# MOVES Validation Efforts To Date

FACA MOVES Review Workgroup Meeting
July 31, 2012

David Choi
John Koupal
U.S. EPA Office of Transportation & Air Quality


# Acknowledgements


- **Michael Rodgers (Georgia Tech University)**
- **Don Stedman, Gary Bishop (University of Denver)**
- **Coordinating Research Council (E-23, E-55/59, E-69)**
- **Phil Heirigs (Chevron)**
- **Robert Crawford (Rincon Ranch Consulting)**
- **Kenneth Reader (Senior Services of America, Inc)**
- **Sri Harsha Kota (Texas A&M University)**
- **Eastern Research Group**
  - Gopi Manne, Rick Baker, Diane Preusse, Scott Fincher, Sandeep Kishan, Tim DeFries, Mike Sabisch
- **Texas Commission of Environmental Quality (TCEQ)**
  - Doug Boyer, Chris Kite
- **EPA Office of Air Quality Planning & Standards**
  - Heather Simon, Sharon Phillips, Alison Eyth

# Introduction

- **Ongoing validation has been an important element of MOVES design and implementation**
  - Key recommendation from National Research Council
- **EPA's validation work on MOVES began with MOVES2004, focused on fuel consumption**
  - *"MOVES2004 Validation Results", U.S EPA 2005*
- **Validation of criteria pollutant version (MOVES2010a) has evaluated model performance using several methods…work is ongoing**
- **Goal is to inform improvements to next version, and identify data gaps**

# What is the objective?

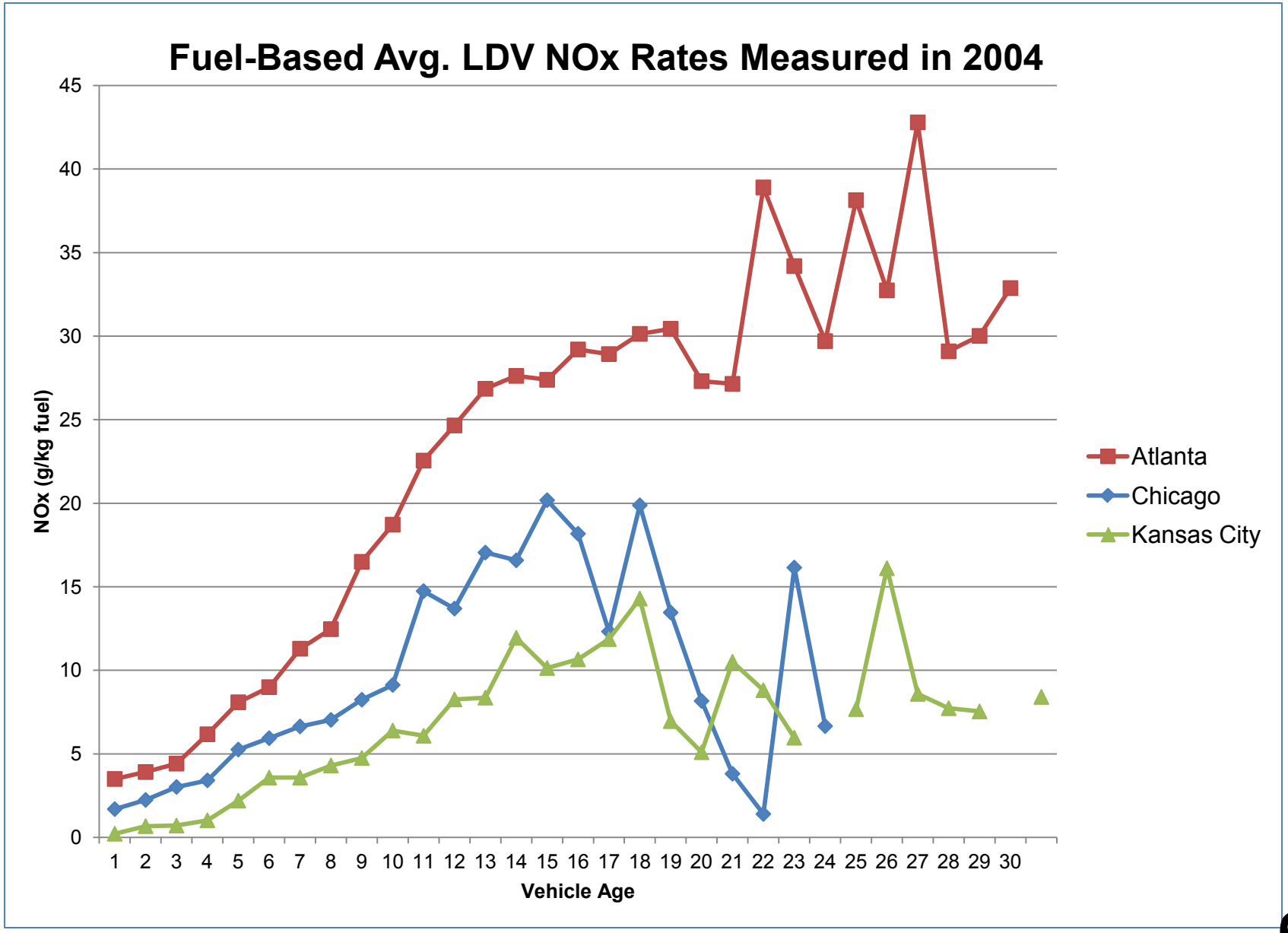
- **Oreskes, et. al (1998): No model can never be truly "validated", i.e. verified as true**
  - We will never know "the truth" (or wouldn't need a model)
    - Nicholson (1992): "You can't handle the truth!"
  - Instead, define "means of evaluation", considering how the model is applied
- **From Michael Rodgers (Georgia Tech):**

  *"model validation" for a complex modeling system such as MOVES is really more a case of evaluating how well it performs against certain metrics rather than validating the model as a whole. (email to J. Koupal 7/20/12)*

# Means of Evaluation

- **Compare model predictions to independent measurements**
  - recognizing limitations and uncertainties in the independent measurements
- **Evaluate predictions of relative trends as well as absolute emissions**
  - SIP, Conformity, and EPA regulatory analyses focus on prediction of emission changes due to time, controls, and/or activity
- **Evaluation of absolute emissions:**
  - Compare MOVES predictions to independent measurements, assess whether *trends in bias* appear across multiple sources.
  - Assess air quality model vs. monitor performance when MOVES is used as source of on-road emissions
- **Evaluation of relative trends:**
  - Compare Δ in MOVES predictions over time vs. observations
  - Compare MOVES sensitivity to operation vs. independent data

# Example of variability in independent data



# Scope of Evaluation

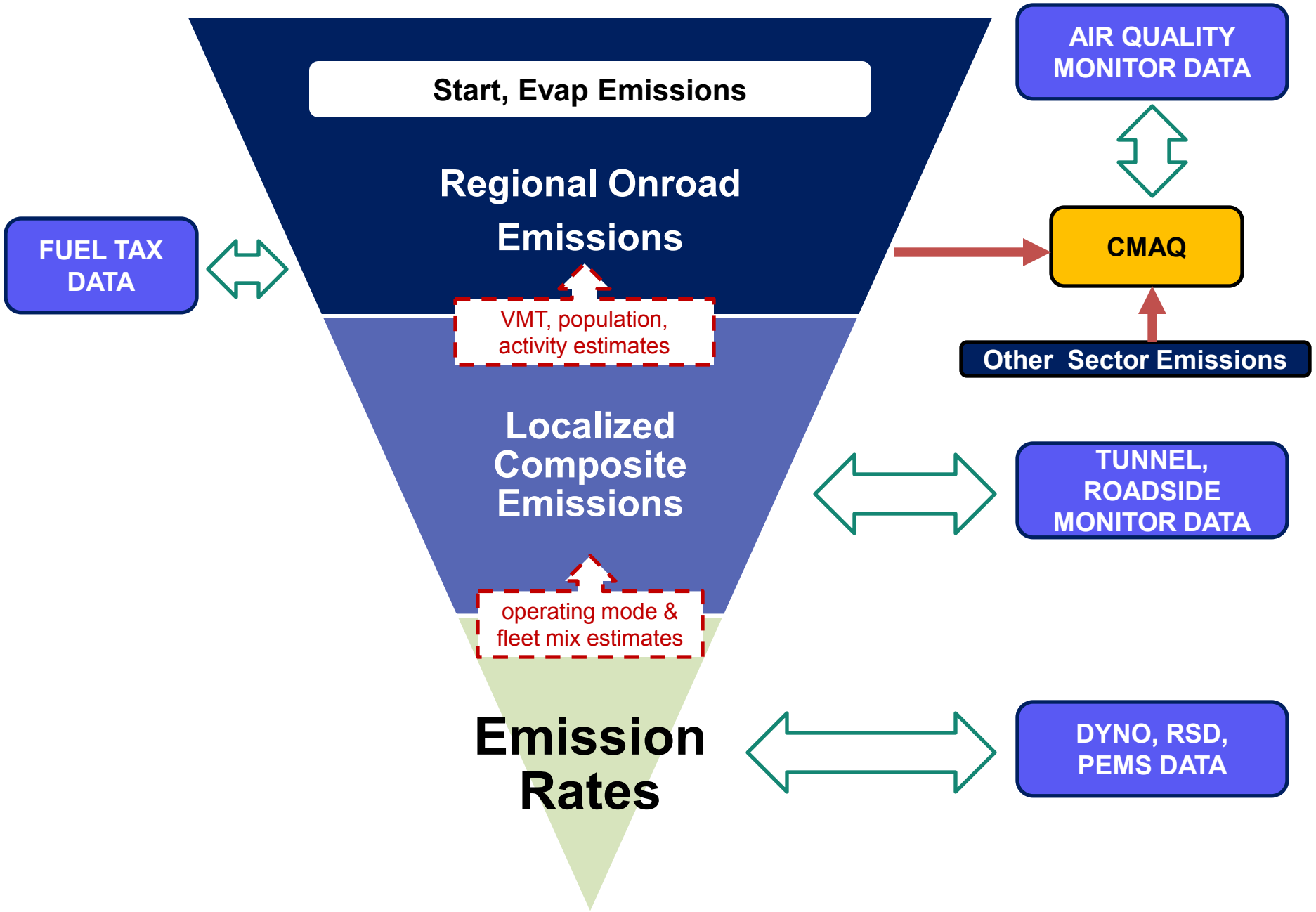
- **"MOVES" is hundreds of submodels**
  - Each pollutant, emission process, vehicle type, etc. is a model
  - Activity components can be considered models as well
- **Evaluation of each submodel not practical**
  - In many cases there is little or no independent data available for evaluation – i.e. for certain submodels, used all data we could find
- **Priorities for evaluation have gravitated towards:**
  - Major emissions sources (e.g., LD gas, HD diesel)
  - Areas of significant update from MOBILE to MOVES
  - Areas where significant independent data / studies available
- **In some cases, important submodels lack ample independent data for evaluation**
  - e.g., Light-duty gasoline start emissions

# Pet Peeves From Validation Efforts We've Seen In Literature

- **Application of MOVES beyond quantification limits**
  - MOVES not designed to predict emissions from an individual vehicle, and/or second-by-second emissions
- **Not sufficiently customizing MOVES inputs to match measurement conditions**
  - Evaluation of MOVES requires matching the fleet and activity observed under those conditions
- **Tunnel Studies ≠ Regional Air Quality**
  - In one study, we estimated that tunnel conditions represent < 2% of emission modes contributing to regional VOC

# Methods used to evaluate MOVES2010a predictions

- **Emission rates**
  - Compare emissions measurements made on individual vehicles under known operating conditions to MOVES predictions under those conditions
- **"Localized composite" emissions**
  - Compare composite emission measurement from tunnel or roadside emission monitors to MOVES predictions at these locations
- **Regional air quality**
  - Evaluation of air quality model results (CMAQ) vs. air quality monitor data
- **National fuel consumption**
  - Comparison of "bottom-up" fuel consumption to "top down" fuel tax data on national level


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

# Overview of Evaluation Studies

**evaluation work conducted by EPA/OTAQ unless otherwise noted**

| Type | Completed | | In Progress | Planned |
|---|---|---|---|---|
| Emission Rates | **Light Duty**<br>Atlanta RSD<br>CRC E-23 Chicago RSD<br>Chicago I/M Dyno<br>Kansas City Study Dyno<br>NCSU PEMS (NC State) | **Heavy Duty**<br>CRC E-55 Dyno<br>Compliance PEMS | CNG Buses<br>Houston Drayage<br>LD Cold Temp | LD Tier 2 PEMS |
| Localized Composite | Caldecott Tunnel - range analysis<br>Van Nuys Tunnel (Fujita, et. al)<br>Borman Expressway | | | Caldecott Tunnel - parameterized |
| Air Quality | CMAQ Evaluation for HD GHG Rule (EPA/OAQPS)<br>CMAQ Evaluation MOBILE vs. MOVES (OAQPS)<br>Dallas-Fort Worth SIP (TCEQ)<br>Houston (Texas A&M) | | CRC A-76 (CRC/Environ) | Ongoing CMAQ evaluation (OAQPS) |
| Fuel | FHWA Fuel Sales 2000-2007 | | | FHWA 2008+ |

# Emission Rate Evaluation: Light-Duty

- **Sources of independent data**
  - Dynamometer (complete emission tests)
    - Chicago I/M (2000): ~74,000 tests on IM240 cycle (moderate)
    - E-69 Kansas City Program (2004-05): ~450 tests on LA92 (more aggressive)
  - Remote Sensing (1 second readings, or "hits") – aka RSD
    - E-23 Chicago (2004): ~9,000 hits at low/moderate acceleration
    - Atlanta (2004 & 2008): ~ 150,000 hits at more aggressive acceleration
  - Portable Emissions Measurement System (PEMS)
    - Bin Liu and Chris Frey. "Comparison of Trends in MOVES and Real-World Emission Factors for Driving Cycles, Vehicle Age, and Road Type", proceedings from 22nd CRC Real World Emissions Workshop, March 26, 2012
- **Comparing to MOVES**
  - MOVES2010a run with age distribution, operating mode distribution and meteorology to match each independent data source
  - Fuel specs and I/M program from MOVES county defaults
  - Fuel-specific rates (gram/kg fuel) based on MOVES total energy output
  - Gasoline Light-Duty Cars and Trucks (SCC output)
  - Running NOx, CO, and (dyno only) HC

# RSD measurement conversion

- **Conc. of pollutant to fuel specific rates (g/kg fuel)**

$$\frac{\left(\frac{[\text{pollutant}]}{[CO_2]}\right)}{\left(\frac{[CO]}{[CO_2]}\right)+\left(\frac{[CO_2]}{[CO_2]}\right)+6\times2\times\left(\frac{[HC]}{[CO_2]}\right)}\times\frac{MW\left(\frac{g}{mole}\right)}{0.014\left(\frac{kg\ fuel}{mole}\right)}$$

*

  - Atlanta – HC reported as hexane equivalents
  - Chicago & KC – HC reported as propane equivalents

* On-road Remote Sensing of Automobile Emissions in the Denver Area: Year 6, January 2007. G. Bishop and D. Stedman

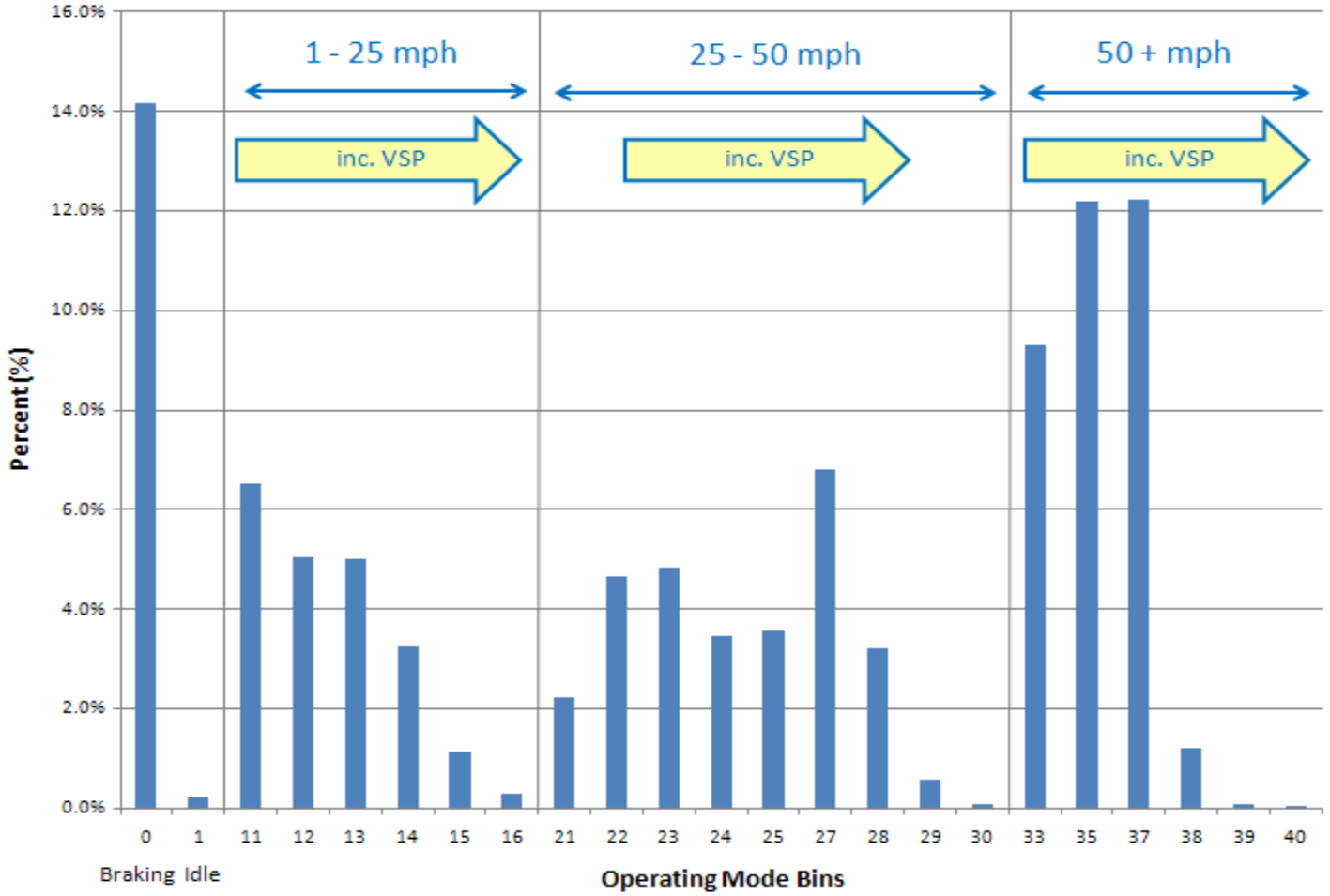
# MOVES conversion

- **Pollutant mass to fuel specific rates (g/kg fuel)**

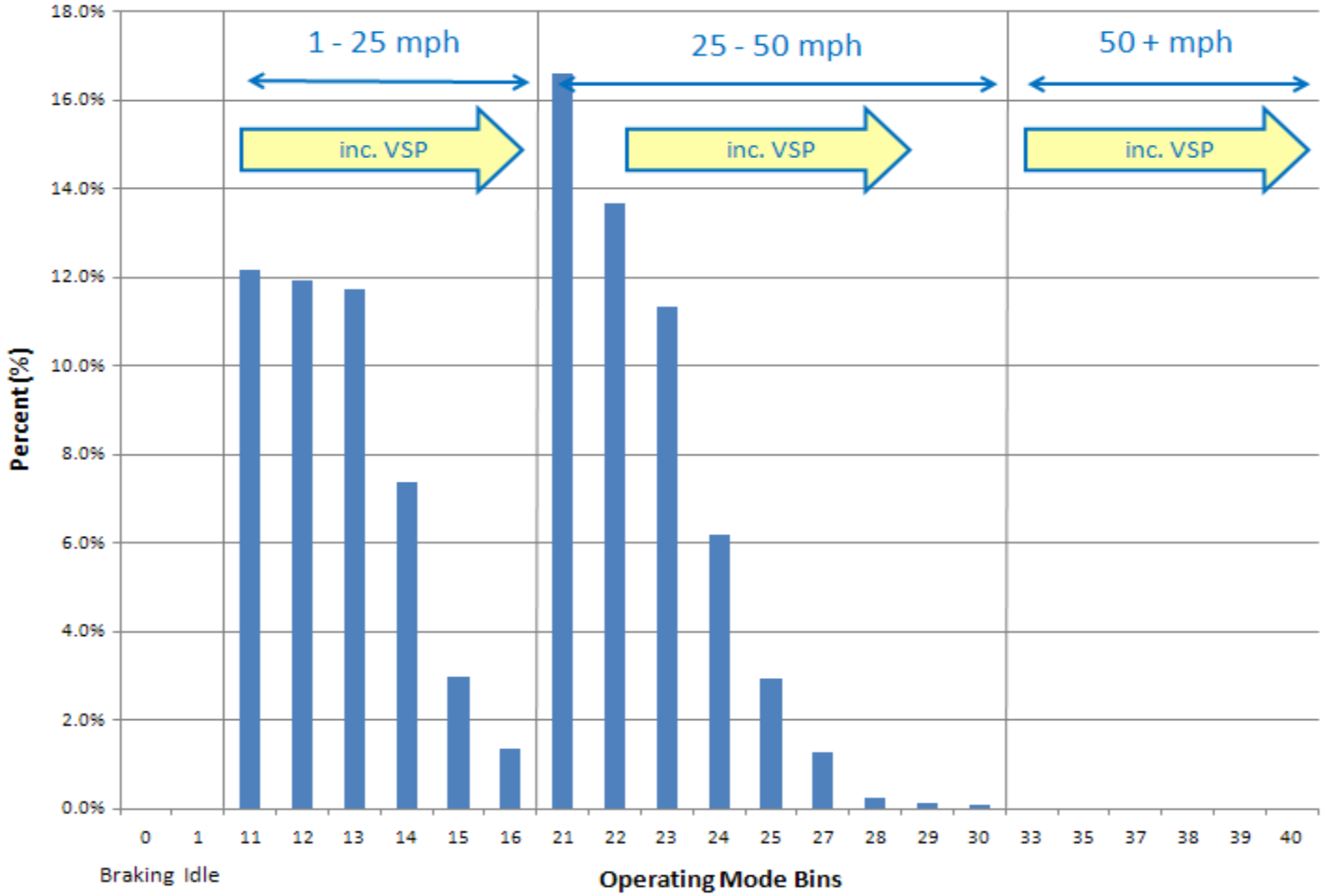
$$\frac{pollutant\ mass\ (g)}{Fuel\ Consumption\ (kg\ fuel)} = \frac{pollutant\ mass\ (g)}{\frac{Total\ Energy\ Consumption}{Heating\ Value}}$$

$$where\ Heating\ Value = 44.0\ \frac{kJ}{g\ fuel}$$

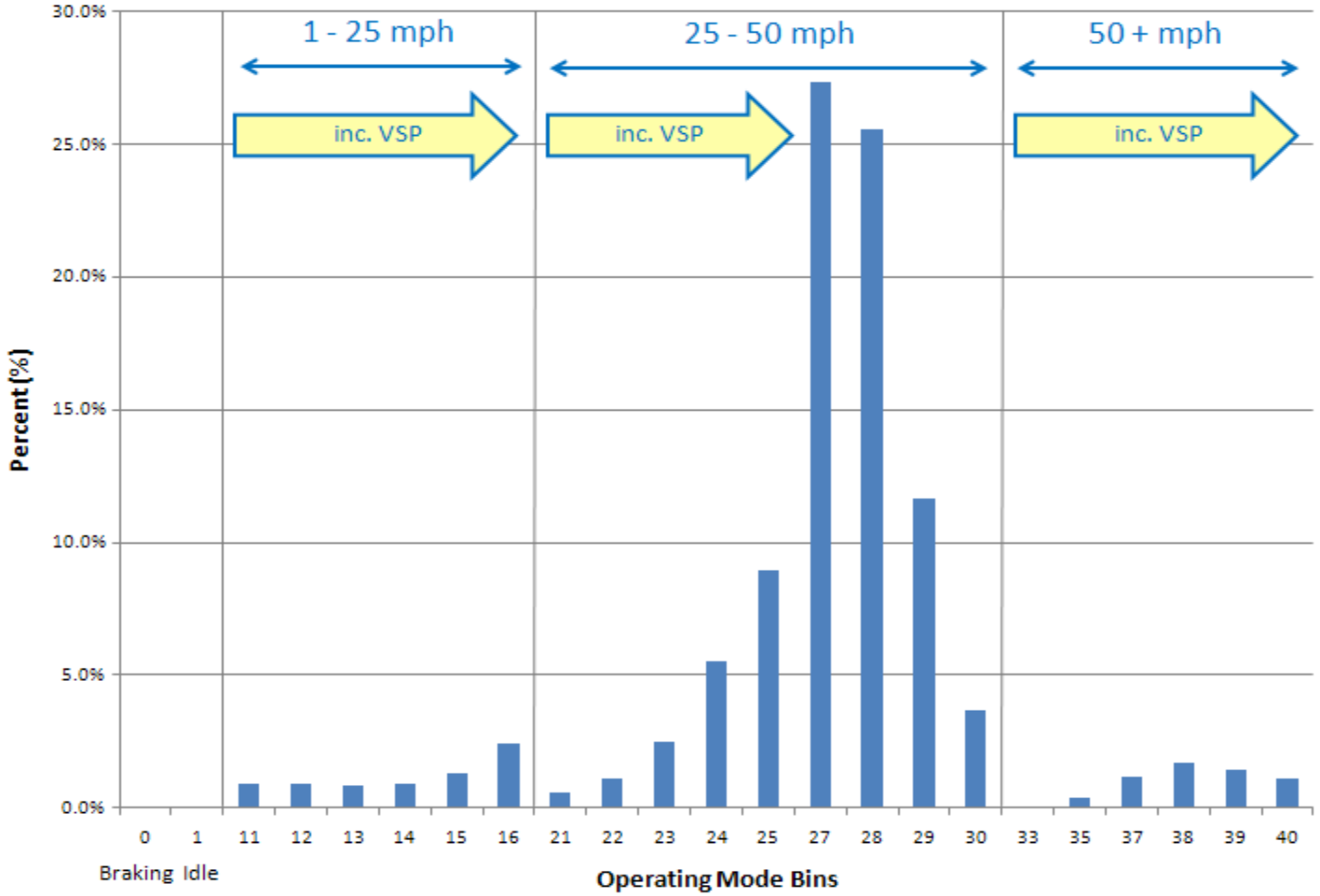
# Chicago I/M
# Opmode Distribution



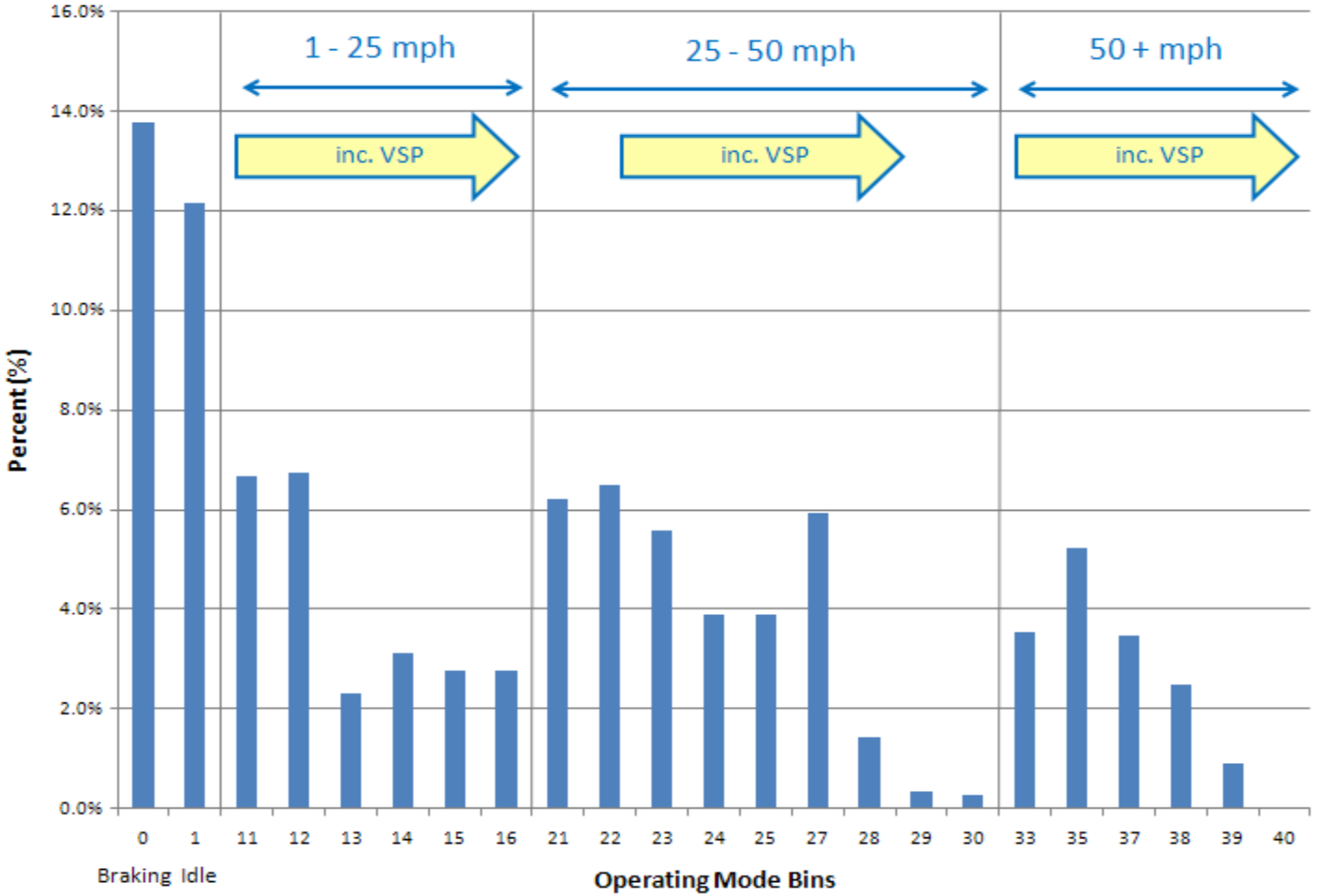
# Chicago RSD Opmode Distribution



# Atlanta RSD
# Opmode Distribution



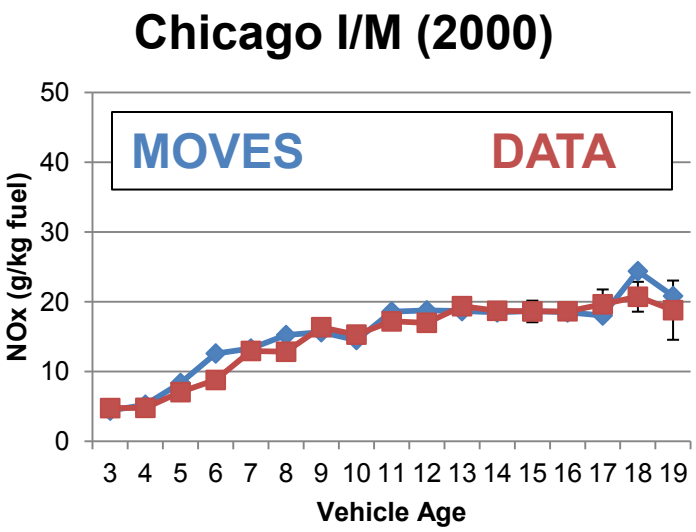
# Kansas City Dyno Opmode Distribution

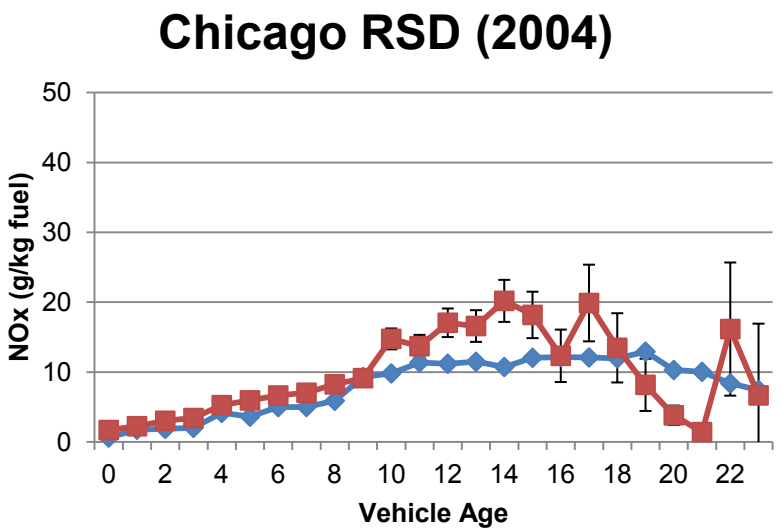


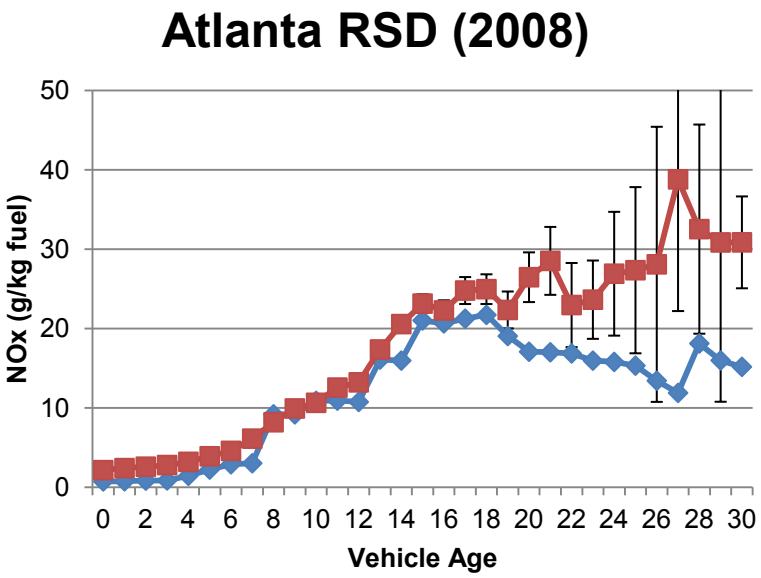
# Limitations

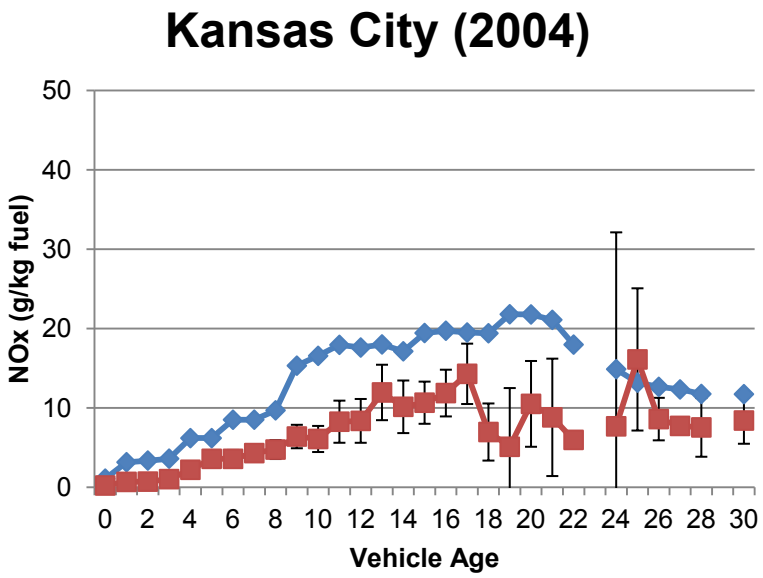
- **Representativeness of independent data**
  - Single measurement characterizes the vehicle's emission profile
  - Obtained measurements define the vehicle population and are assumed to be representative
- **Comparison made in fuel-based emission rates**
  - Potential differences between MOVES estimation of fuel consumption and actual fuel consumption measured in each dataset
  - Differences in fuel properties such as sulfur level, and RVP
- **Operating mode bin misclassification**
  - For RSD measurements, assignment into opmode bins based on VSP calculations already included in the data
  - MOVES' calculation and data-specific calculation of VSP may be different
- **Composition of light-duty truck classes**

# Emission Rate Evaluation: LDV NOx



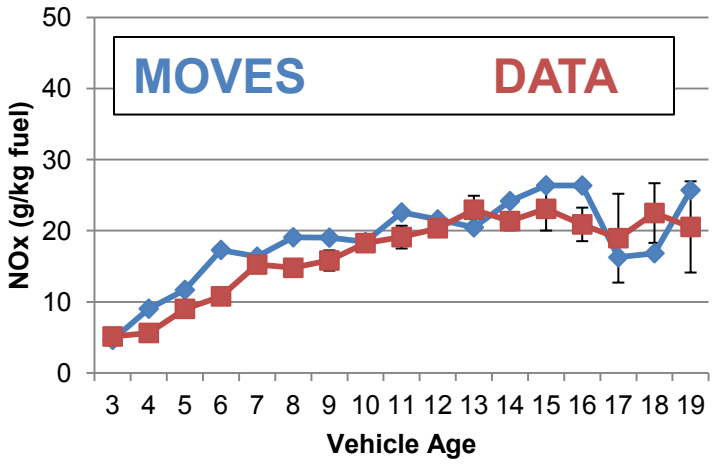



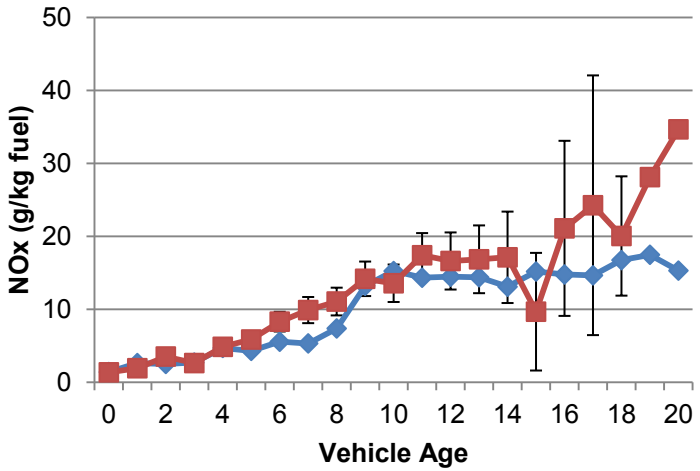



# Emission Rate Evaluation: LDT NOx

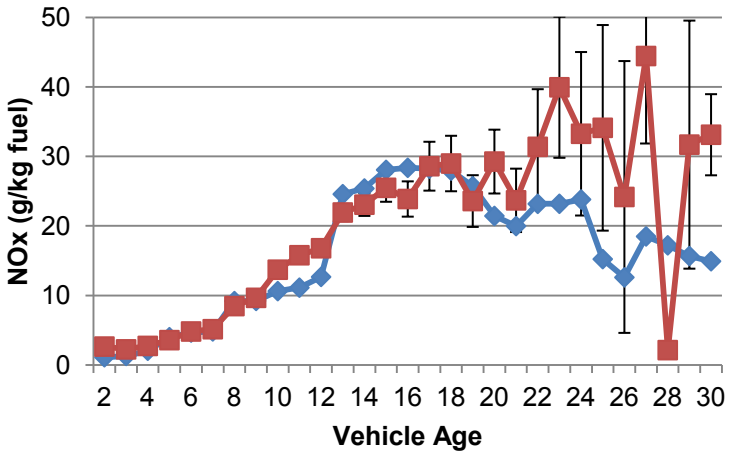
## Chicago I/M (2000)



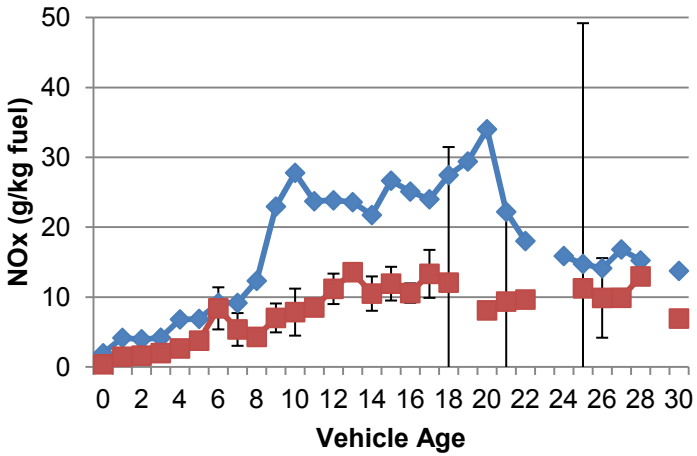

## Chicago RSD (2004)



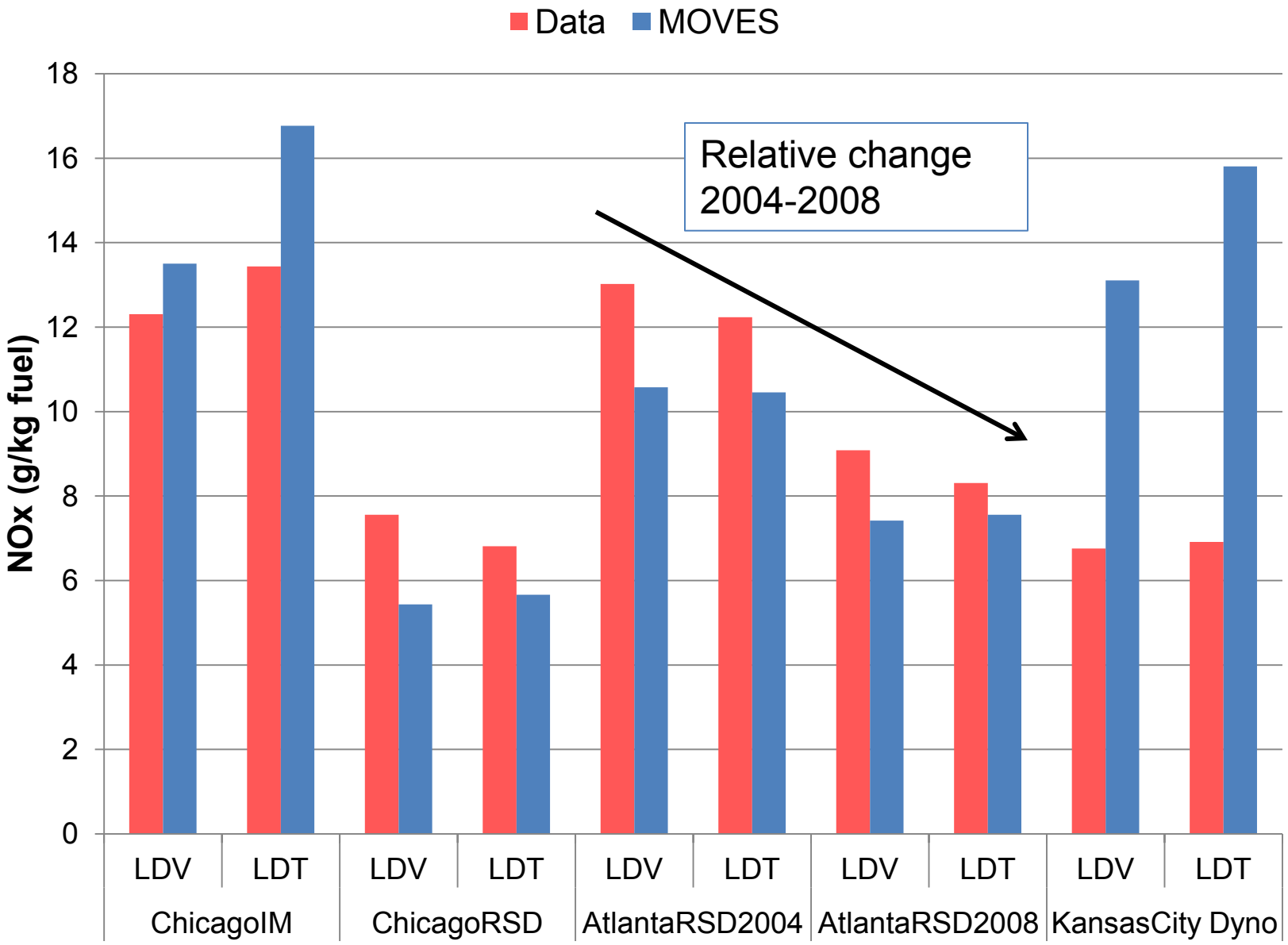

## Atlanta RSD (2008)



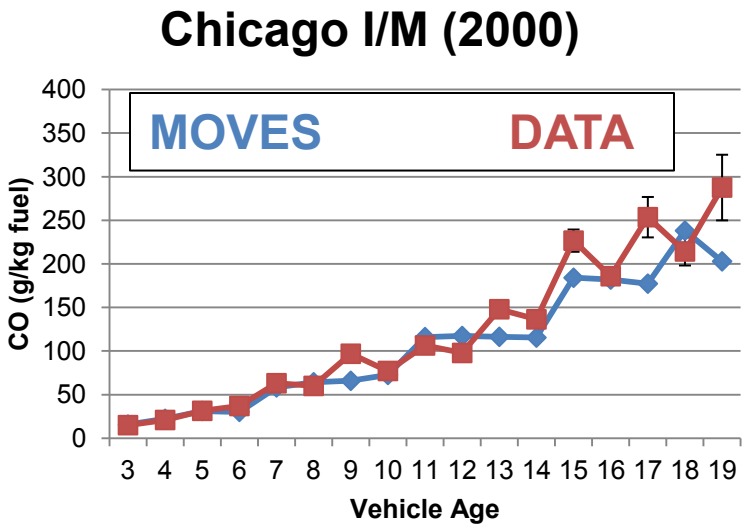

## Kansas City (2004)

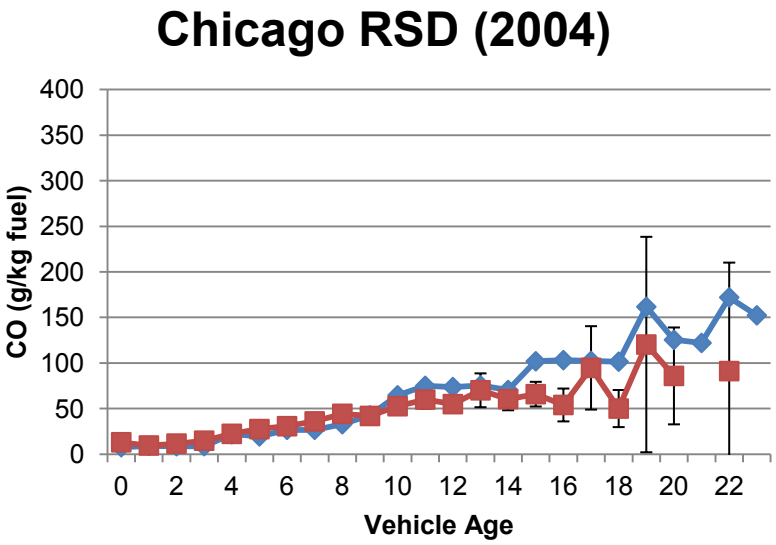


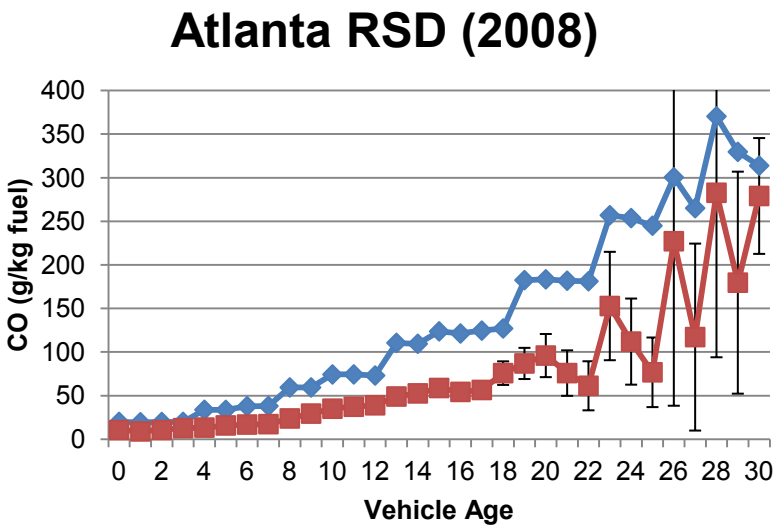
# Light Duty Fleet Average Rates: NOx

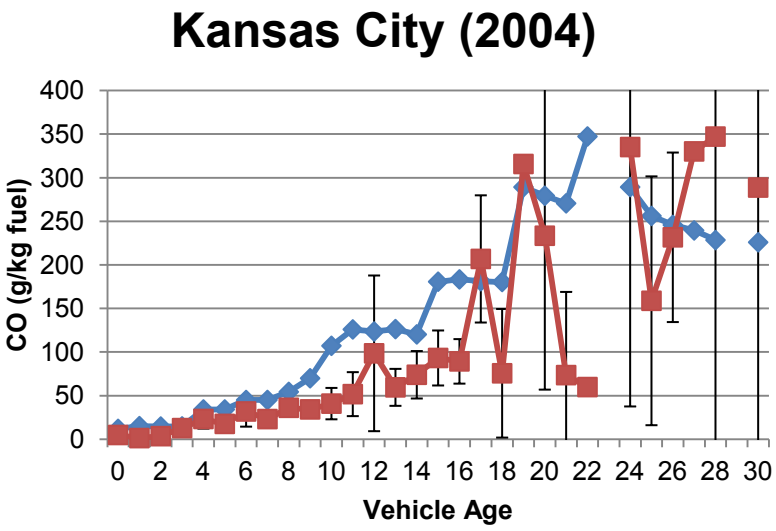


# Emission Rate Evaluation: LDV CO

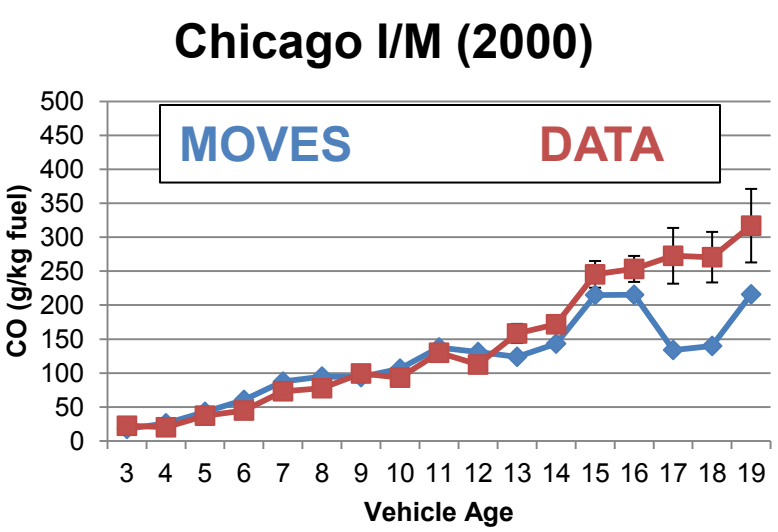


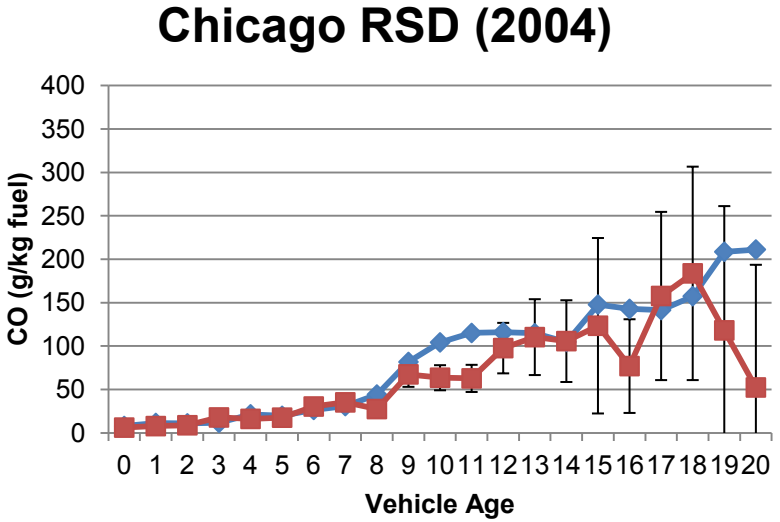



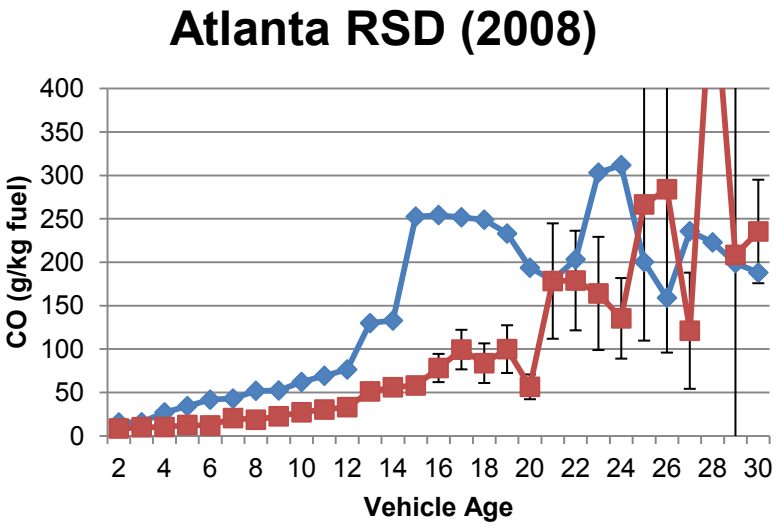



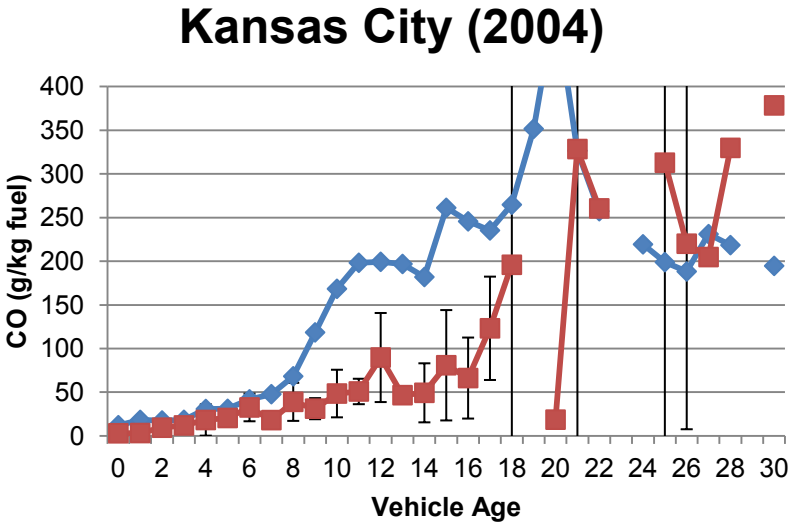



# Emission Rate Evaluation: LDT CO

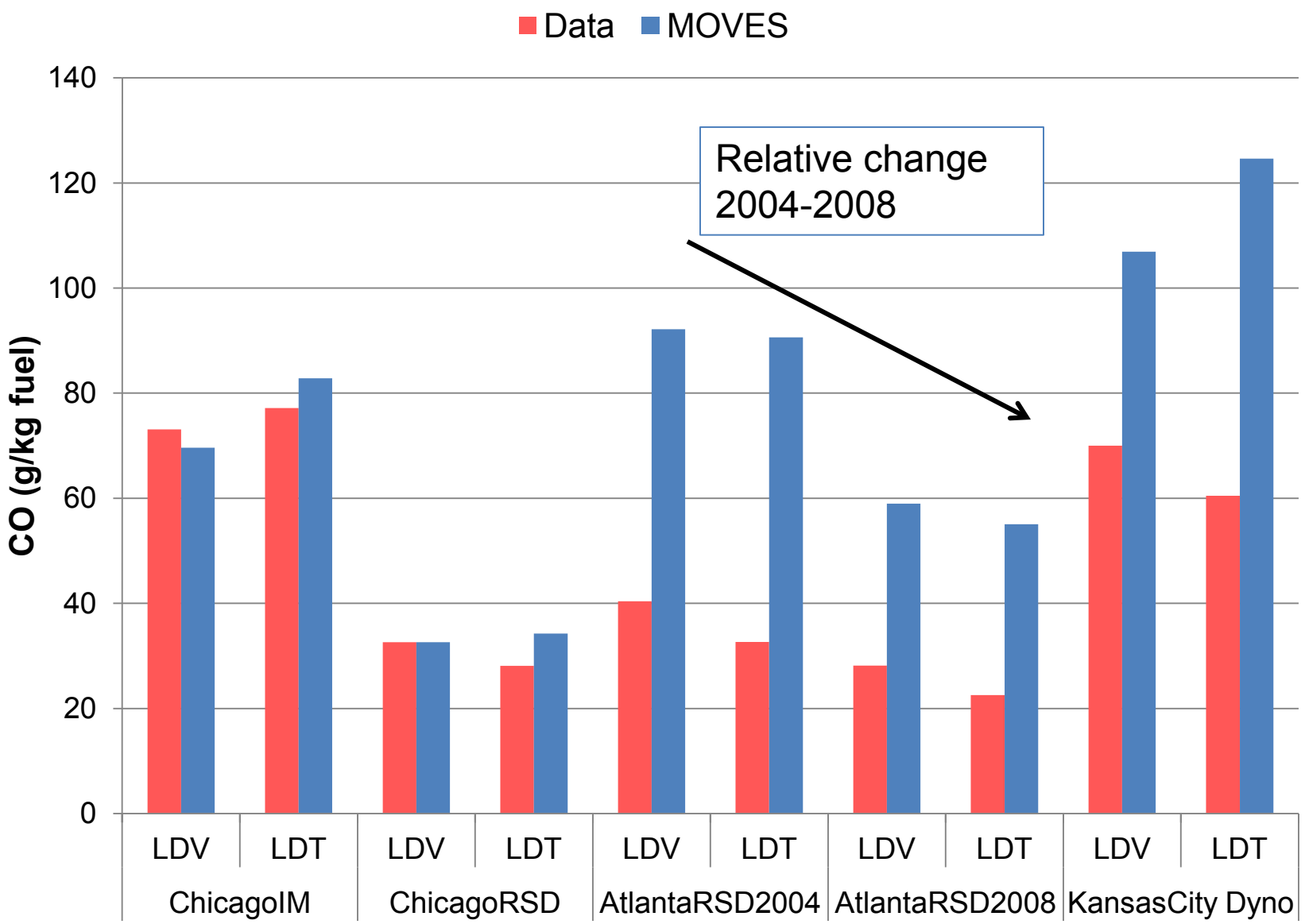


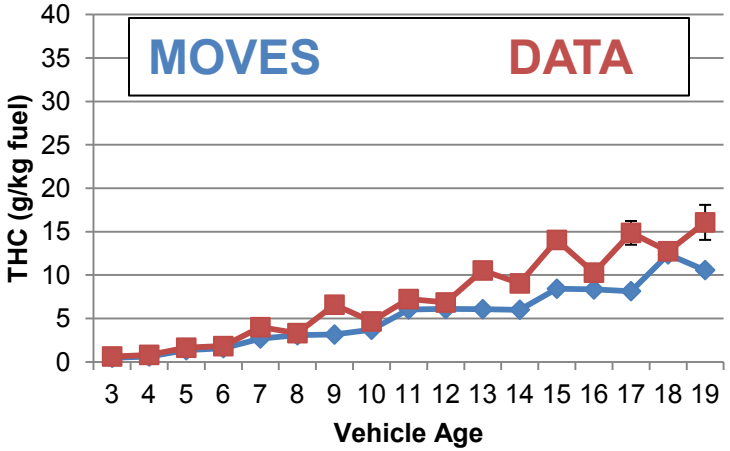



# Light Duty Fleet Average Rates: CO

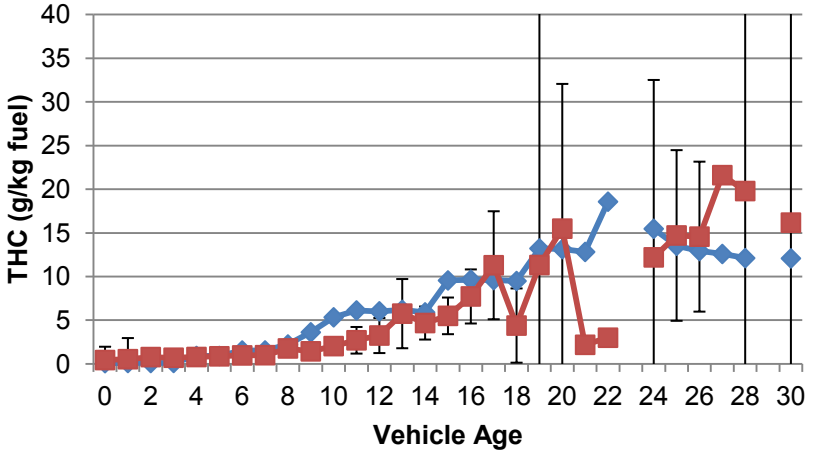


# Emission Rate Evaluation: HC

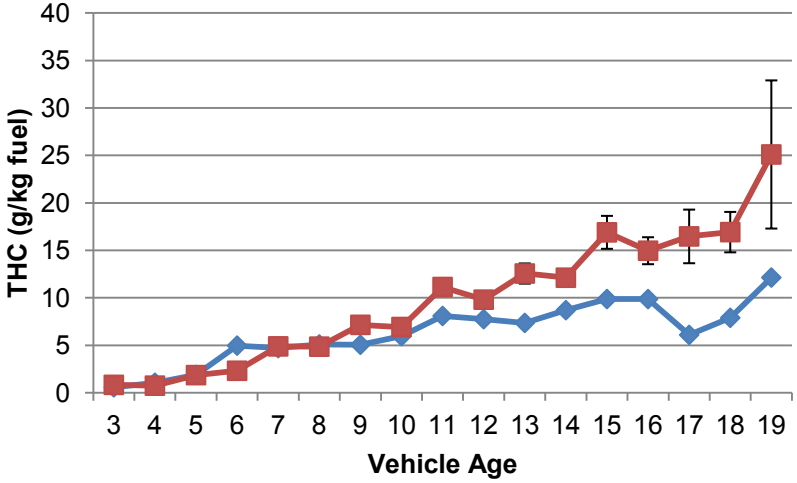
## Chicago I/M LDV (2000)



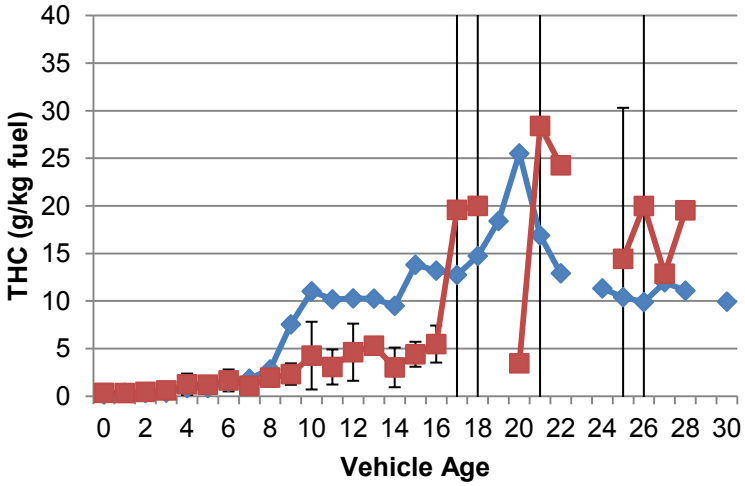

## Kansas City LDV (2004)



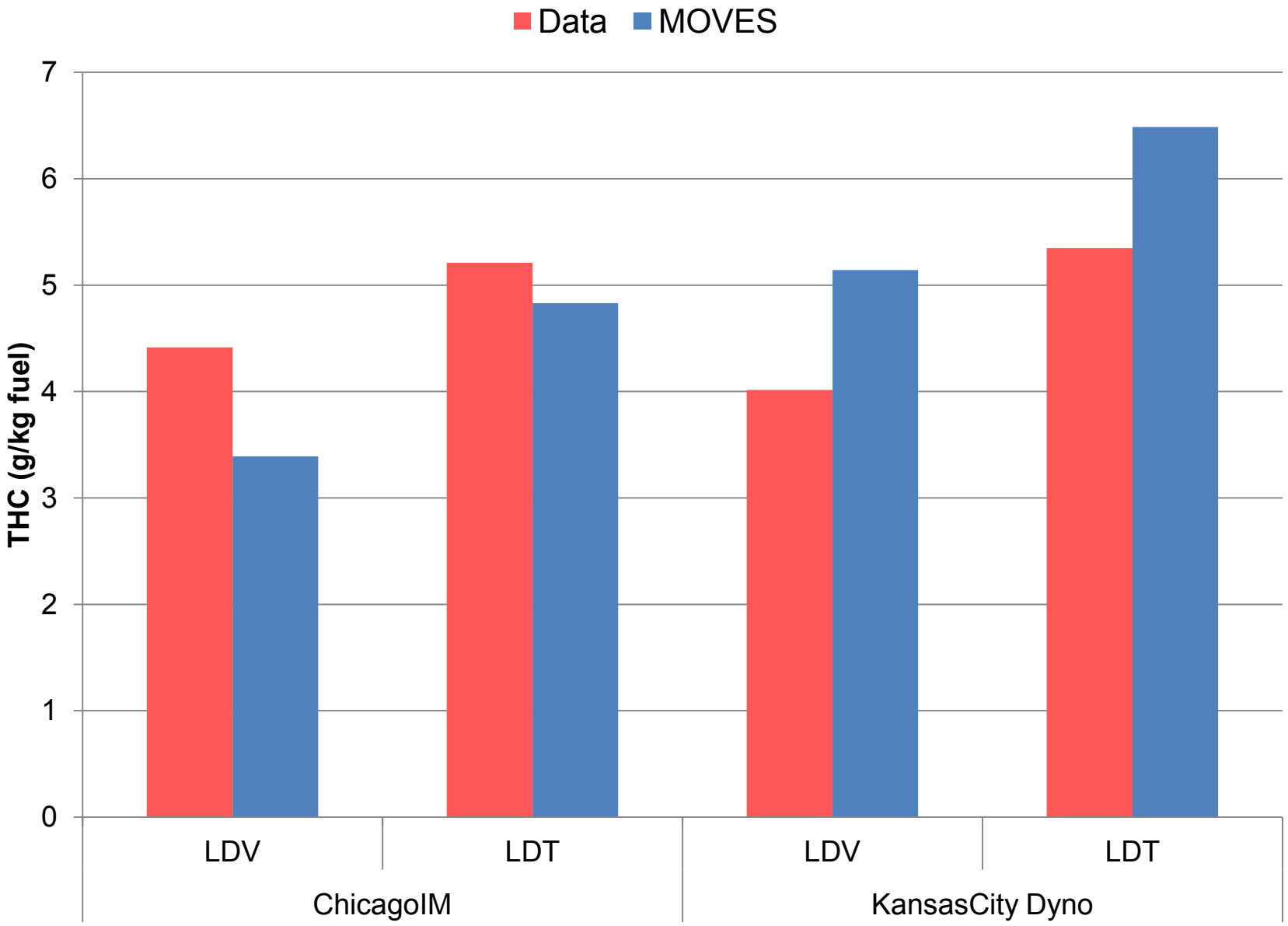

## Chicago I/M LDT (2000)




## Kansas City LDT (2004)



# Light Duty Fleet Average Rates: HC



# Comparison of Trends in MOVES and Real-World Emission Factors for Driving Cycles, Vehicle Age, and Road Type

**Bin Liu**

**H. Christopher Frey, Ph.D.**

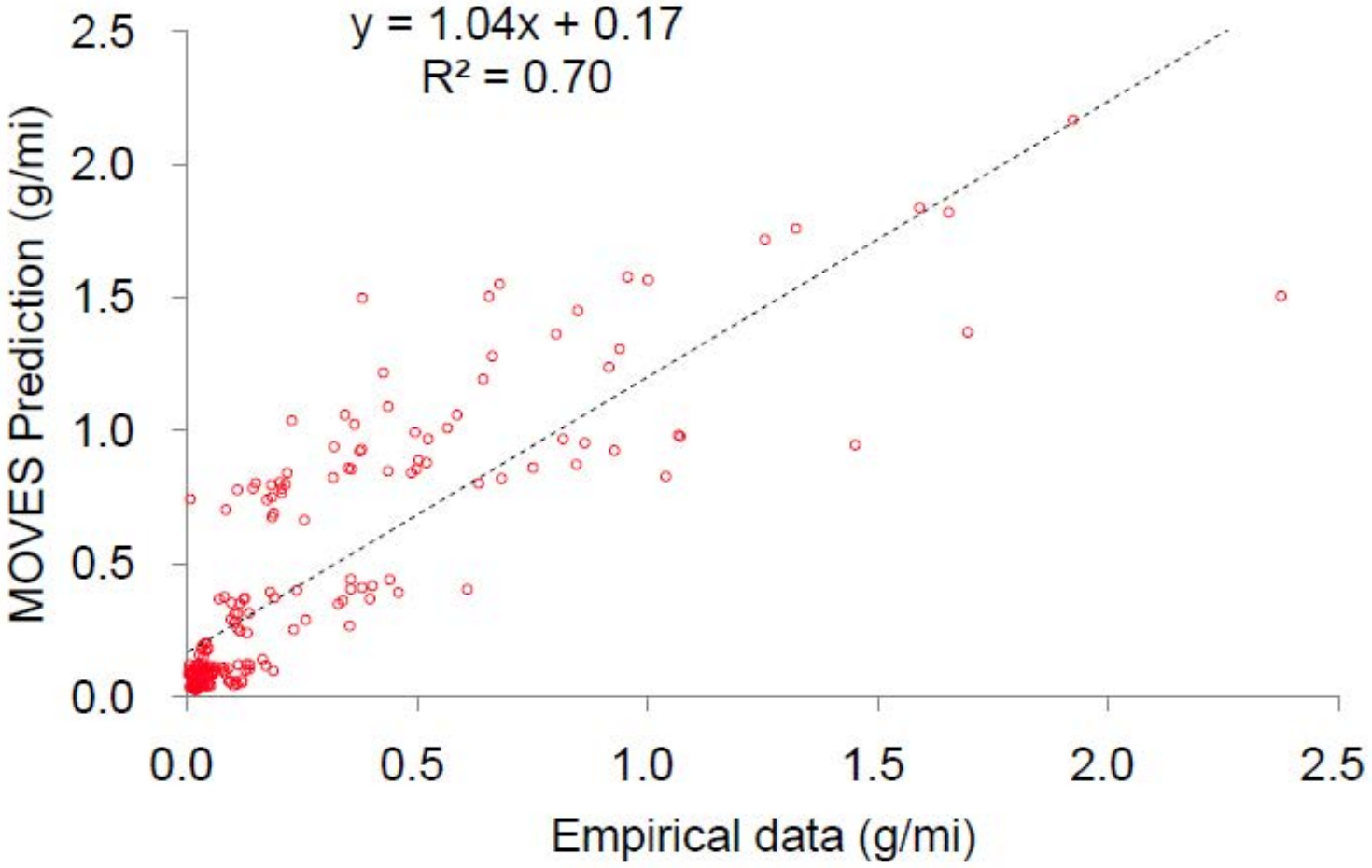
NC STATE UNIVERSITY

Dept. of Civil, Construction, and Environmental Engineering
North Carolina State University
Raleigh, NC 27695

Prepared for:
22nd CRC Real World Emissions Workshop
San Diego, California

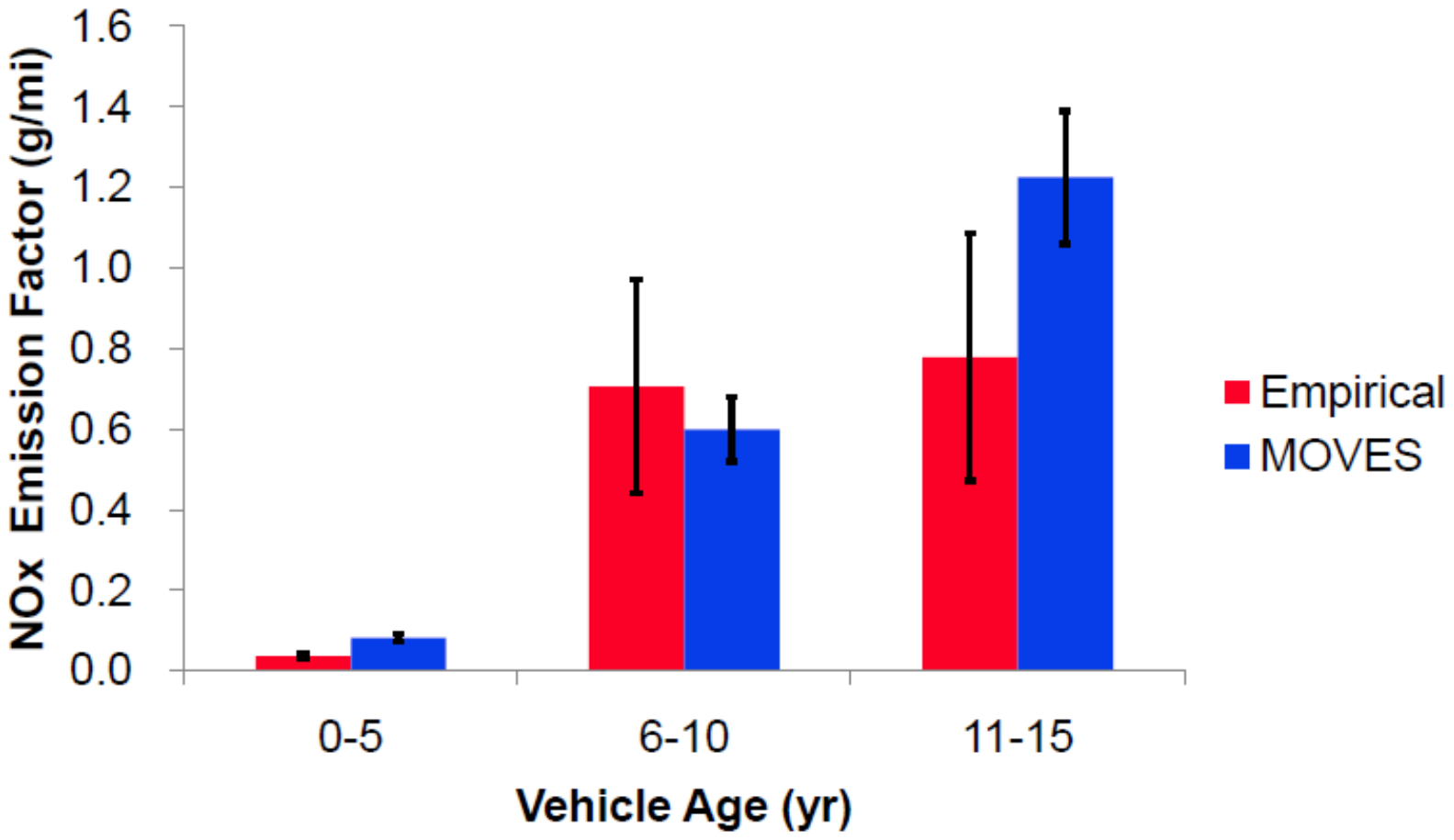
March 26, 2012

# MOVES Predictions and Empirical Data for $NO_x$ Emission Factors: All Routes and Road Type

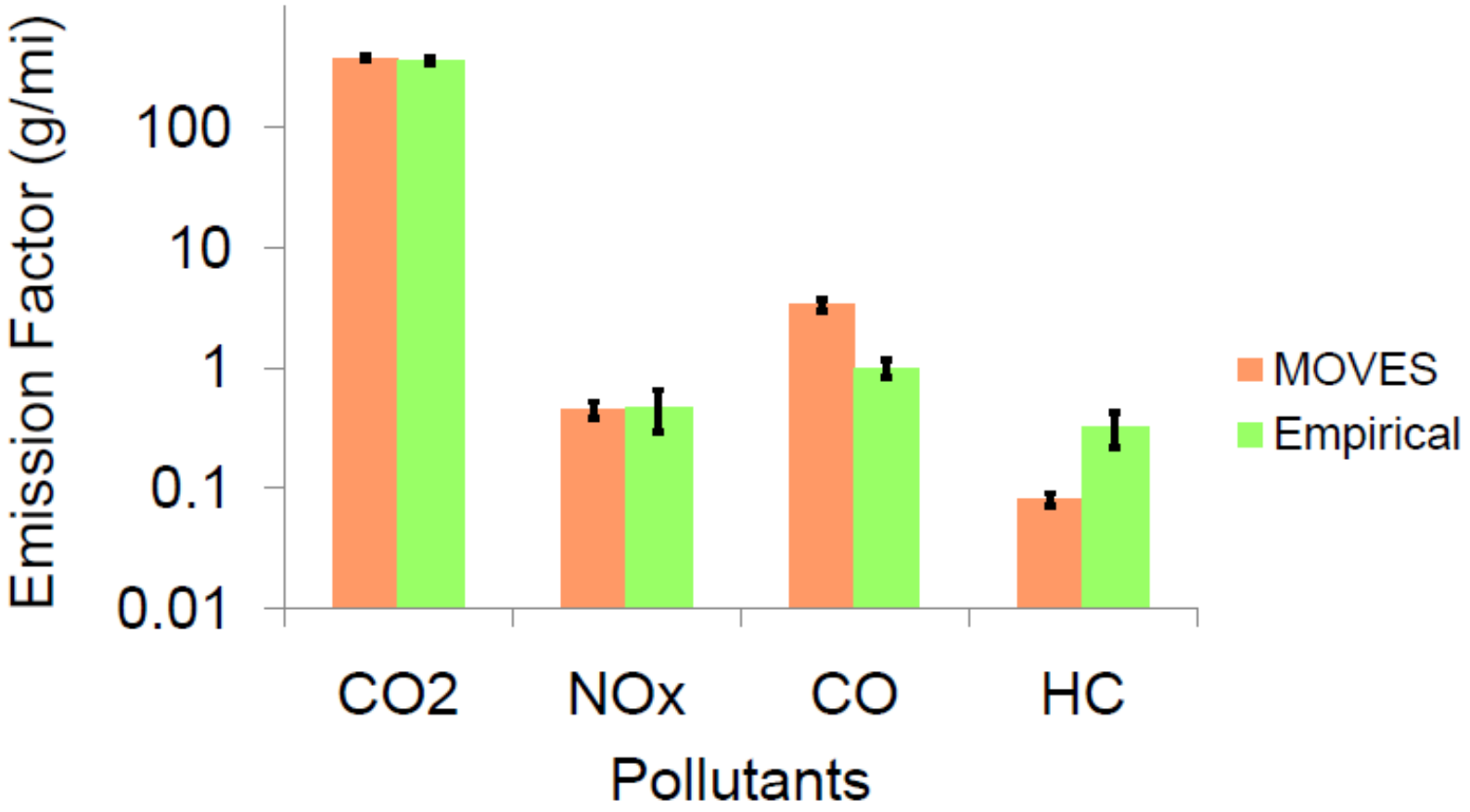


NC STATE UNIVERSITY

# Empirical and MOVES $NO_x$ Emission Factors versus Vehicle Age



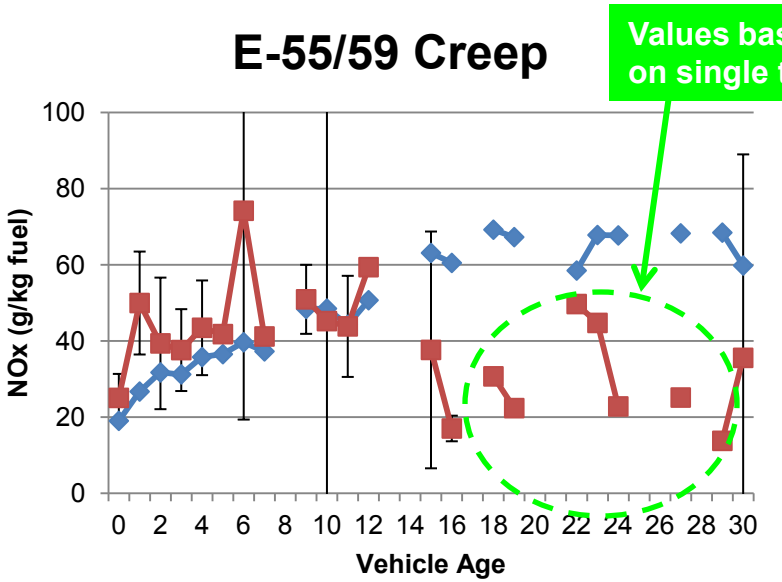
# Comparison of MOVES Predictions and Empirical Emission Factors For All Vehicles and Cycles

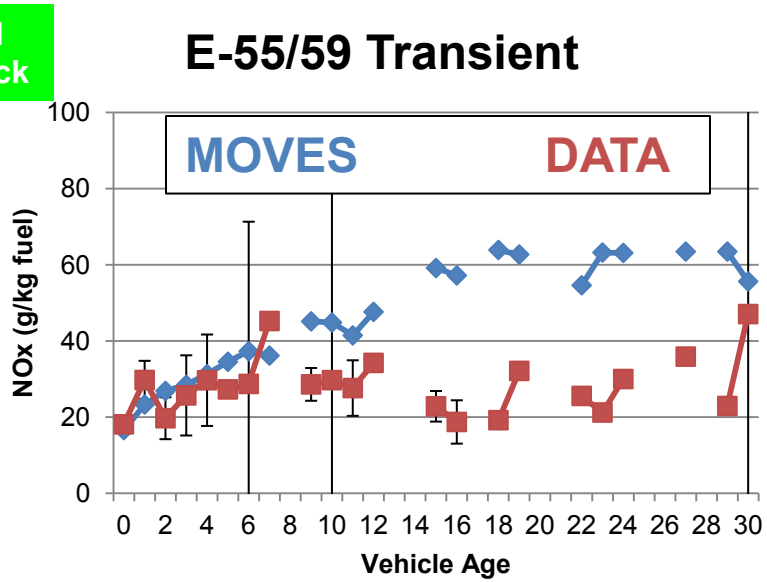


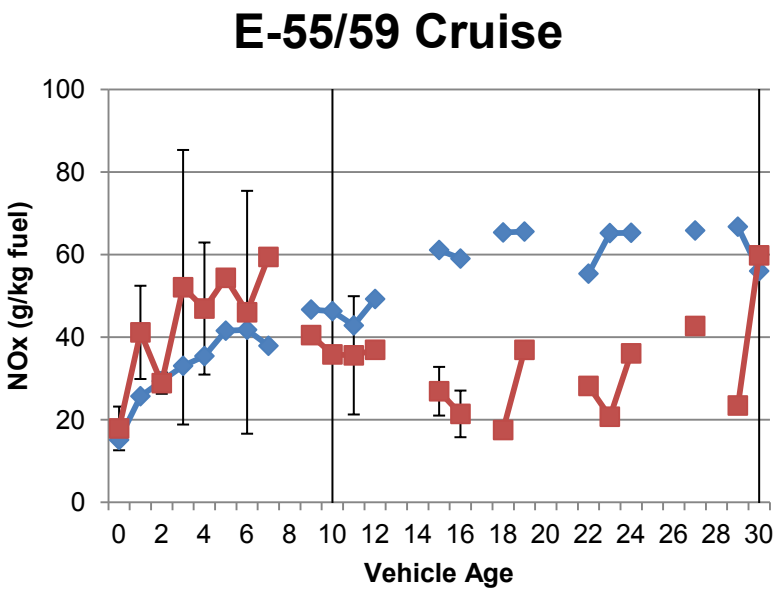
# Emission Rate Evaluation: Heavy-Duty

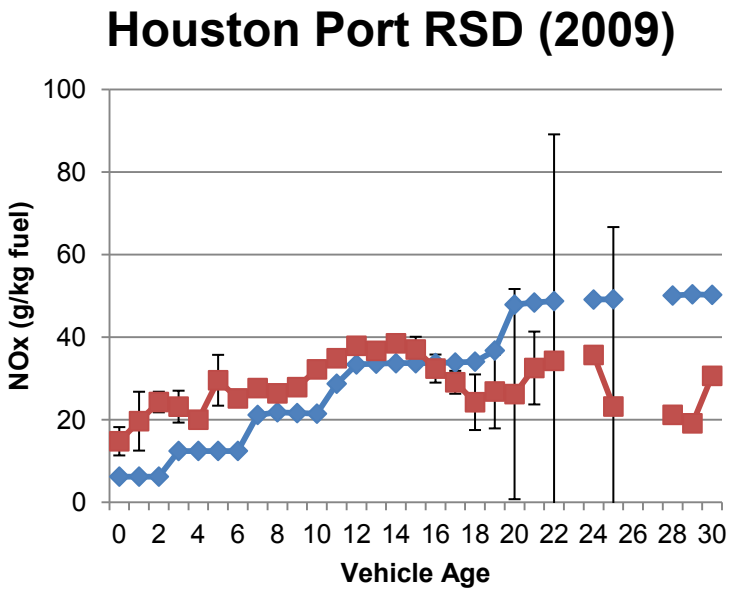
- **Sources of independent data**
  - Dynamometer (complete emission tests)
    - E-55/59 Research Program (2001-05): ~250 tests
    - multiple cycles covering range of operation
  - Remote Sensing
    - EPA/TCEQ/HGAC Houston Port Drayage Project (2009-10): ~3,200 hits at low speed/accel
  - Portable Emissions Measurement System (PEMS)
    - In-Use Compliance Program
    - Houston Port Drayage Project
- **Comparing to MOVES**
  - MOVES2010a run with age distribution, operating mode distribution and meteorology to match each independent data source
  - Fuel-specific rates based on MOVES total energy output
  - Diesel HD Trucks
  - Running NOx

# Emission Rate Evaluation: HDD NOx

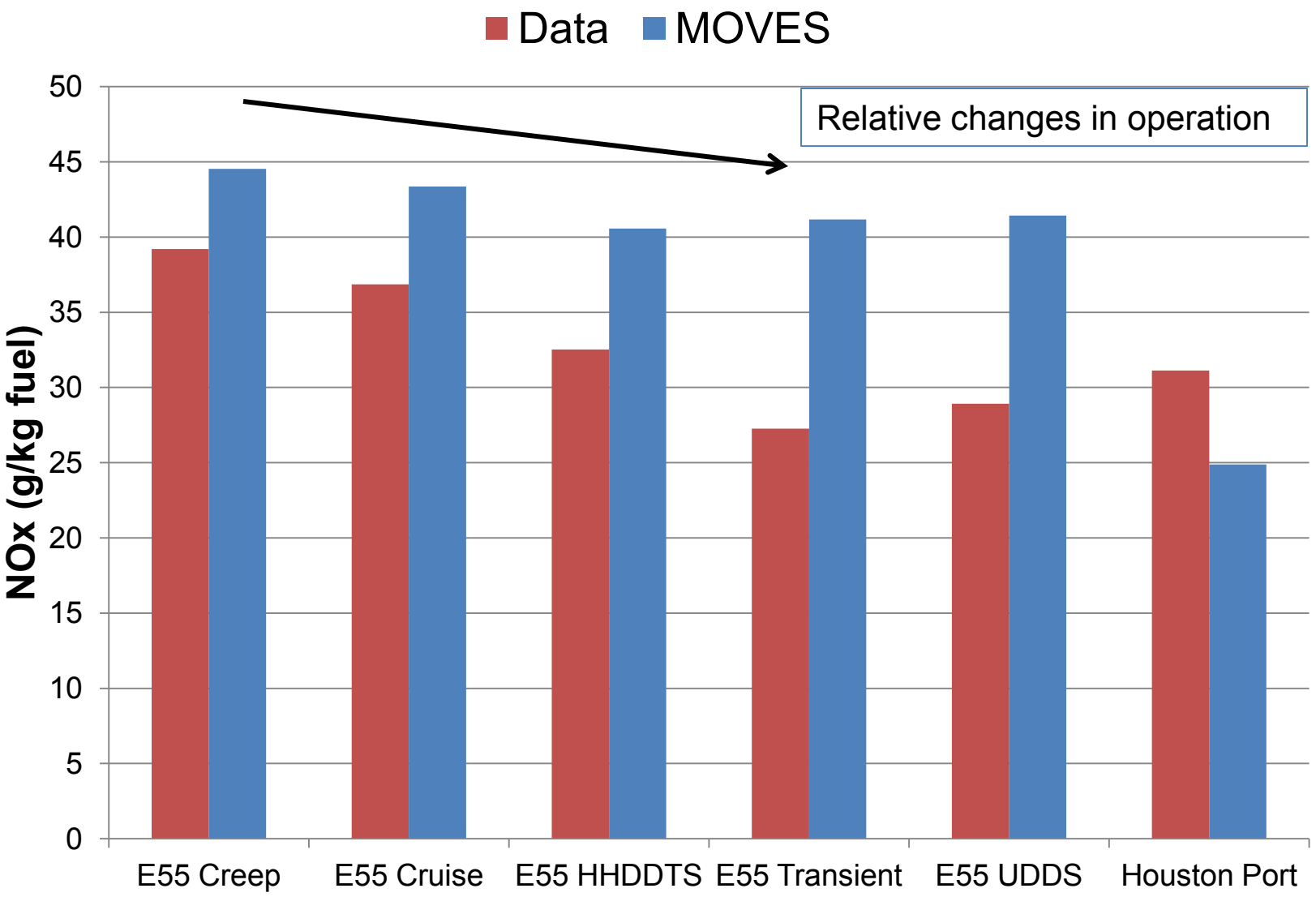


# Heavy-Duty Fleet Average Rates: NOx



# 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)**
- **MY: 2005-2009**
  - 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 |

† excludes vehicles using AB & T for HHD

# Houston Port Drayage Project

- **Collected emissions and activity data on HD drayage trucks using PEMS and PAMS in 2009-10**
- **Trucks selected for PEMS testing based on RSD scores[1]**
- **Generally higher mileage (> useful life)**

| Model Year | Number of Trucks with PEMS |
|---|---|
| 1989 and prior | 1 |
| 1990 | - |
| 1991-1997 | 10 |
| 1998 | 3 |
| 1999-2002 | 13 |
| 2003-2006 | 10 |

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

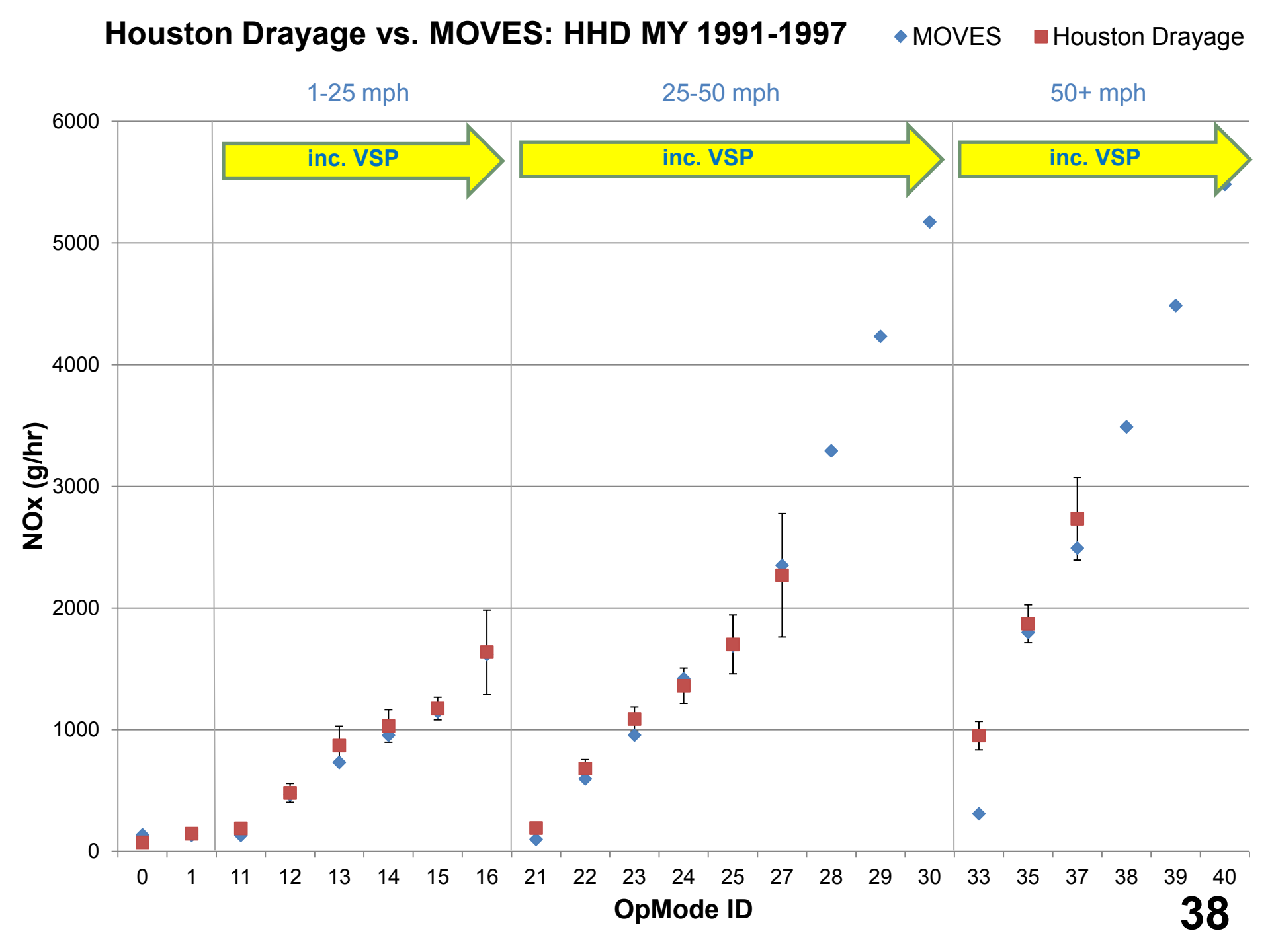
# Data summarized by MOVES operating mode bins

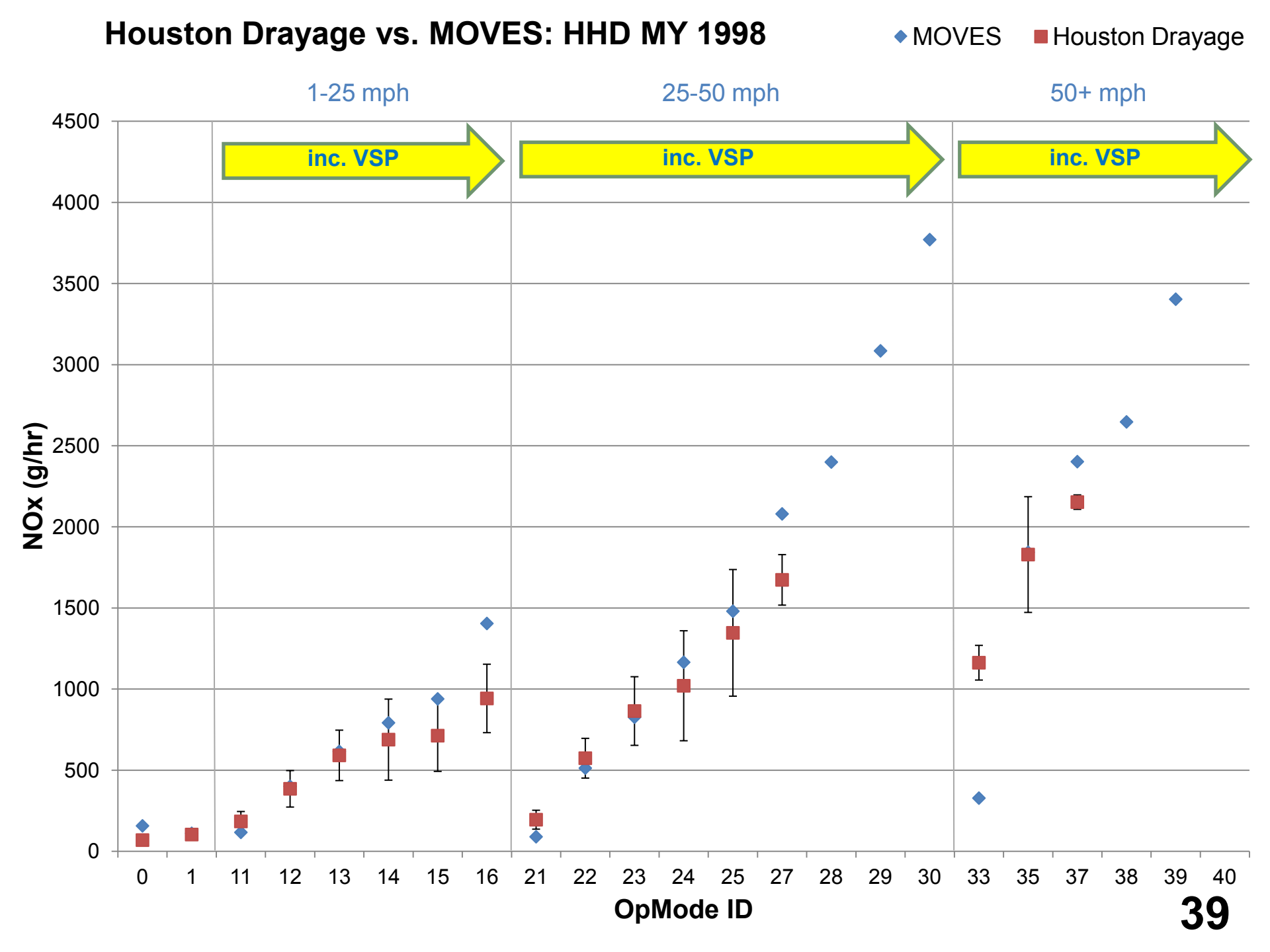
- **Allows "in the wild" PEMS data to be compared directly across program/vehicle/trip, and with MOVES rates**
- **Constructed based on vehicle speed and Scaled Tractive Power (STP)**
  - STP = update of VSP for heavy trucks

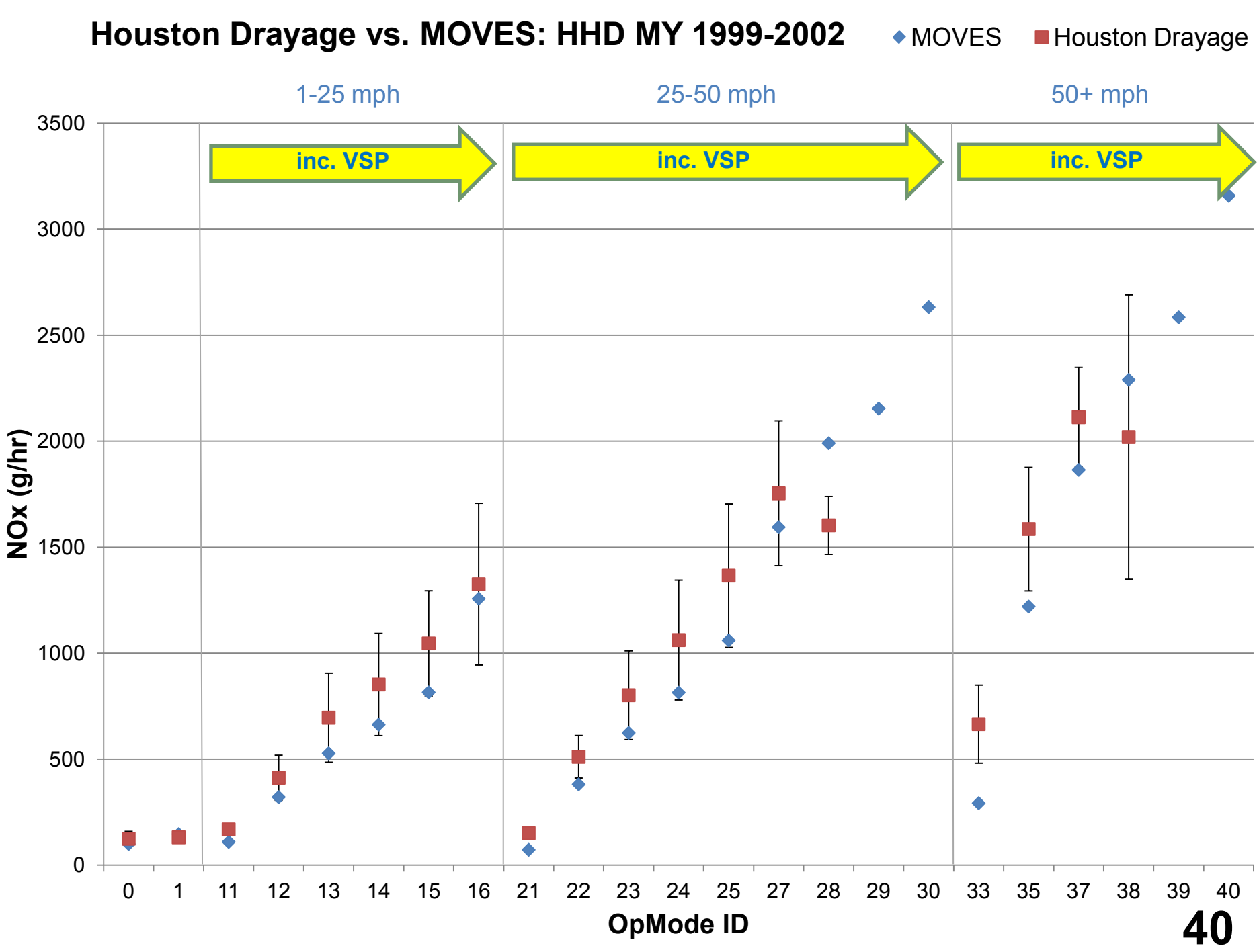
$$STP = \frac{P_{axle}}{f_{scale}}$$

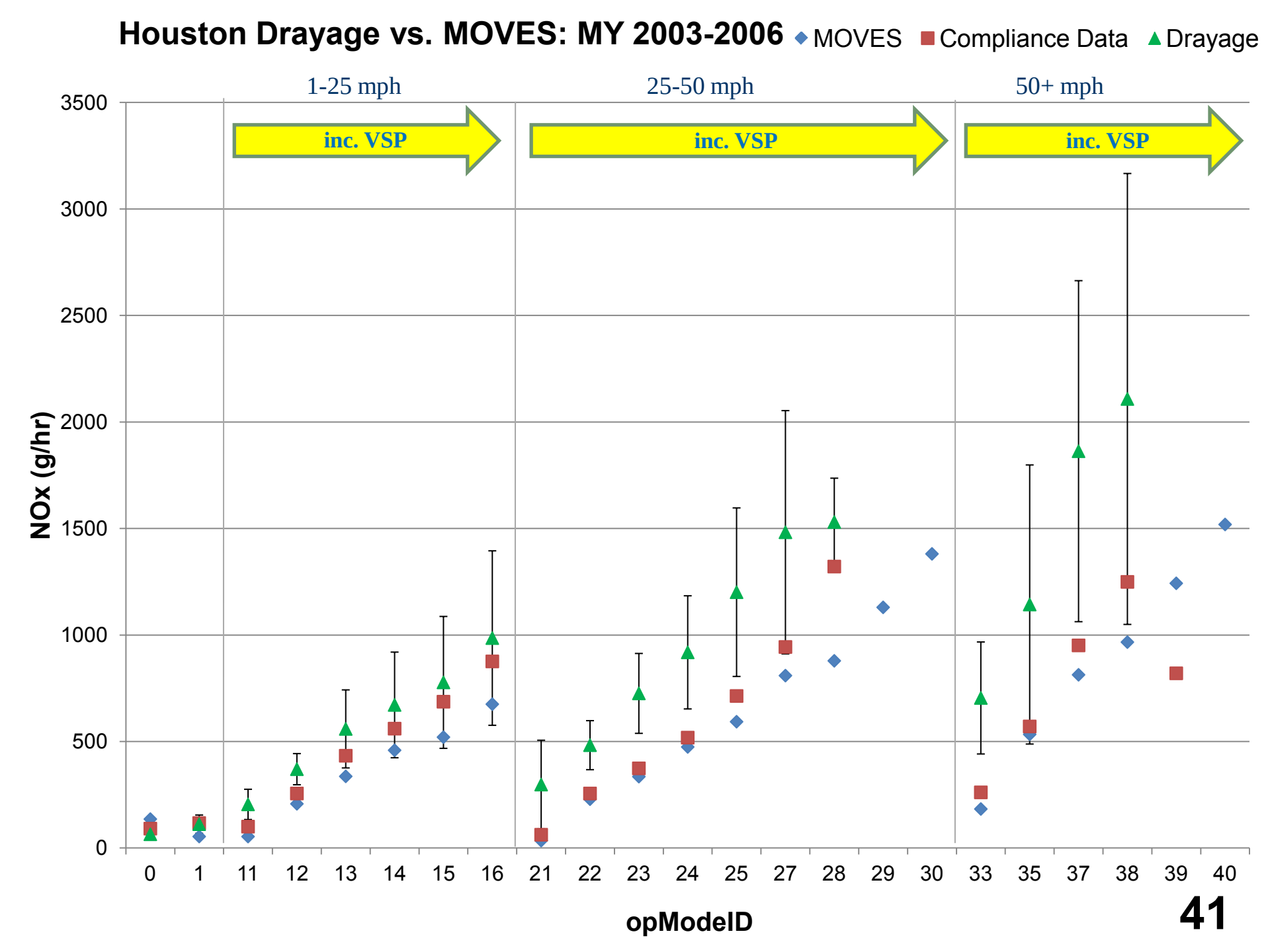
$$P_{axle} = \eta_{driveline}(P_{eng} - P_{loss,acc})$$

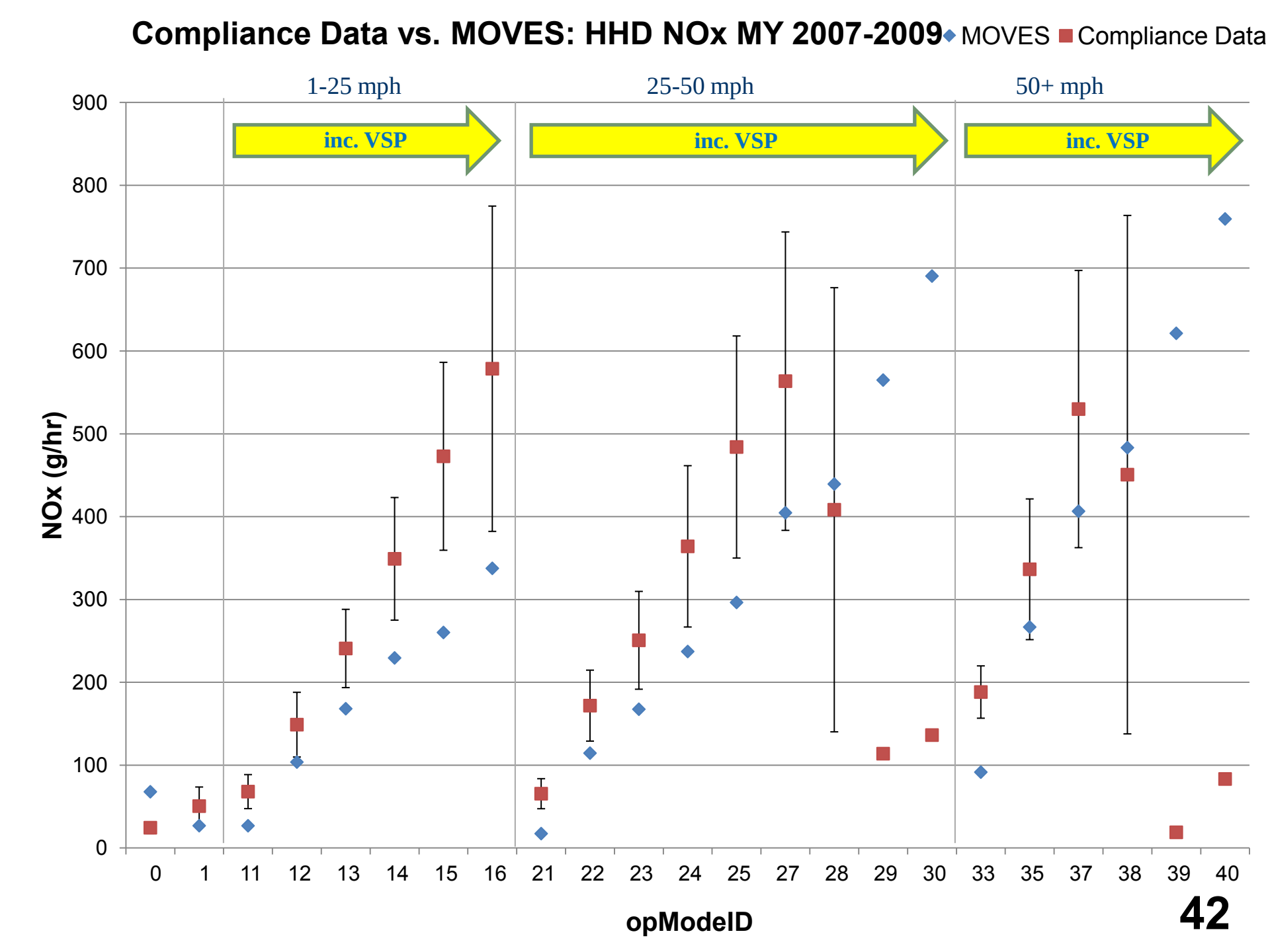
| Regulatory Class | Power scaling factor ($f_{scale}$) |
|---|---|
| MHD, HHD, Bus | 17.1 |
| LHD | 2.06 |


Houston Drayage vs. MOVES: HHD MY 1991-1997
MOVES
Houston Drayage
1-25 mph
25-50 mph
50+ mph
inc. VSP
inc. VSP
inc. VSP
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
OpMode ID


Houston Drayage vs. MOVES: HHD MY 1998
MOVES
Houston Drayage
1-25 mph
25-50 mph
50+ mph
inc. VSP
inc. VSP
inc. VSP
NOx (g/hr)
4500
4000
3500
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
OpMode ID


Houston Drayage vs. MOVES: HHD MY 1999-2002
MOVES
Houston Drayage
1-25 mph
25-50 mph
50+ mph
inc. VSP
inc. VSP
inc. VSP
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
28
29
30
33
35
37
38
39
40
OpMode ID


Houston Drayage vs. MOVES: MY 2003-2006
MOVES
Compliance Data
Drayage
1-25 mph
25-50 mph
50+ mph
inc. VSP
inc. VSP
inc. VSP
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
28
29
30
33
35
37
38
39
40
opModeID


Compliance Data vs. MOVES: HHD NOx MY 2007-2009
MOVES
Compliance Data
1-25 mph
25-50 mph
50+ mph
inc. VSP
inc. VSP
inc. VSP
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

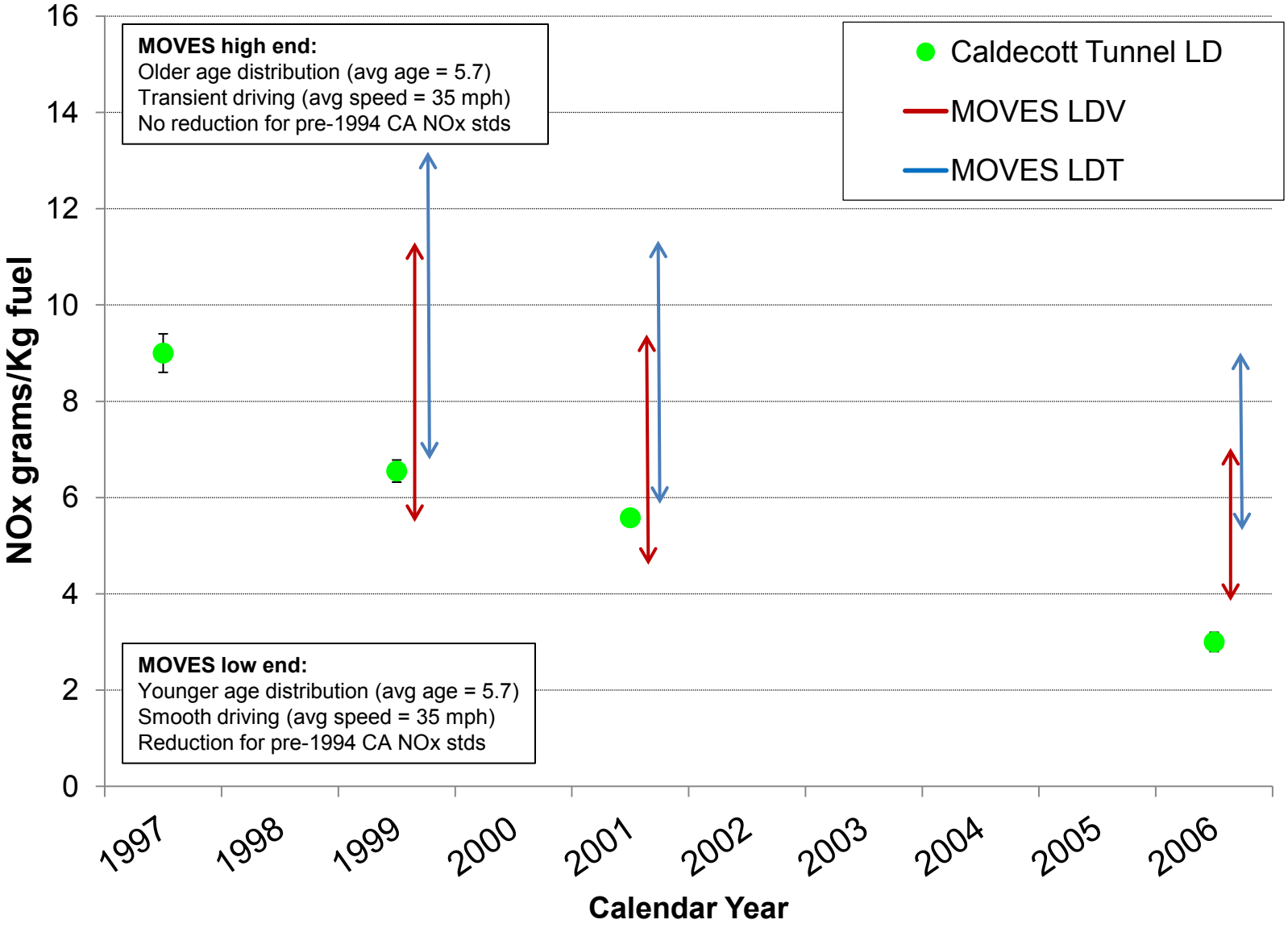
# Comparison to Tunnel & Roadside Monitoring Studies

- **Caldecott Tunnel (Bay Area, CA)**
  - LD and HDD NOx, PM2.5 in 2006; compared to previous years too
  - Ban-Weiss et. al, "Long-term changes in emissions of nitrogen oxides and particulate mater from on-road gasoline and diesel vehicles" *Atmospheric Environment* 42:220–232 (2008)
- **Borman Expressway (outside Chicago)**
  - Derived HDD PM2.5 emissions from roadside monitor in 2004/5
  - Soliman and Jacko, "Development of an Empirical Model to Estimate Real-World Fine Particulate Matter Emission Factors: The Traffic Air Quality Model", *J. Air & Waste Manage. Assoc.* 56:1540-1549 (2006)
- **MOVES run to approximate conditions based on information reported in the studies**

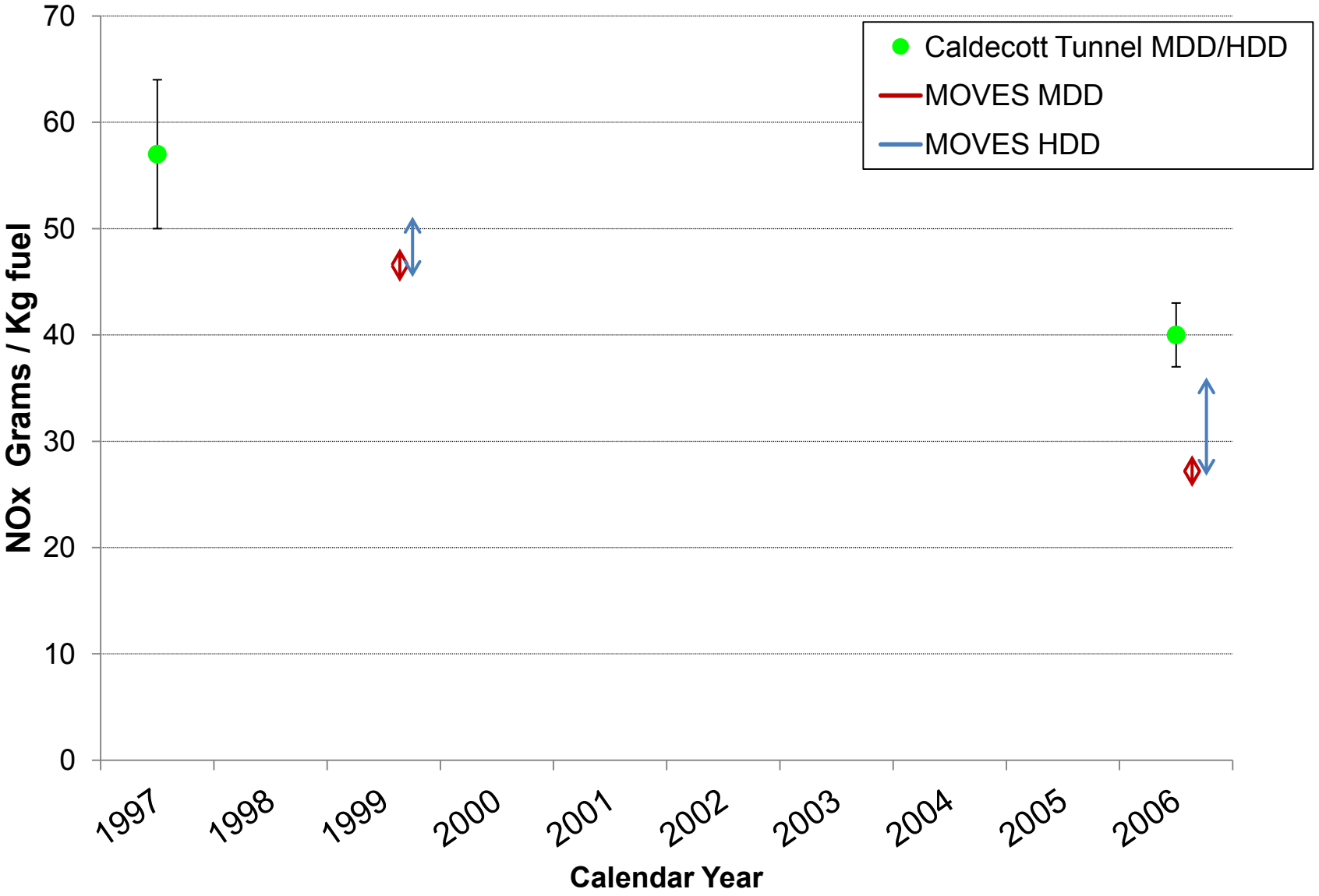
# Uncertainties in Tunnel & Roadside Monitoring Comparison

- **Don't know specific driving patterns**
  - Used average speed distribution reported in paper
  - Modeled range of accel/decel behind these average speeds
- **Don't know details of vehicle mix or age distribution**
  - Modeled range of age distribution based on average age (5.7 years)
  - Showing vehicle classes separately (LDV & LDT…MHD & HHD)
- **Estimating emissions in CA based on non-CA fleet**
  - Modeled CA LEV program for MY 1994+ LD
  - Sensitivity case for lower LD NOx standards pre-1994 MY
  - Not accounted for:
    - 30 ppm fuel introduced ~10 years earlier in California
    - More stringent California aftermarket catalyst requirements
- **Default fuel, meteorology and I/M program used**

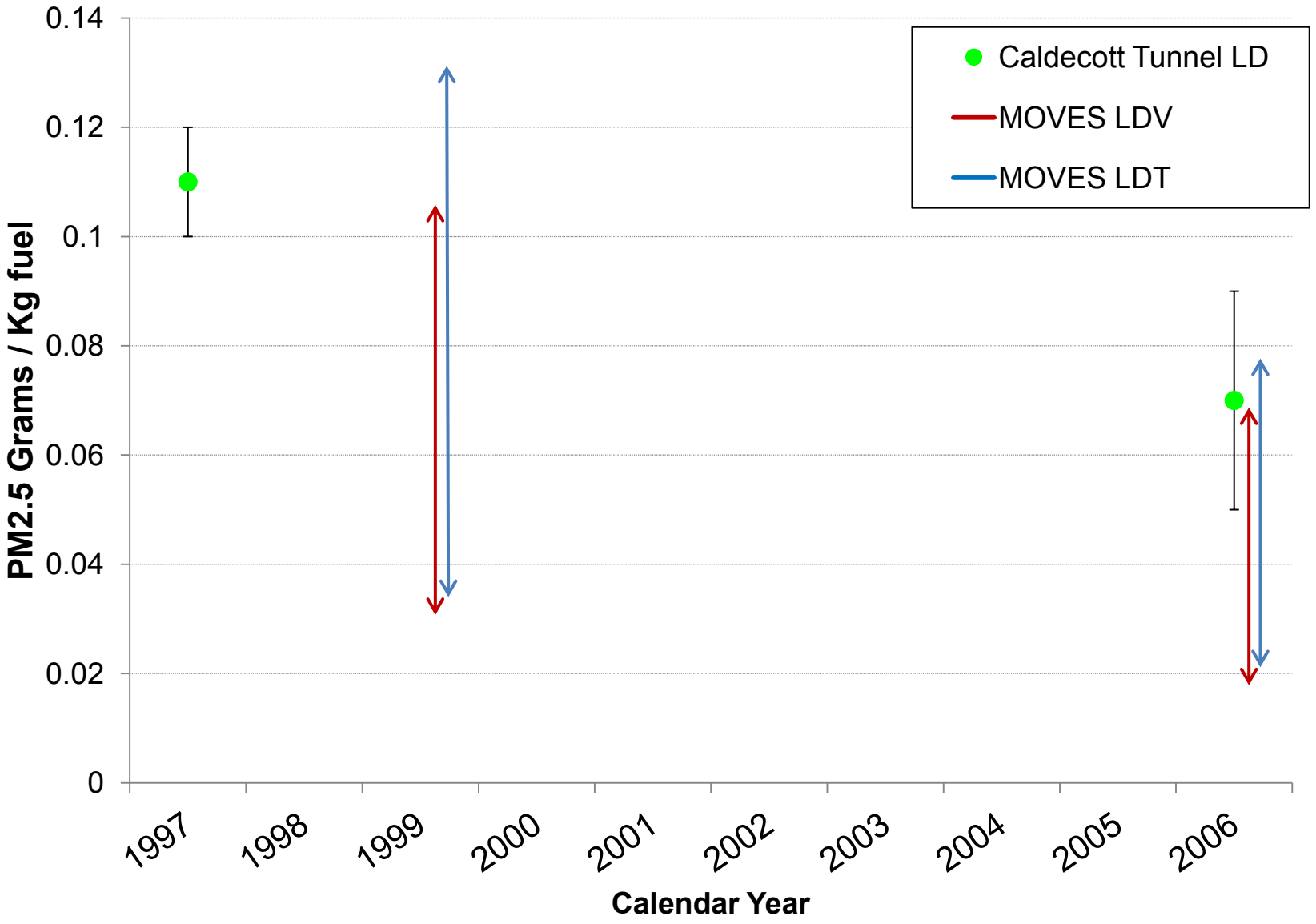
# MOVES LD NOx vs. Tunnel Results



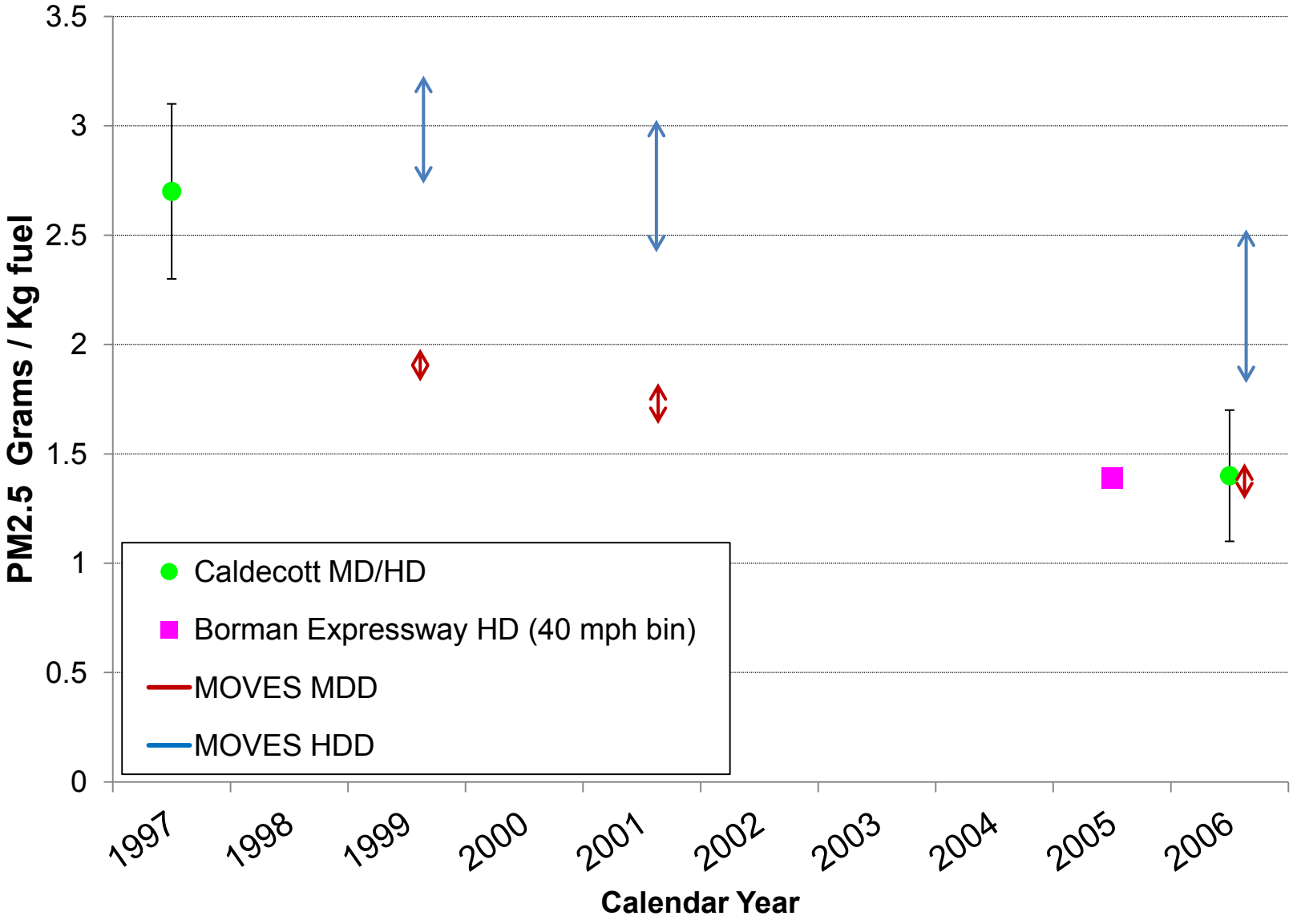
# MOVES HHD & MHD NOx vs. Tunnel Results



# MOVES LD $PM_{2.5}$ vs. Tunnel Results



# MOVES HHD & MHD $PM_{2.5}$ to Tunnel & Roadside Results



# On-Road Vehicle Emissions in a Southern California Traffic Tunnel

## Project Team

Desert Research Institute
ENVIRON
University of Denver
National Renewable Energy Laboratory

## Sponsor

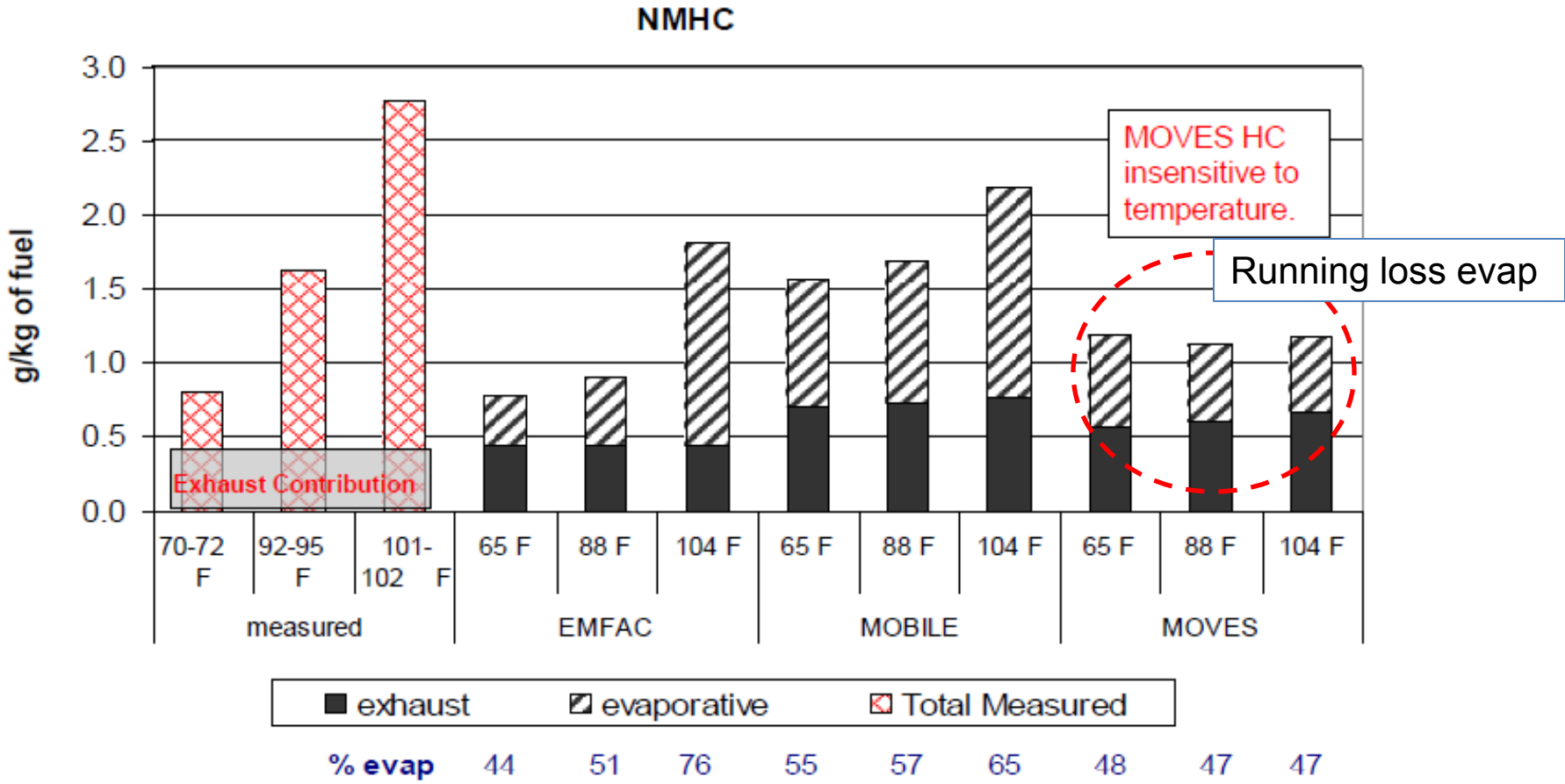
U.S. Department of Energy Office of Vehicle Technologies

## Support

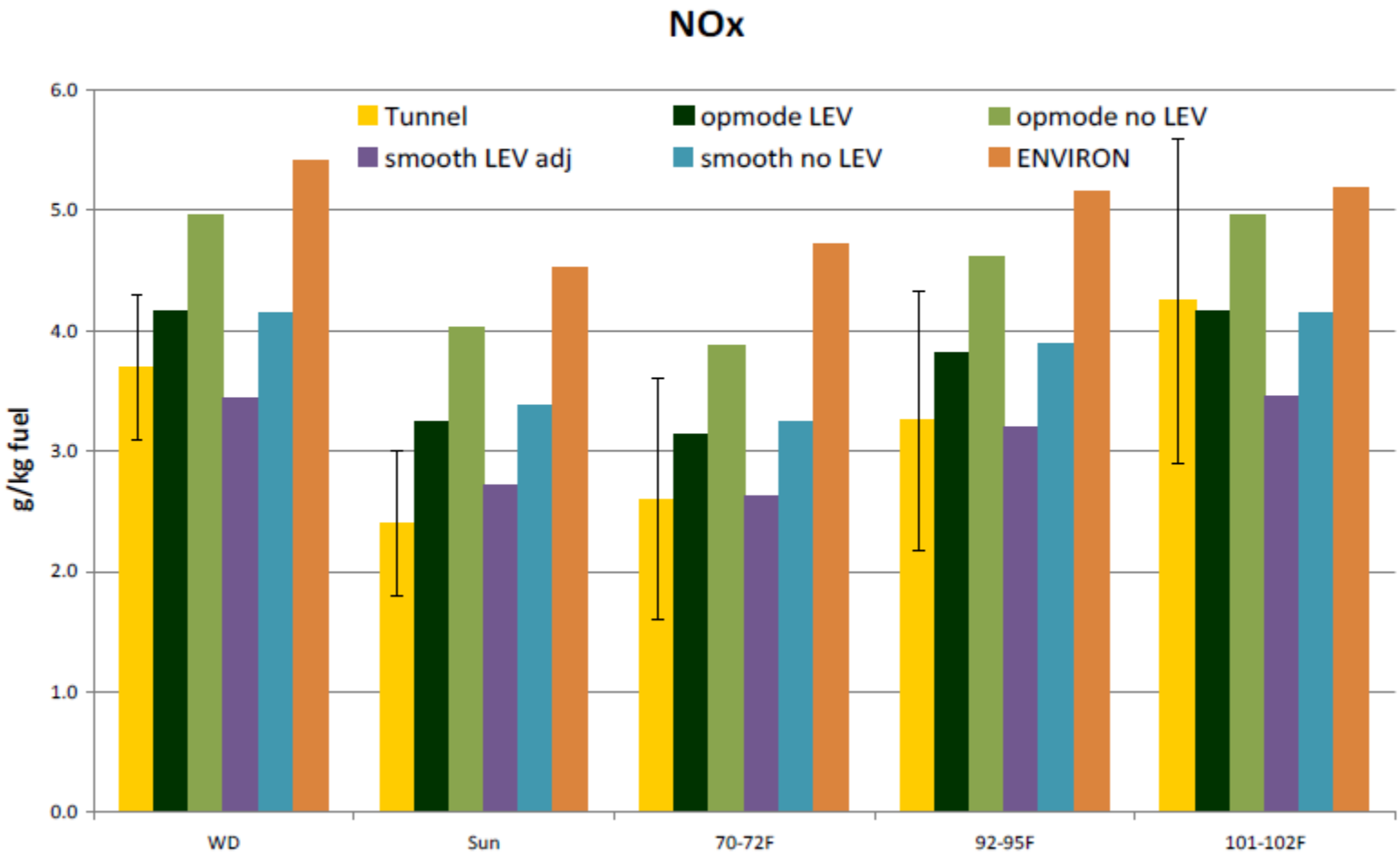
DRI Organic Analytical Laboratory and Environmental Analysis
LAWA, Van Nuys Airport, Airport Hotel in Van Nuys CA, Los Angeles DOT
Andy's Automotive

Fujita, E.M., Campbell, D.E., Zielinska, B., Chow, J.C., Lindhjem, C.E., DenBleyker, A., Lawson, D.R. (2011). Comparison of the MOVES2010a, MOBILE6.2 and EMFAC2007 Mobile Source Emissions Models with On-Road Traffic Tunnel and Remote Sensing Measurements. Submitted to J. Air Waste Manage. Assoc.

# Temperature Sensitivity of NHMC Emission Factors



# Variations in MOVES NOx EFs with driving cycle and LEV adiustments




from material provided by John Koupal, U.S. EPA Office of Transportation & Air Quality

13

# CHANGES IN ON-ROAD DIESEL VEHICLE EMISSIONS IN CALIFORNIA

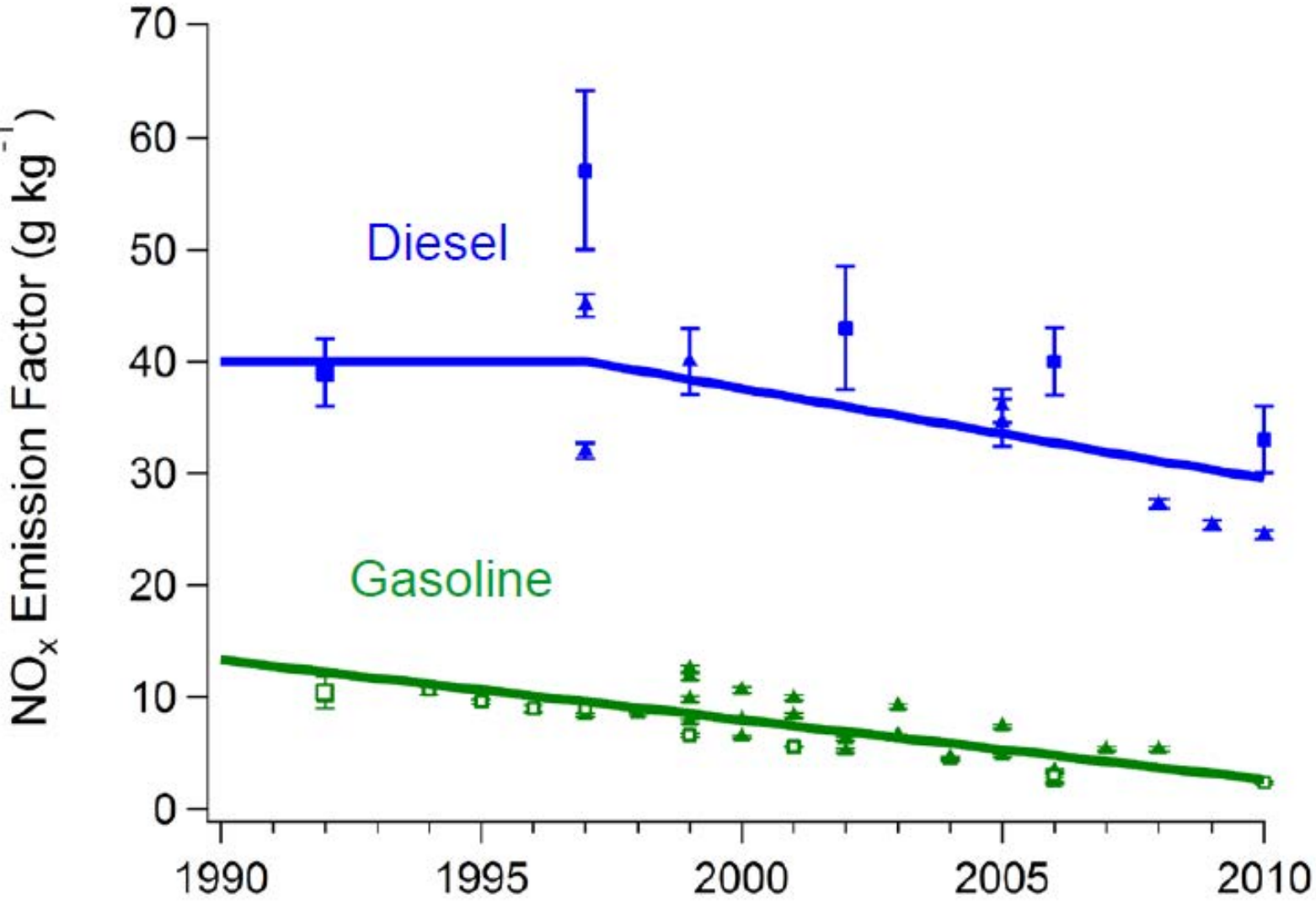
**Brian McDonald and Robert Harley**

Department of Civil and Environmental Engineering
University of California, Berkeley

CRC Workshop

March 26, 2012

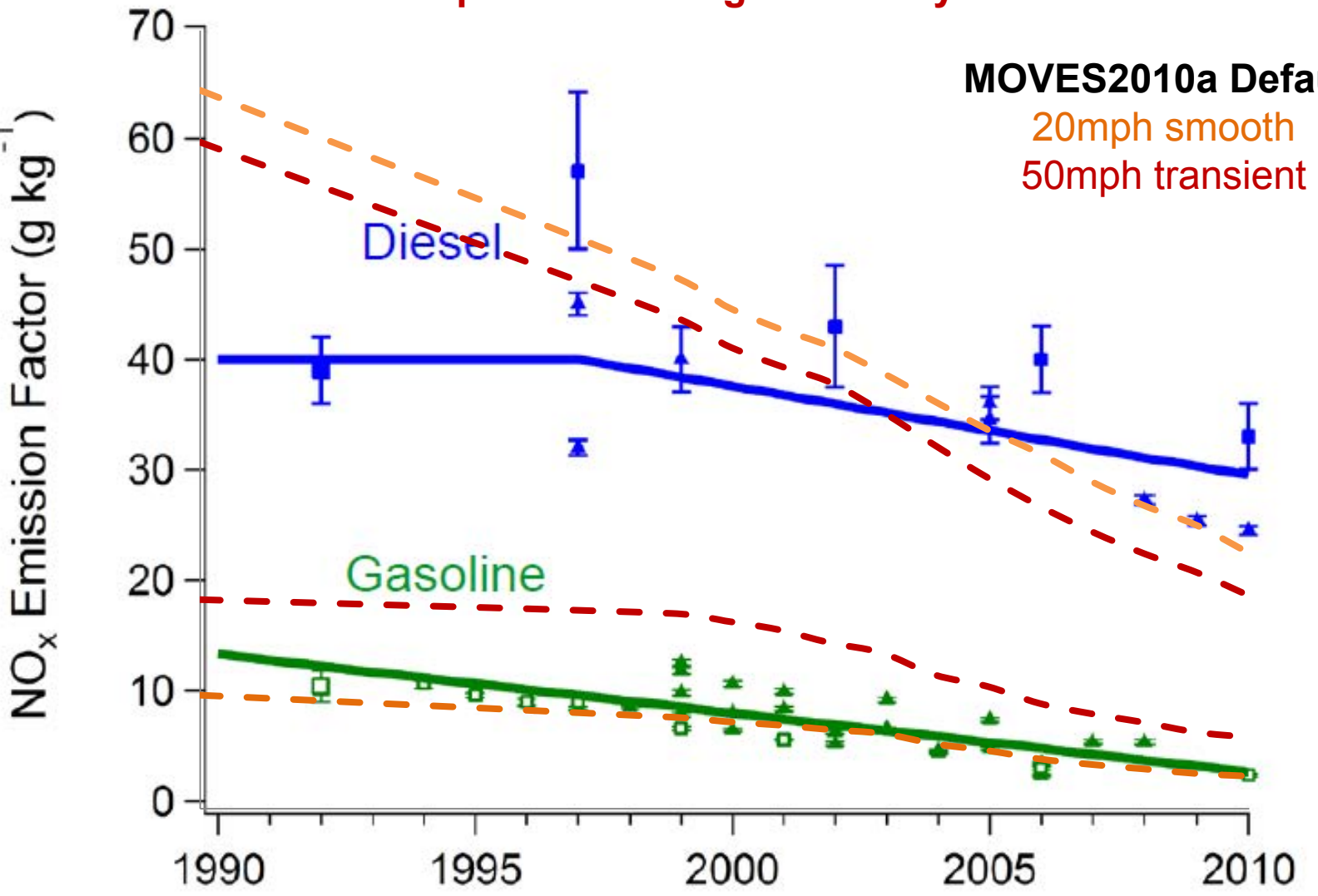
# On-Road Vehicle $NO_x$ Emission Factors




Dallmann and Harley (*JGR* 2010)
Bishop and Stedman (*ES&T* 2008, 2012)

# On-Road Vehicle $NO_x$ Emission Factors

**MOVES prediction range added by EPA**




Dallmann and Harley (*JGR* 2010)
Bishop and Stedman (*ES&T* 2008, 2012)

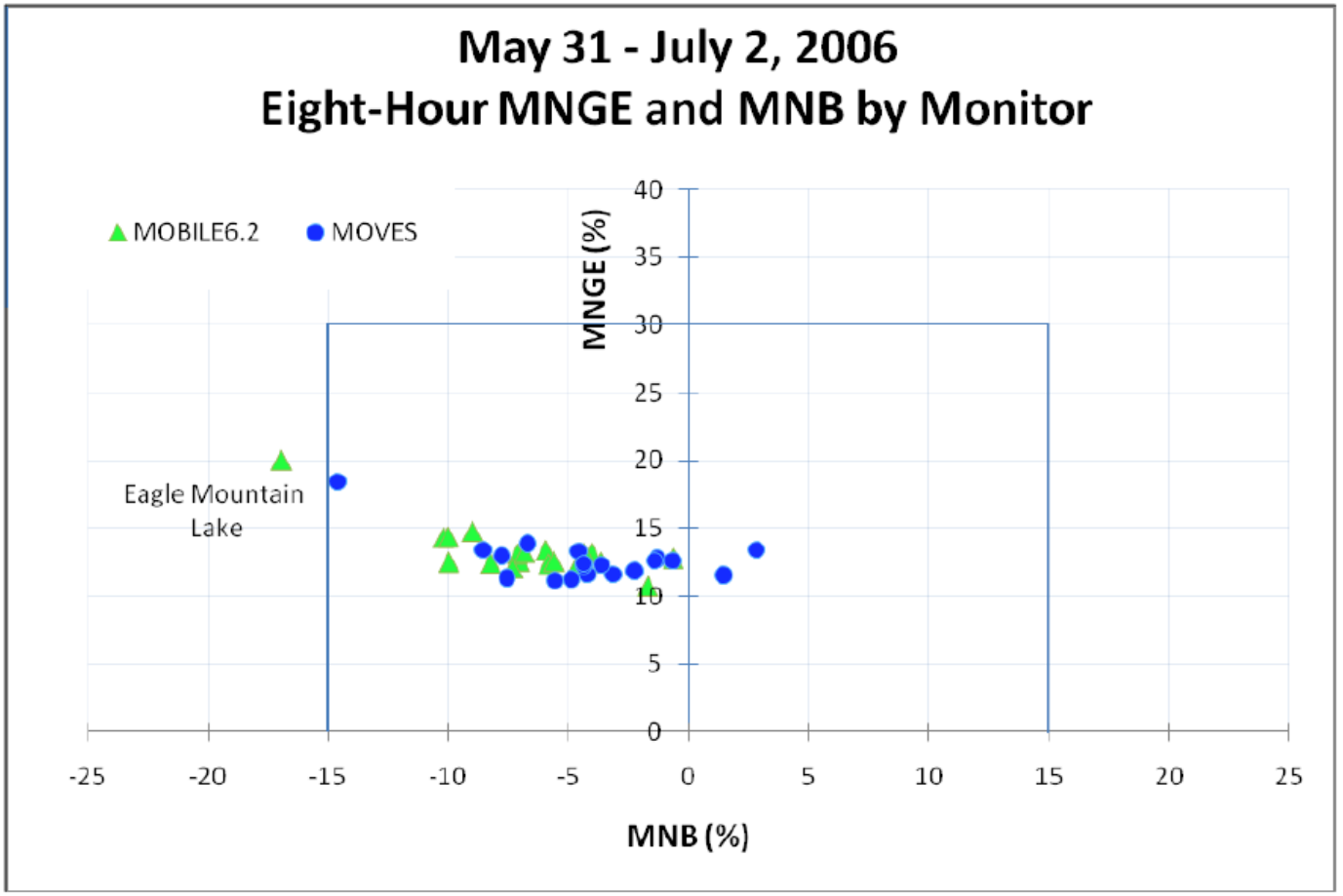
Speed range chosen to bound speeds typical in tunnel/RSD studies. Does not account for specific age distributions, vehicle operation, control programs, or fuels in each study

# Air Quality Model (CMAQ) vs. Monitor Evaluations Using MOVES

- **Heavy Duty GHG Rule (U.S. EPA)**
  - Compared 8-hour daily maximum ozone on monitors across U.S.
  - Normalized bias range -4 to +7% ; Normalized error within 15%
- **Simon, et. al, 2011 CMAS Conference (U.S. EPA)**
  - MOVES resulted in less NOx bias than MOBILE6 in Northeast during periods of cleanest onroad signal (urban/winter/am)
- **Kota, et. al, TRB Paper No. 12-4438 (Texas A&M)**
  - MOVES resulted in less $O_3$ and NOx bias than MOBILE6 for majority of monitor sites in Houston area
- **Boyer, Dallas-Fort Worth Attainment Demonstration (TCEQ)**
  - MOVES resulted in less $O_3$ and NOx bias than MOBILE6 across Dallas-Fort Worth area

# TCEQ Evaluation

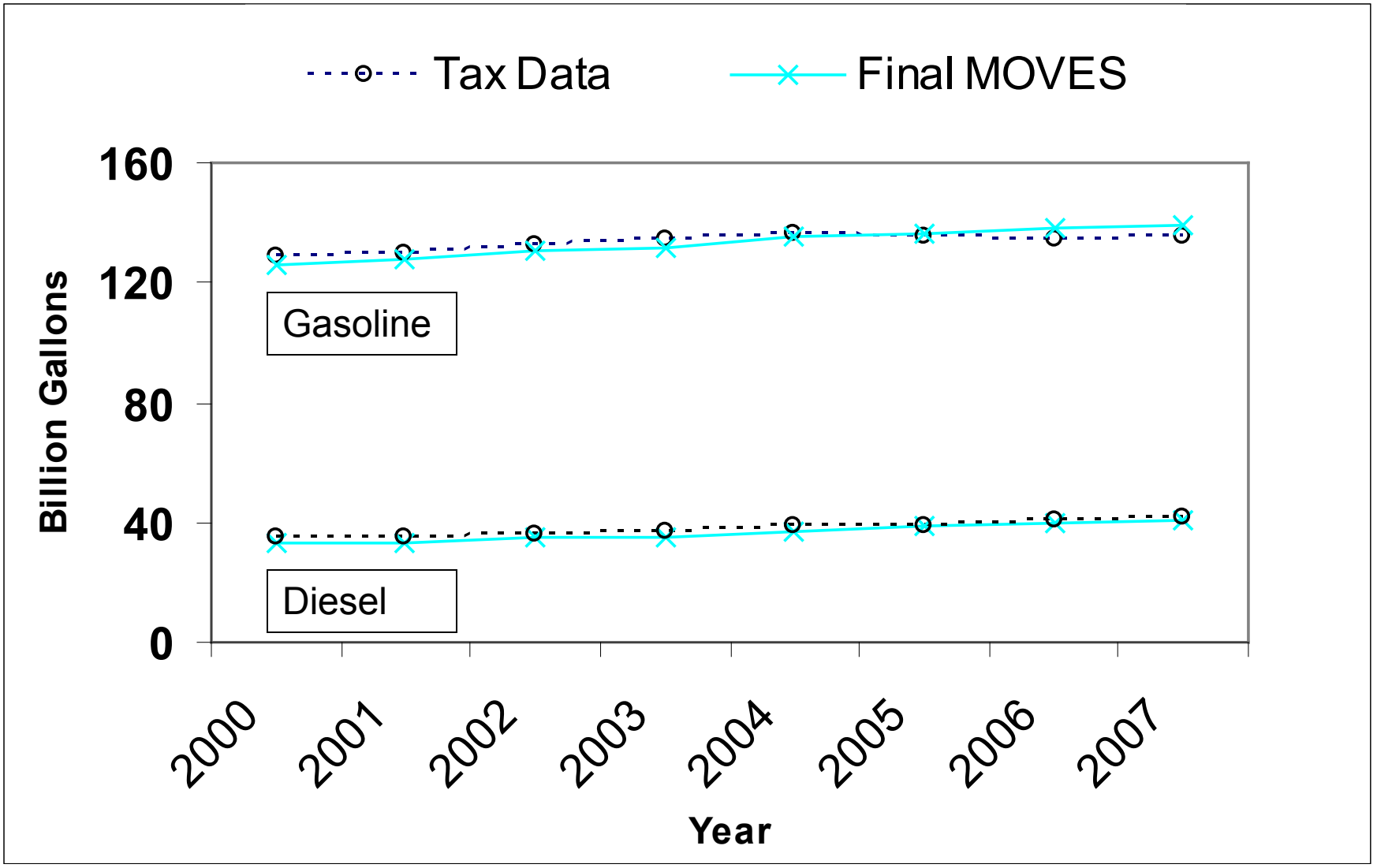
## 2006 Base Case Evaluation




Source: Texas Commission on Environmental Quality

MOVES MOBILE6.2

# Comparison of MOVES-based Fuel Consumption vs. Tax Data



# Summary

- **EPA has evaluated MOVES2010a predictions using several methodologies**
- **Emission rate comparison generally favorable**
  - Does not show systematic bias for NOx or HC
  - Atlanta and Kansas City results suggest MOVES CO may be too high at high speed/accel conditions
- **Tunnel comparisons show consistent trends over time**
  - Uncertainties in driving patterns, vehicle and age mix affect comparison
  - Differences in gasoline sulfur between CA and rest of U.S. may affect LD NOx
  - MOVES results compare well with tunnel and roadside PM2.5 results
- **Air quality model evaluations using MOVES show low bias, improved performance vs. MOBILE6**
- **Evaluation work is ongoing – will inform improvements for next version of MOVES, and research needs**