MOVES Validation:

MOVES Workshop
June 14, 2011

David Choi and John Koupal
Office of Transportation & Air Quality, USEPA

MOVES

Outline

- **Goals & caveats of validation work**
- **Comparisons performed**
  - National fuel consumption
  - Light duty emission rates
    - Chicago Inspection & Maintenance data
    - Chicago RSD
    - Atlanta RSD
    - Kansas City dynamometer
  - Heavy duty emission rates
    - CRC E-55/59 dynamometer data
    - Port of Houston drayage study RSD (unpublished)
  - Previously published tunnel, RSD & roadside studies

Goals of Validation Work

- **Respond to National Research Council's call for enhanced model evaluation & validation**
  - National Research Council, *"Modeling Mobile Source Emissions"* (2000)
- **Establish methods for comparing model predictions to independent data**
- **Recognizing variability in independent data sources, assess broad trends of model over- or under- prediction**

MOVES

Caveats on Validation Work

- **No perfect check on modeled emissions**
- **Fuel sales provides a "top down" check on the total of many "bottom up" parts**
- **Emission rates are the core of MOVES – can better control for sources of uncertainty in comparison**
  - But error still introduced via differences in fuels, operating conditions, meteorology, fleet composition
  - Fuel-specific rates compared; common basis for all target data
- **Tunnel and roadside monitor comparisons introduce additional uncertainties**
  - Car/truck distribution, fleet age, activity, ambient mixing

Fuel Validation

- MOVES "bottom-up" estimates of fuel consumption compared to Federal Highway Administration's "top-down" fuel sales estimates
- Annual total energy output
- "National" scale
- Calendar years: 1999 – 2007
- Gasoline and Diesel vehicles
  - Diesel exclude "public" vehicles – refuse trucks, transit buses, and school buses
- Energy content conversion

Fuel	Lower Heating Value (KJ/gram)	Density (Kg/gallon)	Energy Content (MJ/gallon)
Gasoline	44.0	2.8	124
Diesel	43.2	3.2	137

Limitations

- **FHWA**
  - Potential inaccuracies in state tax data
  - Methodologies employed by FHWA to allocate between highway use and off-road use
- **MOVES**
  - Conversion of total energy to fuel consumption
  - Attempt to replicate FHWA “public vehicles”
  - Uncertainties in adjustment factors and activity estimates

Fuel Consumption (in billion gallons)

	Gasoline			Diesel		
Year	*Highway Statistics* MF-21	*MOVES2010*	*% diff*	*Highway Statistics* MF-21	*MOVES2010*	% diff
1999	128.7	124.3	**-4%**	31.9	33.8	**6%**
2000	128.9	126.0	**-2%**	33.4	34.6	**4%**
2001	129.7	128.0	**-2%**	33.4	35.1	**5%**
2002	133.0	130.4	**-2%**	34.8	36.1	**4%**
2003	134.6	132.0	**-2%**	35.2	36.7	**4%**
2004	136.5	135.5	**-1%**	37.4	38.4	**3%**
2005	135.2	136.7	**1%**	39.1	39.2	**0%**
2006	134.8	138.2	**2%**	40.1	40.5	**1%**
2007	135.4	138.9	**3%**	40.8	41.9	**3%**

Light-Duty Emission Rate Validation

- **Sources of independent emissions data**
  - Chicago I/M
  - Chicago RSD
  - Atlanta RSD
  - Kansas City Dynamometer
- **Comparison to MOVES**
  - Gasoline Light-Duty Cars and Trucks (SCCs)
  - Running exhaust only (focus on acceleration and cruise)
  - Pollutants: THC, CO, and NOx (fuel-specific)
  - Customized age and operating mode distribution

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 – 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)**

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

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

Independent emissions data

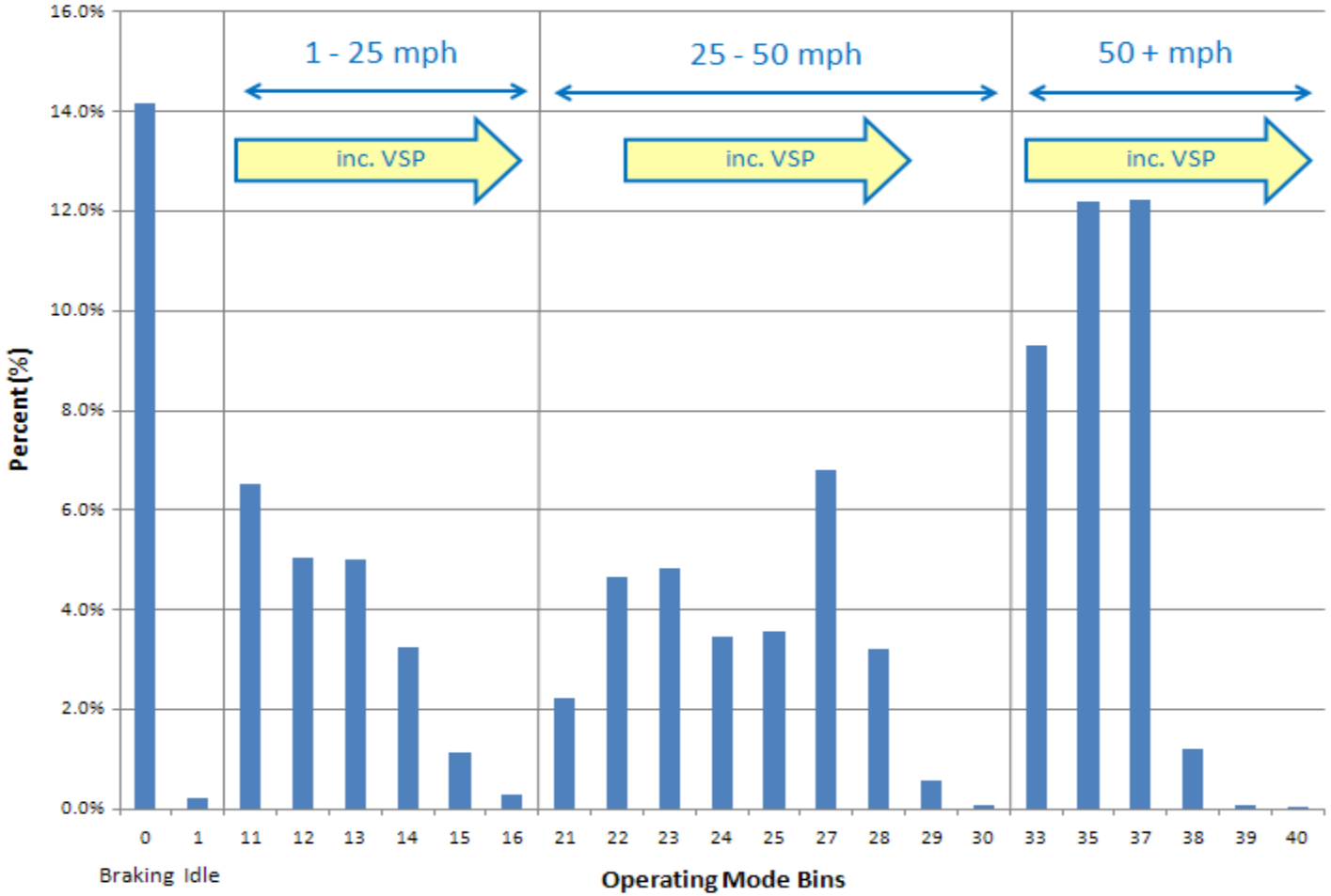
- **Chicago IM240**
  - CY 2000 – 2004
  - "F-sample"
    - Given random full-duration IM240 tests regardless of pass/fail status
    - Single test (no replication)
  - Issues with conditioning
    - Engines cool down during the wait time
    - Addressed by excluding the first 120 seconds – "IM120"
  - **Number of tests: 74,248** (compared test averages)
- **Chicago remote sensing data (CRC-E23)**
  - Biennially from 2000 – 2006
  - Location: On-ramp from Algonquin Rd. to I-290 E in Northwest Chicago
  - **Number of RSD hits: 9,133** (compared RSD hits)

Independent emissions data (cont'd)

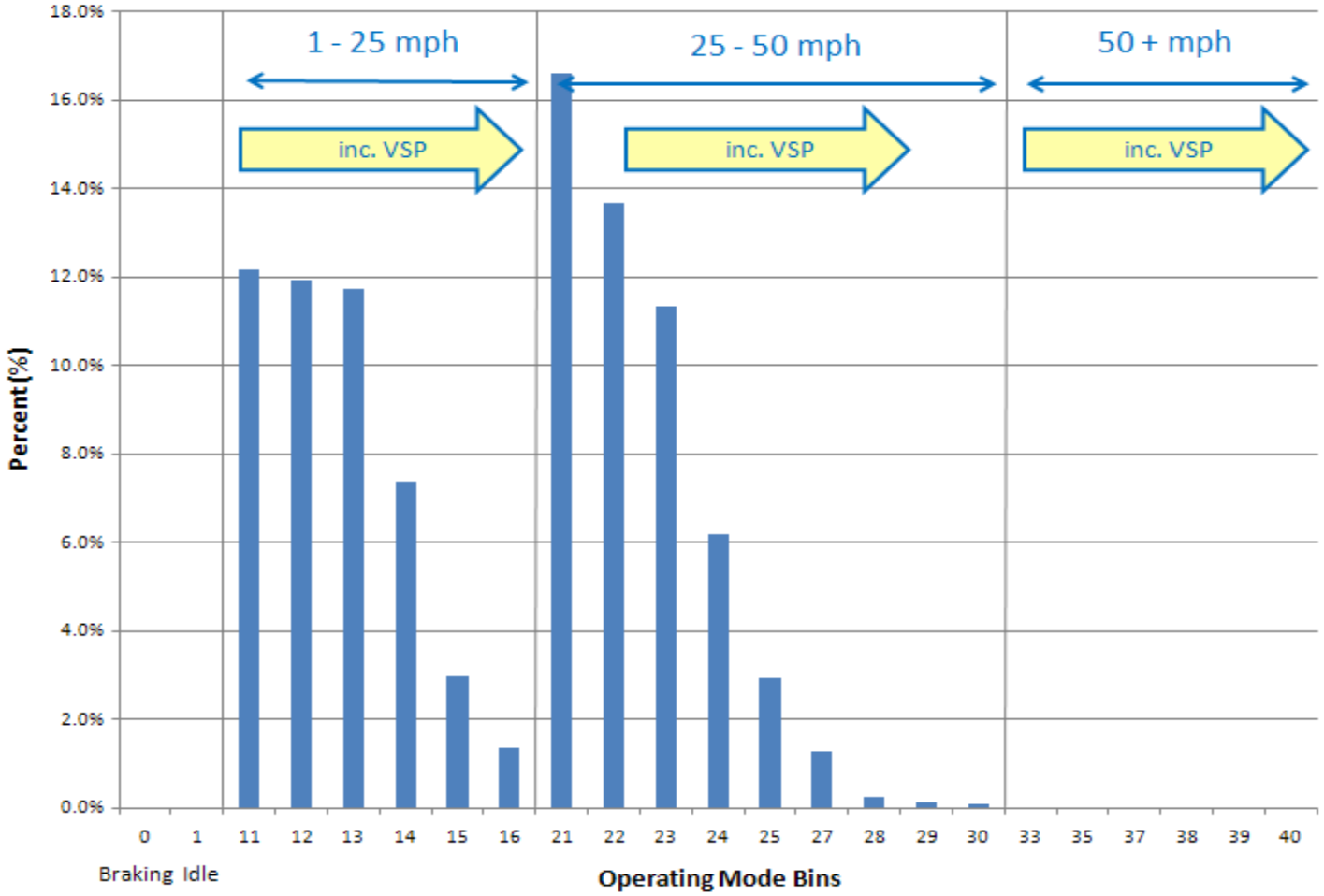
- **Atlanta remote sensing data**
  - Continuous Atlanta Fleet Evaluation (CAFE)[1]
  - CY 2001 – 2008
  - **Number of RSD hits: 58,585** (compared RSD hits)
- **Kansas City dynamometer**
  - KC metropolitan area
  - CY 2004 – 2005
  - LA92 test cycle
    - Bag 2, hot running only (1100 seconds)
  - **Number of tests: 445** (compared test averages)

[1] Performed by Michael Rodgers et.al , Georgia Tech University

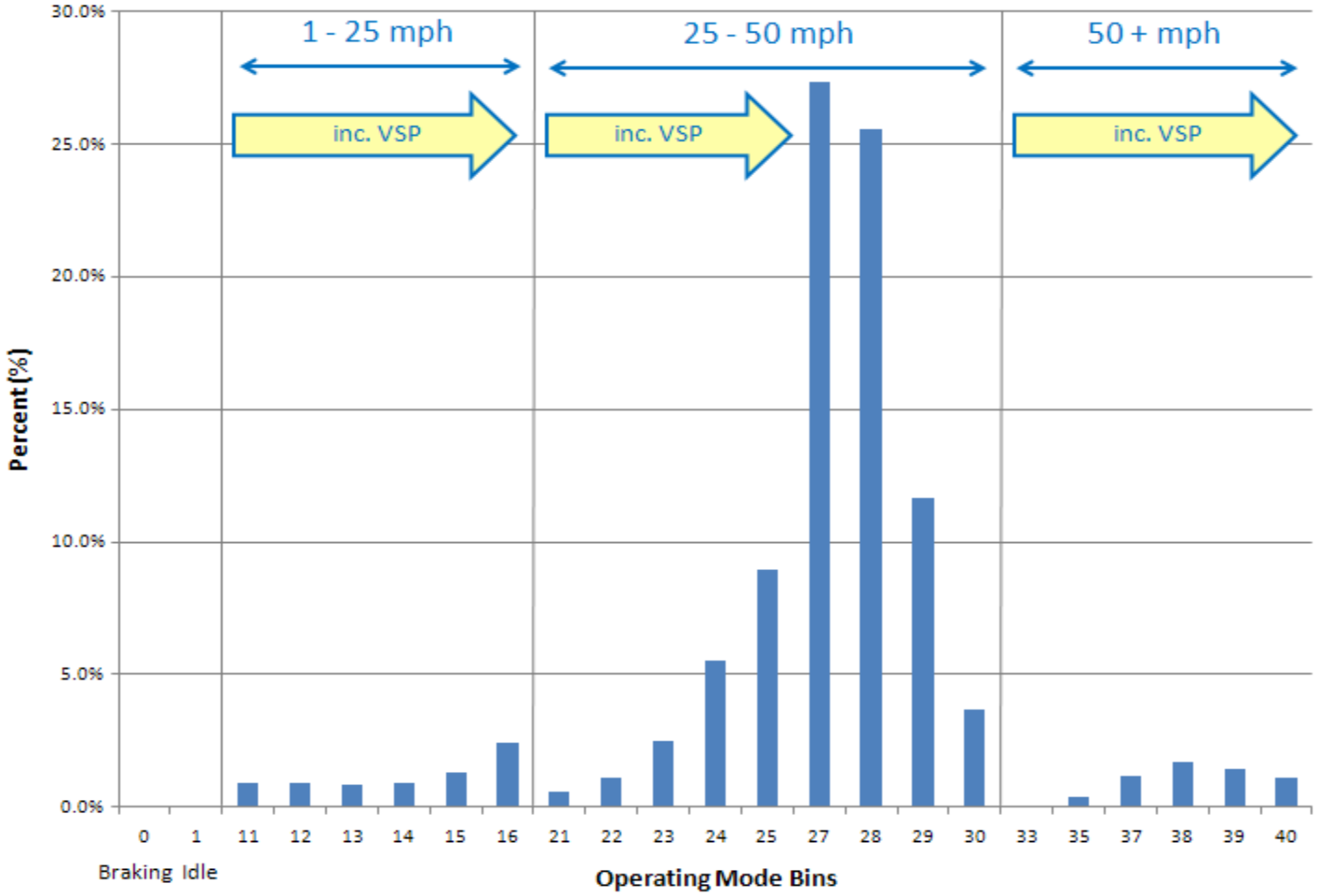
Chicago I/M Opmode Distribution



Chicago RSD Opmode Distribution

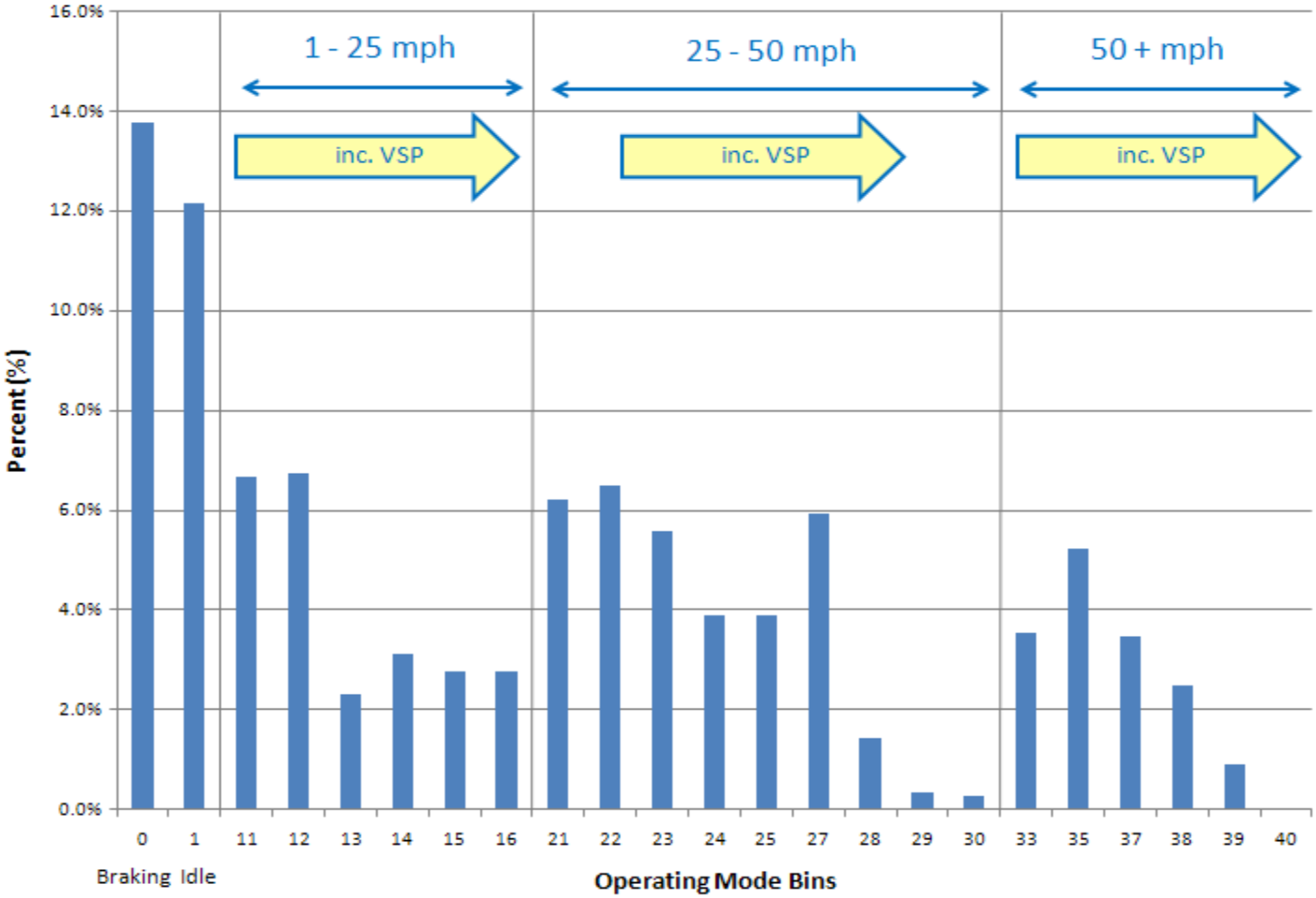


Atlanta RSD
Opmode Distribution



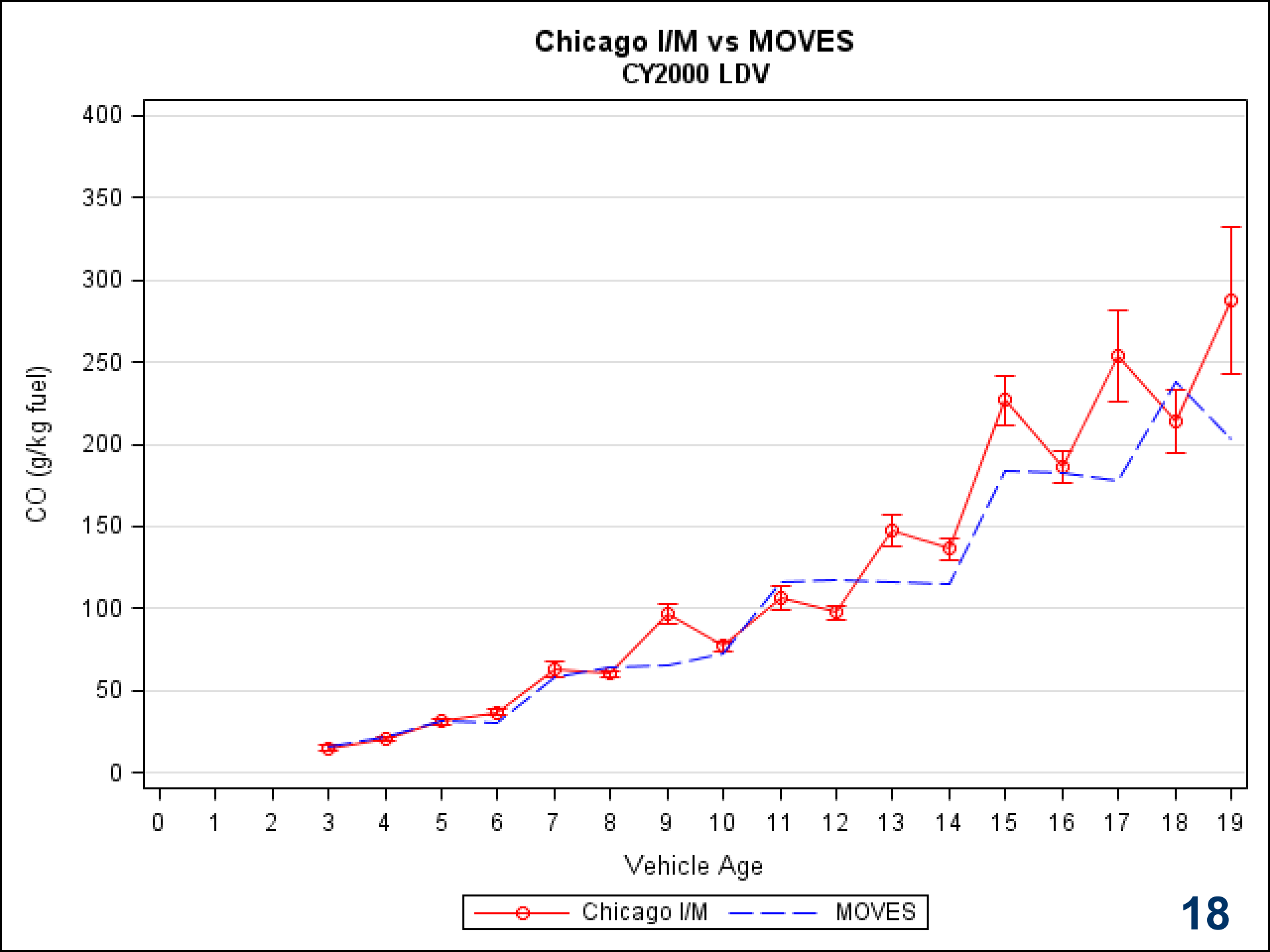
MOVES

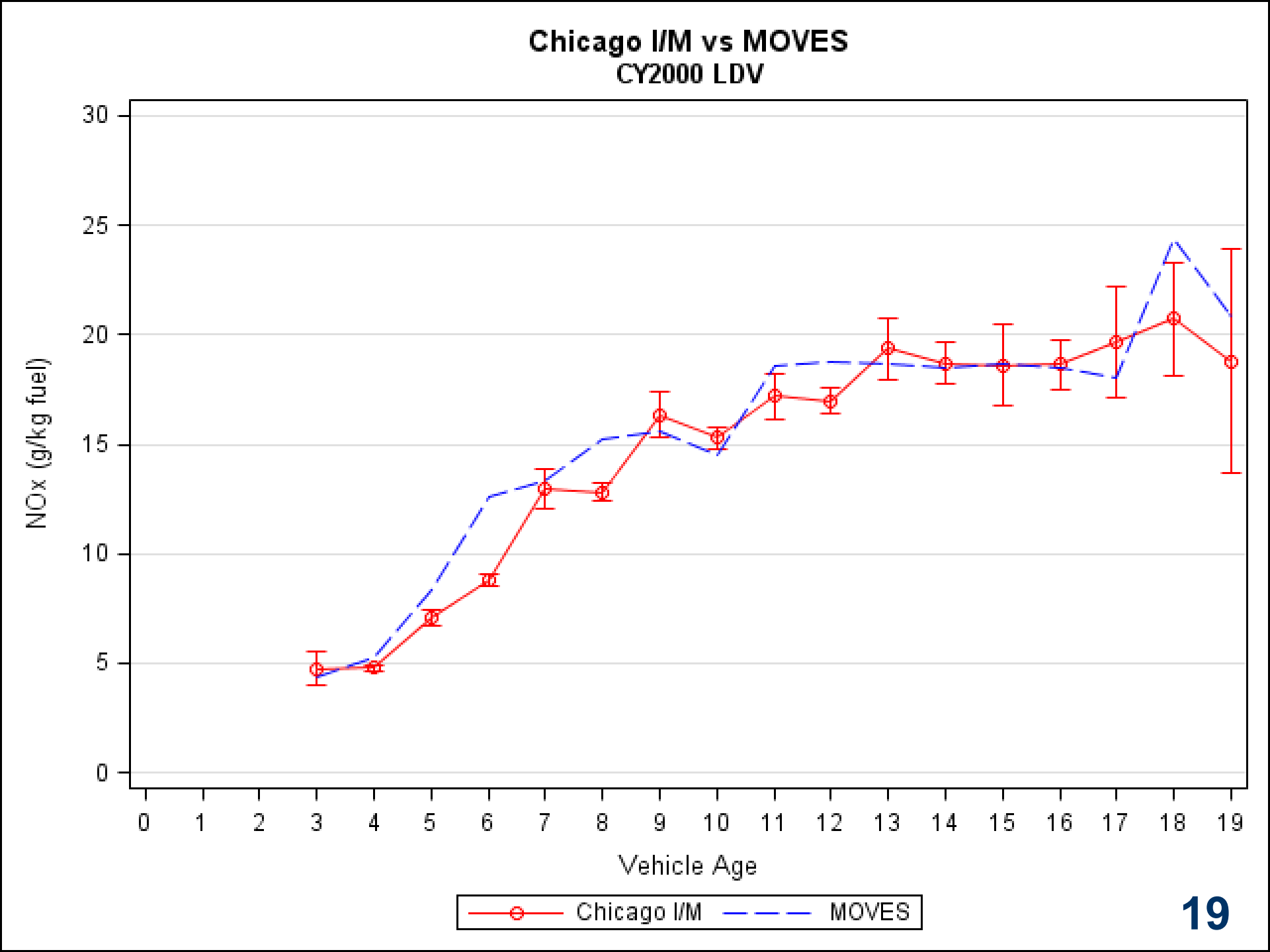
Kansas City Dyno Opmode Distribution

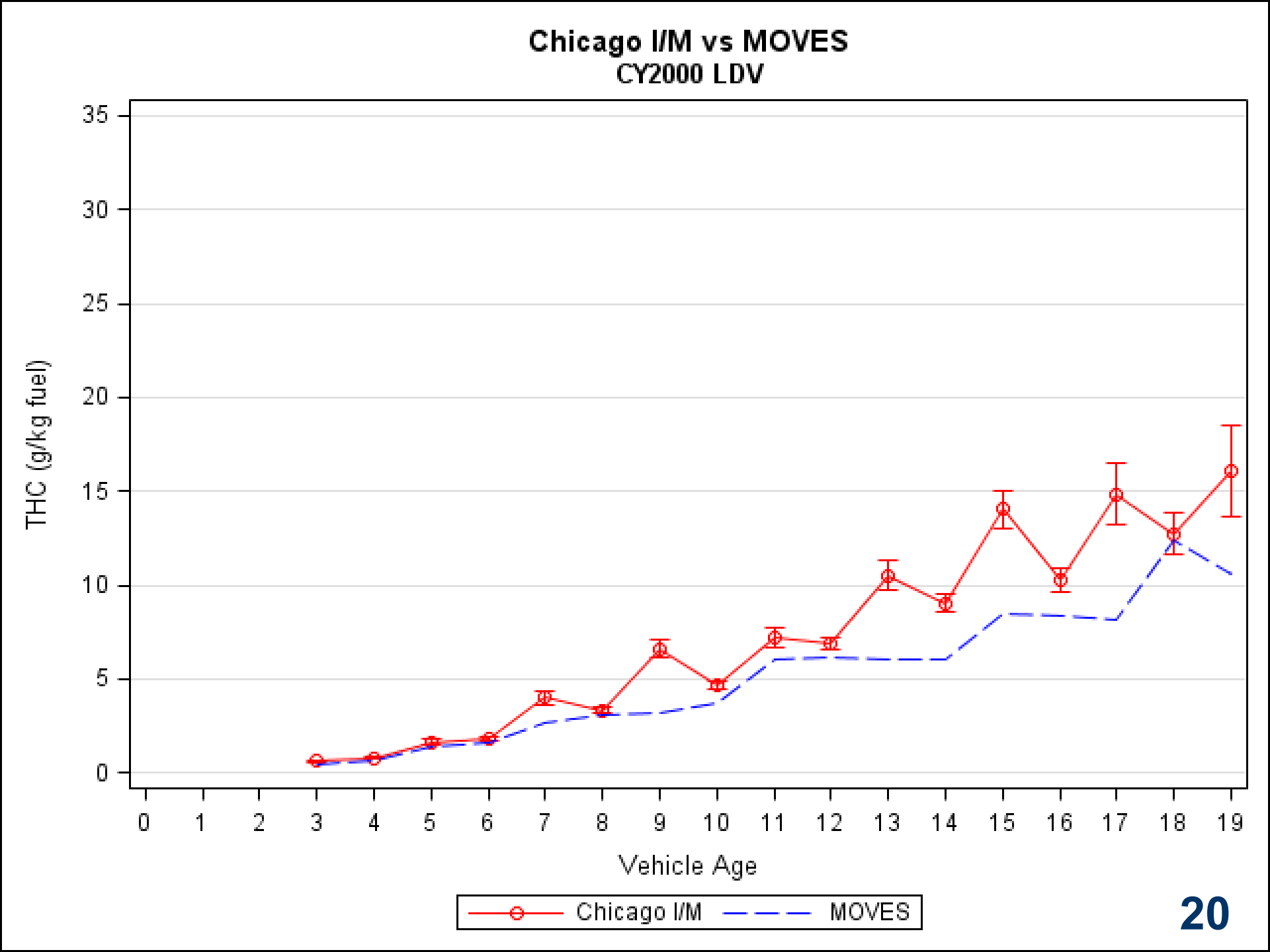


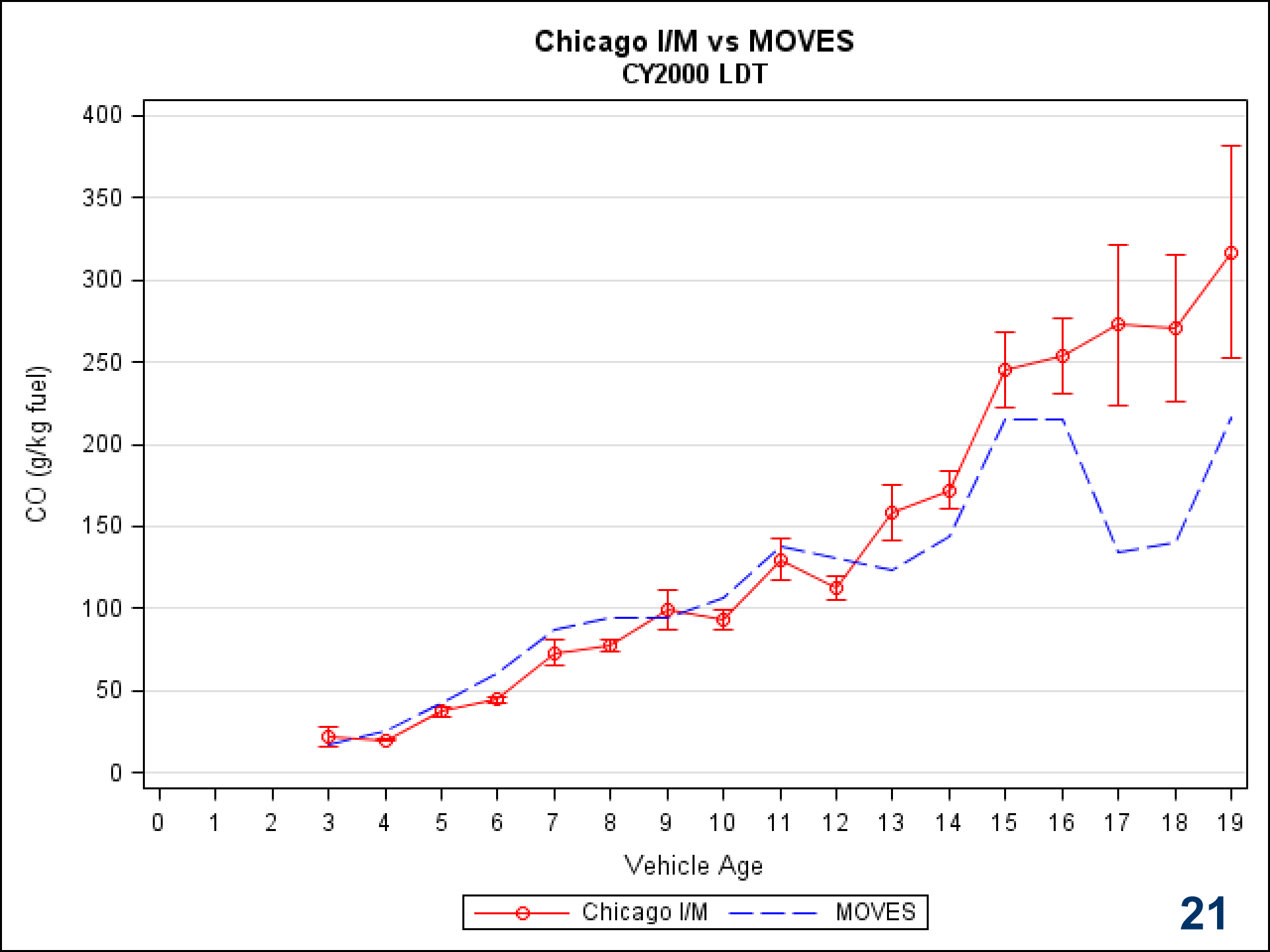
Limitations

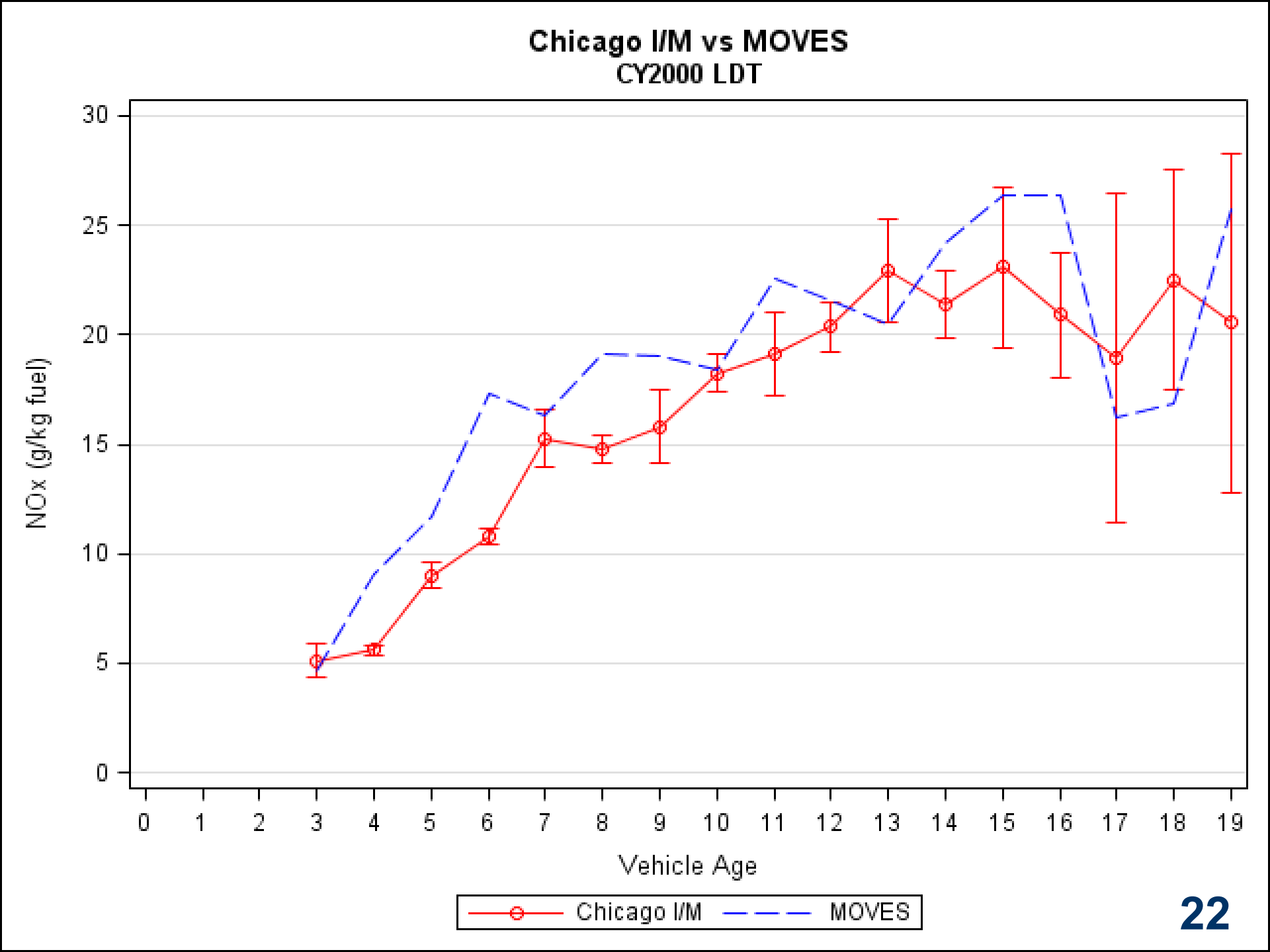
- **Representativeness of independent data**
  - Single measurement characterizes the vehicle's emission profile
  - Obtained measurements define the vehicle population and are assumed to be representative
- **Comparison made in fuel-based emission rates**
  - Potential differences between MOVES estimation 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**

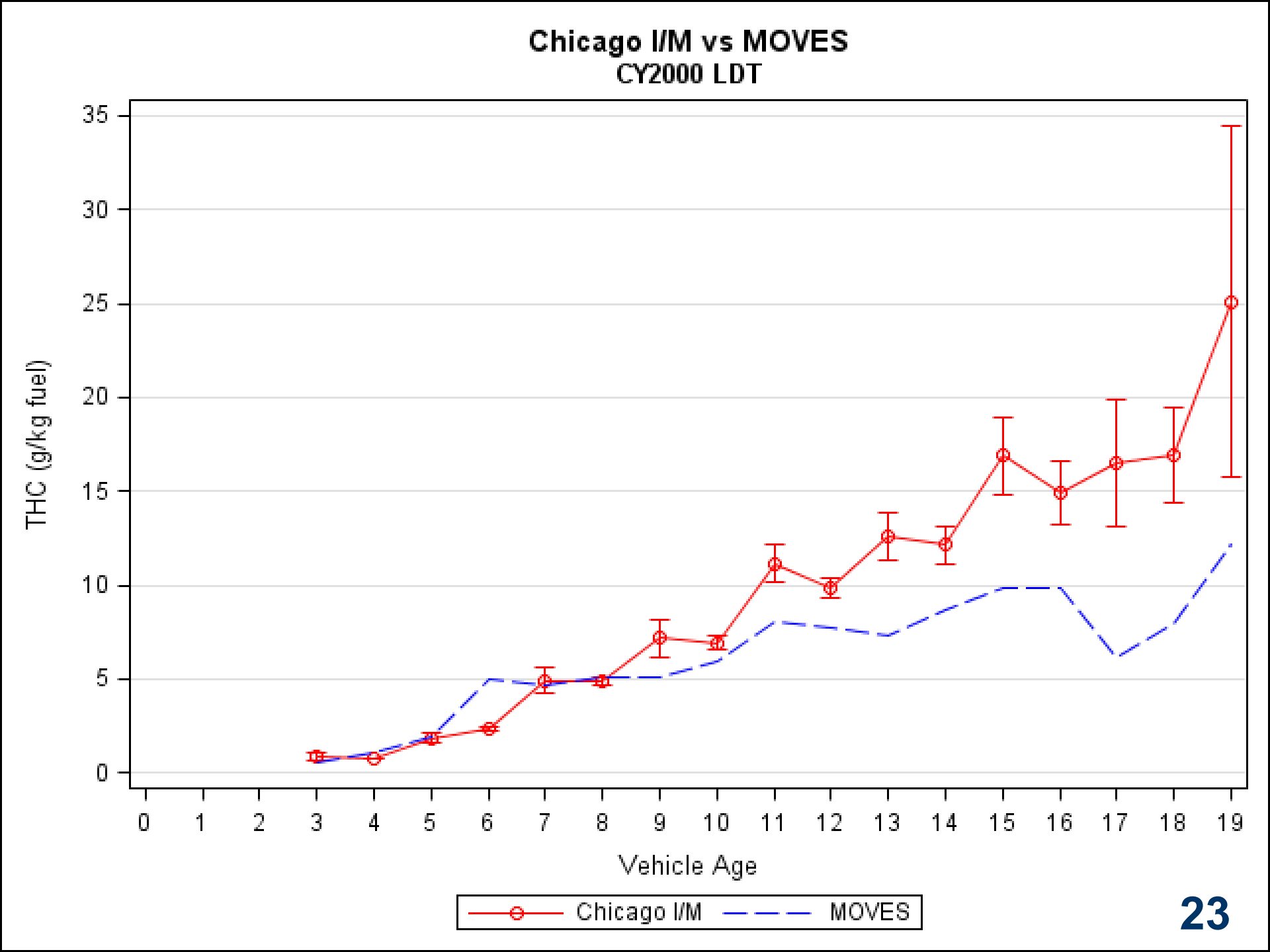

Chicago I/M vs MOVES
CY2000 LDV
CO (g/kg fuel)
400
350
300
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Vehicle Age
Chicago I/M
MOVES

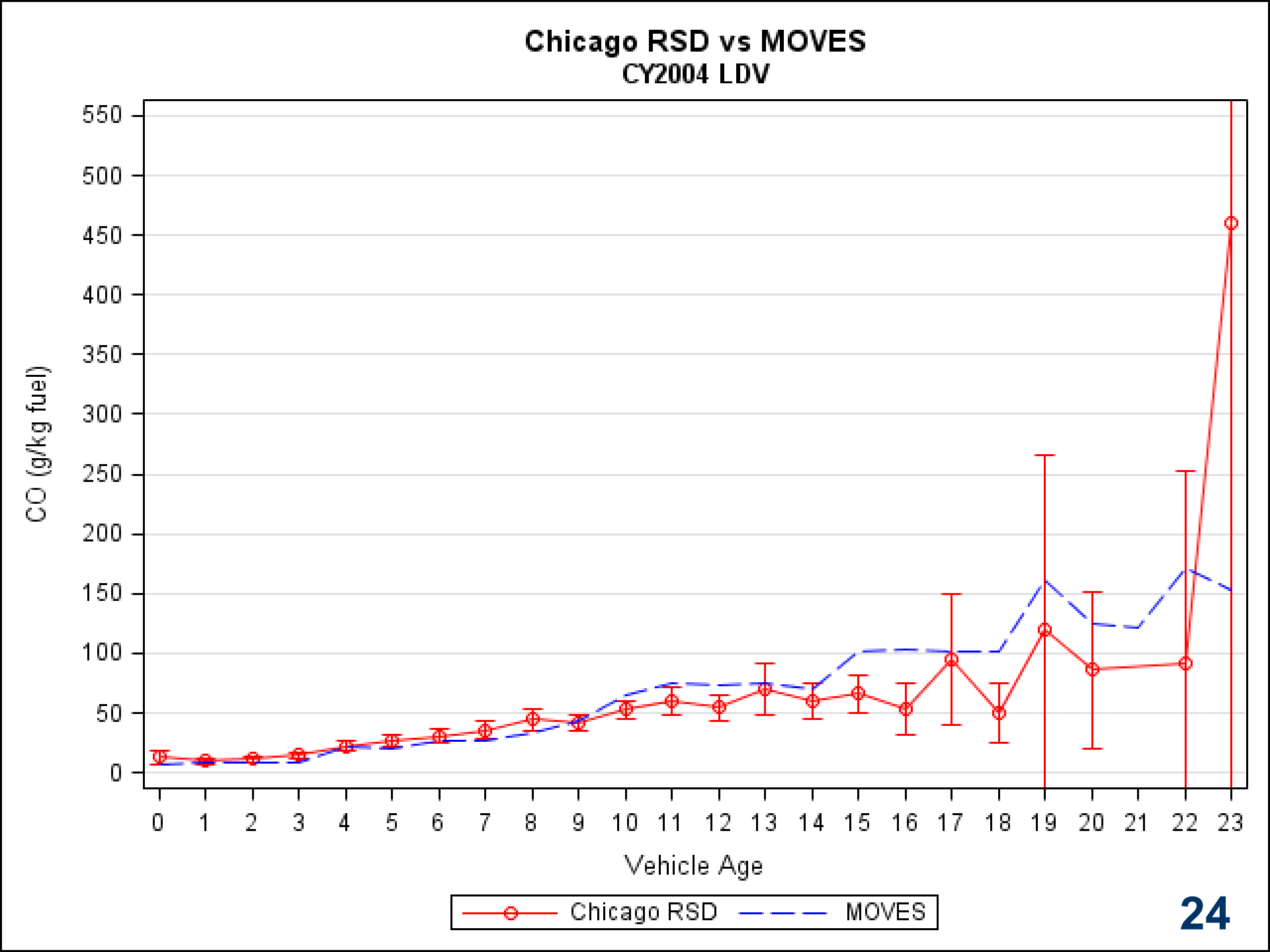

Chicago I/M vs MOVES
CY2000 LDV
NOx (g/kg fuel)
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Vehicle Age
Chicago I/M
MOVES

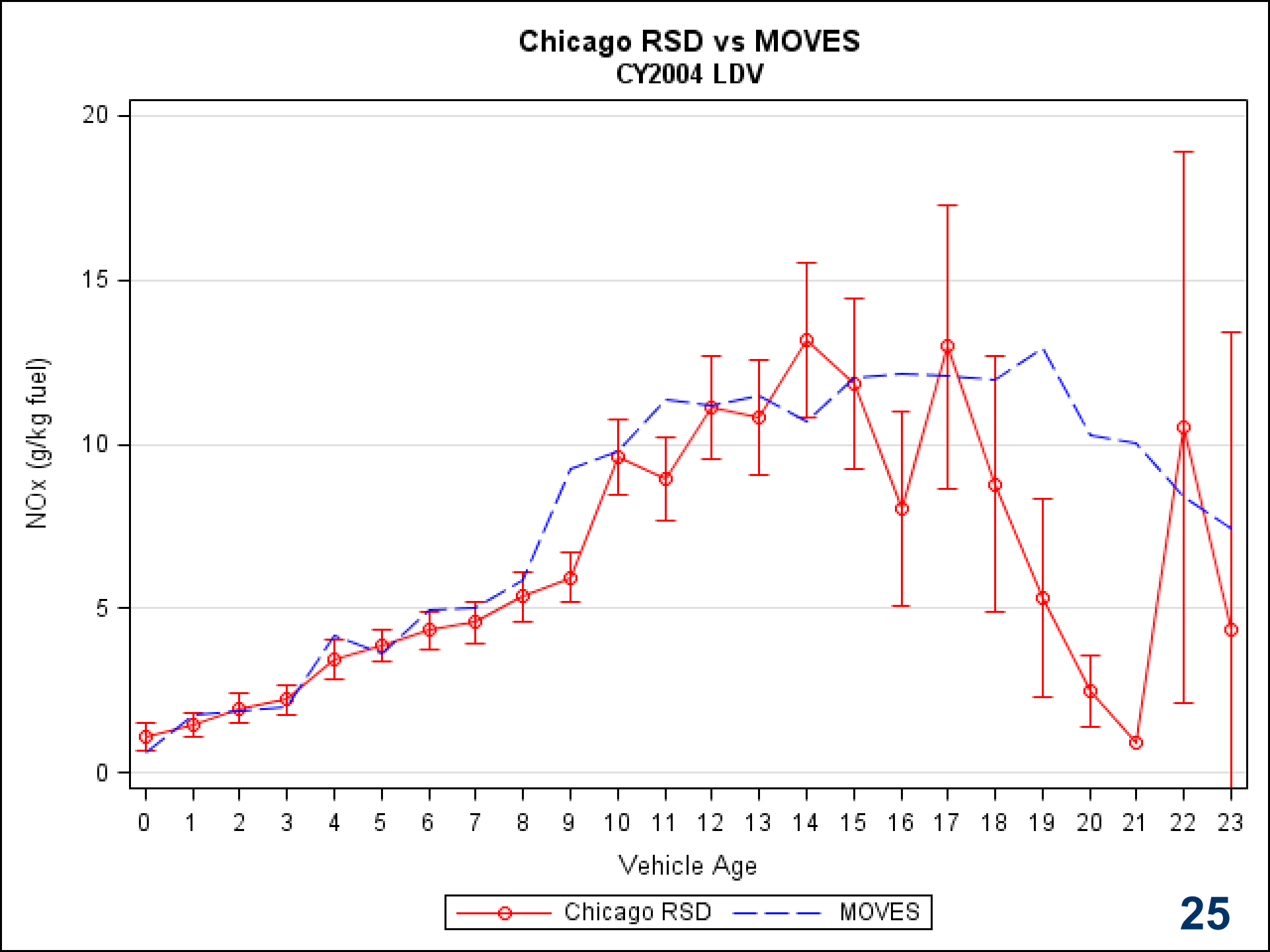

Chicago I/M vs MOVES
CY2000 LDV
THC (g/kg fuel)
35
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Vehicle Age
Chicago I/M
MOVES

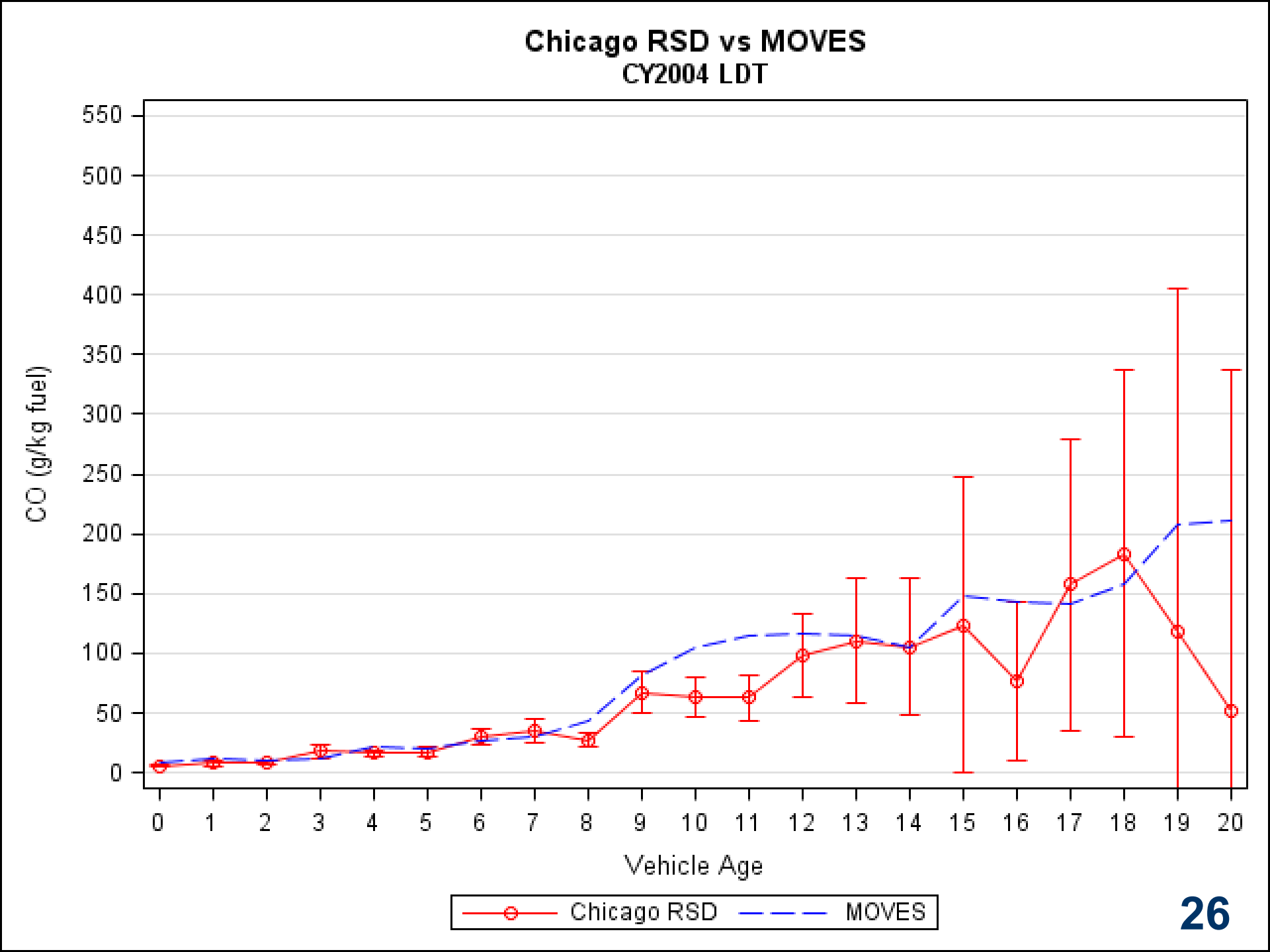

Chicago I/M vs MOVES
CY2000 LDT
CO (g/kg fuel)
400
350
300
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Vehicle Age
Chicago I/M
MOVES

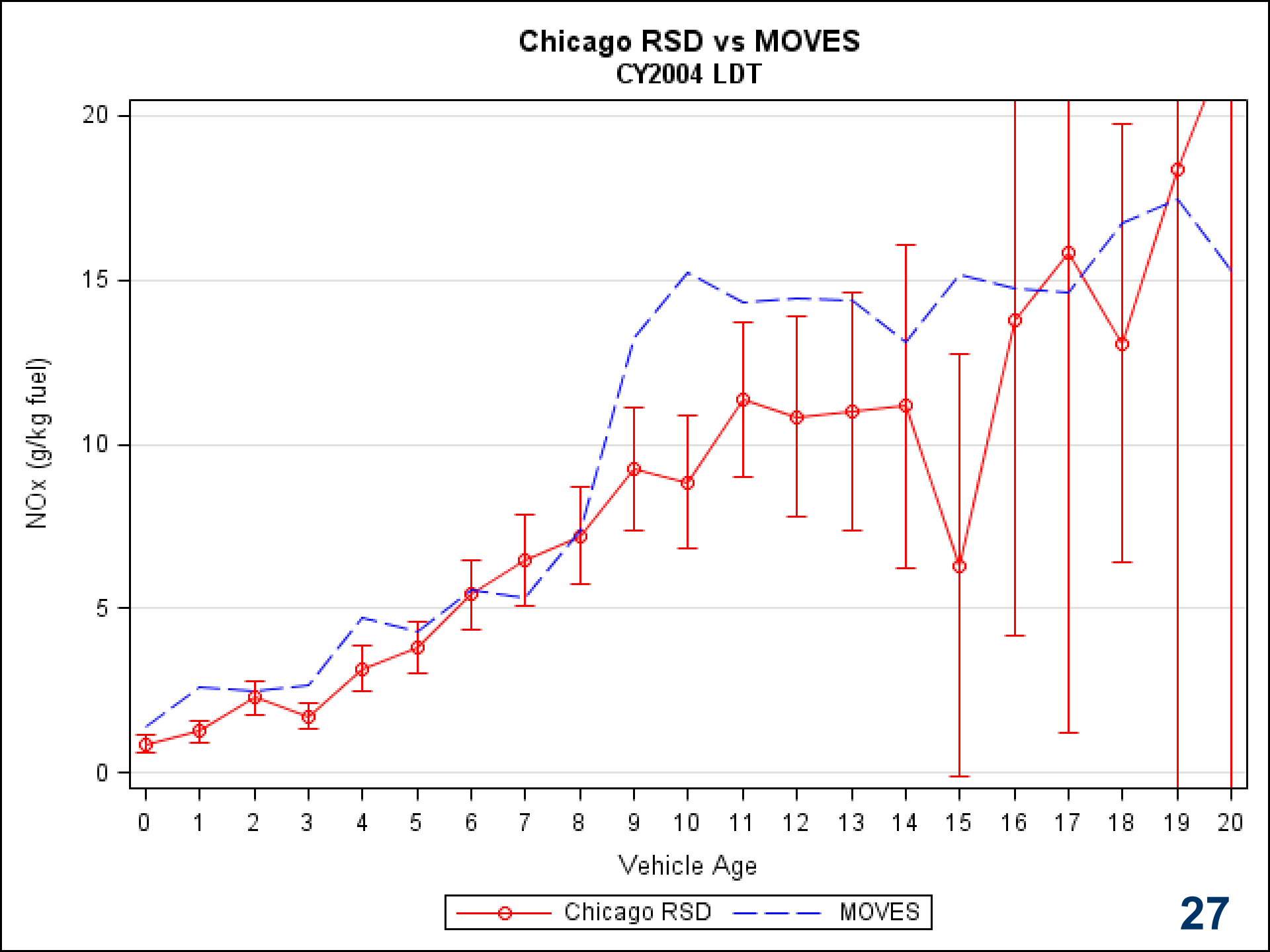

Chicago I/M vs MOVES
CY2000 LDT
NOx (g/kg fuel)
0
5
10
15
20
25
30
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Vehicle Age
Chicago I/M
MOVES

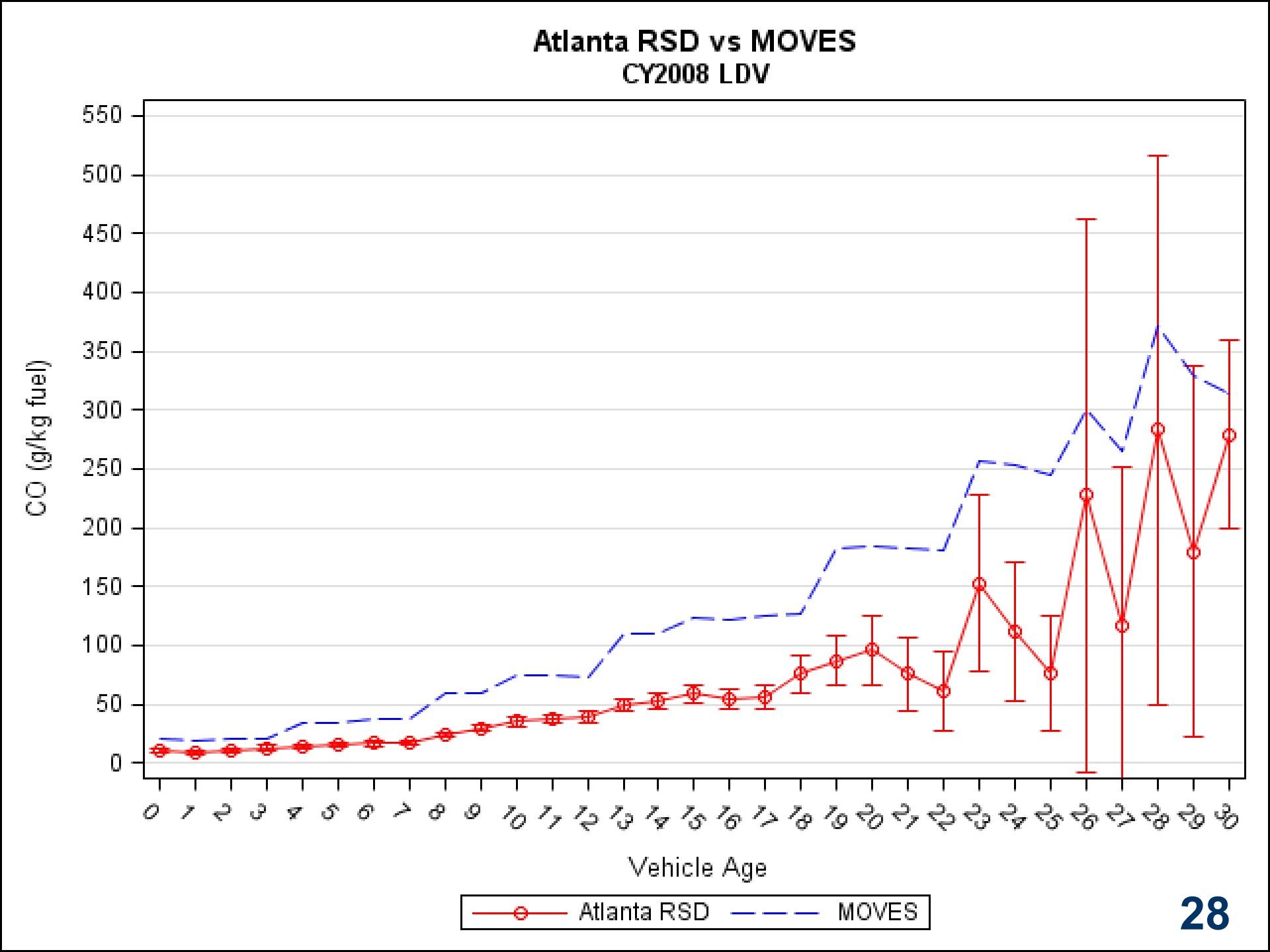

Chicago I/M vs MOVES
CY2000 LDT
THC (g/kg fuel)
35
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Vehicle Age
Chicago I/M
MOVES

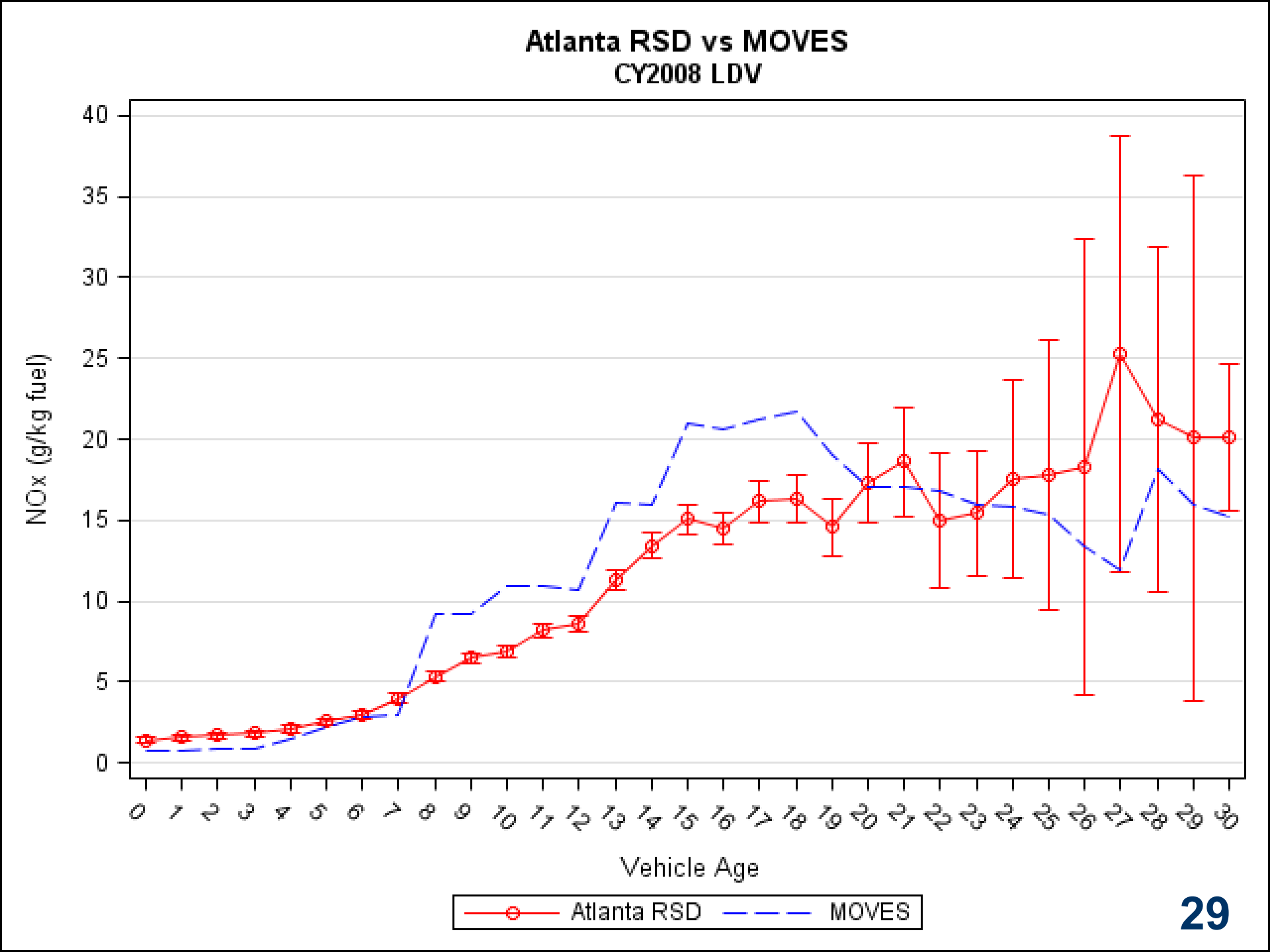

Chicago RSD vs MOVES
CY2004 LDV
CO (g/kg fuel)
550
500
450
400
350
300
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Vehicle Age
Chicago RSD
MOVES

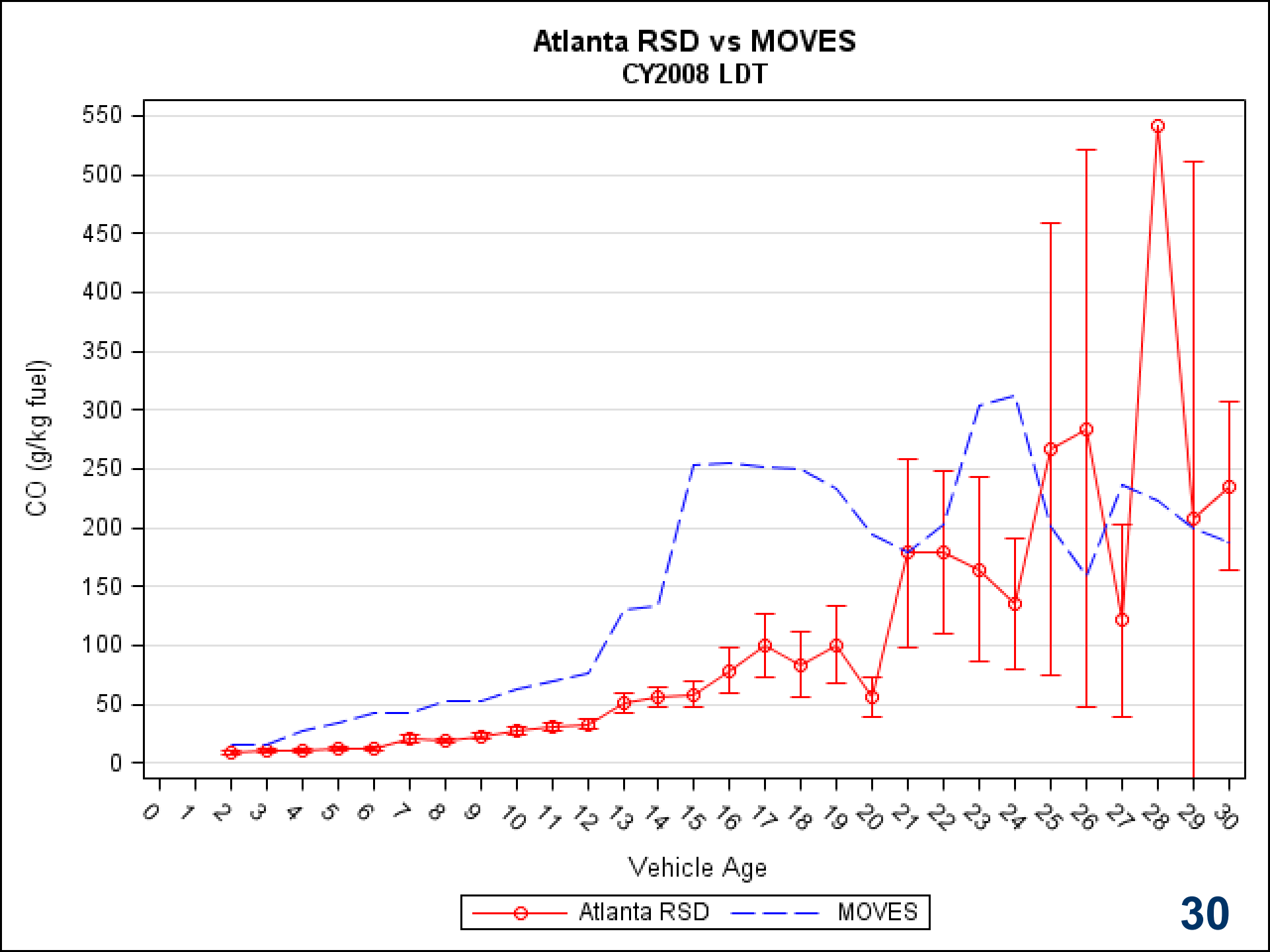

Chicago RSD vs MOVES
CY2004 LDV
NOx (g/kg fuel)
0
5
10
15
20
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Vehicle Age
Chicago RSD
MOVES

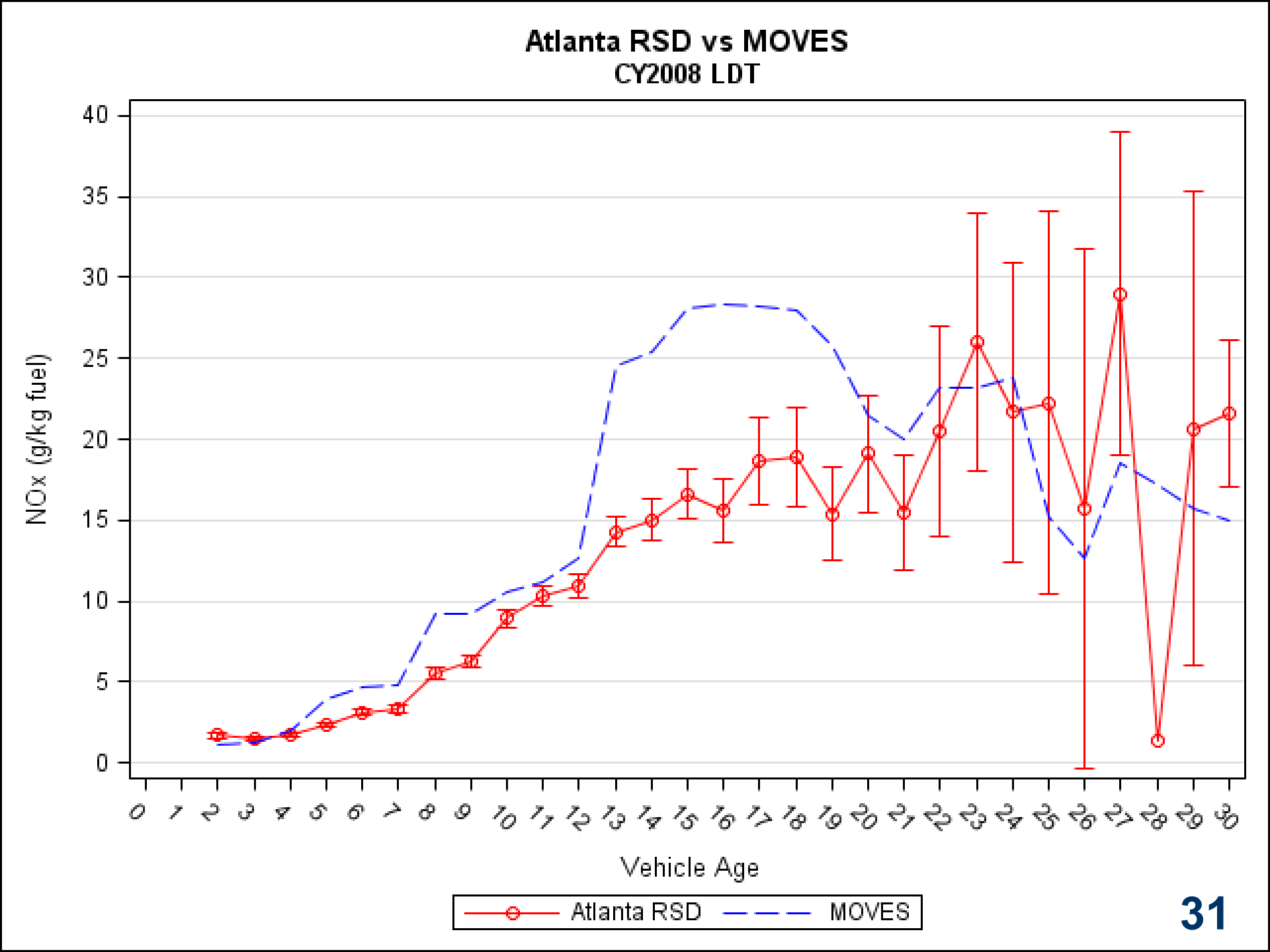

Chicago RSD vs MOVES
CY2004 LDT
CO (g/kg fuel)
550
500
450
400
350
300
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Vehicle Age
Chicago RSD
MOVES

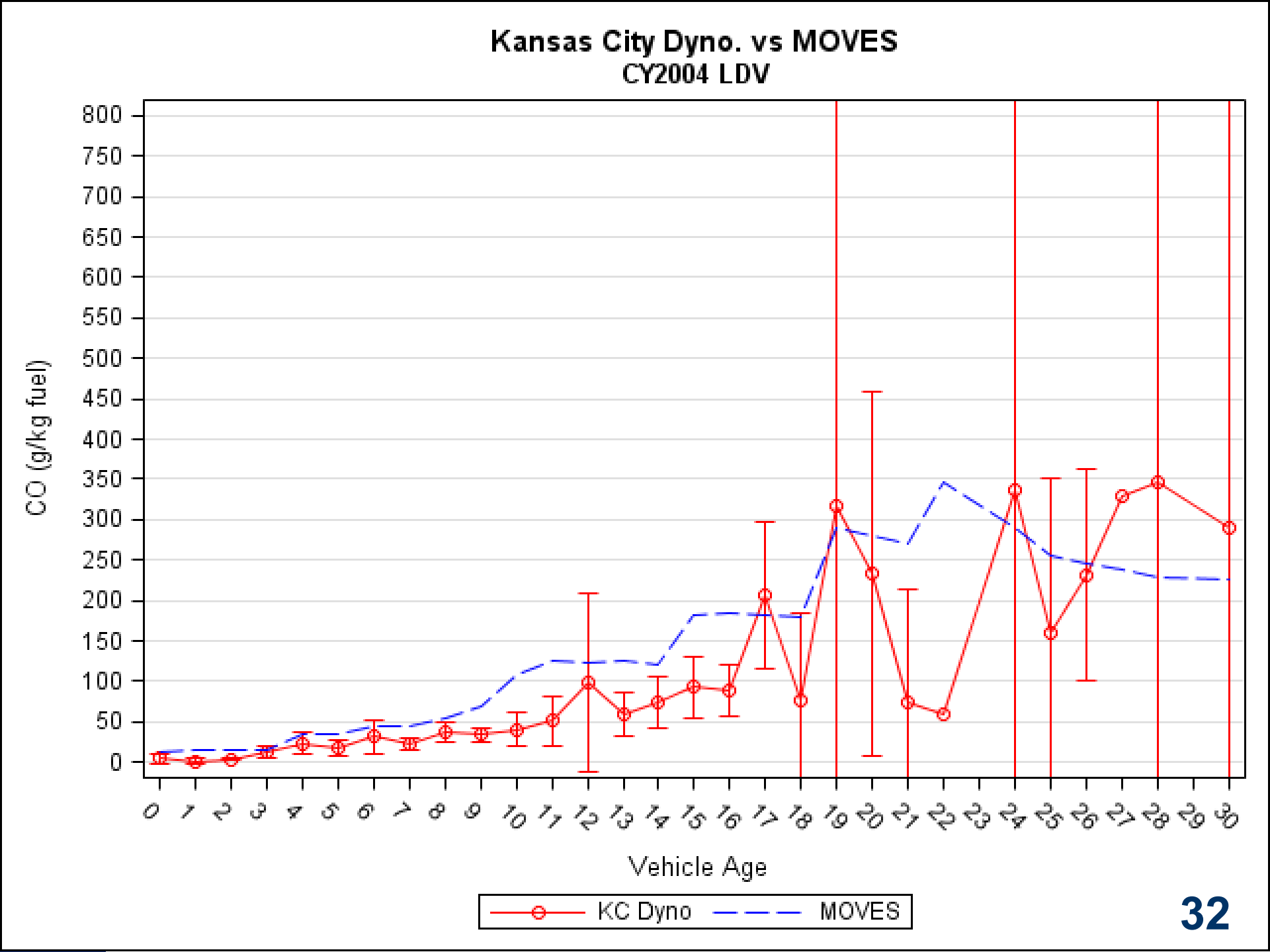

Chicago RSD vs MOVES
CY2004 LDT
NOx (g/kg fuel)
0
5
10
15
20
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Vehicle Age
Chicago RSD
MOVES

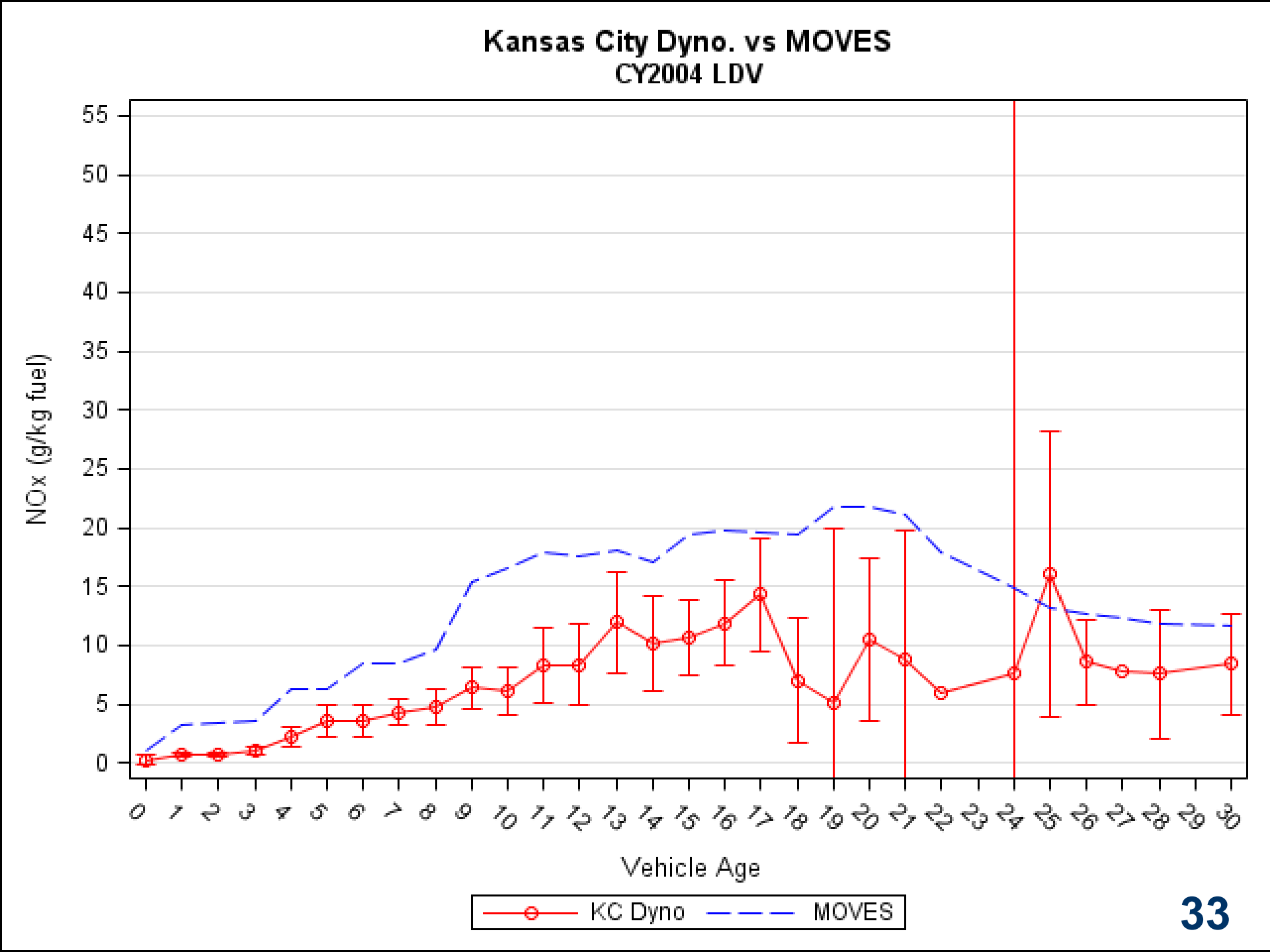

Atlanta RSD vs MOVES
CY2008 LDV
CO (g/kg fuel)
550
500
450
400
350
300
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Vehicle Age
Atlanta RSD
MOVES

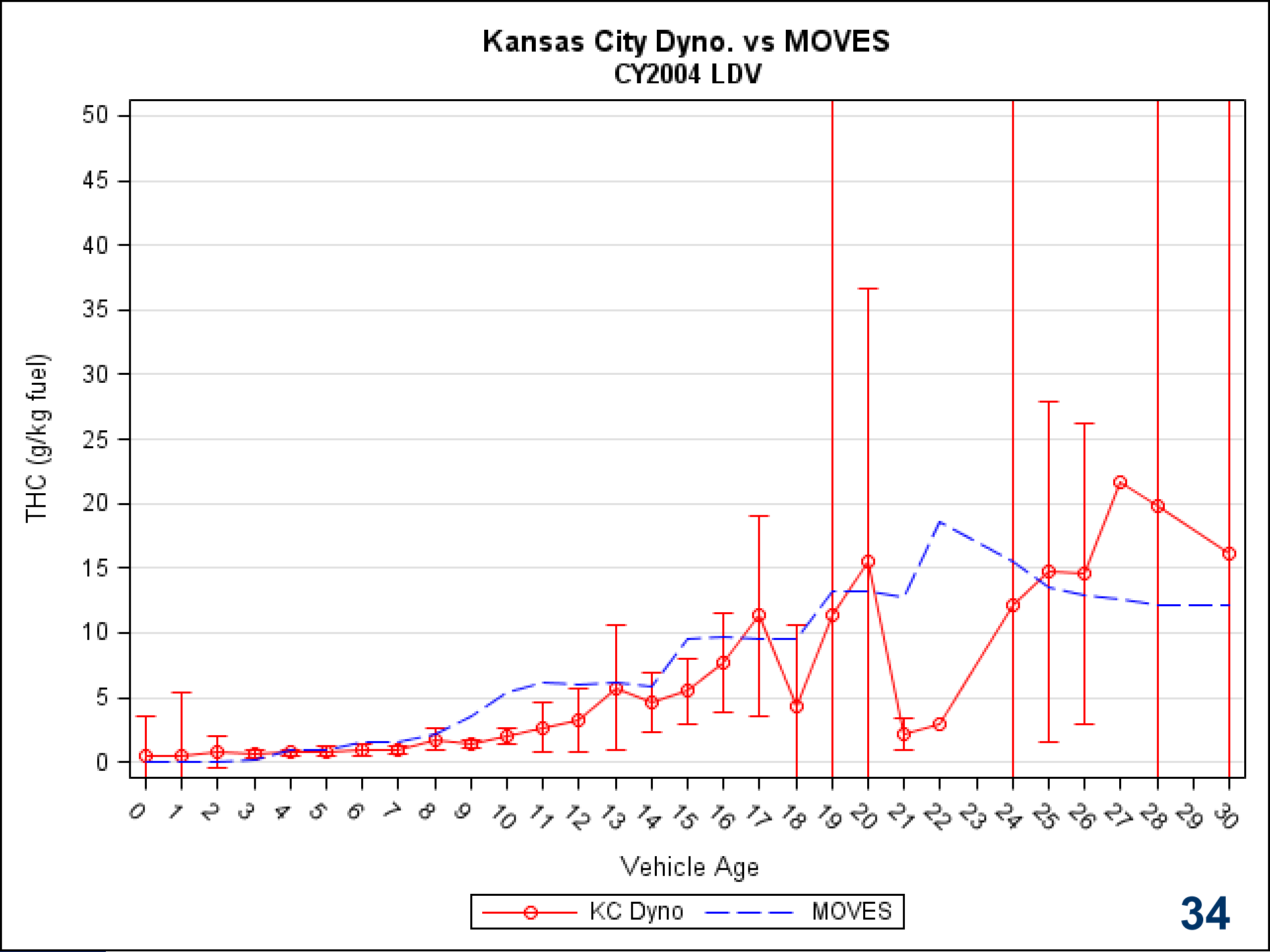

Atlanta RSD vs MOVES
CY2008 LDV
NOx (g/kg fuel)
0
5
10
15
20
25
30
35
40
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Vehicle Age
Atlanta RSD
MOVES

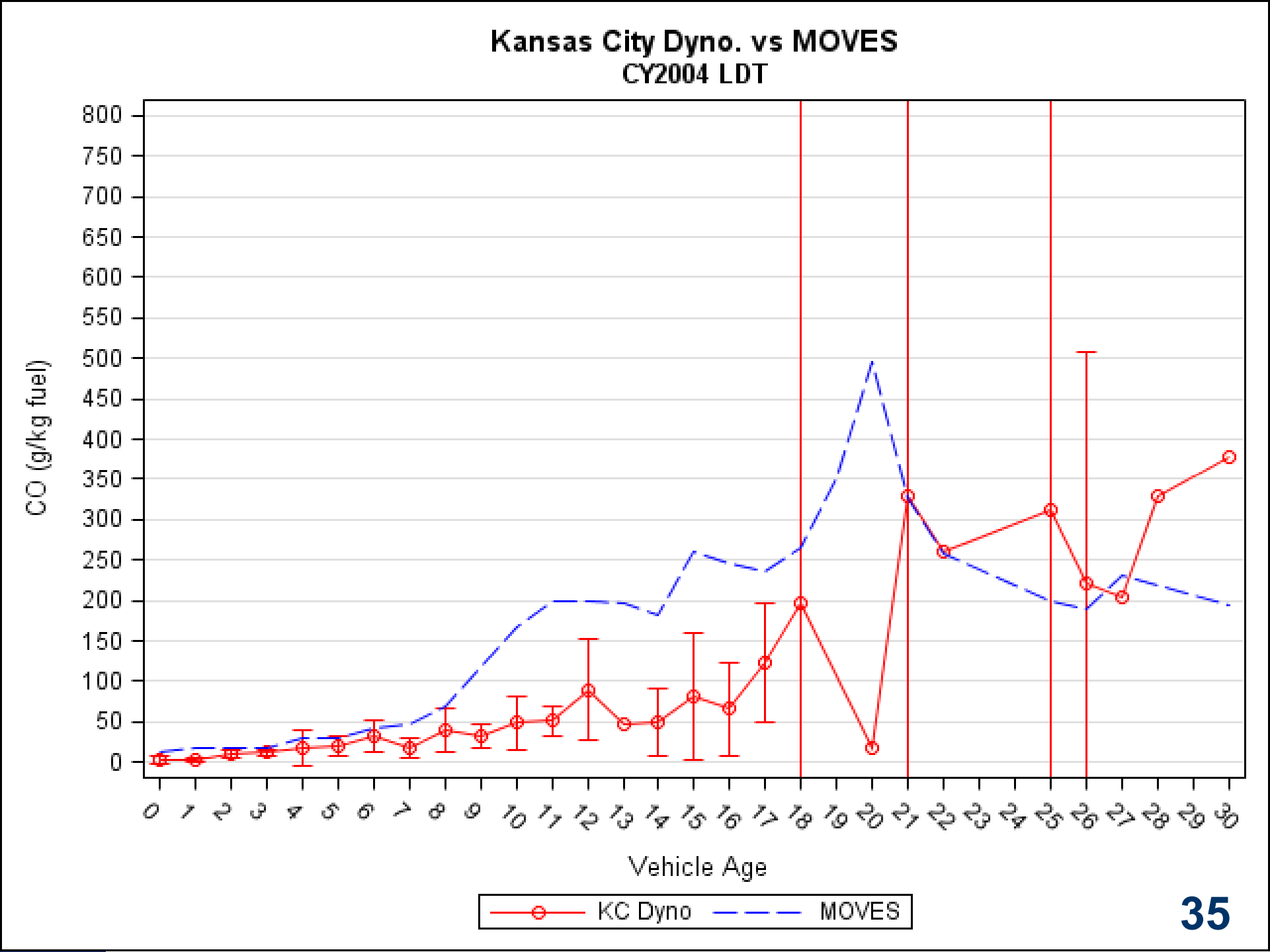

Atlanta RSD vs MOVES
CY2008 LDT
CO (g/kg fuel)
550
500
450
400
350
300
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Vehicle Age
Atlanta RSD
MOVES

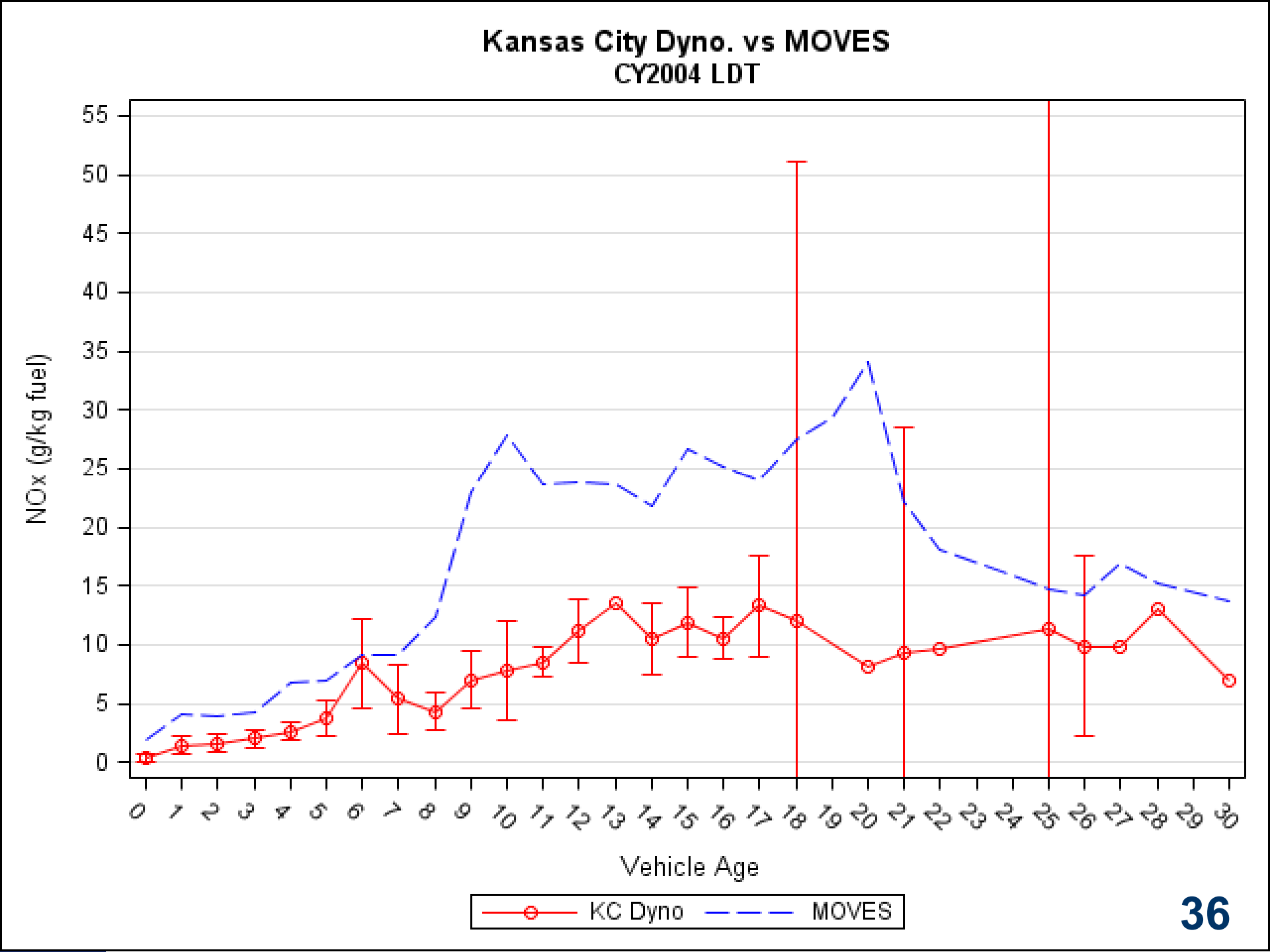

Atlanta RSD vs MOVES
CY2008 LDT
NOx (g/kg fuel)
0
5
10
15
20
25
30
35
40
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Vehicle Age
Atlanta RSD
MOVES

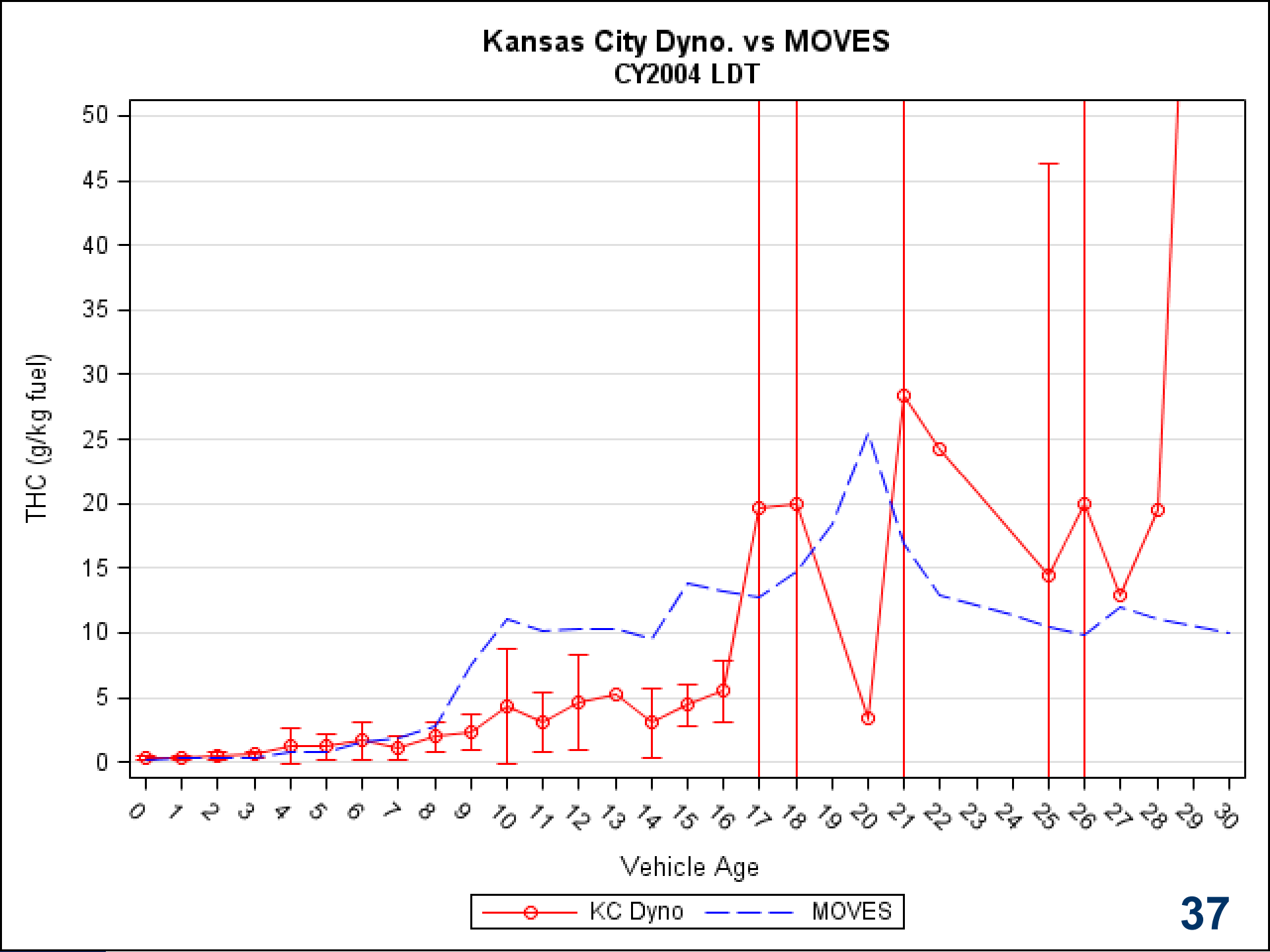

Kansas City Dyno. vs MOVES
CY2004 LDV
CO (g/kg fuel)
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Vehicle Age
KC Dyno
MOVES


Kansas City Dyno. vs MOVES
CY2004 LDV
NOx (g/kg fuel)
55
50
45
40
35
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Vehicle Age
KC Dyno
MOVES

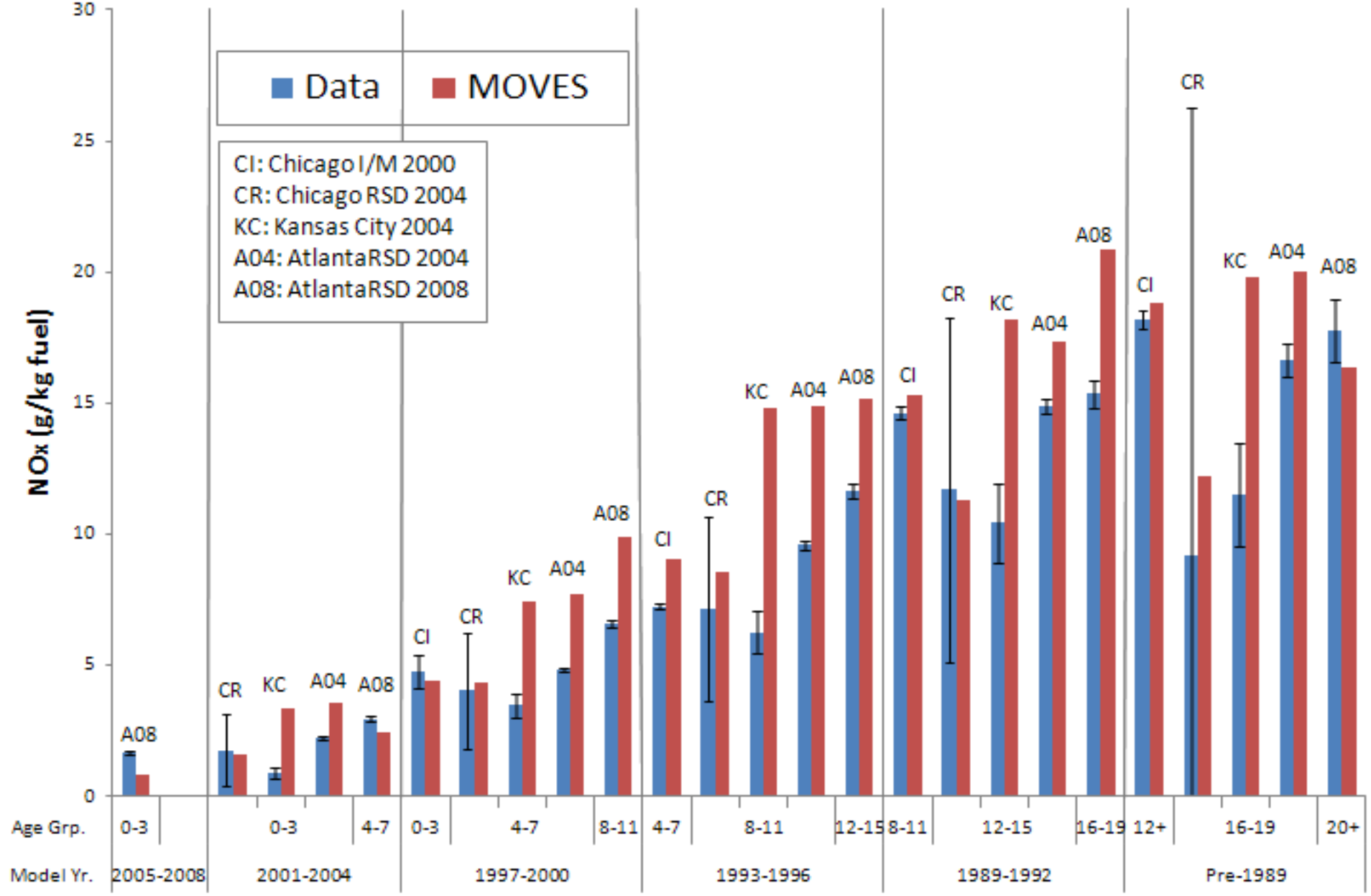

Kansas City Dyno. vs MOVES
CY2004 LDV
THC (g/kg fuel)
50
45
40
35
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Vehicle Age
KC Dyno
MOVES


Kansas City Dyno. vs MOVES
CY2004 LDT
CO (g/kg fuel)
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Vehicle Age
KC Dyno
MOVES

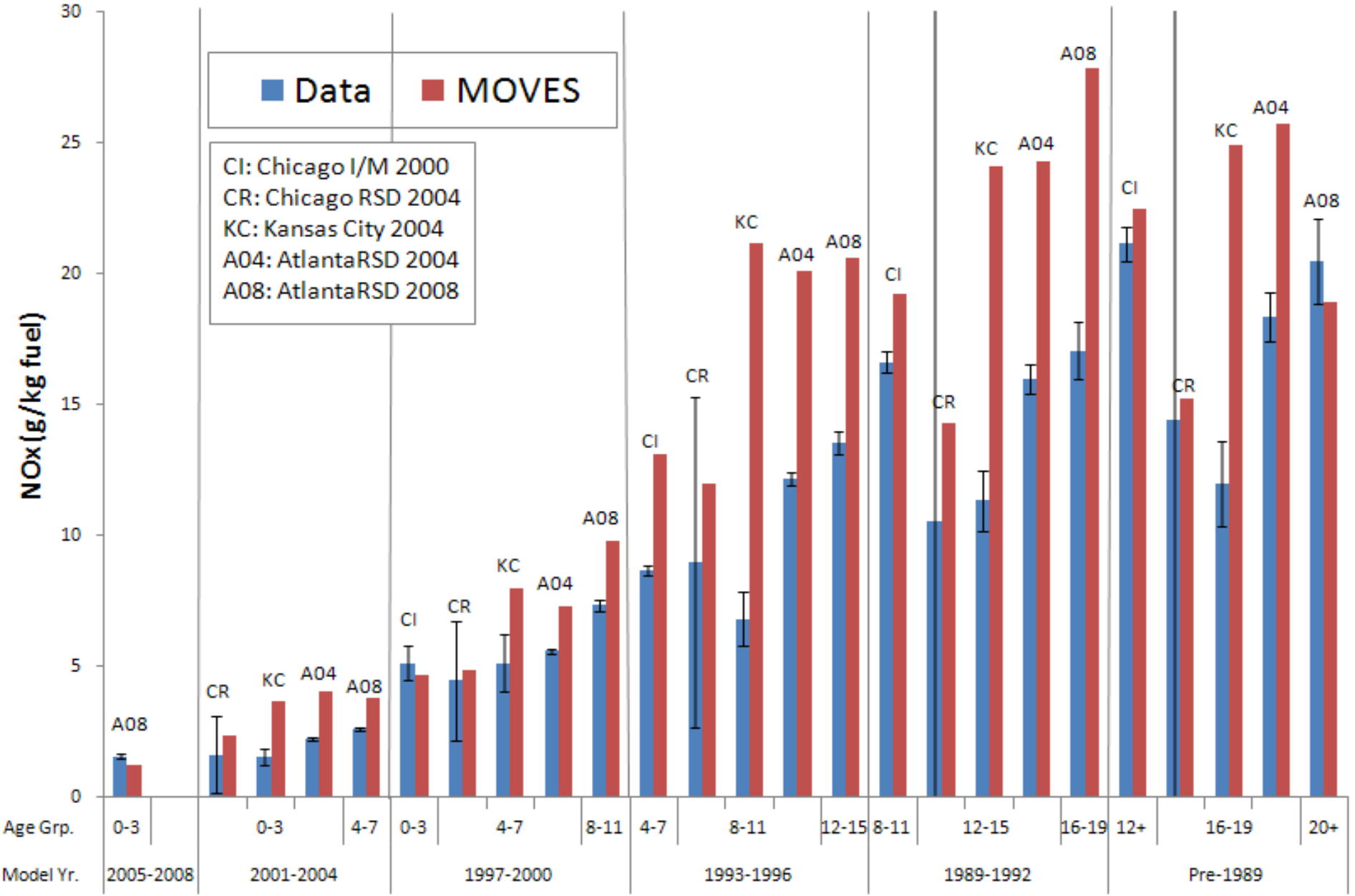

Kansas City Dyno. vs MOVES
CY2004 LDT
NOx (g/kg fuel)
0
5
10
15
20
25
30
35
40
45
50
55
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Vehicle Age
KC Dyno
MOVES


Kansas City Dyno. vs MOVES
CY2004 LDT
THC (g/kg fuel)
50
45
40
35
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Vehicle Age
KC Dyno
MOVES

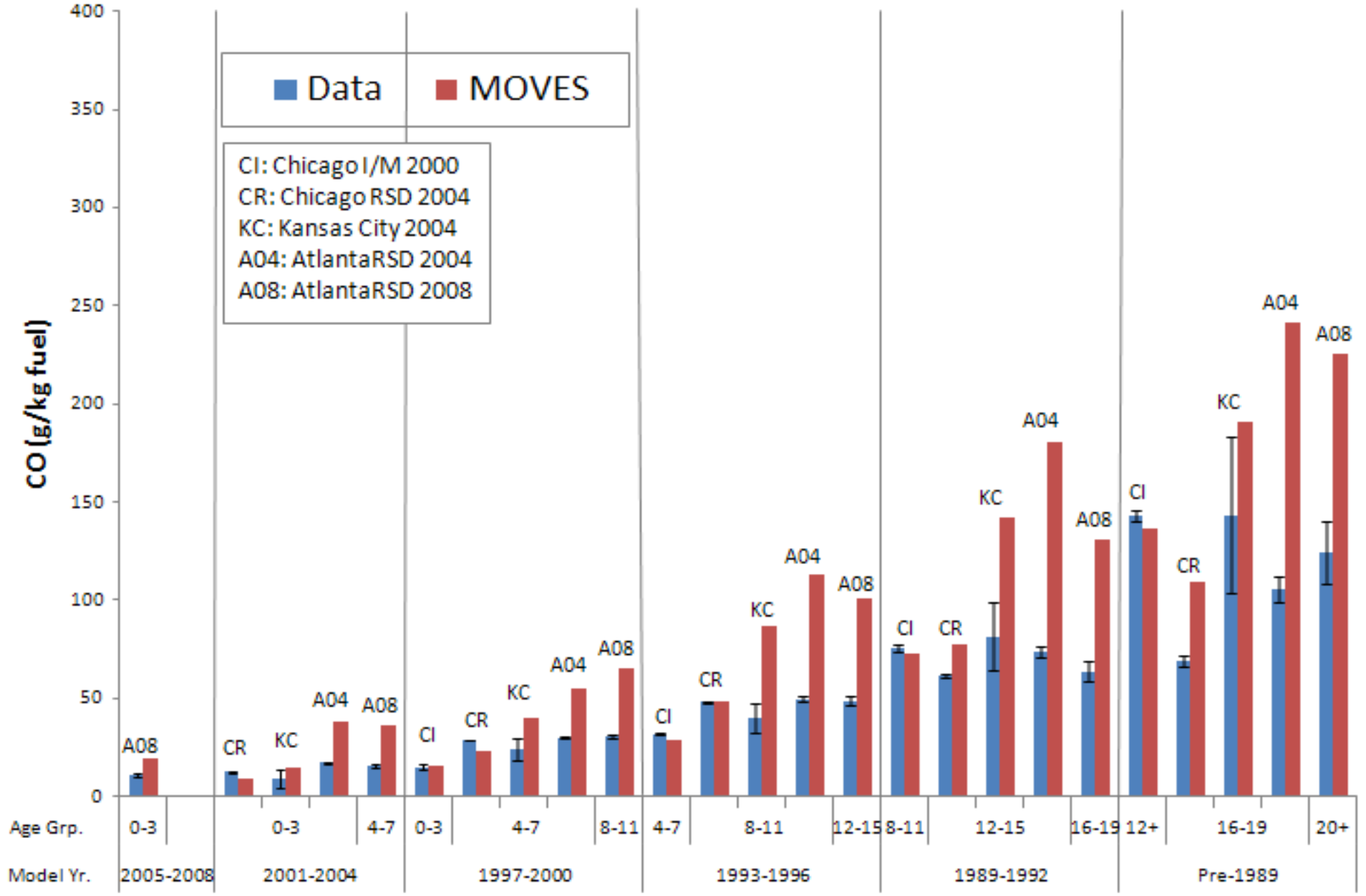
MOVES Validation: Light-Duty Vehicles



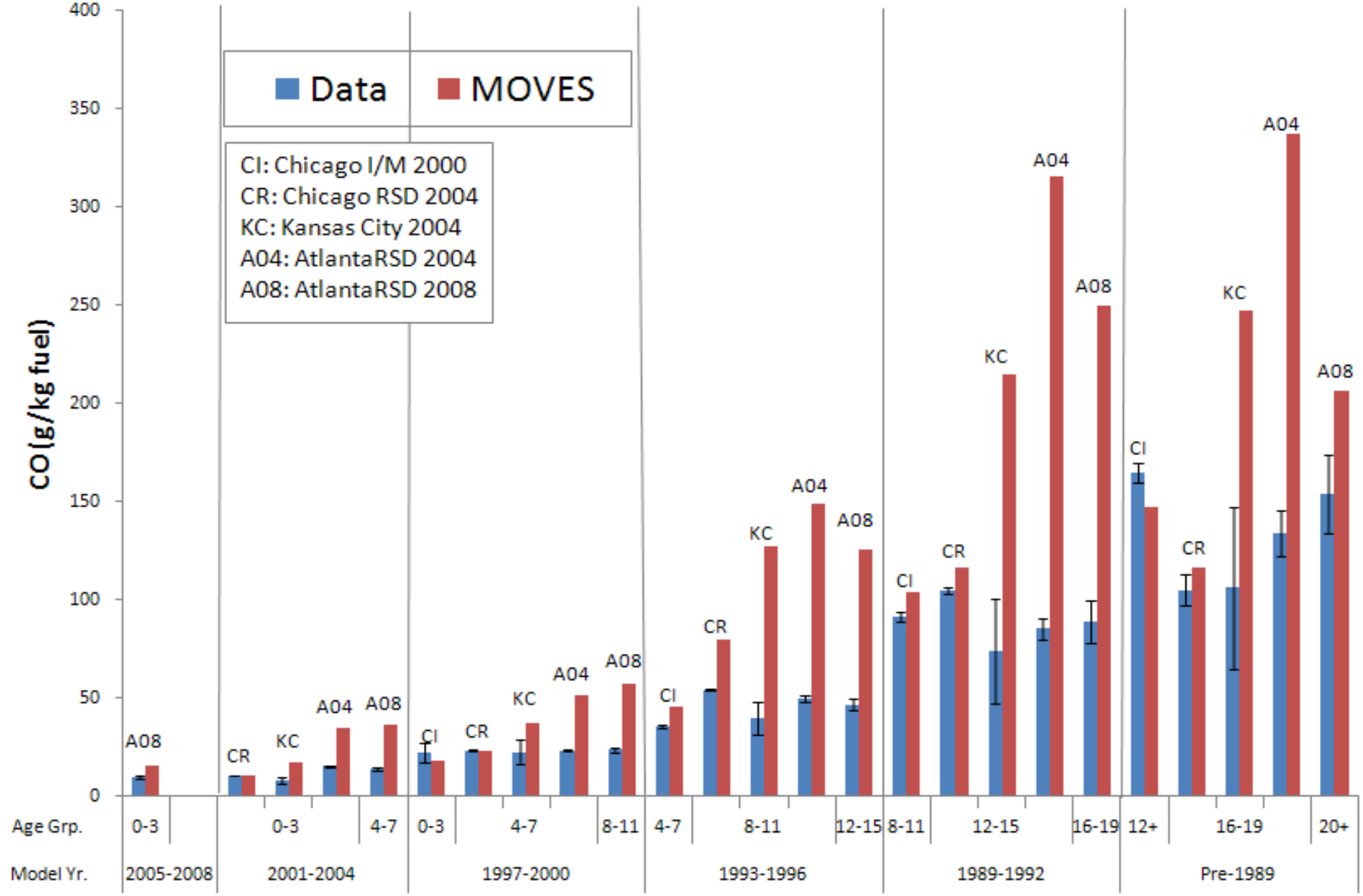
MOVES Validation: Light-Duty Trucks



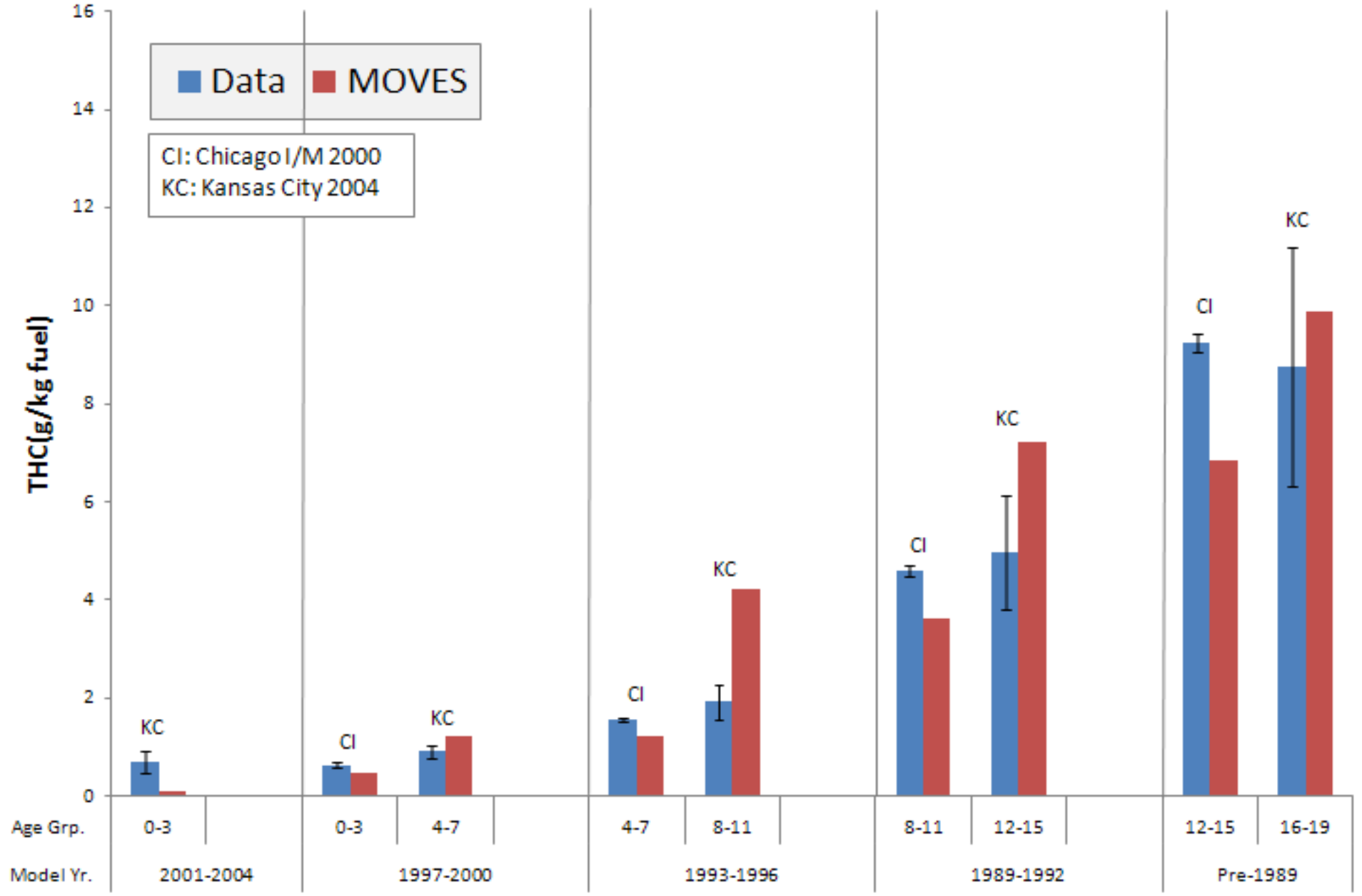
MOVES Validation: Light-Duty Vehicles



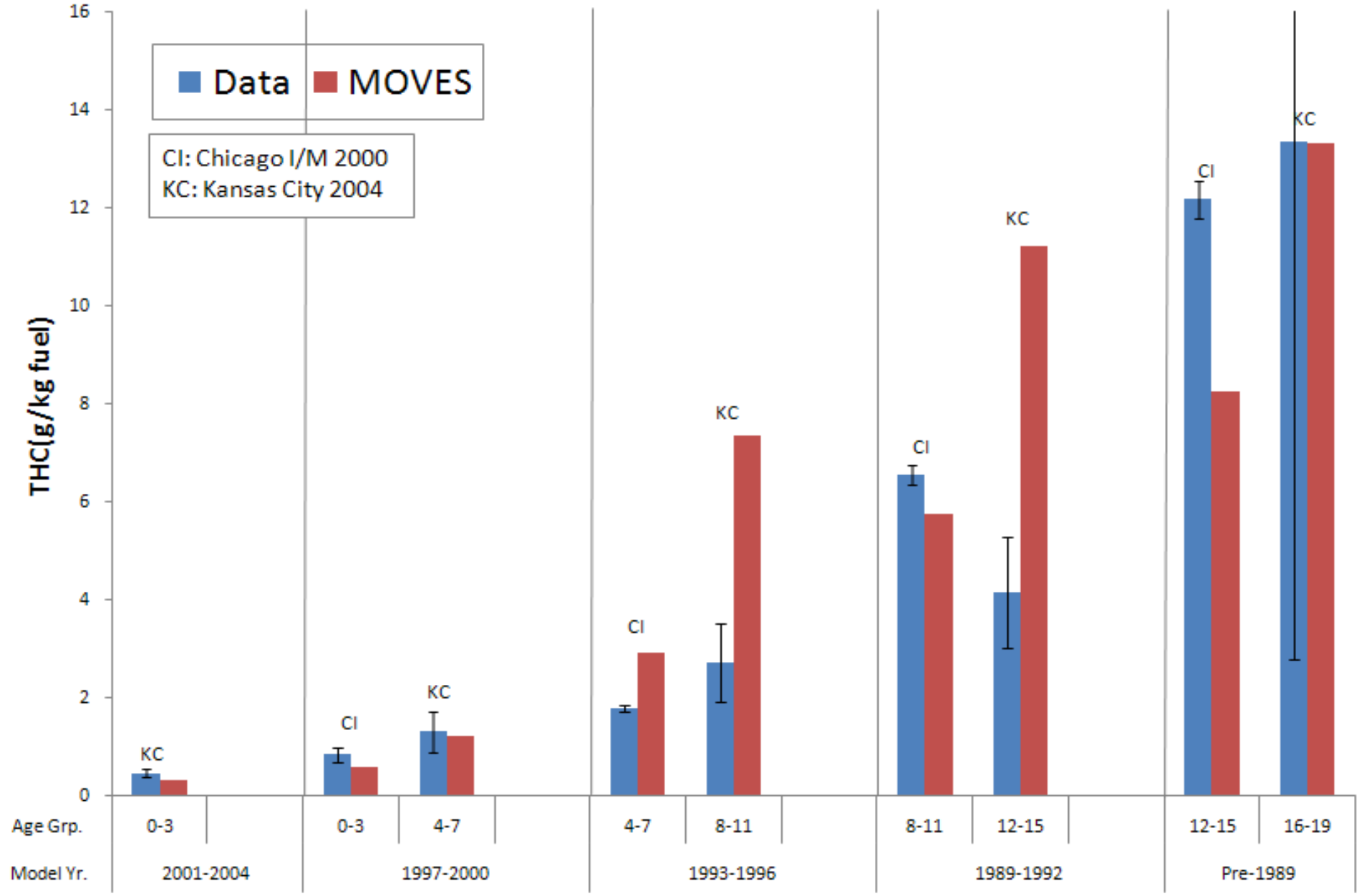
MOVES Validation: Light-Duty Trucks



MOVES Validation: Light-Duty Vehicles



MOVES Validation: Light-Duty Trucks



MOVES

Heavy-Duty Emission Rate Validation: CRC E55/59

- **Conducted in 4 phases from 2001 to 2005**
- **Test Fleet**
  - **52 HHDDT**
  - 15 MHDDT
  - 4 MHDGT
- **Test Cycles**
  - Urban Dynamometer Driving Schedule (UDDS)
  - Creep
  - Transient
  - Cruise
  - “high speed” cruise mode (HHDDT S)

MOVES

Heavy-Duty Emission Rate Validation: Port of Houston Drayage Study RSD[1]

- Conducted by University of Denver & Eastern Research Group
- 2 weeks in July of 2009
- Measured at entry gate of Barbour's Cut port
- Number of unique vehicles: 1,661
- RSD readings: 3,203

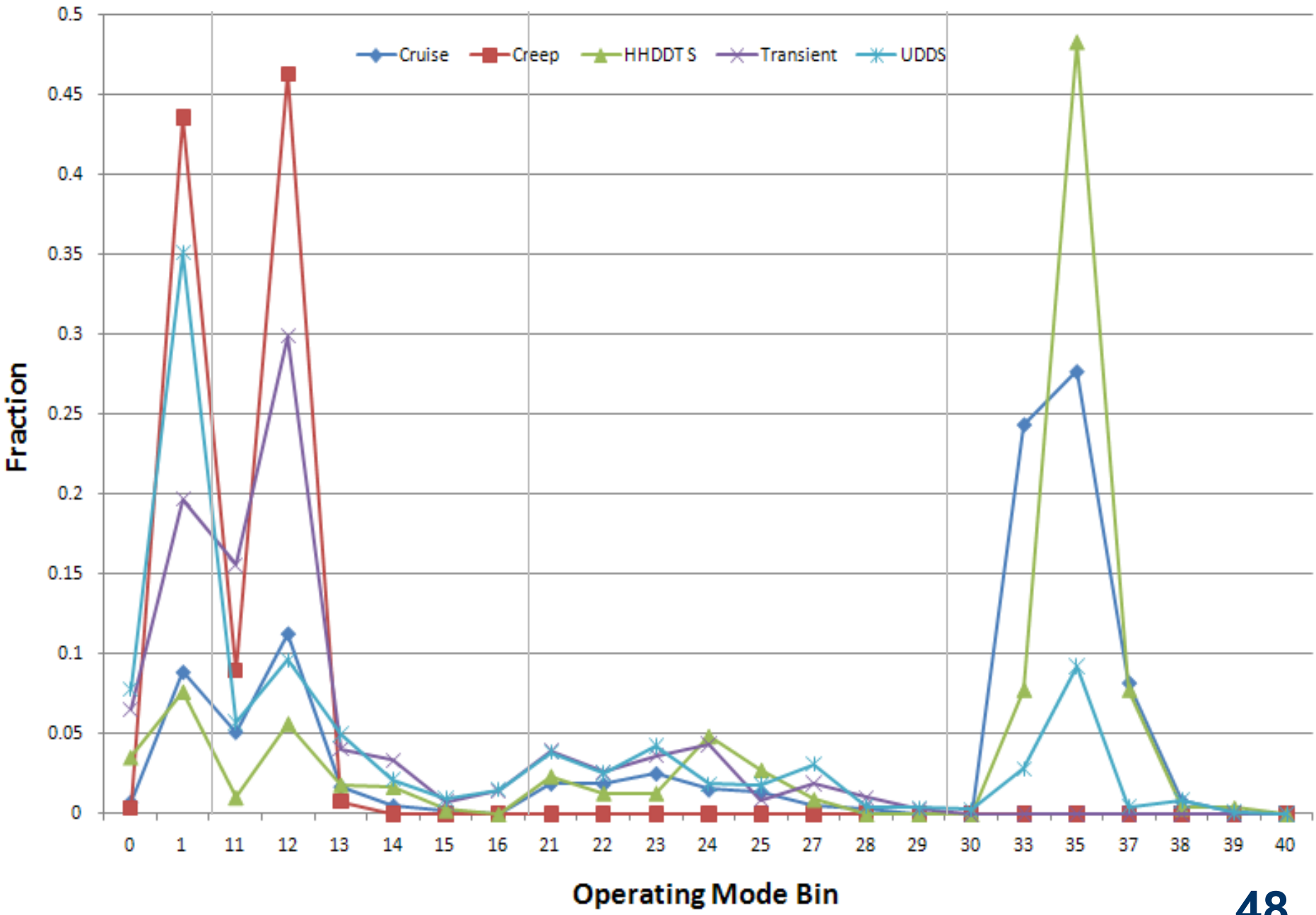
[1] "Development of real-world data for MOVES – The Houston Drayage Characterization Study", proceedings from 21st CRC On-Road Vehicle Emissions Workshop, March 2011

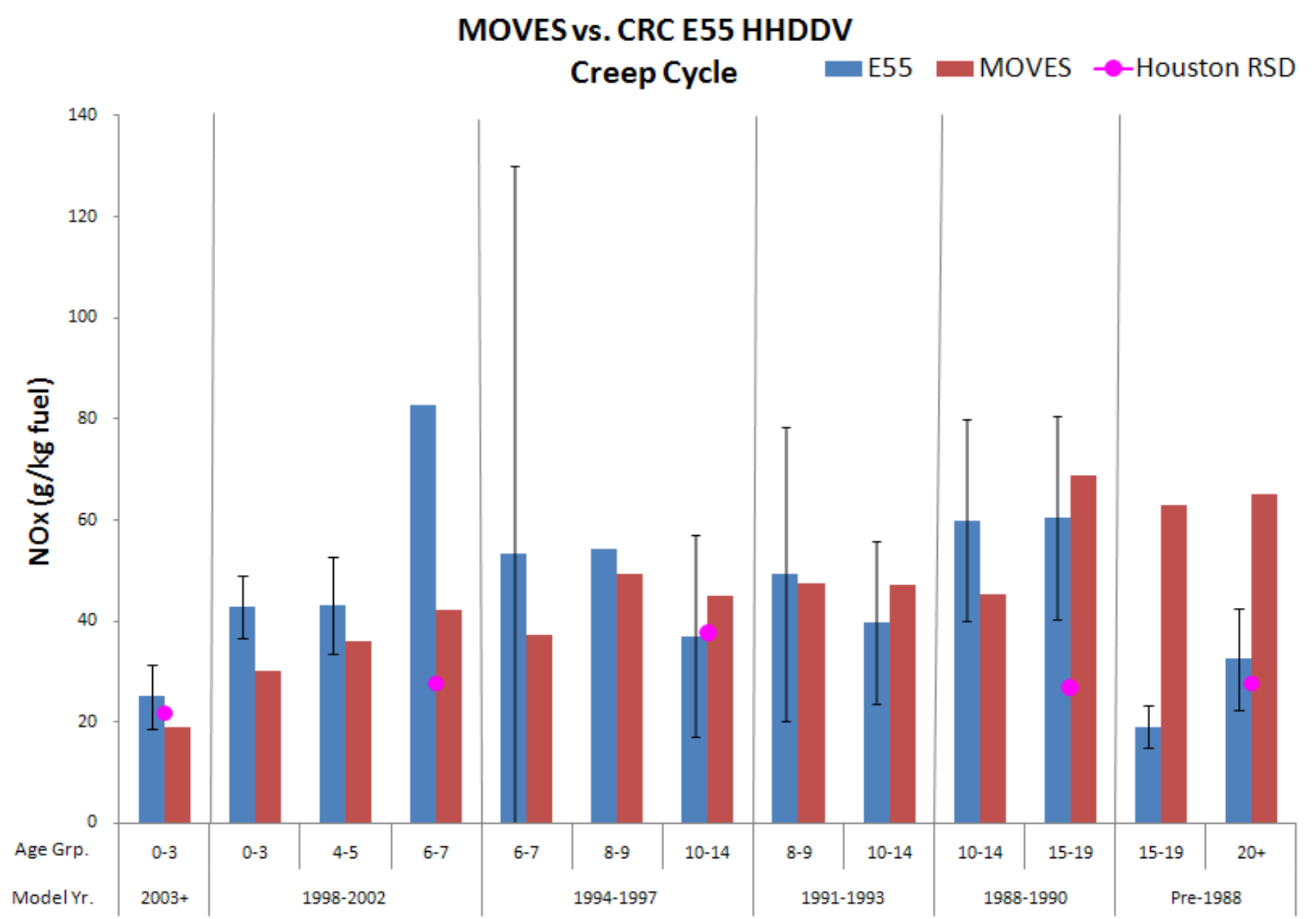
Heavy-Duty Emission Rate Validation: MOVES run

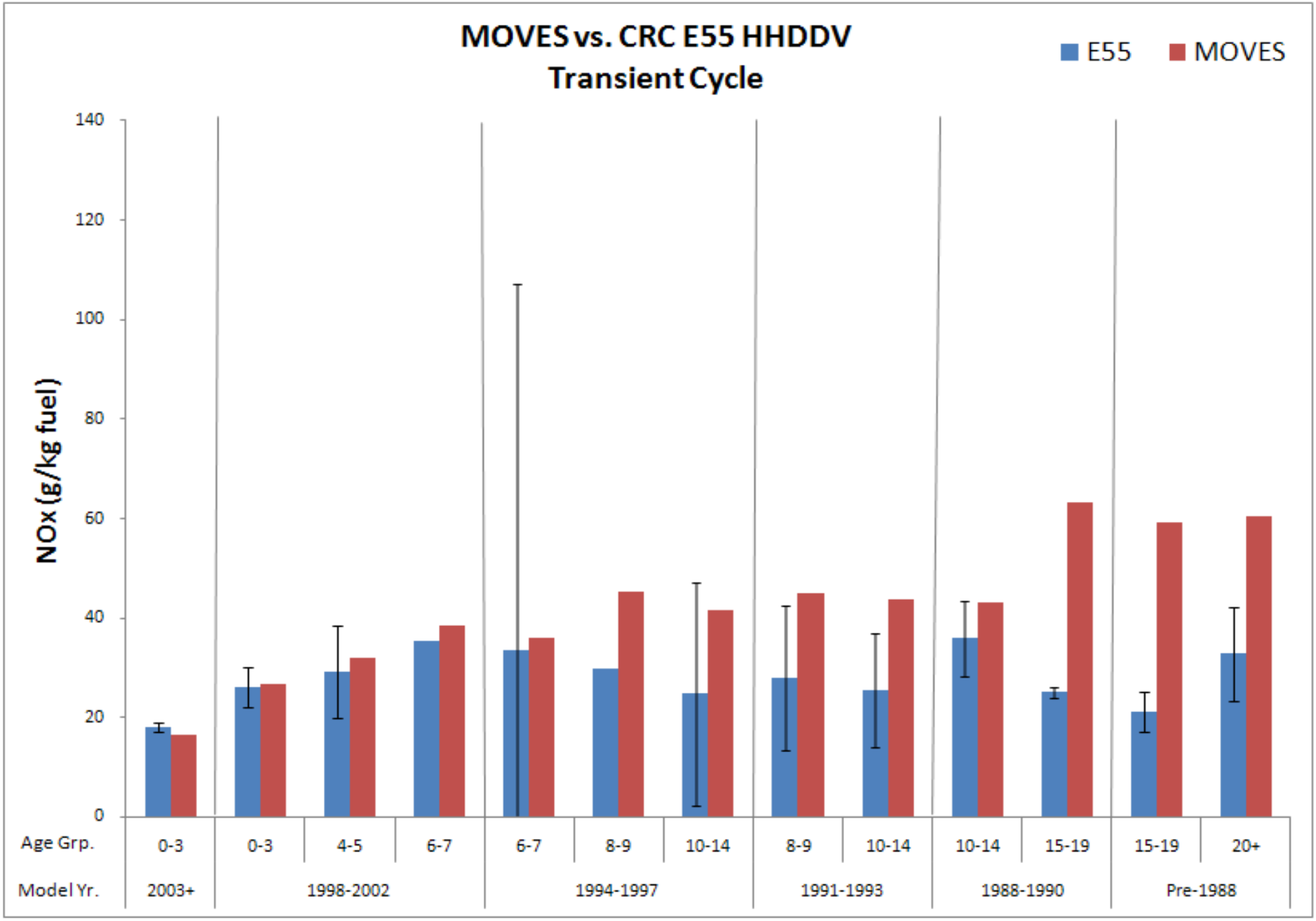
- **"Project" scale**
- **Corresponding calendar years in July**
- **County: Los Angeles County**
- **Diesel vehicles**
  - Single unit and combination short- and long-haul truck
  - Refuse truck
- **Project input**
  - Age distribution
  - Fuel supply
    - CRC E55 analyzed three fuel samples
    - Average sulfur of 0.0172 wt% = 172 ppm
  - Driving schedule
  - Average temperature and humidity from the tests
- **SourceUseType table modified**
  - Sourcemass: reflecting average test weight
  - Adjusted tire rolling loss coefficient and drag coefficient to dynamometer testing

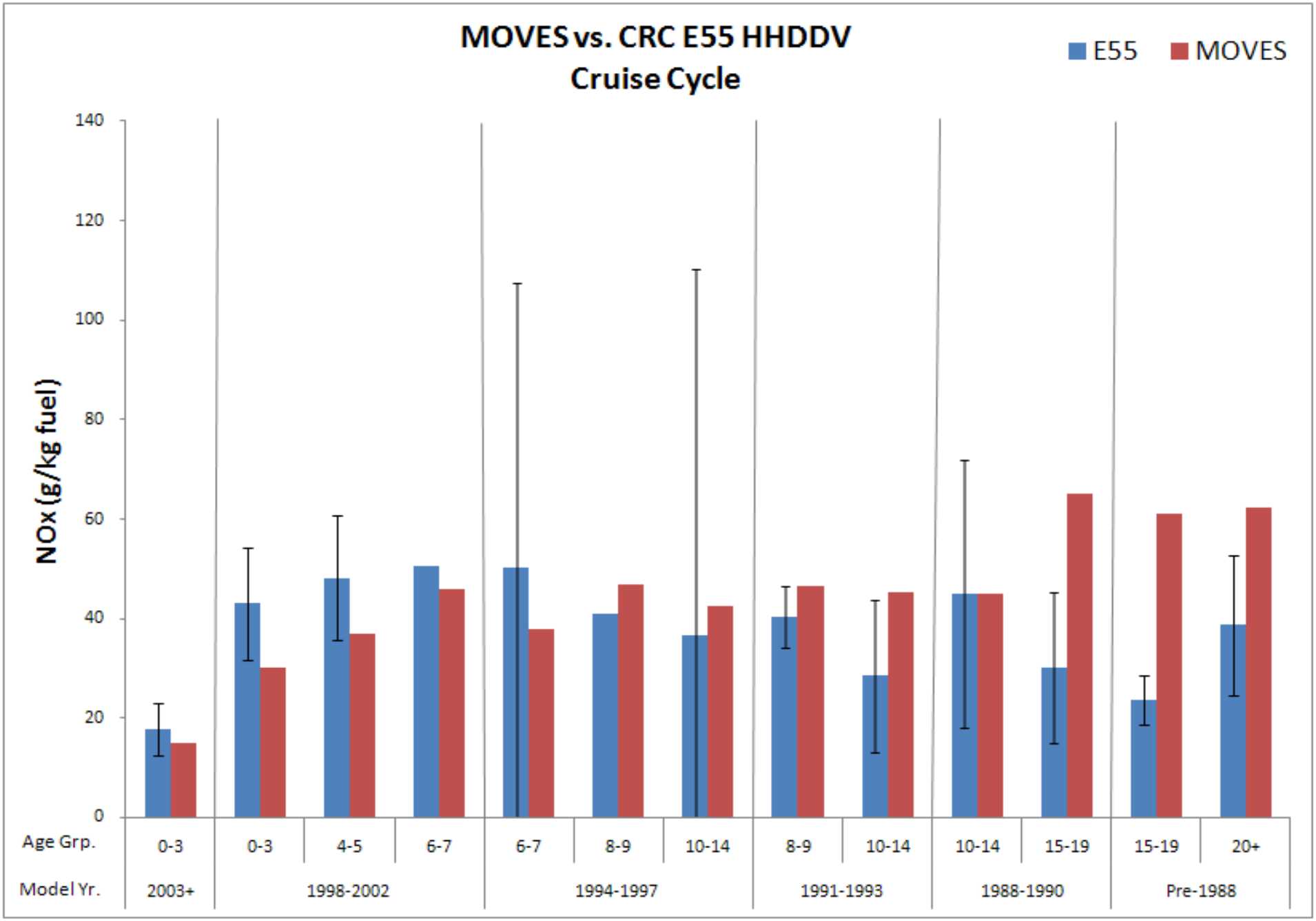
Limitations

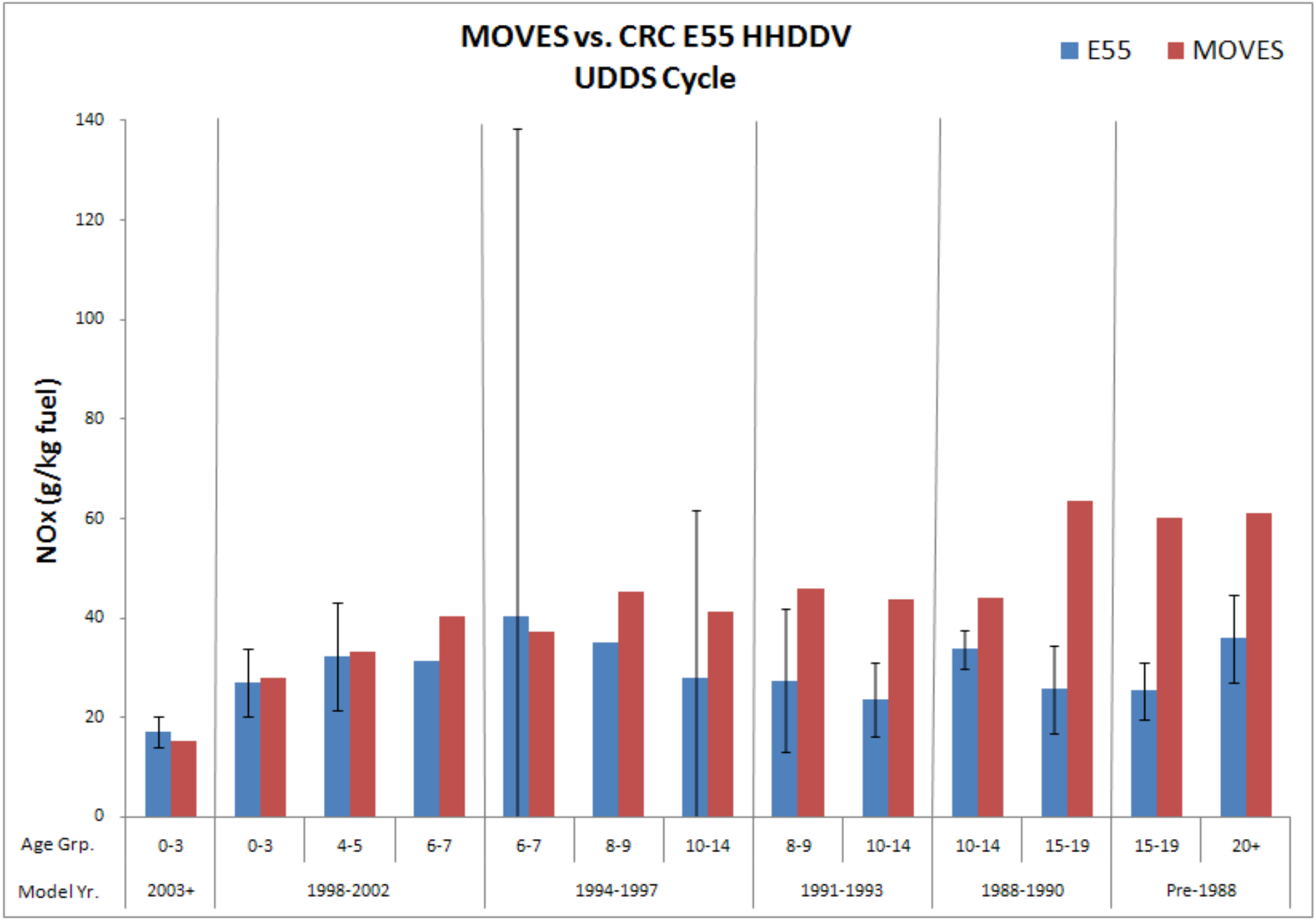
- **Vehicle MY and engine MY could differ resulting in misclassification**
- **Vehicle variability**
  - Small number of vehicles in each model year groups
- **Differences in calculation of VSP between MOVES and remote sensing data**

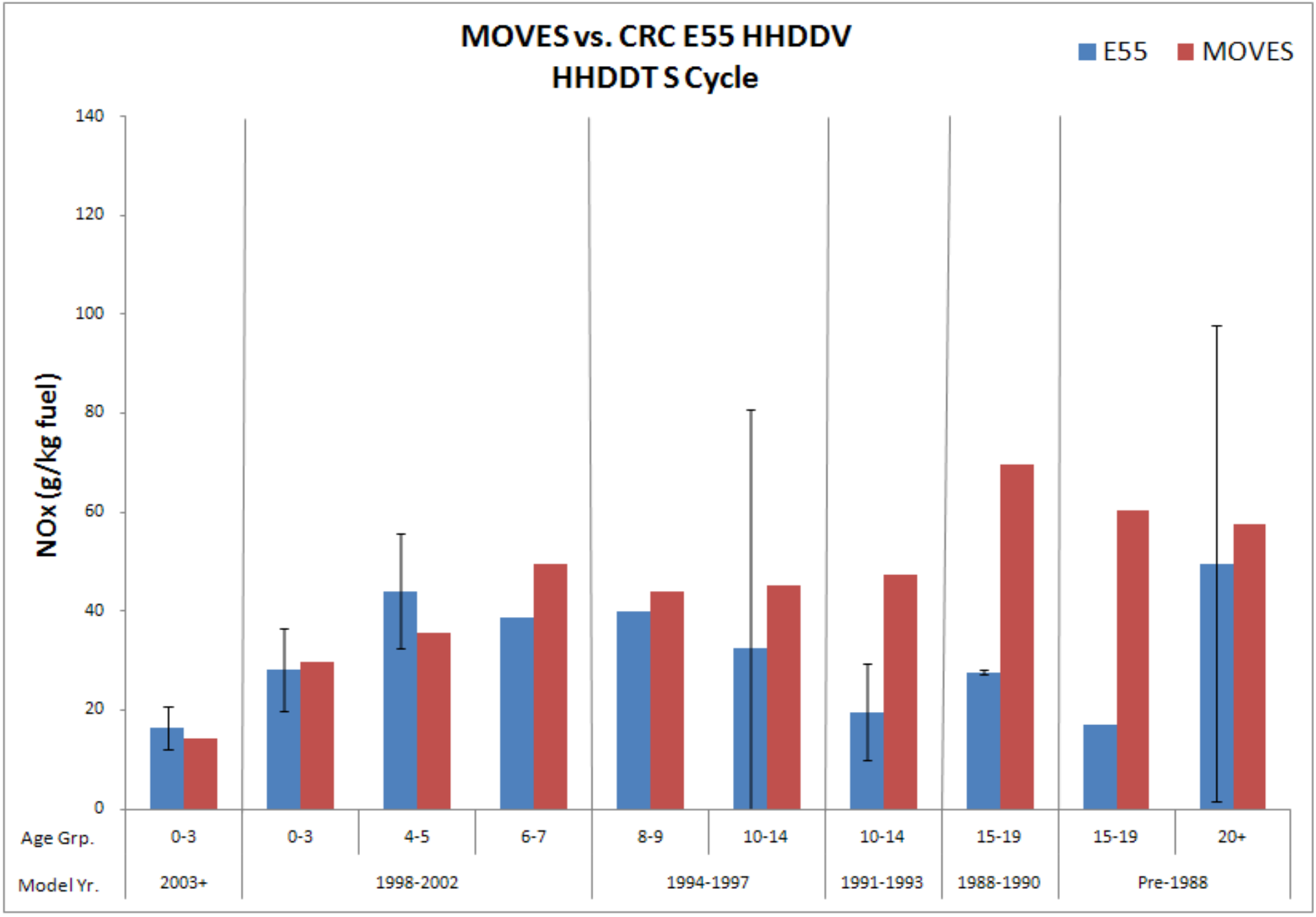

CRC E55 Test Cycle Opmode Distribution
Cruise
Creep
HHDDT S
Transient
UDDS
Fraction
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
1
11
12
13
14
15
16
21
22
23
24
25
27
28
29
30
33
35
37
38
39
40
Operating Mode Bin


MOVES vs. CRC E55 HHDDV
Creep Cycle
E55
MOVES
Houston RSD
NOx (g/kg fuel)
140
120
100
80
60
40
20
0
Age Grp.
0-3
0-3
4-5
6-7
6-7
8-9
10-14
8-9
10-14
10-14
15-19
15-19
20+
Model Yr.
2003+
1998-2002
1994-1997
1991-1993
1988-1990
Pre-1988


MOVES vs. CRC E55 HHDDV
Transient Cycle
E55
MOVES
NOx (g/kg fuel)
140
120
100
80
60
40
20
0
Age Grp.
0-3
0-3
4-5
6-7
6-7
8-9
10-14
8-9
10-14
10-14
15-19
15-19
20+
Model Yr.
2003+
1998-2002
1994-1997
1991-1993
1988-1990
Pre-1988


MOVES vs. CRC E55 HHDDV
Cruise Cycle
E55
MOVES
NOx (g/kg fuel)
140
120
100
80
60
40
20
0
Age Grp.
0-3
0-3
4-5
6-7
6-7
8-9
10-14
8-9
10-14
10-14
15-19
15-19
20+
Model Yr.
2003+
1998-2002
1994-1997
1991-1993
1988-1990
Pre-1988


MOVES vs. CRC E55 HHDDV
UDDS Cycle
E55
MOVES
NOx (g/kg fuel)
140
120
100
80
60
40
20
0
Age Grp.
0-3
0-3
4-5
6-7
6-7
8-9
10-14
8-9
10-14
10-14
15-19
15-19
20+
Model Yr.
2003+
1998-2002
1994-1997
1991-1993
1988-1990
Pre-1988


MOVES vs. CRC E55 HHDDV
HHDDT S Cycle
E55
MOVES
NOx (g/kg fuel)
140
120
100
80
60
40
20
0
Age Grp.
0-3
0-3
4-5
6-7
8-9
10-14
10-14
15-19
15-19
20+
Model Yr.
2003+
1998-2002
1994-1997
1991-1993
1988-1990
Pre-1988

On-Road Fleet Comparisons

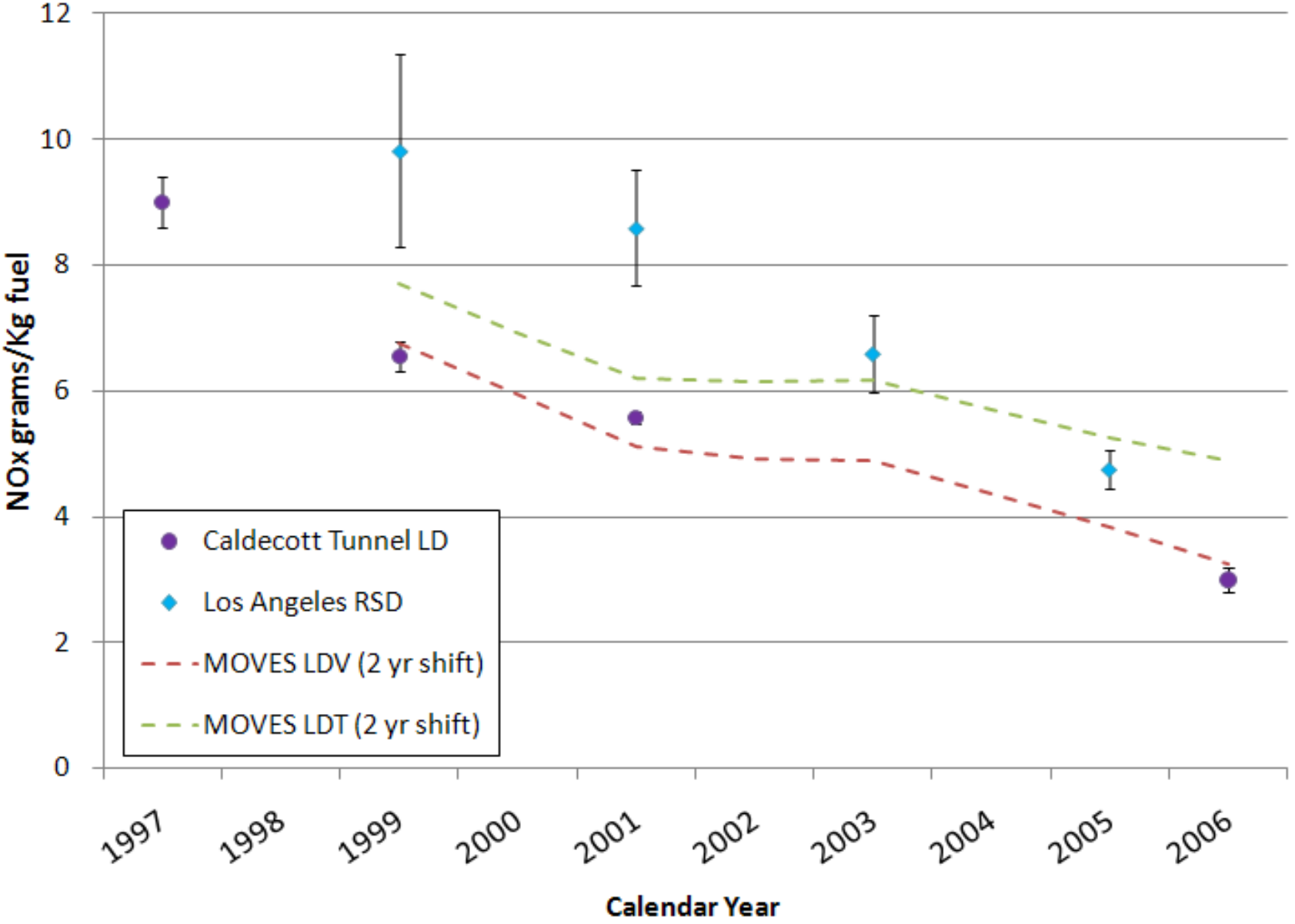
- **Ban-Weiss et. al, tunnel study**
  - Caldecott tunnel (Bay Area, CA)
    - Light duty and Heavy-duty NOx and PM2.5
  - Included some other remote sensing studies for comparison purposes
  - "Long-term changes in emissions of nitrogen oxides and particulate mater from on-road gasoline and diesel vehicles" *Atmospheric Environment* 42:220–232 (2008)
- **Soliman A. and Jacko, R., roadside PM study**
  - Borman Expressway (near Chicago)
  - Derived HDD PM2.5 emissions from roadside monitor
  - "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)

Comparison Methodology

- **MOVES run to mimic reported tunnel conditions**
  - Running emissions only
  - Average speed: 35 mph for LD, 40 mph for MD/HD
    - Steady-state driving schedules developed
  - Did not account for tunnel grade
  - Default meteorology and fuel – may contribute differences
- **California LEV program included for LD**
  - MY 1994 forward only, so earlier emission differences between California and Federal fleets not accounted for
- **LD fleet in tunnel two years younger than assumed by default MOVES age distribution**
  - For this comparison, MOVES LD results shifted back 2 years
  - More refined approach would enter alternate age distribution

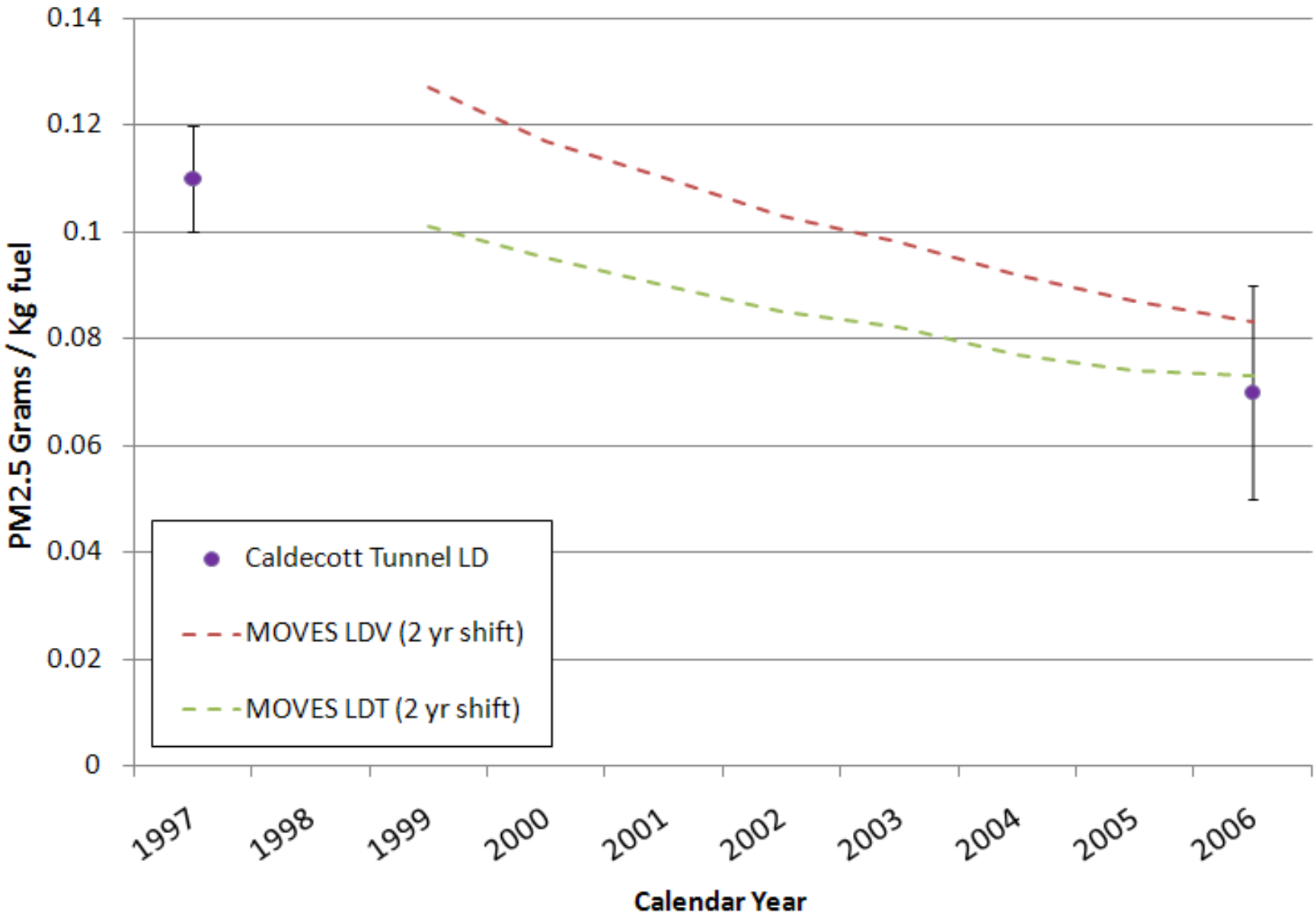
Comparison of MOVES LD NOx to Tunnel & RSD Results

Tunnel & RSD results reprinted from Ban-Weiss, G. et al., Atmospheric Environment 42 (2008) 220-232



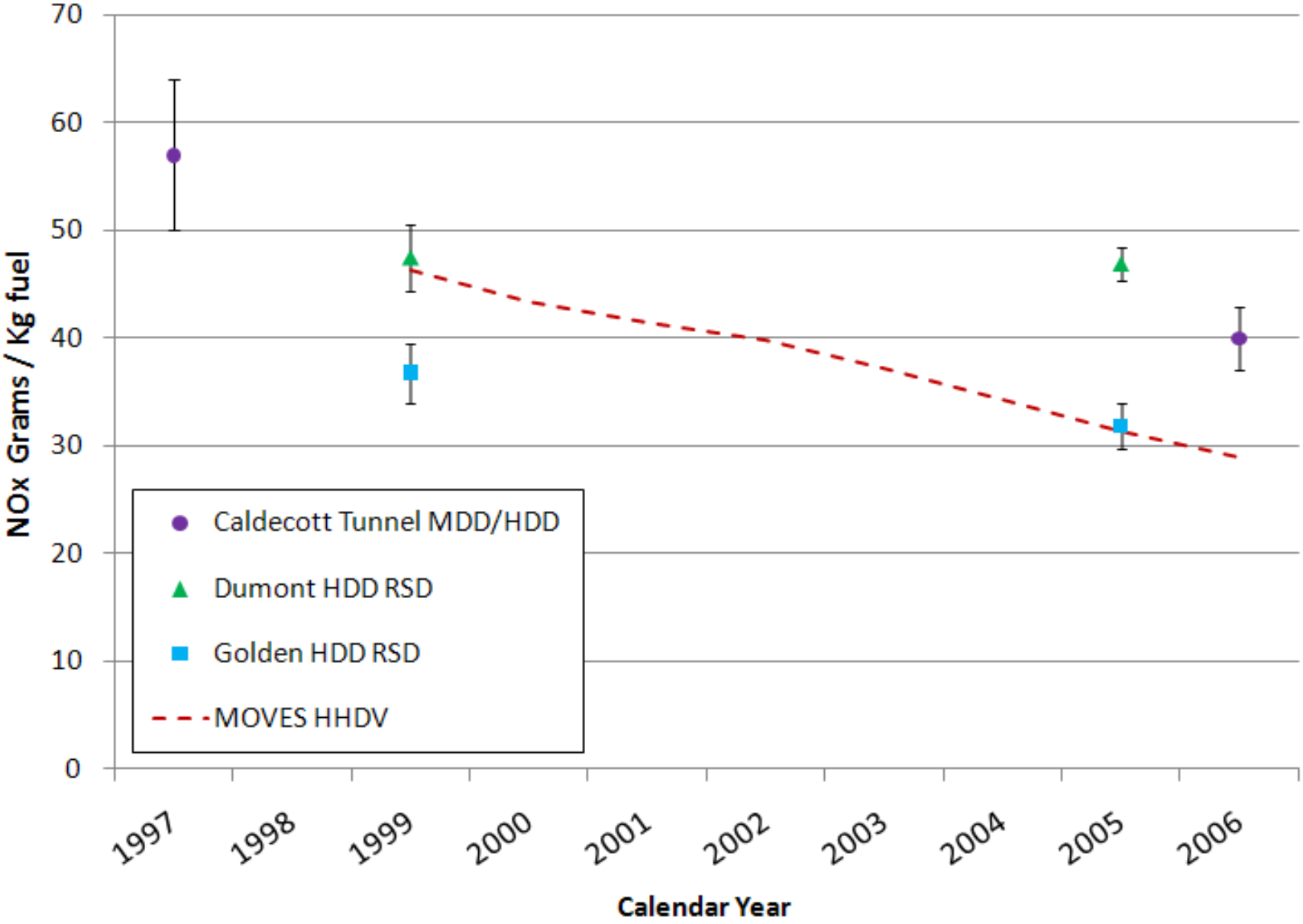
Comparison of MOVES LD $PM_{2.5}$ to Tunnel Results

Tunnel results reprinted from Ban-Weiss, G. et al., Atmospheric Environment 42 (2008) 220-232



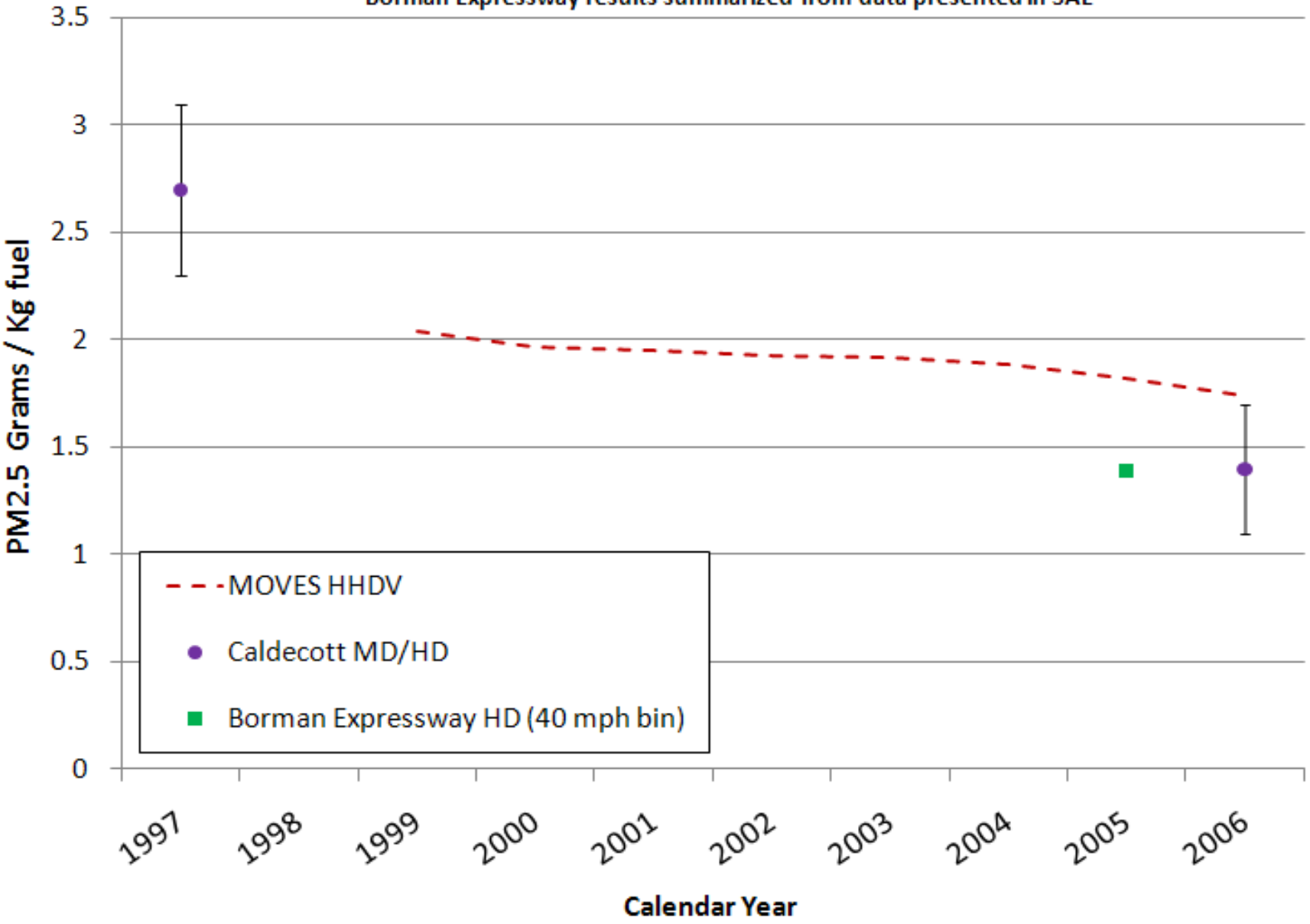
Comparison of MOVES HDD NOx to Tunnel & RSD Results

Tunnel & RSD results reprinted from Ban-Weiss, G. et al., Atmospheric Environment 42 (2008) 220-232



Comparison of MOVES HDD $PM_{2.5}$ to Tunnel & Roadside Results

Tunnel results reprinted from Ban-Weiss, G. et al., Atmospheric Environment 42 (2008) 220-232
Borman Expressway results summarized from data presented in SAE



Conclusion

- **Fuel consumption**
  - Generally a good agreement between the bottom-up MOVES results and top-down fuel sales for the U.S. as a whole.
  - Percent differences between MOVES and FHWA
    - Gasoline: -4 to +3%
    - Diesel: 0 to 6%
    - MOVES ~ 3% high in most recent year

Conclusion (cont'd)

- **Light-Duty emission rates**
  - Low power operation (Chicago IM and Chicago RSD)
    - MOVES estimation is in good agreement with the data
  - High power operation (Atlanta RSD and Kansas City dyno.)
    - Model performance better for vehicles < 8 years
    - MOVES overestimates for 8 < years < 20 years, particularly for CO and NOx
    - MOVES generally within the broad variability of the data for vehicles > 20 years
  - Agreement is better for Light-duty cars than trucks
    - May be explained by differences in composition of LDTs
  - Agreement is better for younger vehicles
    - MOVES' prediction of deterioration may be more aggressive than what is observed in the data

Conclusion (cont'd)

- **Heavy-Duty emission rates**
  - MOVES estimation matches the data well
    - Generally within the broad variability of the data
  - Overestimation for age 15+ trucks
    - Data for these trucks at same level or lower than younger trucks
- **On-road fleet comparisons**
  - MOVES prediction in reasonable agreement
    - Considering the limitations of differences in meteorology, fuel properties, and the composition of vehicle fleet

Summary

- Most comprehensive validation efforts to date
- Adaptability of MOVES allows comparisons to broad range of independent data
- Highlights the need for care in performing model comparisons to control for uncertainties
- Overall comparisons are good; reveals potential areas of model over-prediction for middle-aged light-duty vehicles
- Results will contribute to refinement and improvement of MOVES

MOVES

Acknowledgements

- **Dr. Michael Rodgers (Georiga Tech University)**
- **Drs. Don Stedman, and Gary Bishop (University of Denver)**
- **Coordinating Research Council**
- **Phil Heirigs (Chevron)**
- **Robert Crawford (Rincon Ranch Consulting)**
- **George Ban-Weiss (University of California, Berkeley)**
- **Kenneth Reader (SSAI)**
- **Eastern Research Group**
  - Gopi Manne, Rick Baker, Diane Preusse, Scott Fincher, Sandeep Kishan, Tim DeFries, Mike Sabisch
- **Houston-Galveston Area Council (HGAC)**
  - Shelly Whitworth, Patricia Franco
- **Texas Commission of Environmental Quality (TCEQ)**
  - Donna Huff, Mary McGarry-Barber, Amy Muttoni, David Brymer
- **Port of Houston Authority**
  - Dian Blume, Ken Gathright
- **EPA Region 6**
  - Sandra Rennie, Carl Young