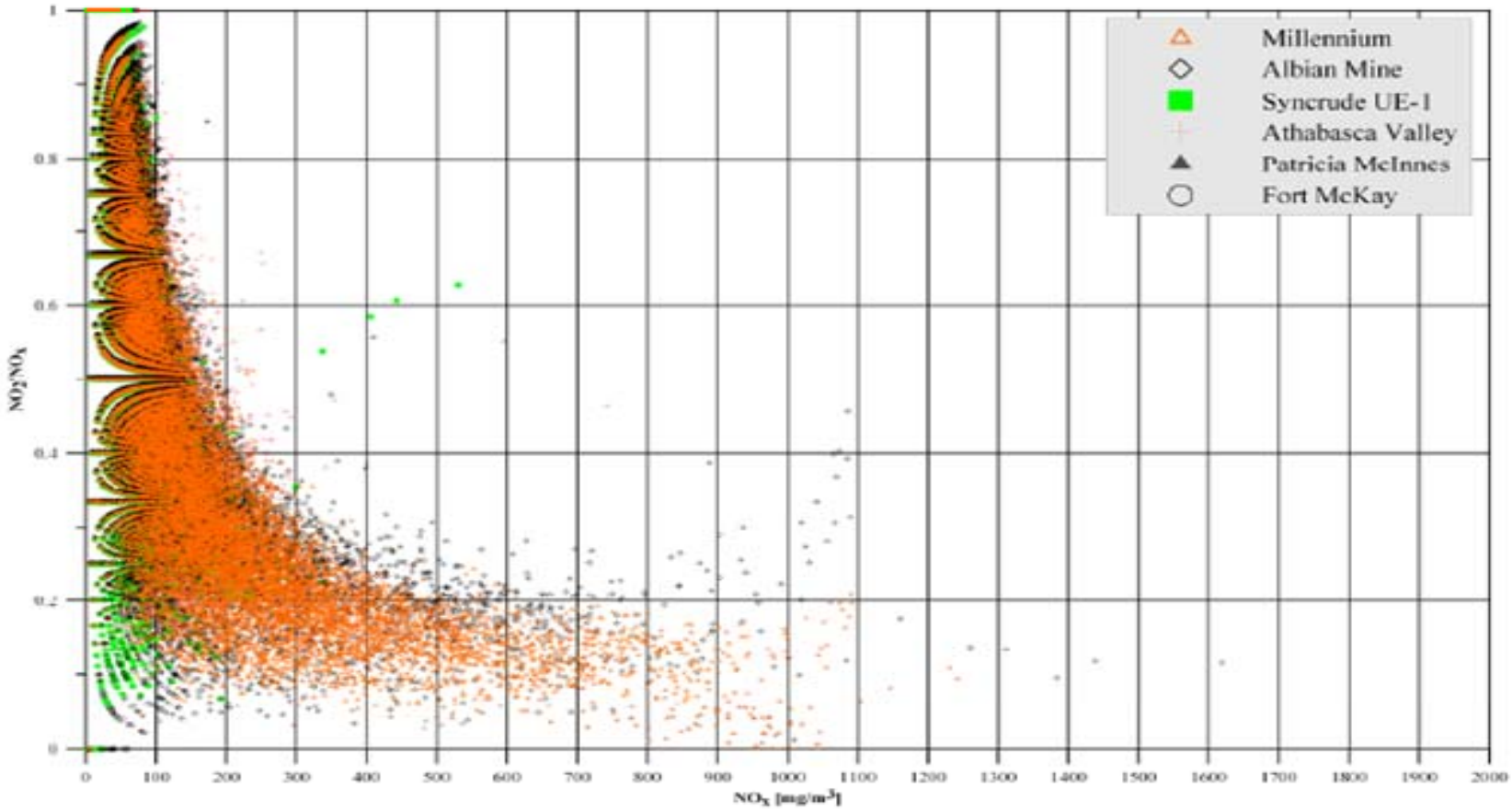

New Mexico ED Monitoring Data
NO2/NOx Ratios as a Function of NOx Concentration
NO2/NOX
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.000
0.100
0.200
0.300
0.400
0.500
0.600
NOx (ppm)

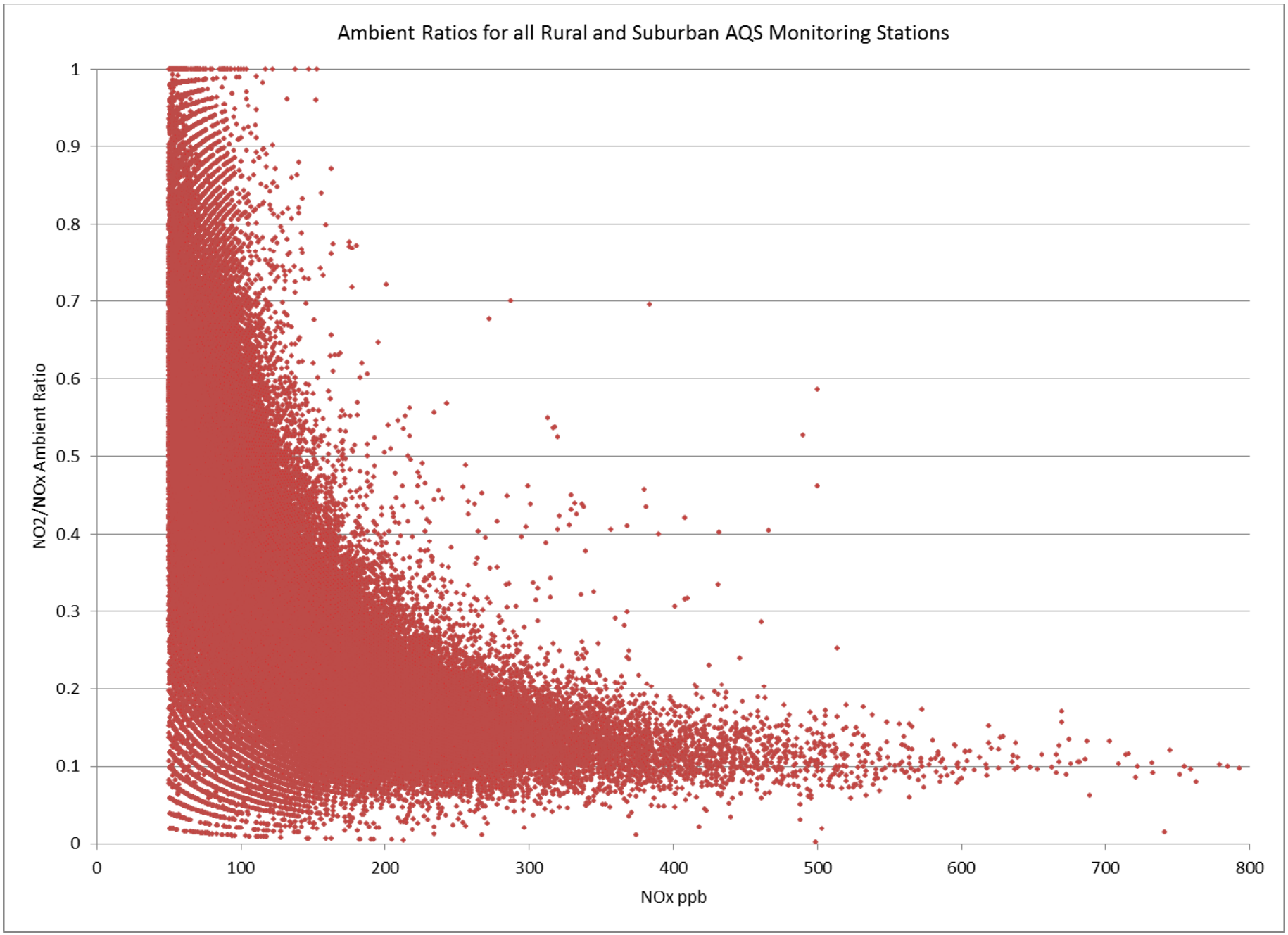
Figure 1. Hourly NO_2 and NO_X Measurements at WBEA monitoring Stations *



0 500 1000

approximate NOx in ppb

* from Rahul Jain et.al, Golder Associates Ltd,, Paper # 2011-A-467-AWMA

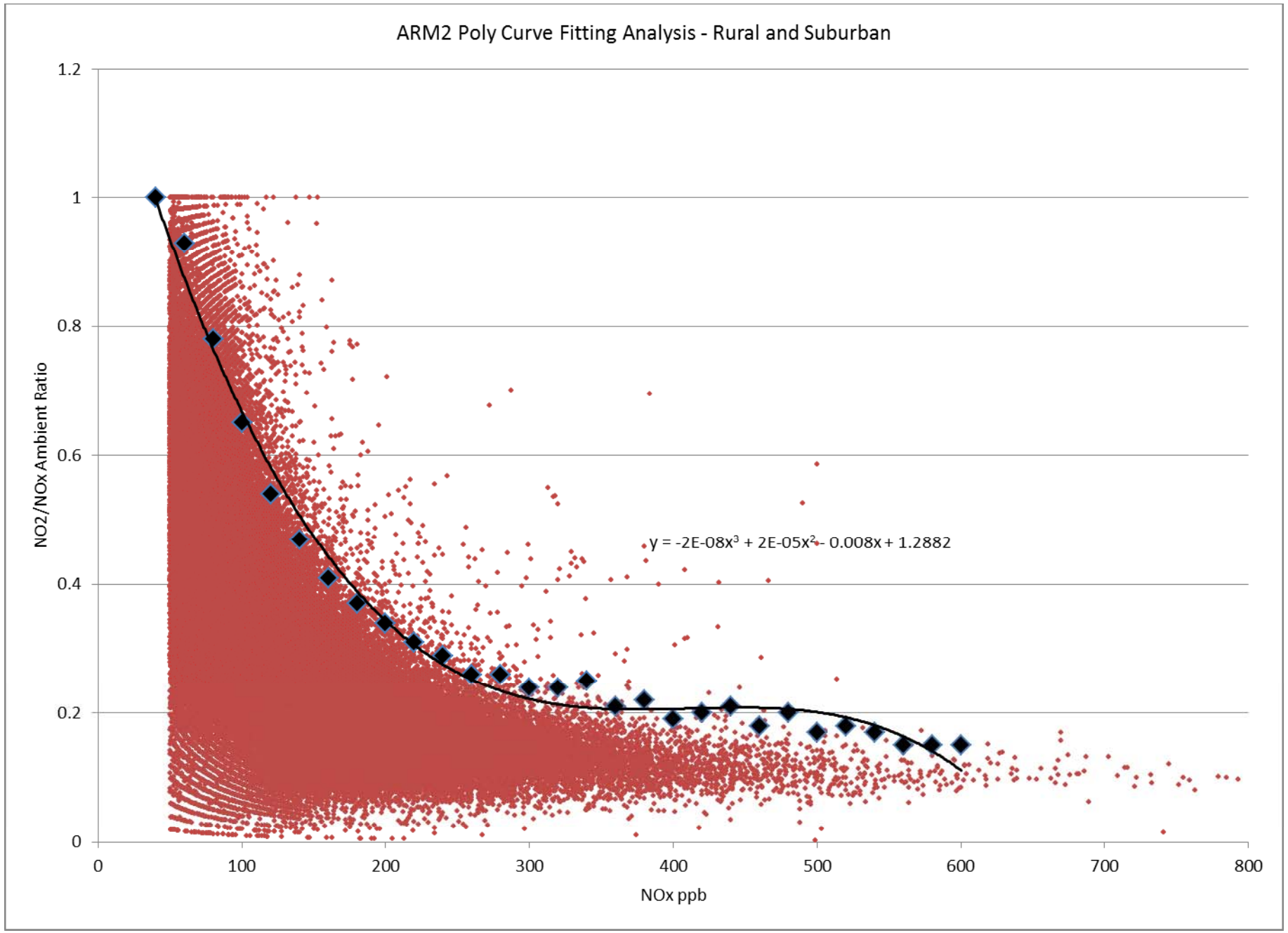

Ambient Ratios for all Rural and Suburban AQS Monitoring Stations
NO2/NOx Ambient Ratio
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
100
200
300
400
500
600
700
800
NOx ppb

1-hr Monitoring Data Indicates …

* All plots indicate that lower ratios are observed at higher NOx concentrations, and a wide range of ratios are observed at lower NOx concentrations
* At lower NOx concentrations, the observed ratio could result from either a smaller, nearby source (with less entrainment and conversion) or a larger, more distant source (that has more entrainment and conversion). In addition, plume centerline versus edge effects could also be contributing to the observed range of ratios (the entrainment and conversion is not uniform throughout the plume cross-section).

Development of ARM2 Ambient Ratio Curve from 1-hr Monitoring Data

* An upper-bound NO_2/NOx ambient ratio or "conversion" curve was derived for various subsets of monitoring data.
* Because of the large number of data points, the data was sorted into "bins" from 20 to 600 ppb NOx – each bin was 20 ppb wide.
* A reasonable upper bound ratio was estimated for each bin using the 98th percentile of the hourly observed ratios for that bin. The upper bound ratios for each bin were then plotted and fitted using a 3rd order polynomial equation. The tail end of the curve was adjusted for a minimum 0.15 ratio, to represent a typical in-stack ratio.


ARM2 Poly Curve Fitting Analysis - Rural and Suburban
NO2/NOx Ambient Ratio
NOx ppb
y = -2E-08x³ + 2E-05x² - 0.008x + 1.2882
0
0.2
0.4
0.6
0.8
1
1.2
0
100
200
300
400
500
600
700
800

Upper Nox BIN ppb	Rural/Suburban ARM2 Calculated NO2/NOx Ratio	Urban/City Center ARM2 Calculated NO2/NOx Ratio
40	1.00	1.00
60	0.88	0.90
80	0.76	0.79
100	0.67	0.69
120	0.58	0.61
140	0.51	0.53
160	0.44	0.47
180	0.39	0.42
200	0.34	0.37
220	0.31	0.33
240	0.28	0.30
260	0.25	0.28
280	0.23	0.26
300	0.22	0.24
320	0.21	0.23
340	0.21	0.23
360	0.21	0.22
380	0.21	0.22
400	0.21	0.22
420	0.21	0.22
440	0.21	0.22
460	0.21	0.22
480	0.21	0.21
500	0.20	0.21
520	0.19	0.20
540	0.18	0.19
560	0.16	0.17
580	0.15	0.15
600+	0.15	0.15

Upper Nox BIN ppb	Northeast All Sites 2001- 2010 ARM2 Calculated NO2/NOx Ratio	Southeast All Sites 2001- 2010 ARM2 Calculated NO2/NOx Ratio	Midwest All Sites 2001- 2010 ARM2 Calculated NO2/NOx Ratio	Mountain All Sites 2001- 2010 ARM2 Calculated NO2/NOx Ratio	Southwest All Sites 2001- 2010 ARM2 Calculated NO2/NOx Ratio	Max	Min	Ave	All Site NO2/NOx Ratio	Rural Sites NO2/NOx Ratio
40	0.96	1.00	1.00	0.90	1.00	1.00	0.90	0.97	1.00	1.00
60	0.83	0.91	0.89	0.81	0.89	0.91	0.81	0.86	0.88	0.88
80	0.72	0.79	0.77	0.74	0.78	0.79	0.72	0.75	0.77	0.76
100	0.63	0.68	0.67	0.67	0.68	0.68	0.63	0.66	0.68	0.67
120	0.54	0.59	0.58	0.61	0.60	0.61	0.54	0.58	0.59	0.58
140	0.47	0.51	0.50	0.56	0.52	0.56	0.47	0.50	0.52	0.51
160	0.41	0.44	0.43	0.51	0.45	0.51	0.41	0.44	0.46	0.44
180	0.36	0.38	0.38	0.48	0.40	0.48	0.36	0.39	0.40	0.39
200	0.31	0.33	0.34	0.44	0.35	0.44	0.31	0.35	0.36	0.34
220	0.28	0.29	0.30	0.41	0.31	0.41	0.28	0.31	0.32	0.31
240	0.25	0.26	0.27	0.39	0.28	0.39	0.25	0.28	0.29	0.28
260	0.23	0.23	0.25	0.37	0.25	0.37	0.23	0.26	0.27	0.25
280	0.21	0.21	0.24	0.35	0.23	0.35	0.21	0.24	0.25	0.23
300	0.20	0.20	0.23	0.33	0.21	0.33	0.20	0.23	0.24	0.22
320	0.20	0.19	0.22	0.32	0.20	0.32	0.19	0.22	0.23	0.21
340	0.19	0.18	0.22	0.30	0.19	0.30	0.18	0.21	0.22	0.21
360	0.19	0.18	0.22	0.29	0.19	0.29	0.18	0.21	0.22	0.21
380	0.19	0.17	0.21	0.27	0.19	0.27	0.17	0.21	0.22	0.21
400	0.20	0.17	0.21	0.26	0.19	0.26	0.17	0.20	0.22	0.21
420	0.20	0.16	0.21	0.24	0.19	0.24	0.16	0.20	0.22	0.21
440	0.20	0.16	0.20	0.22	0.19	0.22	0.16	0.19	0.22	0.21
460	0.20	0.15	0.19	0.19	0.19	0.20	0.15	0.19	0.22	0.21
480	0.20	0.15	0.18	0.16	0.18	0.20	0.15	0.18	0.22	0.21
500	0.20	0.15	0.16	0.15	0.18	0.20	0.15	0.17	0.21	0.20
520	0.19	0.15	0.15	0.15	0.17	0.19	0.15	0.17	0.20	0.19
540	0.17	0.15	0.15	0.15	0.17	0.17	0.15	0.16	0.19	0.18
560	0.16	0.15	0.15	0.15	0.15	0.16	0.15	0.15	0.17	0.16
580	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
600+	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Number > 100	117239	14583	14318	4165	81091	NA	NA	NA	NA	NA

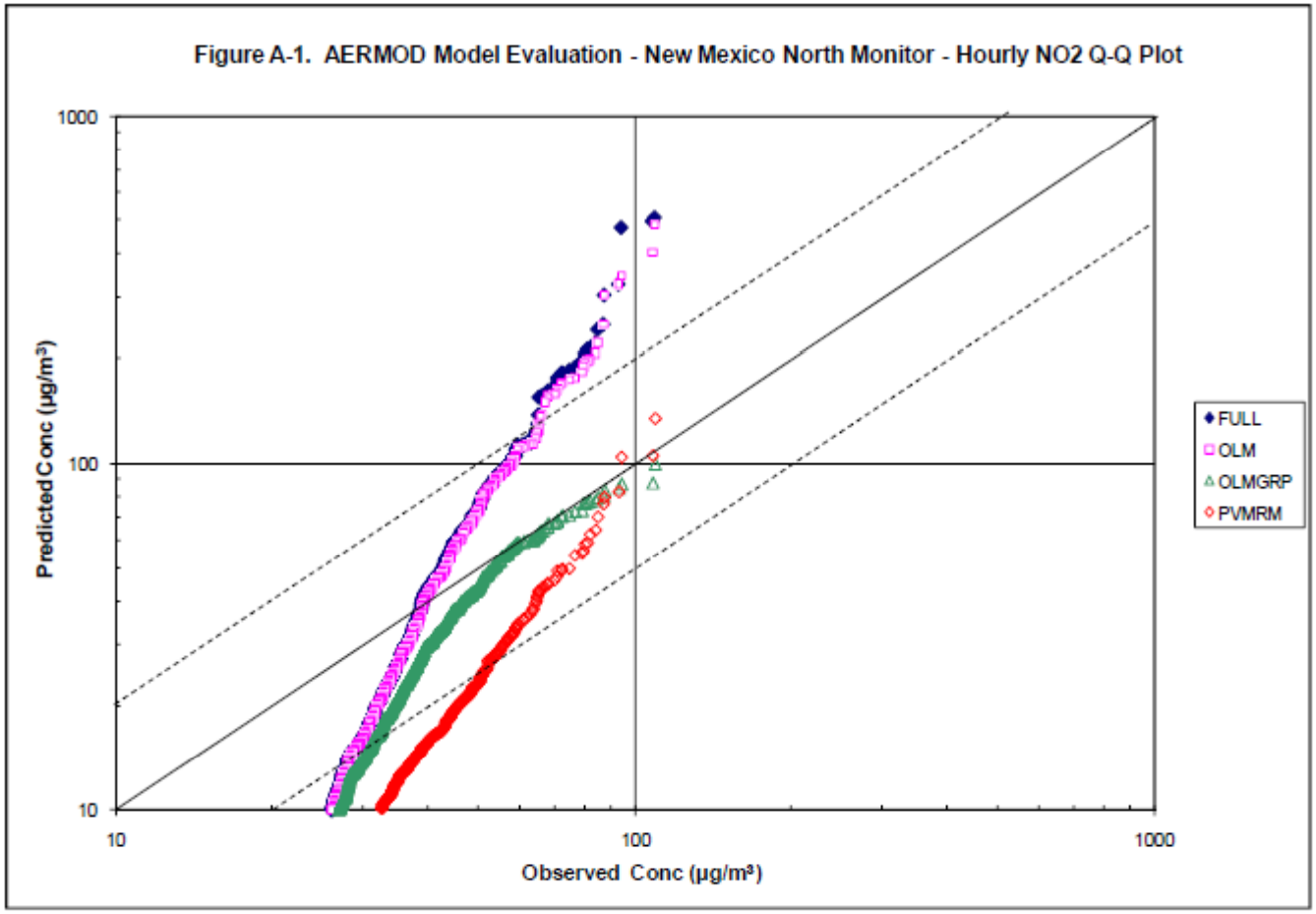
Performance Testing of ARM2 Equation

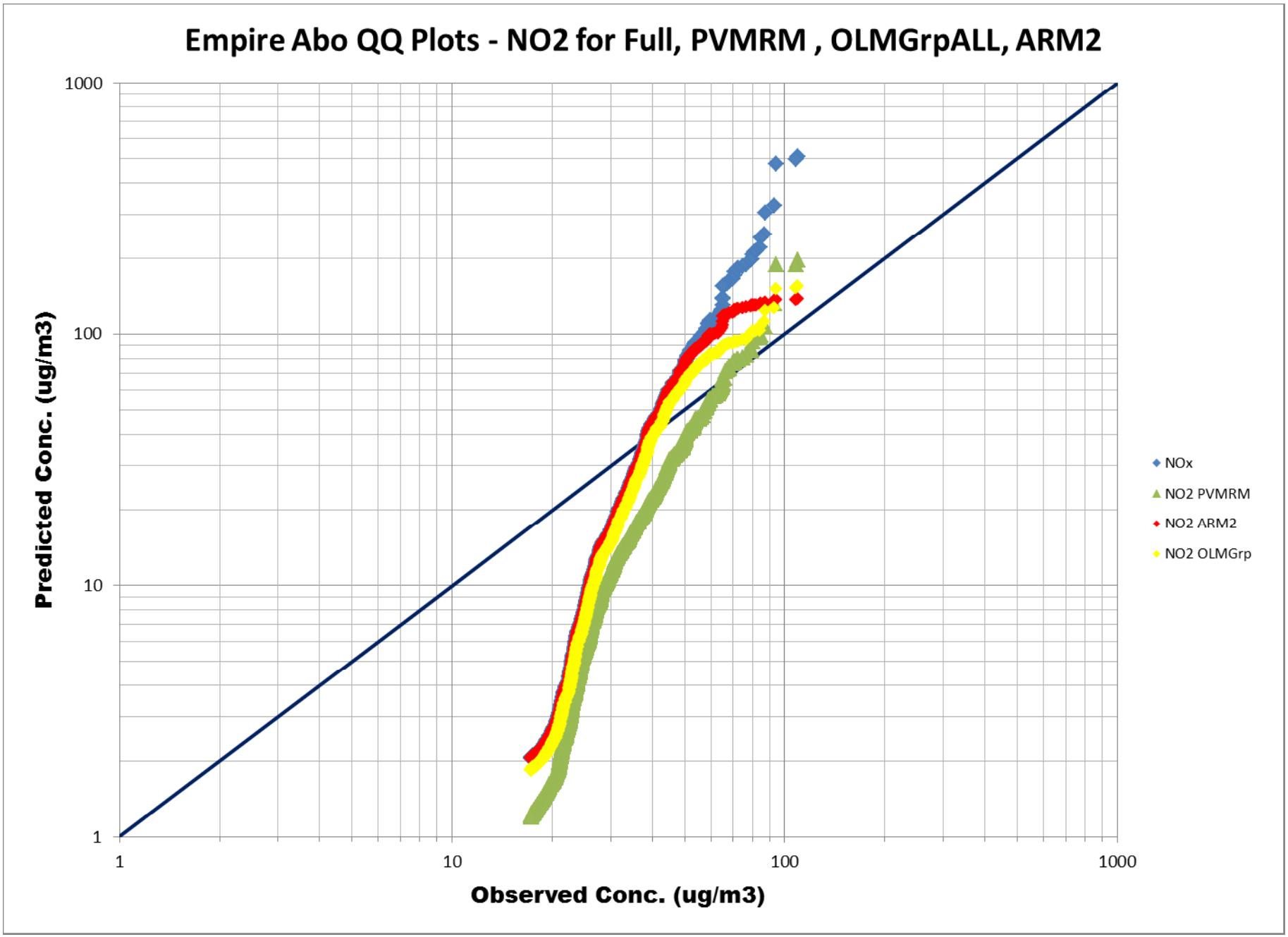
* The performance of the ARM2 "all sites" equation was evaluated for the three available test data sets, Empire Abo North, Palaau, and Wainwright data sets.
* Ran AERMOD to calculate NOx, and then applied ARM2 equation. Also ran AERMOD with PVMRM and OLM GrpALL methods.
* Note on assumptions used for Empire Abo Tier 3 modeling - used higher of North or South site ozone data, to minimize the effects of ozone scavenging – also, an in-stack ratio of 0.2 was used instead of the 0.1 in EPA March 2011 modeling, because most sources are IC engines and 0.2 is closer to current guidance from some state agencies). These updates resulted in high PVMRM modeled NO2 concentrations being ~ 30 ppb higher than results presented by EPA in March 2011 memo. PVMRM obviously sensitive to ozone and in-stack ratio assumptions.
* Plotted QQ results for full conversion (i.e., NOx concentration), ARM2, PVMRM, and OLM/GroupALL for the three data sets.

Empire Abo North
Test Data Set

* North monitoring station is located 1600 m from the source.
* Average of 10 highest hourly monitored concentrations are 375 ug/m3 for NOx and 91 ug/m3 for NO_2 (~1/2 of NO_2 NAAQS).
* Monitored NO2/NOx ambient ratios varied from about 0.1 to 0.96, but the average ambient ratio for the 10 highest hourly monitored NOx concentrations is 0.1.

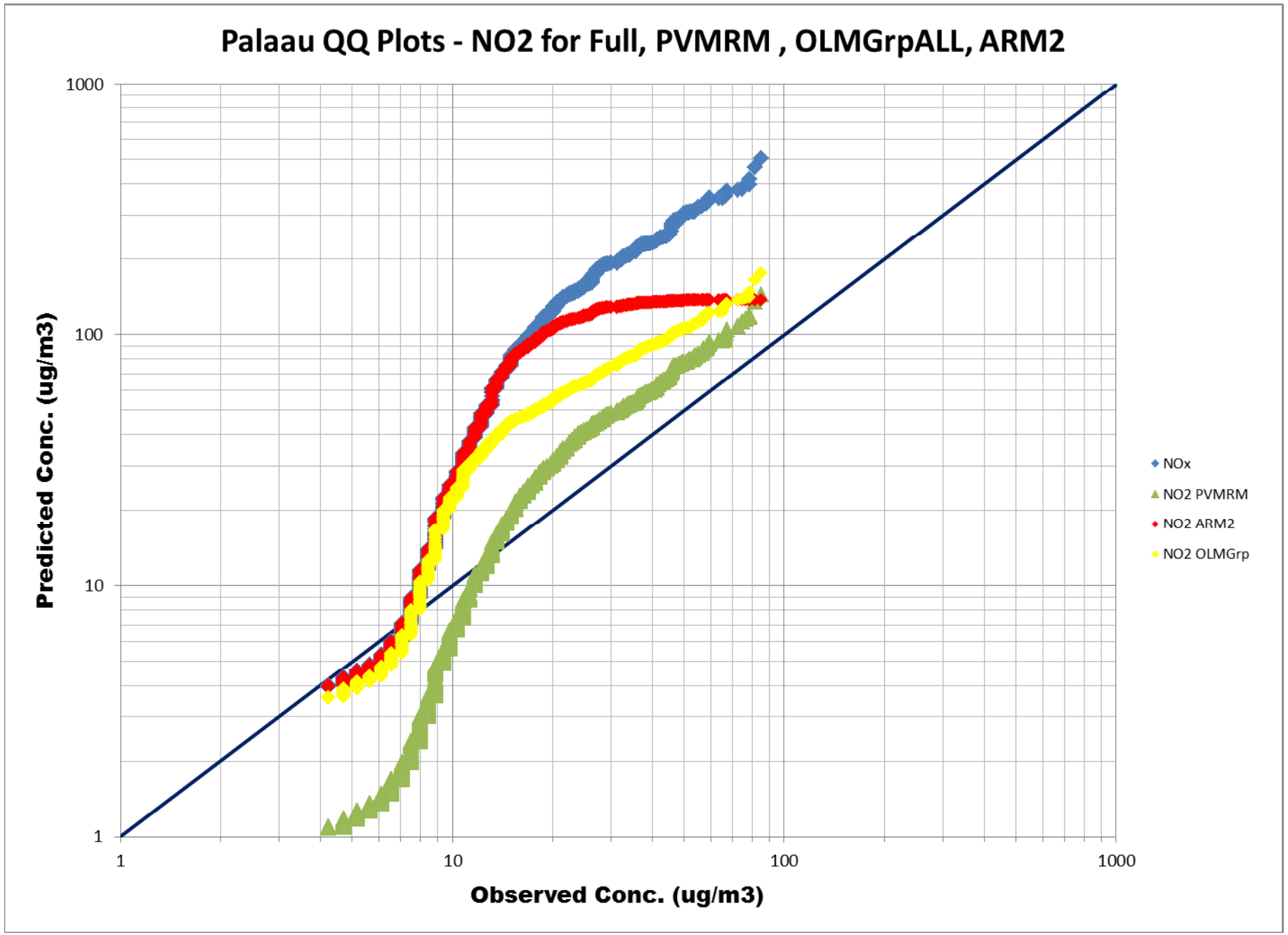
QQ Plot presented in EPA's March 2011 Guidance Memo




Empire Abo QQ Plots - NO2 for Full, PVMRM , OLMGrpALL, ARM2
Predicted Conc. (ug/m3)
1000
100
10
1
1
10
100
1000
Observed Conc. (ug/m3)
NOx
NO2 PVMRM
NO2 ARM2
NO2 OLMGrp

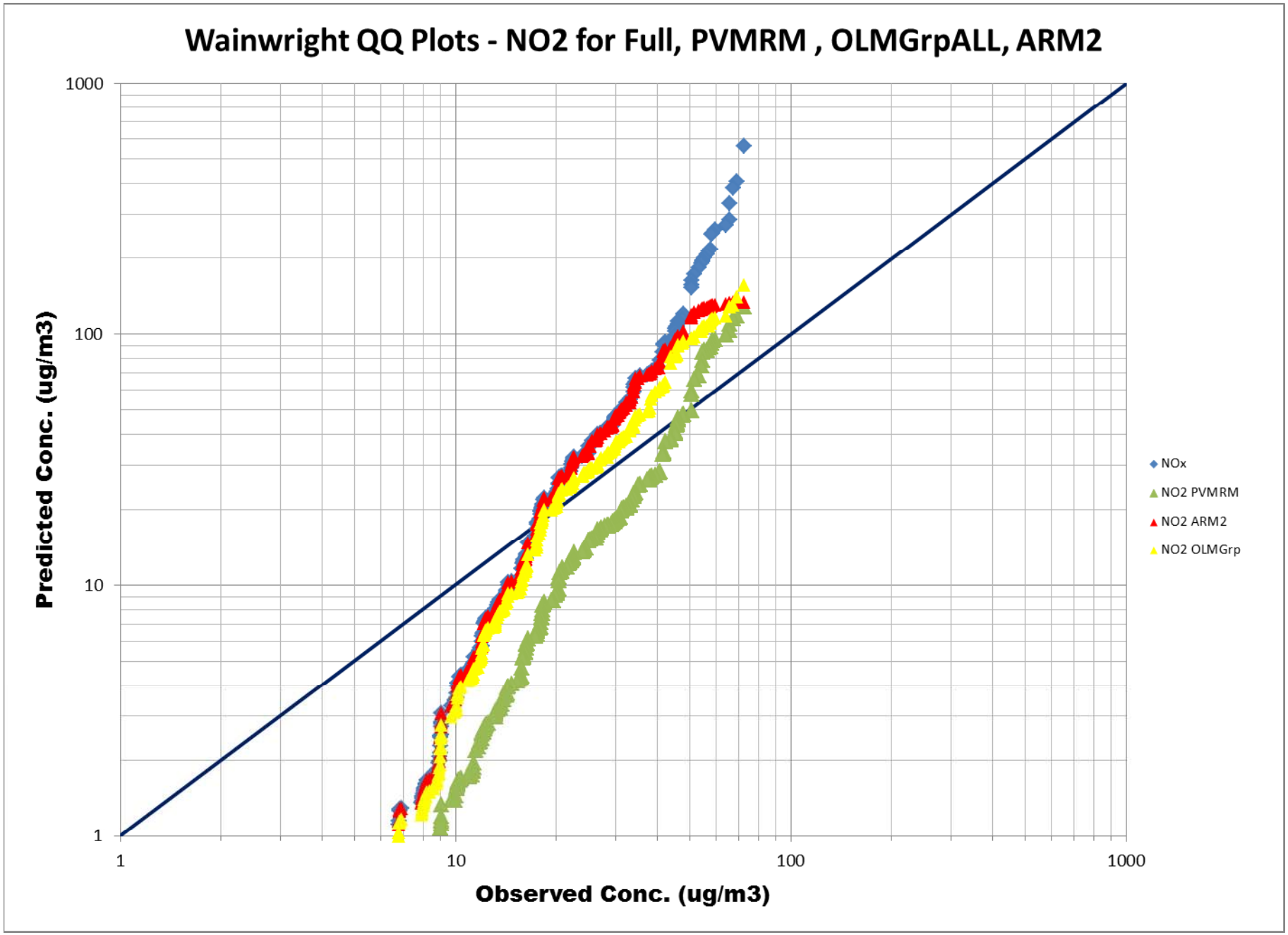
Palaau
Test Data Set

* Monitoring station is located 200 m from the source, so little time for entrainment, mixing, and reaction.
* Average of 10 highest hourly monitored concentrations are 560 ug/m3 for NOx and 75 ug/m3 for NO_2.
* The average monitored NO2/NOx ambient ratio for the 10 highest NOx concentrations is 0.12.
* Ambient ozone concentrations average ~ 25 ppb.
* Source consists of 6 IC engines and 1 CT. Ran AERMOD using an in-stack ratio of 0.2.


Palaau QQ Plots - NO2 for Full, PVMRM , OLMGrpALL, ARM2
Predicted Conc. (ug/m3)
1000
100
10
1
1
10
100
1000
Observed Conc. (ug/m3)
NOx
NO2 PVMRM
NO2 ARM2
NO2 OLMGrp

Wainwright
Test Data Set

* Wainwright monitoring station is located 500 m from the source
* Maximum monitored concentrations are 369 ug/m3 for NOx and 72 ug/m3 for NO_2.
* Monitored conversion ratios from about 0.2 to 0.5.


Wainwright QQ Plots - NO2 for Full, PVMRM , OLMGrpALL, ARM2
Predicted Conc. (ug/m3)
1000
100
10
1
1
10
100
1000
Observed Conc. (ug/m3)
NOx
NO2 PVMRM
NO2 ARM2
NO2 OLMGrp

Conclusions from QQ Analysis

* The relative performance between PVMRM and OLM GrpALL can vary depending upon the data set.
* Tier 3 results are sensitive to input ozone data (scavenging?) and in-stack ratio assumptions. Any performance tests must use similar assumptions as in current EPA guidance.
* ARM2 is much more conservative at lower concentrations than either PVMRM or OLM GrpALL (implications for significant impact modeling procedures?).
* At highest concentrations, ARM2 predicted concentrations "flatten out", related to the inverse exponential shape of the ARM2 conversion curve.
* ARM2 performance at the highest NO2 concentrations is equal or better than the Tier 3 methods.

Sensitivity Testing of ARM2

* Data sets from the MACTEC PVMRM Sensitivity Analyses Report, September 2004, were rerun using PVMRM, OLM GrpALL, and ARM2. Only the non-downwash data sets were modeled because the original BPIP parameters were not available.
* In addition, other hypothetical source configurations were evaluated.
* Results follow, with similar conclusions as from the analysis of the three primary test data sets (i.e., relative ranking between the methods varies depending upon the data set, and ARM2 performs similar to the Tier 3 methods).

AERMOD 1-hr NO2 Sensitivity Analyses - MACTEC Scenarios - Concentrations are Highest Hourly (ug/m3)							
Single Point Source Scenario	**NOx (no conversion)**		**PVMRM**		**OLM GrpALL**		**ARM2**
	Highest	**Distance m**	**Highest**	**Distance m**	**Highest**	**Distance m**	**Highest**
35m Stack, 1g/s , Rural, No Downwash	3.9	500	3.5	500	3.5	500	3.9
35m Stack, 50g/s , Rural, No Downwash	193.8	500	58	3000	116	500	126.5
Diesel Generator , Rural, No Downwash	73.6	200	34.1	1000	65.8	200	73.6
Diesel Generator , Complex Terrain	101.9	300	30.7	500	91.7	300	92.7
Gas Turbine , Flat Terrain	35.5	1000	17.2	1000	31.9	1000	35.5
Gas Turbine , Complex Terrain	2038	100	846	200	585	100	306

Project Examples of 1-hr NO2 Modeling Results for ARM2 versus PVMRM - all impact concentrations are 98th percentile in ug/m3				
DESCRIPTION OF SOURCE	NOx	PVMRM NO2	OLM NO2	ARM2 NO2
Five Large IC Gensets at Power Plant	345	103	NA	131
Mainline Compressor station - 10 Mw turbine @ 35ft ht and 500 hp @ 15 ft ht	462	413	204	124
Large Refinery	218	189	153	130
Gas Plant A - Cumulative	1459	580	1379	219
Gas Plant B - Cumulative	2705	1325	655	406

Conclusions

* ARM2 is more conservative than PVMRM and OLM at low and mid-range NO_2 concentrations. At the higher NO_2 concentrations in the test data sets, ARM2 compares well to the best performing Tier 3 method.
* ARM2 fills the gap between current fixed-ratio 1-hr ARM guidance and the more refined Tier 3 methods. EPA should adopt a revised ARM2 method for 1-hr NO_2 analyses via an updated guidance memorandum.
* Additional test data sets with elevated NO_2 impacts at or above the NAAQS, and with better source data, are needed to evaluate the various conversion methods.