Analysis of Recent Heavy-Duty Vehicle Emission Test Programs

FACA MOVES Review Workgroup Meeting
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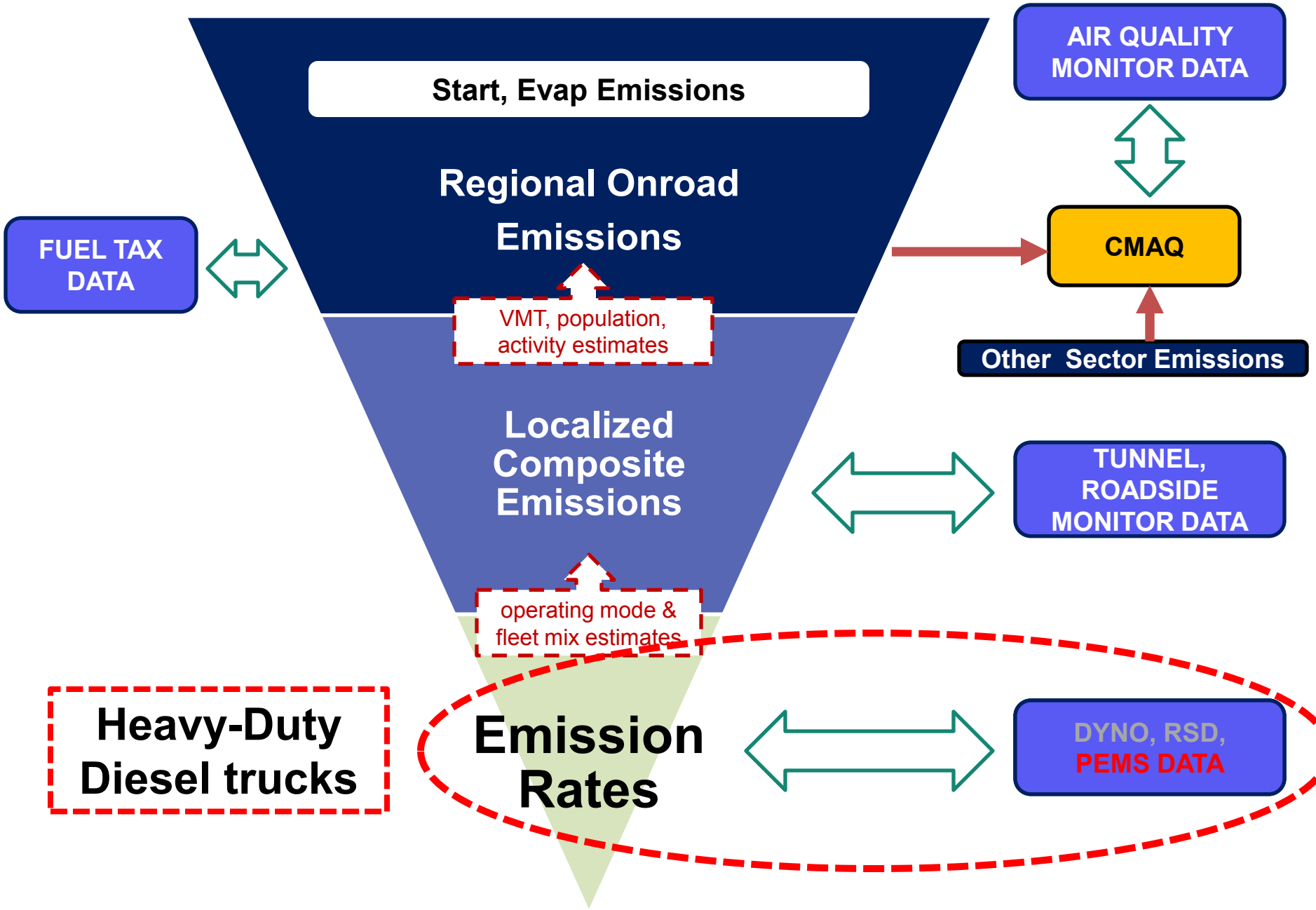

Start, Evap Emissions
Regional Onroad Emissions
VMT, population, activity estimates
Localized Composite Emissions
operating mode & fleet mix estimates
Emission Rates
AIR QUALITY MONITOR DATA
CMAQ
Other Sector Emissions
FUEL TAX DATA
TUNNEL, ROADSIDE MONITOR DATA
DYNO, RSD, PEMS DATA
Heavy-Duty Diesel trucks

Objectives

- **Review current MOVES emissions rates for heavy-duty diesel (HDD) trucks**
- **Present analysis of two recent sources of Portable Emissions Measurement System (PEMS) data on HDD trucks**
  - HD In-Use Compliance Program
  - Houston Port Drayage Study
- **Summarize NOx emission rates from the two independent sources of data and compare to MOVES**
- **Compare and contrast the two datasets**
- **Discuss updating MOVES emission rates based on the analysis**

MOVES HHD NOx Data Sources

- **ROVER – Portable Emissions Measurement System (PEMS)**
  - Developed by EPA to perform compliance testing on in-use vehicles
  - 124 trucks
  - HC, CO, NO_x, CO_2 measured
  - Model years 1999-2006
  - Ages 0-4 years old
  - Routes
    - Marathon runs from Maryland to Colorado and back (predominantly hwy)
    - Approx. 68-mile loop around Aberdeen, MD (highway and local driving)
    - Other local routes ad hoc

MOVES HHD NOx Data Sources (cont'd)

- **West Virginia University – Mobile Emissions Measuring Systems (MEMS)**
  - Used for HD consent decree in-use vehicle testing
  - 188 trucks
  - NO_x and CO_2 measured
  - Model years 1994-2003
  - Ages 0-7 years old
  - Fixed routes in WV and PA involving highway and urban driving

Current MOVES HHD NOx rates

- **Hole-filling and forecasting required some model years to be estimated based on standards and available data from adjacent model year groups**

Model Year Group	Emission Rate Source
1989 and prior	40% increase from MY 1991-1997
1990	20% increase from MY 1991-1997
1991-1997	Data
1998	Data
1999-2002	Data
2003-2006	Data
2007-2009	50% reduction from MY 2003-2006
2010 +	90% reduction from MY 2003-2006

Comparison to MOVES using MOVES operating mode bins

- **Allows "in the wild" PEMS data to be compared directly across program/vehicle/trip, and with MOVES rates**
- **Constructed based on vehicle speed and Scaled Tractive Power (STP)**
  - Similar to VSP, but not normalized by vehicle mass
  - HD vehicles regulated on an engine work basis
  - Preserves emission rate to power relation

$$STP = \frac{P_{axle}}{f_{scale}} \qquad P_{axle} = \eta_{driveline}(P_{eng} - P_{loss,acc})$$

Regulatory Class	Power scaling factor (f_{scale})
MHD, HHD, Bus	17.1
LHD	2.06

Operating Modes for Running Exhaust Emissions

VSP Class (kW/tonne) [Unscaled kW]	Speed Class (mph) 1-25	25-50	50 +
30 +	16	30	40
27-30			
24-27		29	39
21-24		28	38
18-21			
15-18			37
12-15		27	
9-12	15	25	
6-9	14	24	35
3-6	13	23	
0-3	12	22	33
< 0	11	21	

For coast and cruise,

21 operating modes

PLUS
One mode each for
idle (1), and
decel/braking (0)

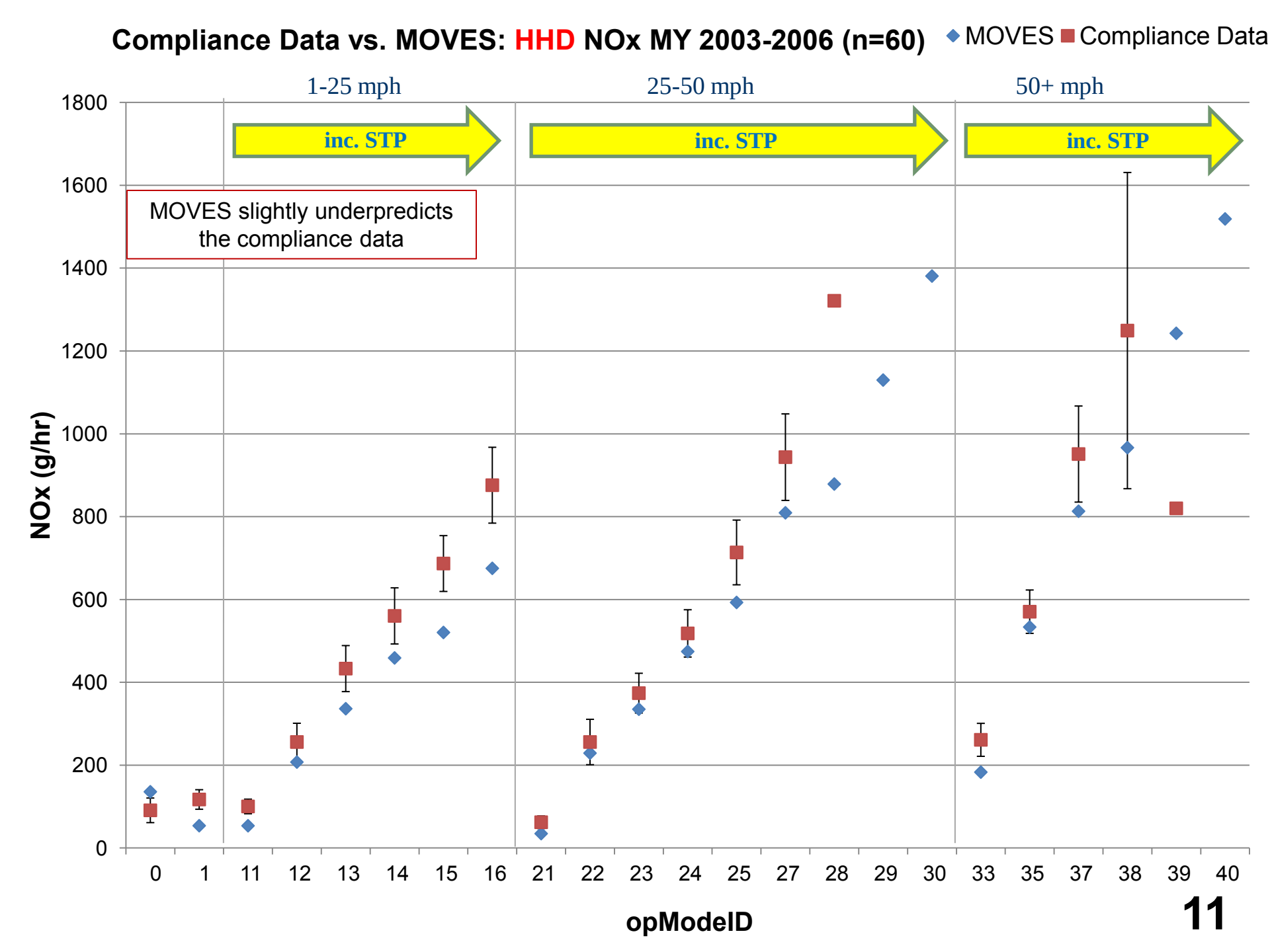
Gives a total of
23 Modes

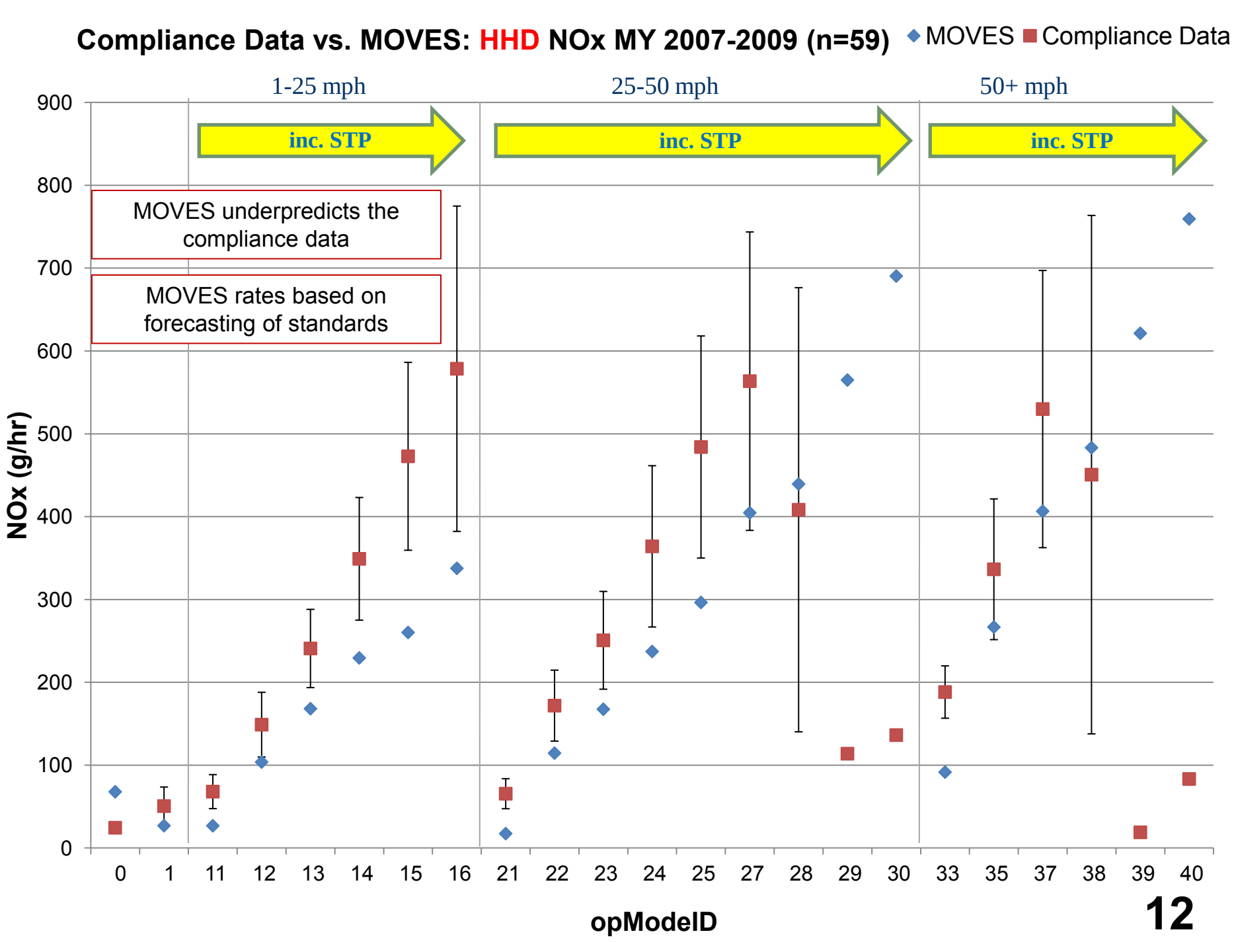
Unscaled power ranges from < 0 to 513+ kW

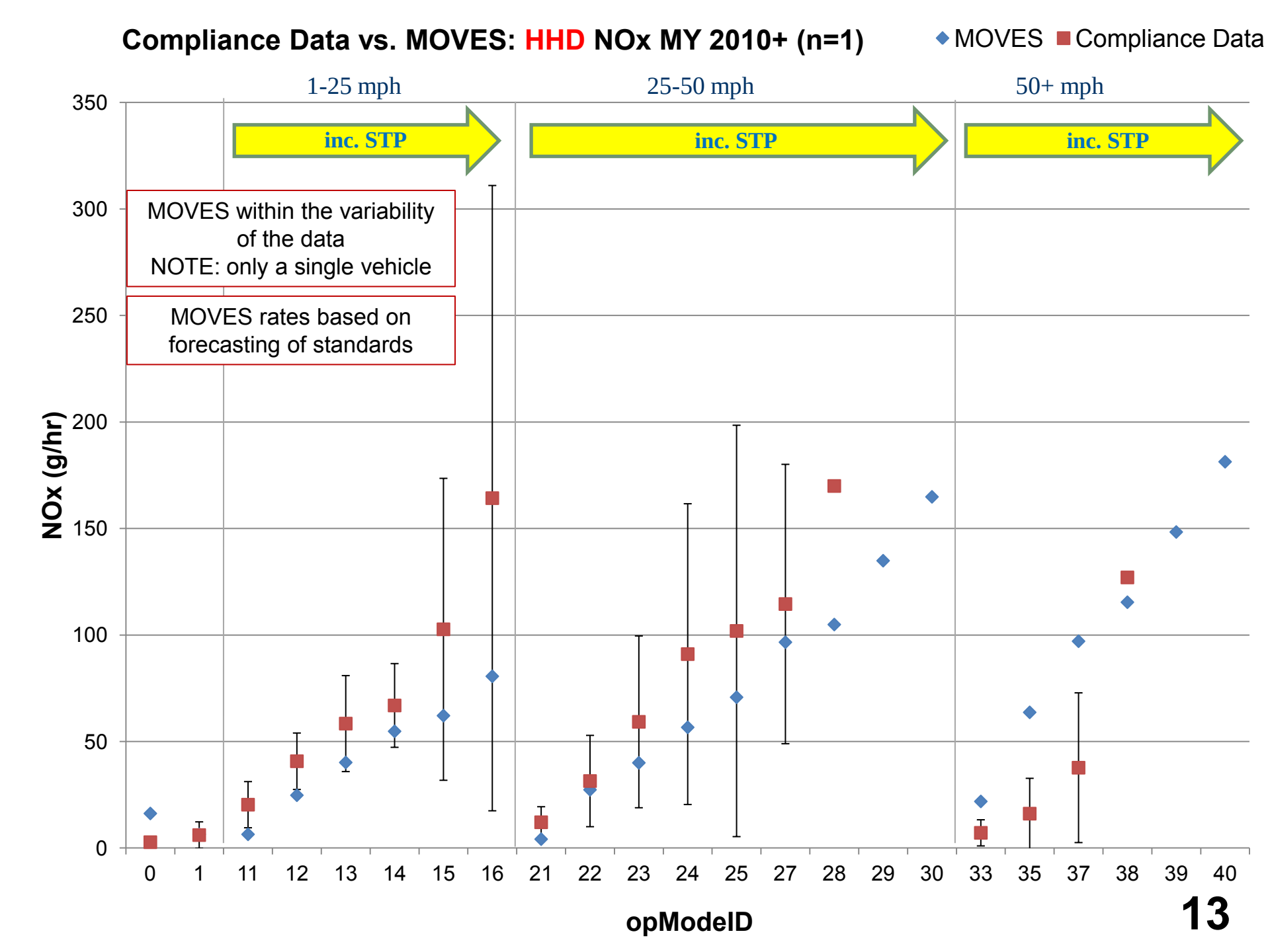
In-use compliance data

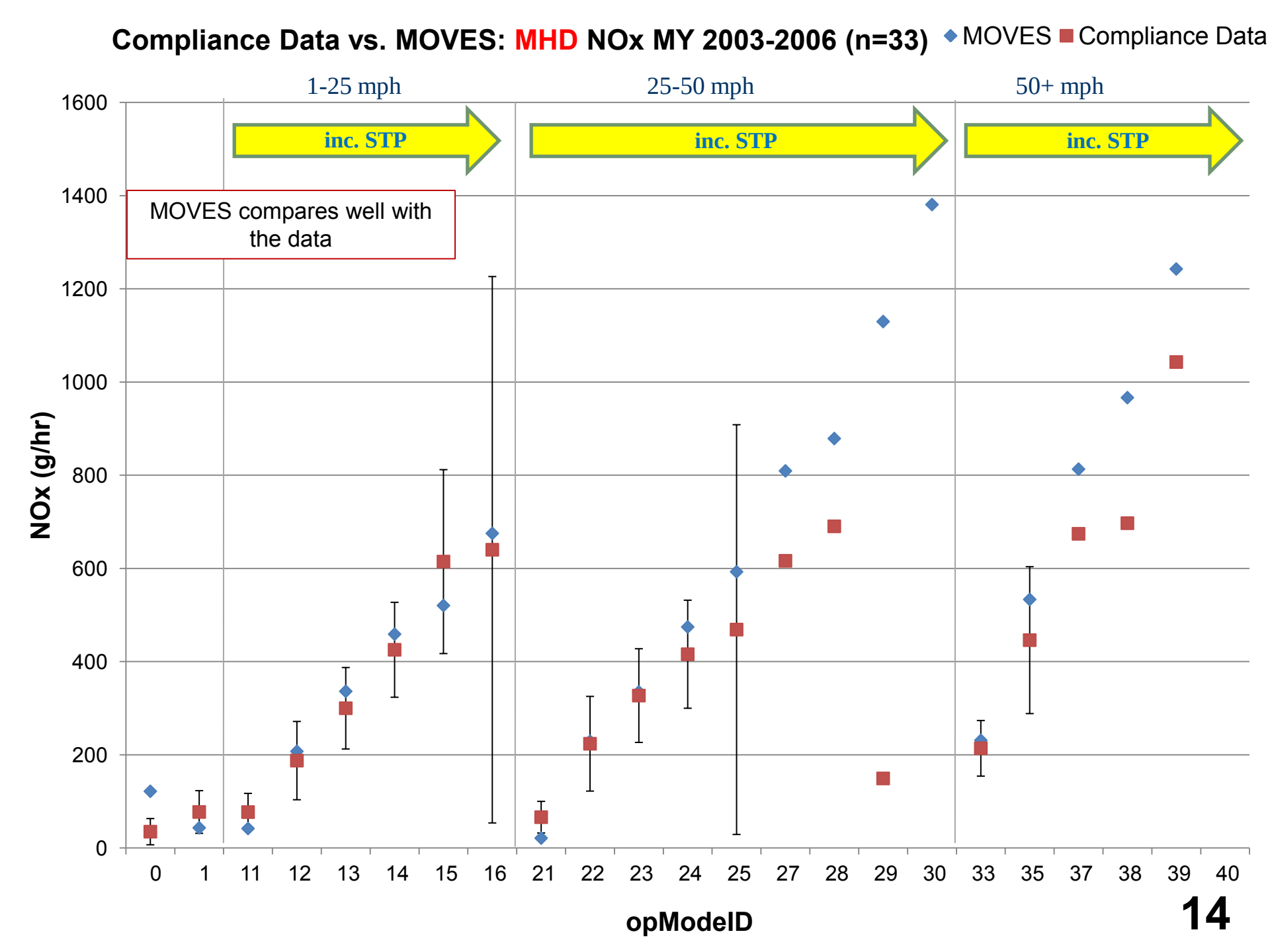
- **Data collected by manufacturers during normal operation and use**
- **Focused on monitoring NTE events**
- **~5 engines tested per family**
- **Within useful life (< 450,000 miles), well-maintained**
- **MY: 2005-2010**
  - Engine families certified using AB & T were excluded from the analysis to allow direct comparison to MOVES rates†

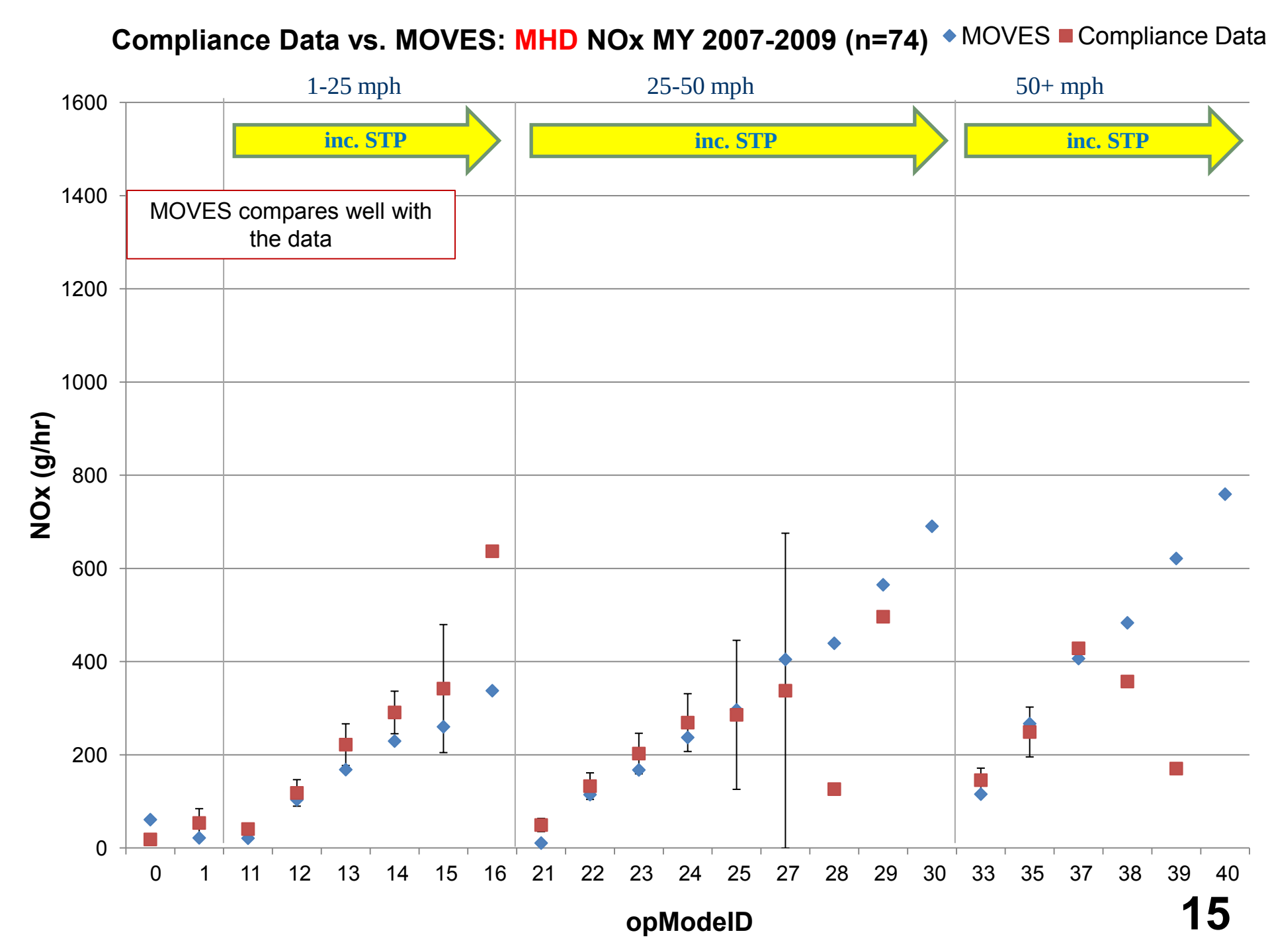
Number of Trucks Analyzed			
MY	**HHD**	**MHD**	**LHD**
2005	35	15	10
2006	25	18	5
2007	21	27	21
2008†	16	10	-
2009†	22	36	4
2010	1	-	-

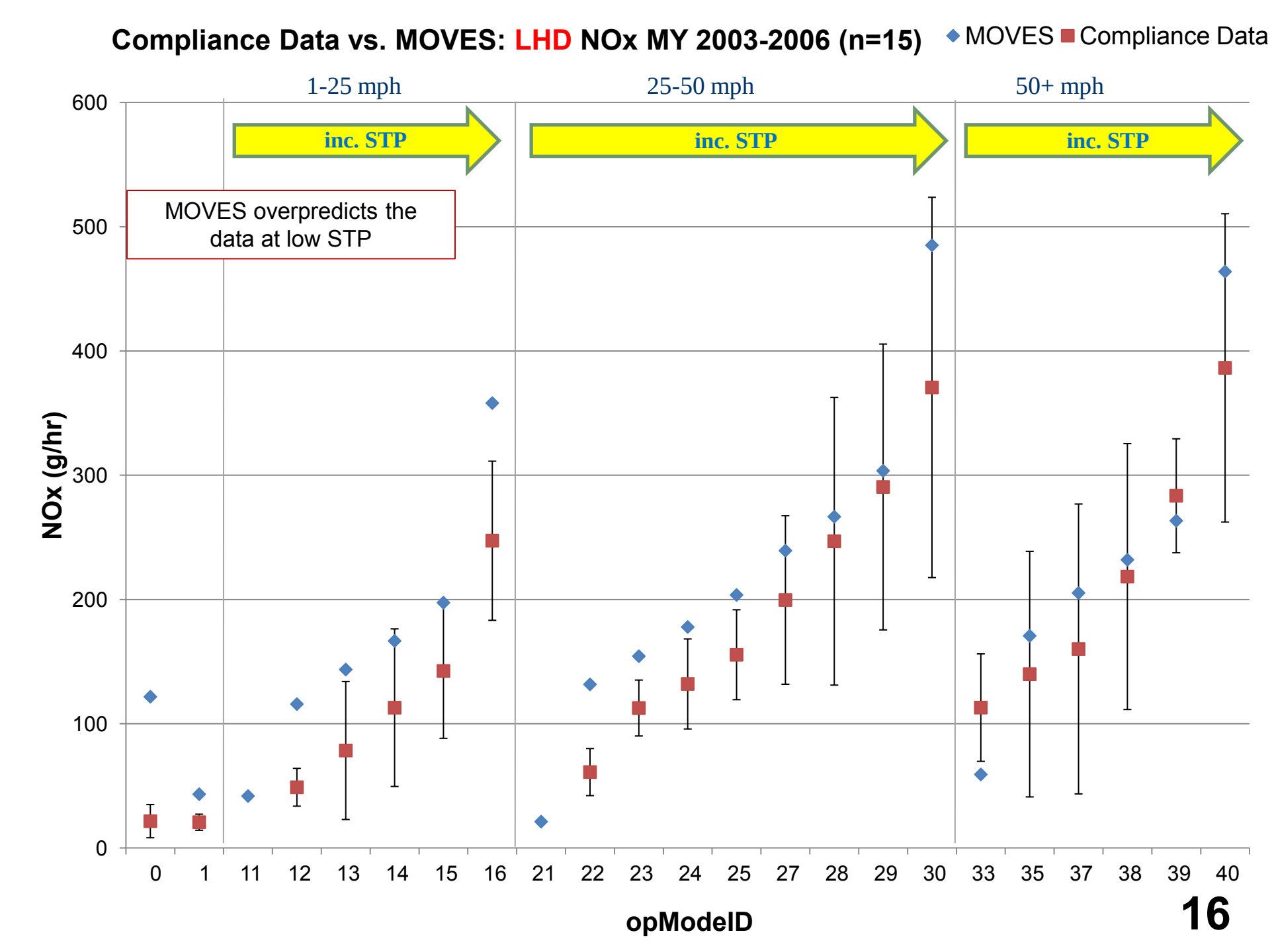

Compliance Data vs. MOVES: HHD NOx MY 2003-2006 (n=60)
MOVES
Compliance Data
1-25 mph
25-50 mph
50+ mph
inc. STP
inc. STP
inc. STP
MOVES slightly underpredicts the compliance data
NOx (g/hr)
opModeID
0
1
11
12
13
14
15
16
21
22
23
24
25
27
28
29
30
33
35
37
38
39
40
0
200
400
600
800
1000
1200
1400
1600
1800

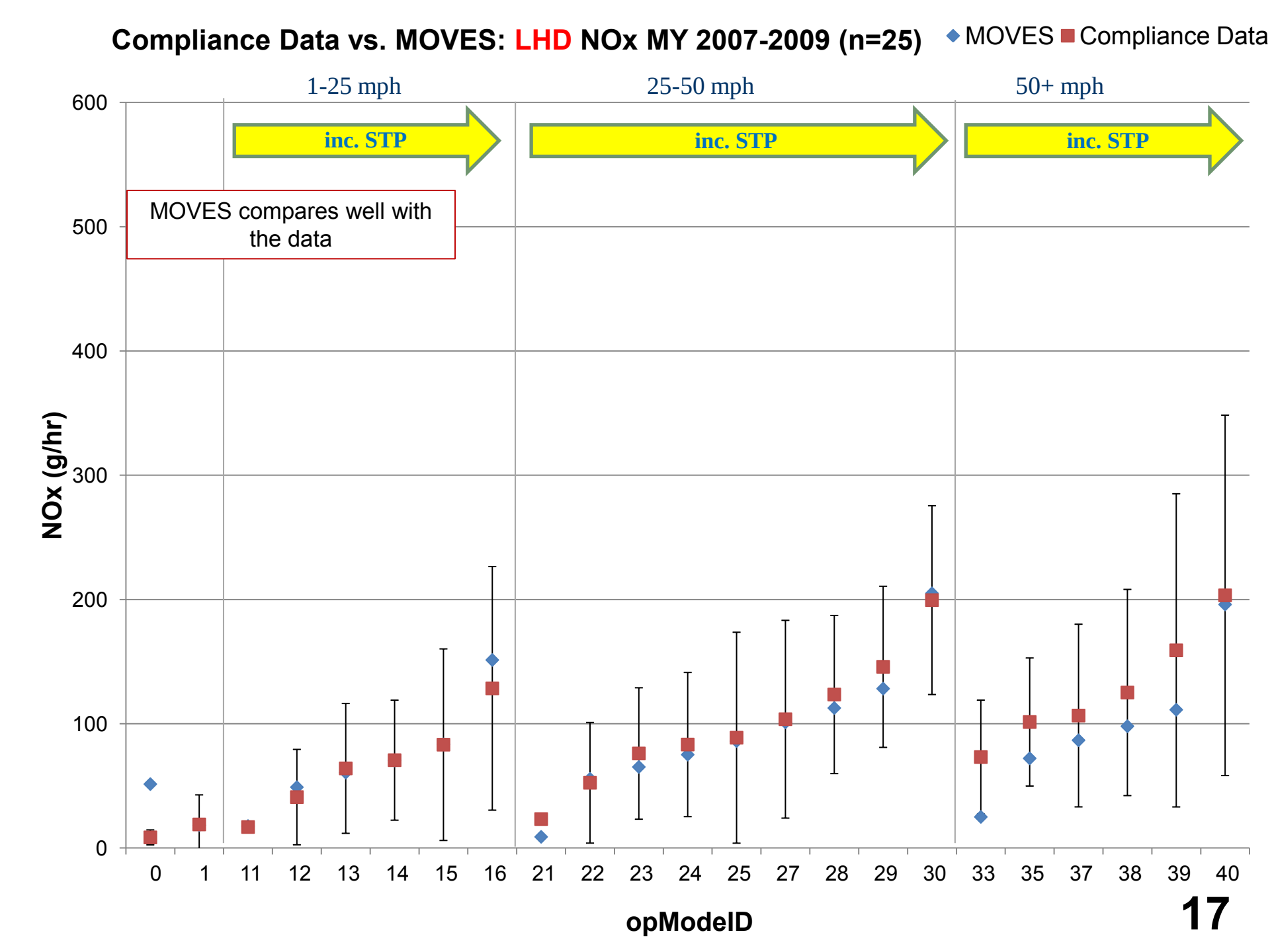

Compliance Data vs. MOVES: HHD NOx MY 2007-2009 (n=59)
MOVES
Compliance Data
1-25 mph
25-50 mph
50+ mph
inc. STP
inc. STP
inc. STP
MOVES underpredicts the compliance data
MOVES rates based on forecasting of standards
NOx (g/hr)
900
800
700
600
500
400
300
200
100
0
0
1
11
12
13
14
15
16
21
22
23
24
25
27
28
29
30
33
35
37
38
39
40
opModeID


Compliance Data vs. MOVES: HHD NOx MY 2010+ (n=1)
MOVES
Compliance Data
1-25 mph
25-50 mph
50+ mph
inc. STP
inc. STP
inc. STP
MOVES within the variability of the data
NOTE: only a single vehicle
MOVES rates based on forecasting of standards
NOx (g/hr)
350
300
250
200
150
100
50
0
0
1
11
12
13
14
15
16
21
22
23
24
25
27
28
29
30
33
35
37
38
39
40
opModeID


Compliance Data vs. MOVES: MHD NOx MY 2003-2006 (n=33)
MOVES
Compliance Data
1-25 mph
25-50 mph
50+ mph
inc. STP
inc. STP
inc. STP
MOVES compares well with the data
NOx (g/hr)
1600
1400
1200
1000
800
600
400
200
0
0
1
11
12
13
14
15
16
21
22
23
24
25
27
28
29
30
33
35
37
38
39
40
opModelID


Compliance Data vs. MOVES: MHD NOx MY 2007-2009 (n=74)
MOVES
Compliance Data
1-25 mph
25-50 mph
50+ mph
inc. STP
inc. STP
inc. STP
MOVES compares well with the data
NOx (g/hr)
1600
1400
1200
1000
800
600
400
200
0
0
1
11
12
13
14
15
16
21
22
23
24
25
27
28
29
30
33
35
37
38
39
40
opModelID


Compliance Data vs. MOVES: LHD NOx MY 2003-2006 (n=15)
MOVES
Compliance Data
1-25 mph
25-50 mph
50+ mph
inc. STP
inc. STP
inc. STP
MOVES overpredicts the data at low STP
NOx (g/hr)
600
500
400
300
200
100
0
0
1
11
12
13
14
15
16
21
22
23
24
25
27
28
29
30
33
35
37
38
39
40
opModeID


Compliance Data vs. MOVES: LHD NOx MY 2007-2009 (n=25)
MOVES
Compliance Data
1-25 mph
25-50 mph
50+ mph
inc. STP
inc. STP
inc. STP
MOVES compares well with the data
NOx (g/hr)
600
500
400
300
200
100
0
0
1
11
12
13
14
15
16
21
22
23
24
25
27
28
29
30
33
35
37
38
39
40
opModelID

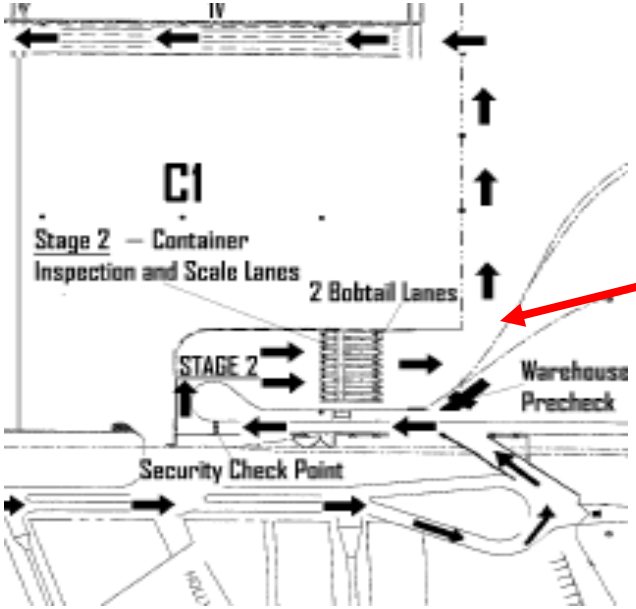
Houston Port Drayage Project

- Collected emissions and activity data on HD drayage trucks (n=36) using PEMS and PAMS in 2009-2010
- Trucks selected for PEMS testing based on remote sensing scores
- Generally higher mileage (> useful life)

Model Year	Number of Trucks with PEMS	
	With RSD measurements	Without RSD measurements
1989 and prior	1	-
1990	-	-
1991-1997	8	2
1998	1	2
1999-2002	10	2
2003-2006	8	2
TOTAL	**28**	**8**

Truck Selection for PEMS testing

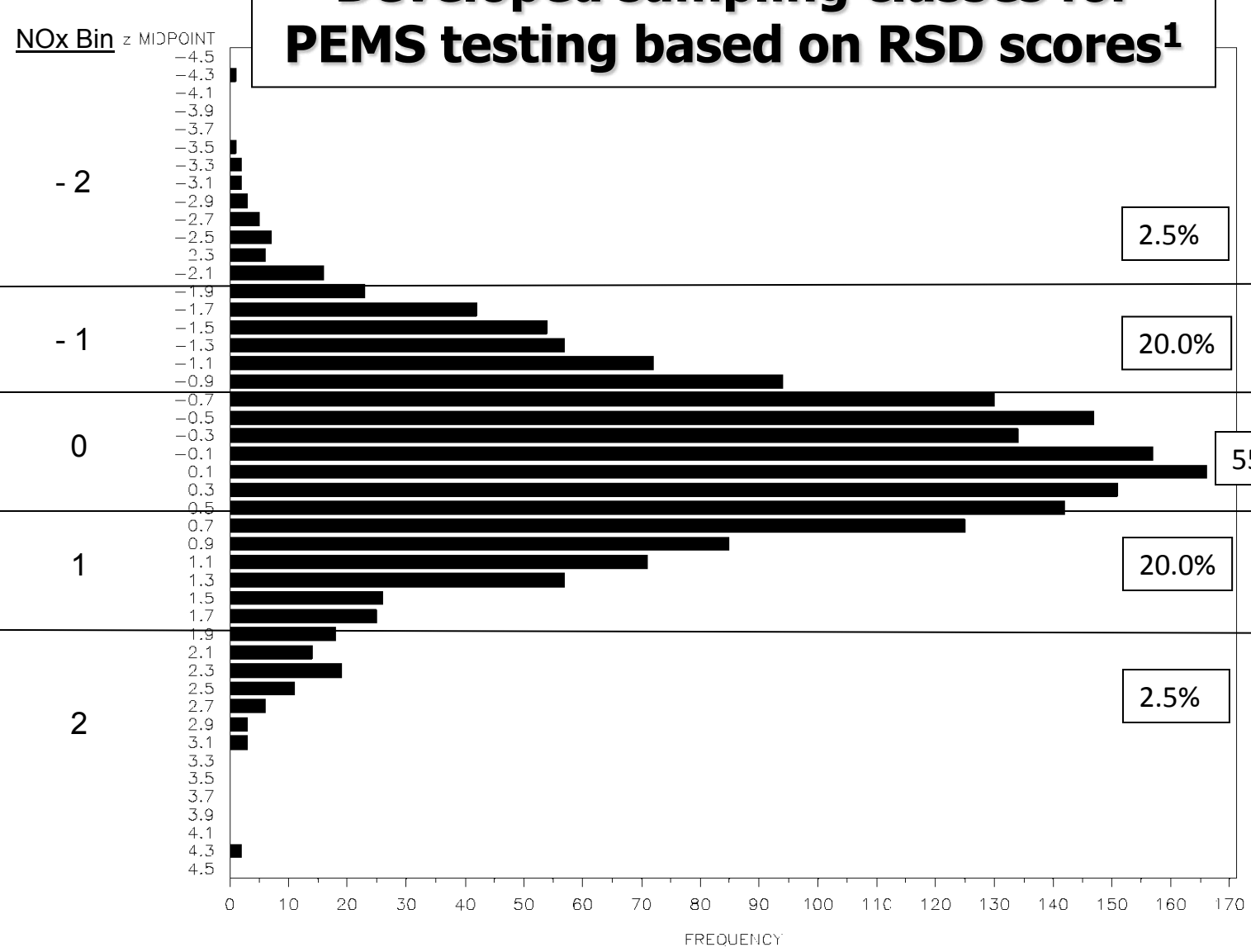
- **RSD Screening**
  - Conducted by University of Denver
  - At entry gate of Barbour's Cut Port
  - Gaseous pollutants: NOx, THC, CO and CO_2
  - Matched license plates to TX DOT database
  - RSD readings: 4,032
  - Unique vehicles: 1,877



Location of RSD equipment

RSD equipment

Developed sampling classes for PEMS testing based on RSD scores[1]



z MIDPOINT	FREQ.	CUM. FREQ.	PCT.	CUM. PCT.
−4.5	0	0	0.00	0.00
−4.3	1	1	0.05	0.05
−4.1	0	1	0.00	0.05
−3.9	0	1	0.00	0.05
−3.7	0	1	0.00	0.05
−3.5	1	2	0.05	0.11
−3.3	2	4	0.11	0.21
−3.1	2	6	0.11	0.32
−2.9	3	9	0.16	0.48
−2.7	5	14	0.27	0.75
−2.5	7	21	0.37	1.12
−2.3	6	27	0.32	1.44
−2.1	16	43	0.85	2.29
−1.9	23	66	1.23	3.52
−1.7	42	108	2.24	5.75
−1.5	54	162	2.88	8.63
−1.3	57	219	3.04	11.67
−1.1	72	291	3.84	15.50
−0.9	94	385	5.01	20.51
−0.7	130	515	6.93	27.44
−0.5	147	662	7.83	35.27
−0.3	134	796	7.14	42.41
−0.1	157	953	8.36	50.77
0.1	166	1119	8.84	59.62
0.3	151	1270	8.04	67.66
0.5	142	1412	7.57	75.23
0.7	125	1537	6.66	81.89
0.9	85	1622	4.53	86.41
1.1	71	1693	3.78	90.20
1.3	57	1750	3.04	93.23
1.5	26	1776	1.39	94.62
1.7	25	1801	1.33	95.95
1.9	18	1819	0.96	96.91
2.1	14	1833	0.75	97.66
2.3	19	1852	1.01	98.67
2.5	11	1863	0.59	99.25
2.7	6	1869	0.32	99.57
2.9	3	1872	0.16	99.73
3.1	3	1875	0.16	99.89
3.3	0	1875	0.00	99.89
3.5	0	1875	0.00	99.89
3.7	0	1875	0.00	99.89
3.9	0	1875	0.00	99.89
4.1	0	1875	0.00	99.89
4.3	2	1877	0.11	100.00
4.5	0	1877	0.00	100.00

[1] "Development of real-world data for MOVES – The Houston Drayage Characterization Study", proceedings from 21st CRC On-Road Vehicle Emissions Workshop, March 2011

Sampling methodology

- **Classification**
  - "stratified sampling"
  - Population divided into separate 'classes' based on RSD NOx emissions and model year groups
  - Each class sampled as an independent sub-population
- **Quota sampling within each class based on**
  - Probability that a vehicle is actually in the assigned NOx Bin
  - Frequency that the vehicle will drive in the Port of Houston during PEMS instrumentation

Population weights

- **Prior to comparing to MOVES, population weights based on RSD NOx readings need to be applied**
- **Why apply the weights?**
  - To correct for 'imperfections' in the sample leading to bias and differences between the sample and reference population
    - To compensate for unequal probabilities of selection
    - To adjust the sample distribution to make it conform to a known population distribution
- **Trucks without RSD measurements excluded from the analysis**

Calculation of population weights

RSD

	NOx Bin					
MYG	-2	-1	0	1	2	TOTAL
Pre-1988	0	3	5	1	0	9
1988-1989	1	4	5	3	0	13
1990	1	3	6	1	0	11
1991-1997	7	47	312	190	27	583
1998	1	16	84	60	6	167
1999-2002	7	193	504	103	10	817
2003-2006	14	90	91	13	4	212
2007-2009	14	20	26	4	0	64
2010+	1	0	0	0	0	1
TOTAL	46	376	1033	375	47	1877

PEMS

	NOx Bin					
MYG	-2	-1	0	1	2	TOTAL
Pre-1988	0	1	0	0	0	1
1988-1989	0	0	0	0	0	0
1990	0	0	0	0	0	0
1991-1997	0	1	3	4	0	8
1998	0	0	1	0	0	1
1999-2002	0	4	6	0	0	10
2003-2006	0	2	3	2	1	8
2007-2009	0	0	0	0	0	0
2010+	0	0	0	0	0	0
TOTAL	0	9	15	7	1	28

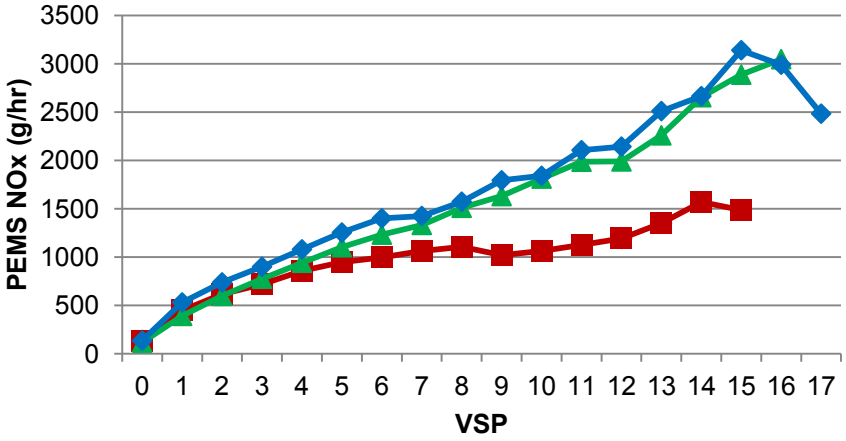
- **Population weights**

$$\pi_k = \frac{N_k / N}{n_k / n}$$

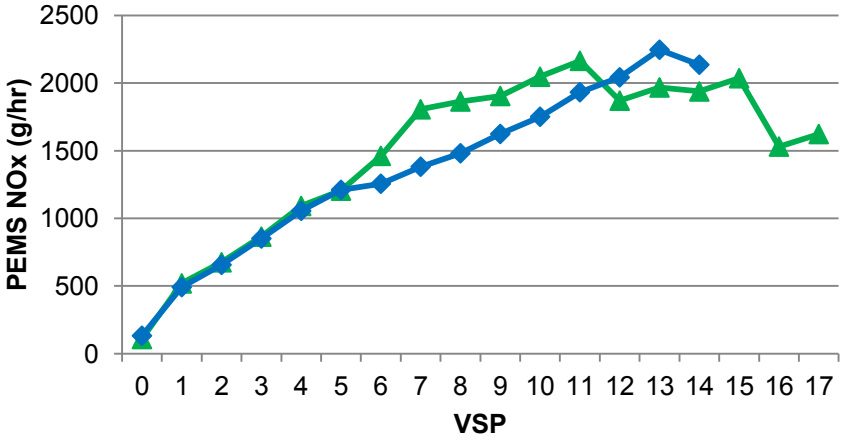
- **Apply proportional weights**
  - Specific to every subdivision of the sample
  - Sampling ratio is homogeneous for each class (k)

PEMS NOx vs. VSP by RSD NOx Bin

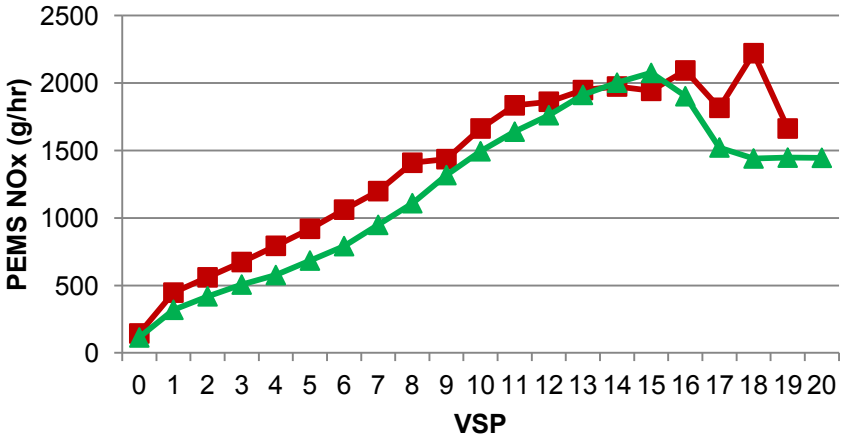
MYG 1991-1997



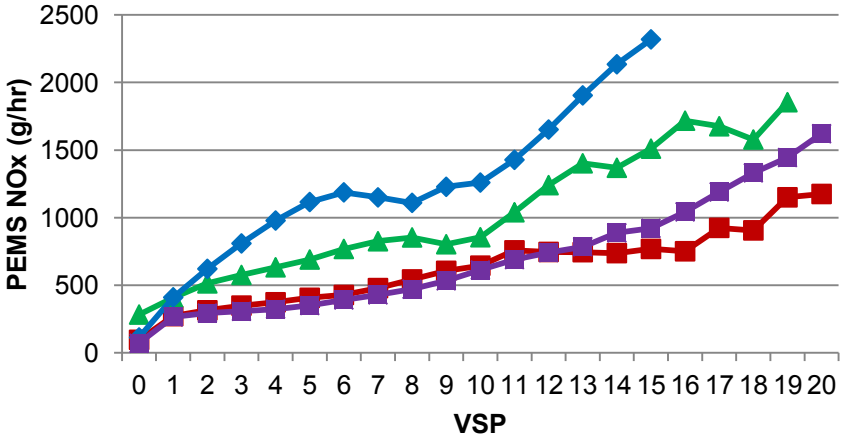
MYG 1998



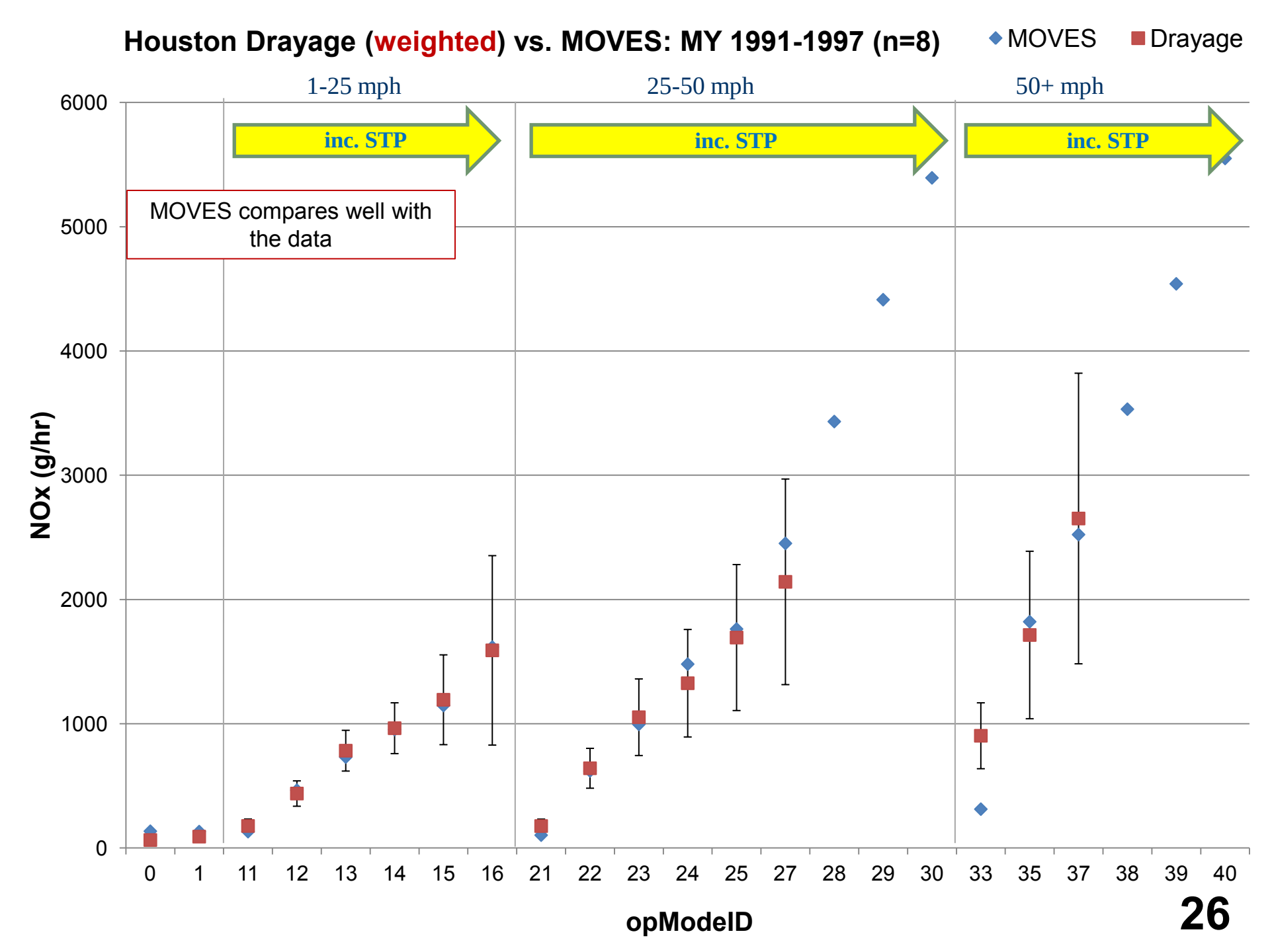
MYG 1999-2002

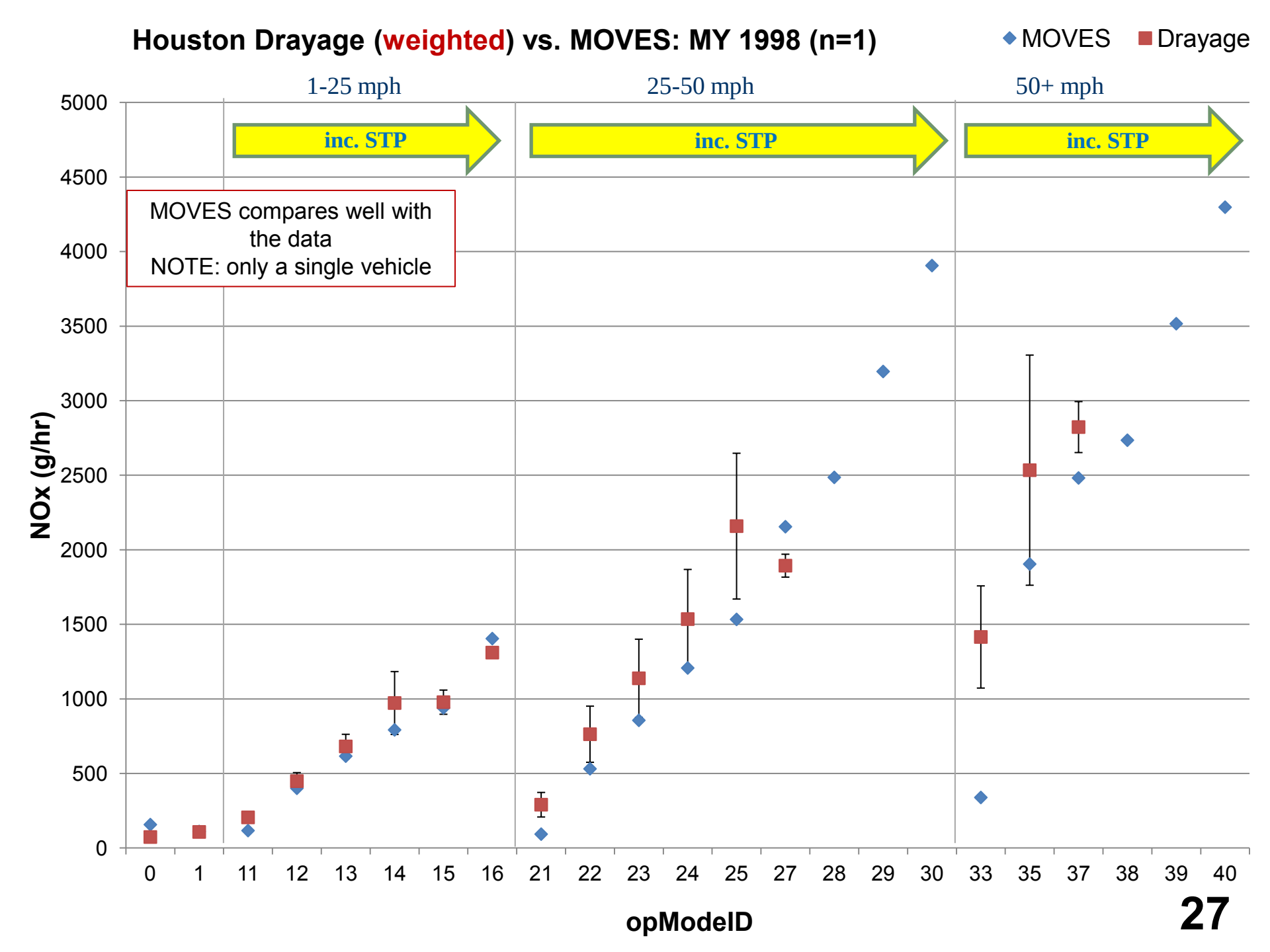


MYG 2003-2006



Bottom line: correlation between RSD readings and PEMS measurements can be improved. Should we still apply the population weights?


Houston Drayage (weighted) vs. MOVES: MY 1991-1997 (n=8)
MOVES
Drayage
1-25 mph
25-50 mph
50+ mph
inc. STP
inc. STP
inc. STP
MOVES compares well with the data
NOx (g/hr)
6000
5000
4000
3000
2000
1000
0
0
1
11
12
13
14
15
16
21
22
23
24
25
27
28
29
30
33
35
37
38
39
40
opModeID


Houston Drayage (weighted) vs. MOVES: MY 1998 (n=1)
MOVES
Drayage
1-25 mph
25-50 mph
50+ mph
inc. STP
inc. STP
inc. STP
MOVES compares well with the data
NOTE: only a single vehicle
NOx (g/hr)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
1
11
12
13
14
15
16
21
22
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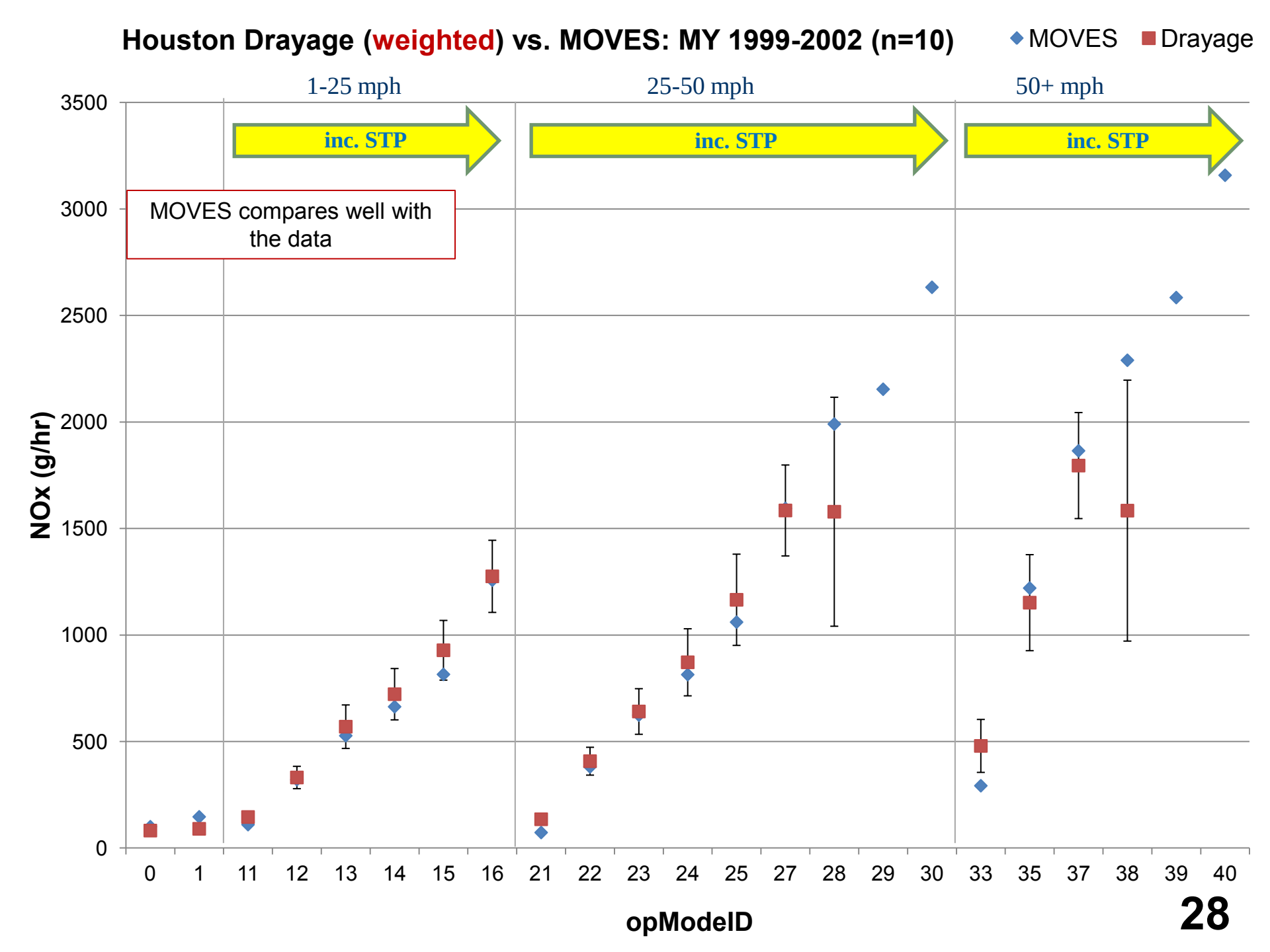
opModelID


Houston Drayage (weighted) vs. MOVES: MY 1999-2002 (n=10)
MOVES
Drayage
1-25 mph
25-50 mph
50+ mph
inc. STP
inc. STP
inc. STP
MOVES compares well with the data
NOx (g/hr)
3500
3000
2500
2000
1500
1000
500
0
0
1
11
12
13
14
15
16
21
22
23
24
25
27
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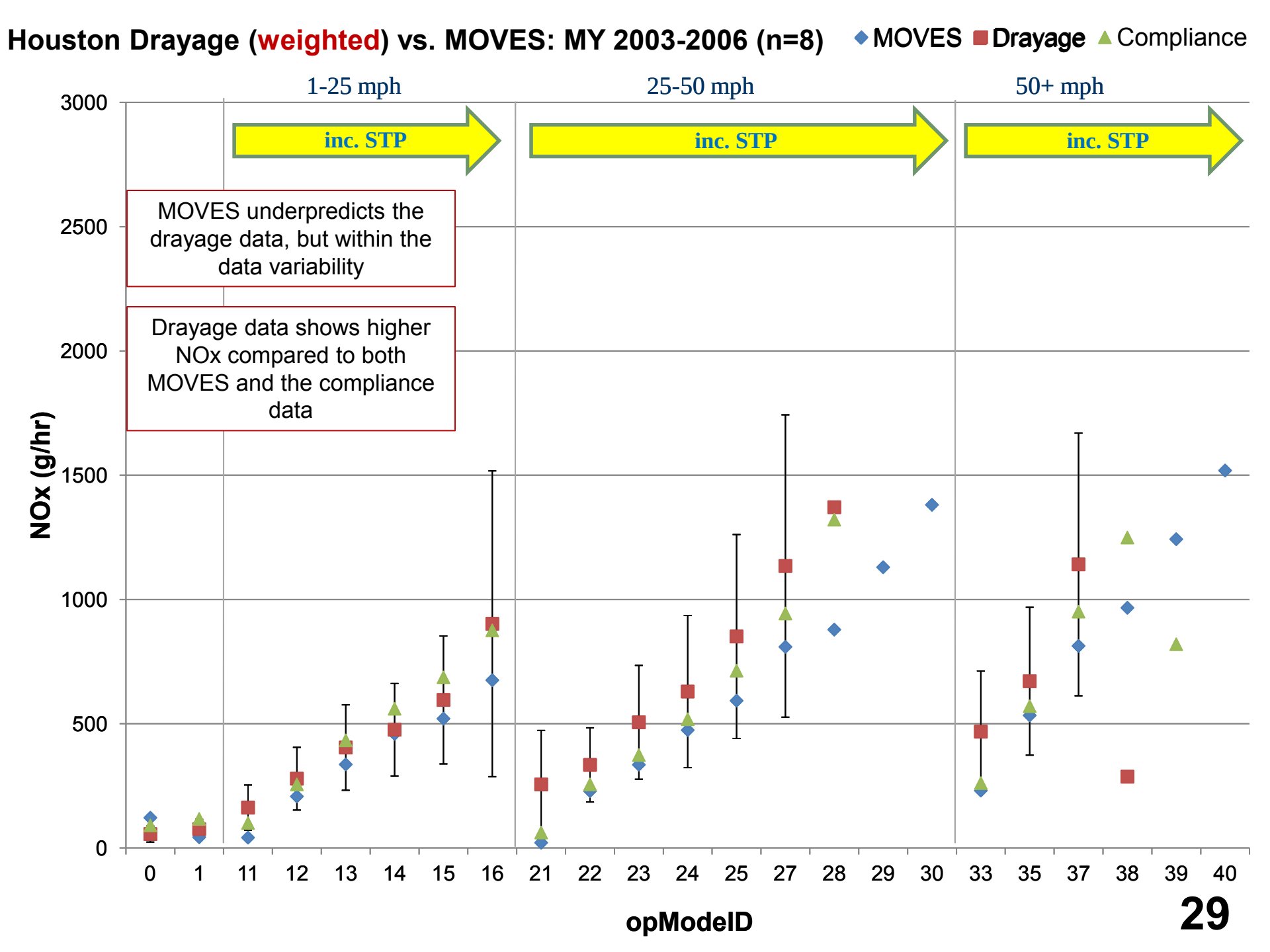
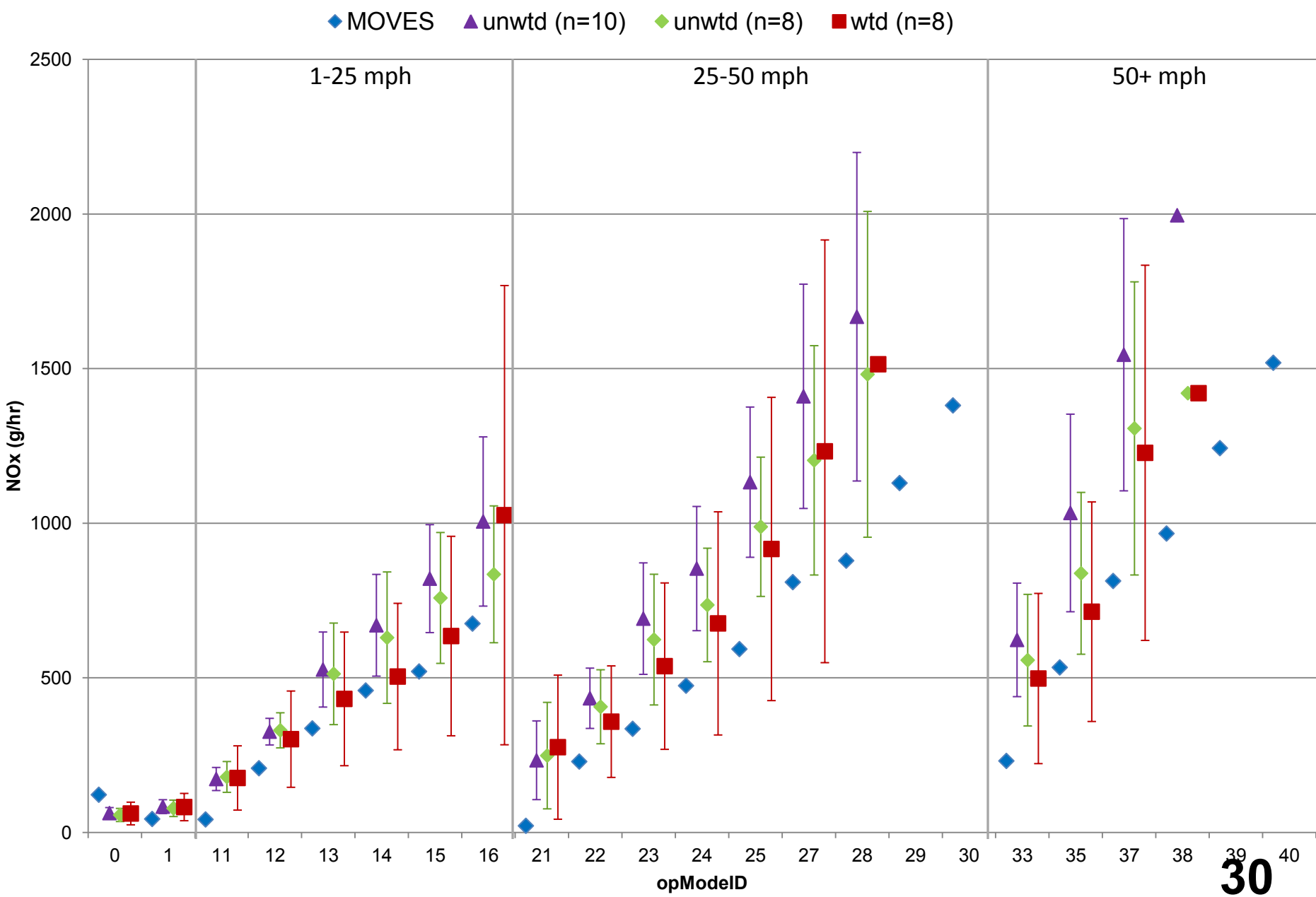
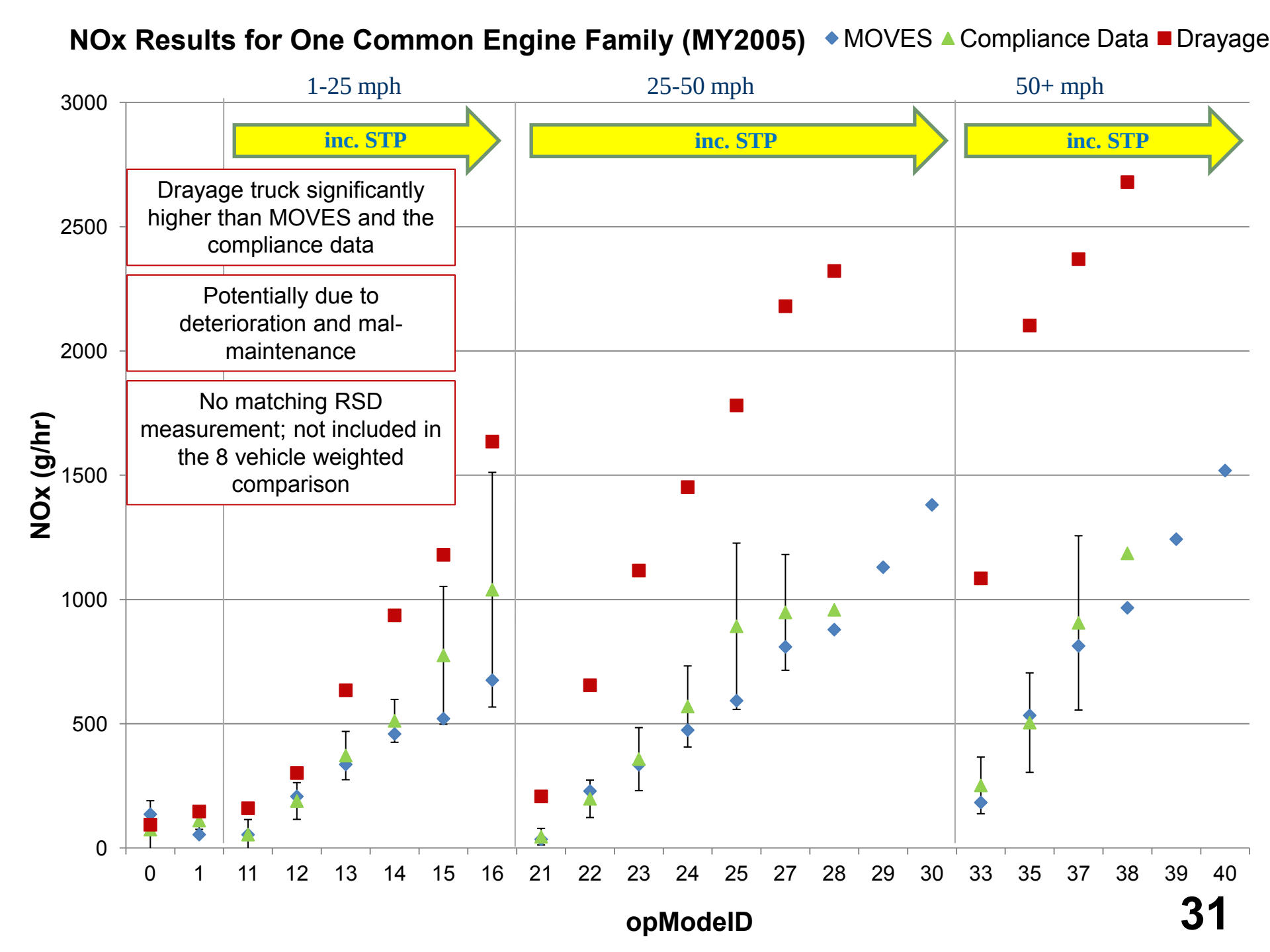
opModelID


Houston Drayage (weighted) vs. MOVES: MY 2003-2006 (n=8)
MOVES
Drayage
Compliance
1-25 mph
25-50 mph
50+ mph
inc. STP
inc. STP
inc. STP
MOVES underpredicts the drayage data, but within the data variability
Drayage data shows higher NOx compared to both MOVES and the compliance data
NOx (g/hr)
3000
2500
2000
1500
1000
500
0
0
1
11
12
13
14
15
16
21
22
23
24
25
27
28
29
30
33
35
37
38
39
40
opModeID

Effect of applying population weights

Houston Drayage vs. MOVES MY 2003-2006

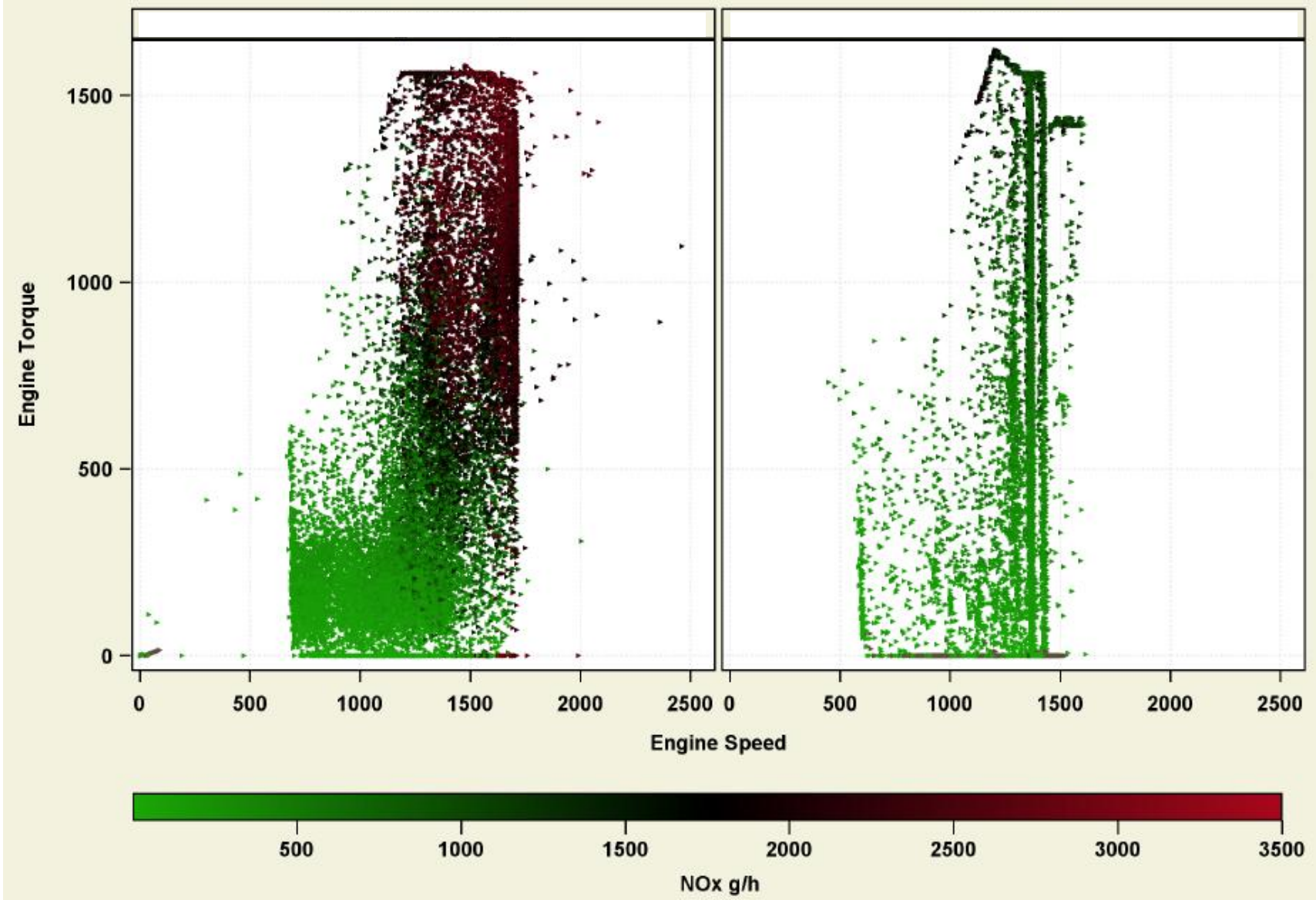



NOx Results for One Common Engine Family (MY2005)
MOVES
Compliance Data
Drayage
1-25 mph
25-50 mph
50+ mph
inc. STP
inc. STP
inc. STP
Drayage truck significantly higher than MOVES and the compliance data
Potentially due to deterioration and mal-maintenance
No matching RSD measurement; not included in the 8 vehicle weighted comparison
NOx (g/hr)
3000
2500
2000
1500
1000
500
0
0
1
11
12
13
14
15
16
21
22
23
24
25
27
28
29
30
33
35
37
38
39
40
opModeID

NOx Maps for Common Engine Family

Houston Drayage
5 yrs old, 750K

Compliance Program
2 yrs old, 350K miles



Summary

- **HHD**
  - Pre-MY2003
    - Drayage compares well with MOVES
    - Applying the population weights does not change the overall picture
    - No proposed update for MOVES2013
  - MYG2003-2006
    - HD compliance shows higher NOx compared to MOVES
    - Different conclusion can be reached for Drayage depending on whether we apply the population weights or not
      - Population-weighted: drayage comparable to MOVES
      - Unweighted: shows significantly higher NOx
      - Works in progress to determine the application of the population weights
    - Issues to resolve if we were to update for MOVES2013
      - How representative is the Houston drayage data compared to the HHD fleet?
      - How to combine/pool different sources of data? (i.e., EPA ROVER, WVU MEMS, HD compliance, and Houston Drayage)

Summary (cont'd)

- **HHD**
  - MYG 2007-2009
    - Propose updating MOVES rates based on HD compliance for MOVES2013
    - Include engines using AB & T by applying sales-weights
  - MYG 2010+
    - May update for MOVES2013 based on the analysis of 2011 HD compliance data, depending on timing
- **MHD**
  - HD compliance compares well with MOVES for both MYG2003-2006 and 2007-2009
- **LHD**
  - HD compliance shows lower NOx compared to MOVES for MYG2003-2006
  - HD compliance compares well for MYG2007-2009

Next Steps

- **HD compliance data**
  - Analyze “2011” data when it becomes available (Dec. 2012)
  - Significant number of MY2010+ trucks with more stringent standards (0.2 g/bhp-hr) expected
- **Houston Drayage**
  - Finalize NOx comparison for MYG2003-2006 considering the issue with applying the population weights
  - Analyze filter-based PM measurements
  - Construct PM time-series by estimating activity behind each filter and compare to MOVES by operating modes

MOVES

EPA

Questions?

Appendix

- **Number of vehicles by model year group from the EPA ROVER and WVU MEMS programs used for MOVES emission rates***

Regulatory class	1991-1997 MY	1998 MY	1999-2002 MY	2003-2006 MY
HHD	19	12	78	91
MHD	0	0	30	32
BUS	2	0	25	19

* Development of Emission Rates for Heavy-Duty Vehicles in the Motor Vehicle Emissions Simulator MOVES2010 Final Report, August 2012