Development of Heavy-Duty Emission Rates for MOVES2010

MOVES Workshop
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Final Technical Report to be posted: http://www.epa.gov/otaq/models/moves/movesback.htm

Regulatory Classes

- Heavy heavy-duty HHD — GVWR > 33000 lb
- Medium heavy-duty MHD — 19500 ≤ GVWR ≤ 33000 lb
- Light heavy-duty — 14000 < GVWR ≤ 19500 lb
- Light heavy-duty — 8500 < GVWR ≤ 14000 lb
- Urban Bus (as defined in 40CFR86.091-2)

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Fuel Types

- Diesel
- Gasoline
- CNG (Compressed Natural Gas)

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Emissions Processes

- Running Exhaust
- Start Exhaust
- Extended Idle Exhaust

1-Hz Data sources

- **On-road**
  - ROVER – PEMS (Portable Emissions Measurement System)
  - Consent decree testing by West Virginia Univ. – MEMS
  - Used for HD diesel NO_x and Energy (through CO_2)
- **Chassis dynamometer**
  - CRC E-55
  - NY Dept of Environmental Conservation
  - Northern Front Range Air Quality Study
  - Other transit and truck fleet testing
  - Light-heavy duty truck programs
  - Used for HD diesel HC, CO, and PM and HD gasoline

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1-Hz Data sources

- **ROVER – Real-time Onboard Vehicle Emissions Reporter**
  - Developed by EPA to perform compliance testing on in-use vehicles
  - 200+ trucks
  - HC, CO, NO_x, CO_2 measured
  - Calendar years 2001-present
  - Model years 1998-2007
  - 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

1-Hz Data sources

- **WVU – MEMS (Mobile Emissions Measuring System)**
  - Used for HD consent decree in-use vehicle testing
  - ~150 trucks
  - NO_x and CO_2 measured
  - Calendar years 2001-2006
  - Model years 1994-2006
  - Ages ~0-7 years old
  - Fixed routes in WV and PA involving highway and urban driving

1-Hz Data sources

- **Chassis testing**
  - Most MHD, HHD, and Bus tests performed by WVU portable HD dynamometer
    - CRC E-55 accounts for ~50% of MHDDT and HHDDT tests
  - LHD trucks tested by Southwest Research
  - ~326 vehicles in total
  - Model years 1969-2005, with bulk in mid to late 1990s
  - Variety of transient, cruising, idle cycles

Scaled Tractive Power (STP)

STP represents the vehicle's tractive power, scaled by a constant to fit existing MOVES operating mode definitions

- **Similar to VSP, but not normalized by vehicle mass**
- **HD vehicles regulated on an engine work basis, not a vehicle distance**
- **Preserves emission rate to power relation**
- **Different calculations for on-road and chassis data**

In MOVES, STP calculation looks similar to VSP:

$$\mathrm{STP}_t = \frac{Av_t + Bv_t^2 + Cv_t^3 + mv_t a_t}{f_{scale}}$$

v = velocity, m/sec
a = acceleration m/sec²
m = mass (metric ton)
A = rolling resistance (kW-sec/m)
B = rotating resistance (kW-sec²/m²)
C = aerodynamic drag (kW-sec³/m³)
f = scaling factor (aka fixedMassFactor)

Operating Modes for Running Exhaust Emissions

VSP or STP class [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

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Calculating STP

- **On-road data**
  - Used engine speed (rpm) and torque data from ECU to calculate gross engine power
  - Subtracted accessory loads and driveline losses
- **Chassis dynamometer data**
  - Used vehicle speed measurements from chassis dynamometer and appropriate (HD) road load coefficients
  - Similar to LD

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Tampering and Malmaintenance

- Existing data not taken longitudinally over time
- Used separate analysis to estimate real world emissions changes as engines age
- Estimated frequencies and emissions impacts of different engine and emissions control component failures
  - Aggregated to get a net change in emissions for each pollutant
- Modeled no change until end of warranty period, and linear increase up to end of useful life
- HD OBD: reduces emissions impacts by 33%
- Used only for HD diesel; Age effects in data used for HD gasoline

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Age Groups

Same as light-duty

- 0-3 years old
- 4-5
- 6-7
- 8-9
- 10-14
- 15-19
- 20+

HD trucks usually accrue high mileage within first few years

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HD DIESEL

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NO_x Running Exhaust

Model year groups

Based on current and previous standards and HD diesel consent decree

- Pre-1985
- 1985-1987
- 1988-1989
- 1990
- 1991-1993
- 1994-1997
- 1998
- 1999-2002
- 2003-2006
- 2007-2009
- 2010-2012
- 2013+

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Analysis

MHD, HHD, Bus

- **Calculate STP for each data point**
- **Convert STP to operating modes**
- **Average NOx rates for each operating mode, model year group**
- **Hole filling**
  - Model years before 1991: Proportion rates by certification levels
  - Model years after 2006: Proportion rates by decrease in standards
  - Defeat device: Adjust for model years 1991-1998 to account for low-NOx rebuilds (reflashes), as mandated by HD diesel consent decree

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Analysis

LHD

- **Model years before 2006**
  - Used MHD data results (MHD and LHD are similar in engine size)
- **Model years after 2007+**
  - Used data from in house PEMS testing of Lean NOx trap equipped vehicle
  - Similar to HHD analysis using ECU power
- **Proportion rates to standards for all other MYs**

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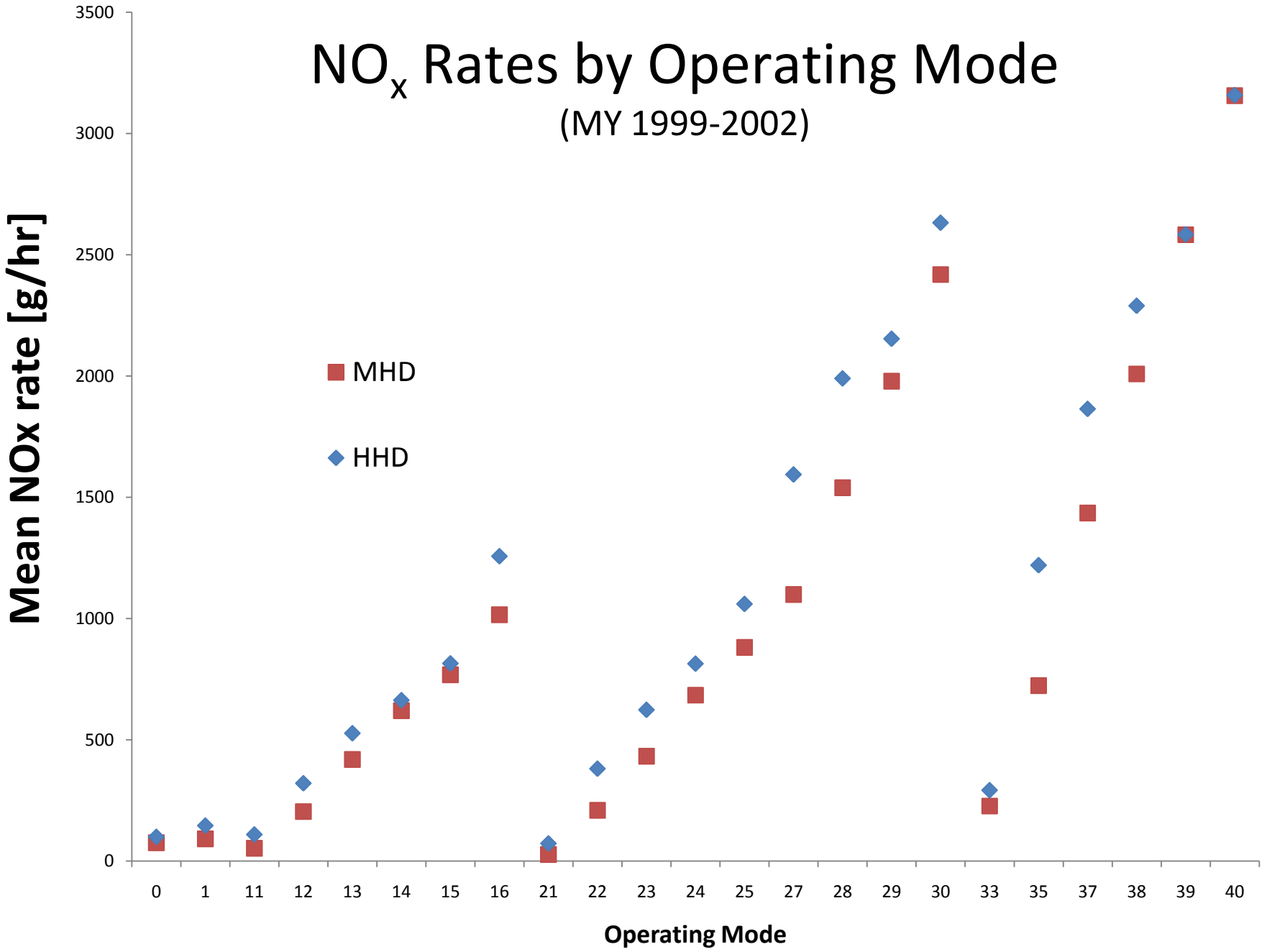
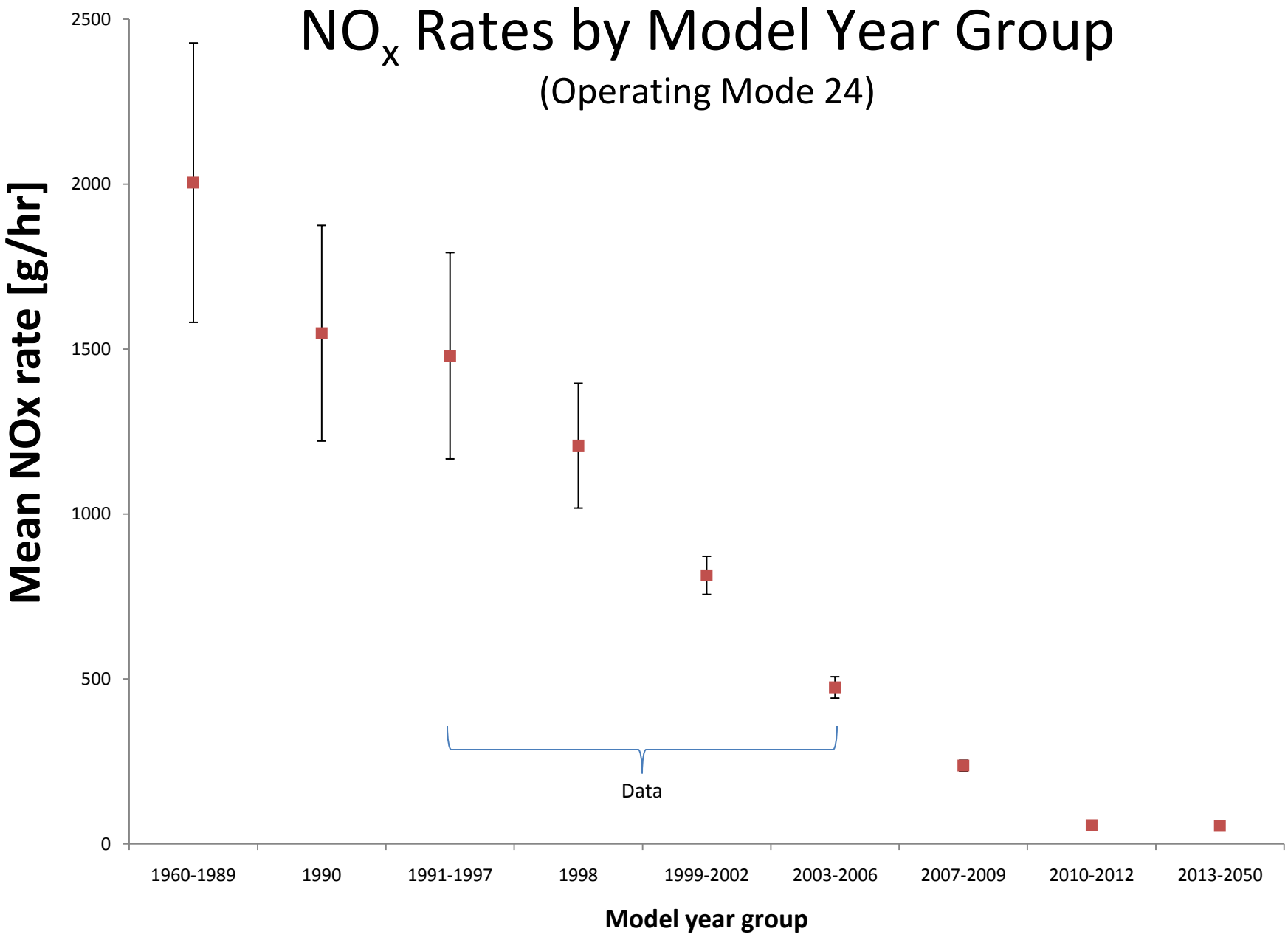
Tampering and Malmaintenance

- **No age effect modeled for non-aftertreatment engines**
- **Assumptions for vehicles with aftertreatment**
  - Lean NOx traps
    - ~25% of MY 2007 LHDDT fleet
    - Aggregated 72% NOx increase over useful life for full fleet
  - Urea SCR
    - Most systems post 2010
    - Aggregated 87% NOx increase over useful life for full fleet


NOx Rates by Operating Mode
(MY 1999-2002)
Mean NOx rate [g/hr]
3500
3000
2500
2000
1500
1000
500
0
MHD
HHD
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


NOx Rates by Model Year Group
(Operating Mode 24)
Mean NOx rate [g/hr]
2500
2000
1500
1000
500
0
Data
1960-1989
1990
1991-1997
1998
1999-2002
2003-2006
2007-2009
2010-2012
2013-2050
Model year group

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PM Running Exhaust

Available data

- **Existing engine and chassis test data by cycle**
  - CRC test programs
  - Engine certification results
- **Limited 1 hz real time data with TEOM**
  - CRC E-55 program
    - TEOM - Tapered Element Oscillating Microbalance only on a subset of tests

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Model Year Groups

- 1960 – 1987
- 1988 – 1990
- 1991 – 1993
- 1994 – 1997
- 1998 – 2006
- 2007+ (no data)

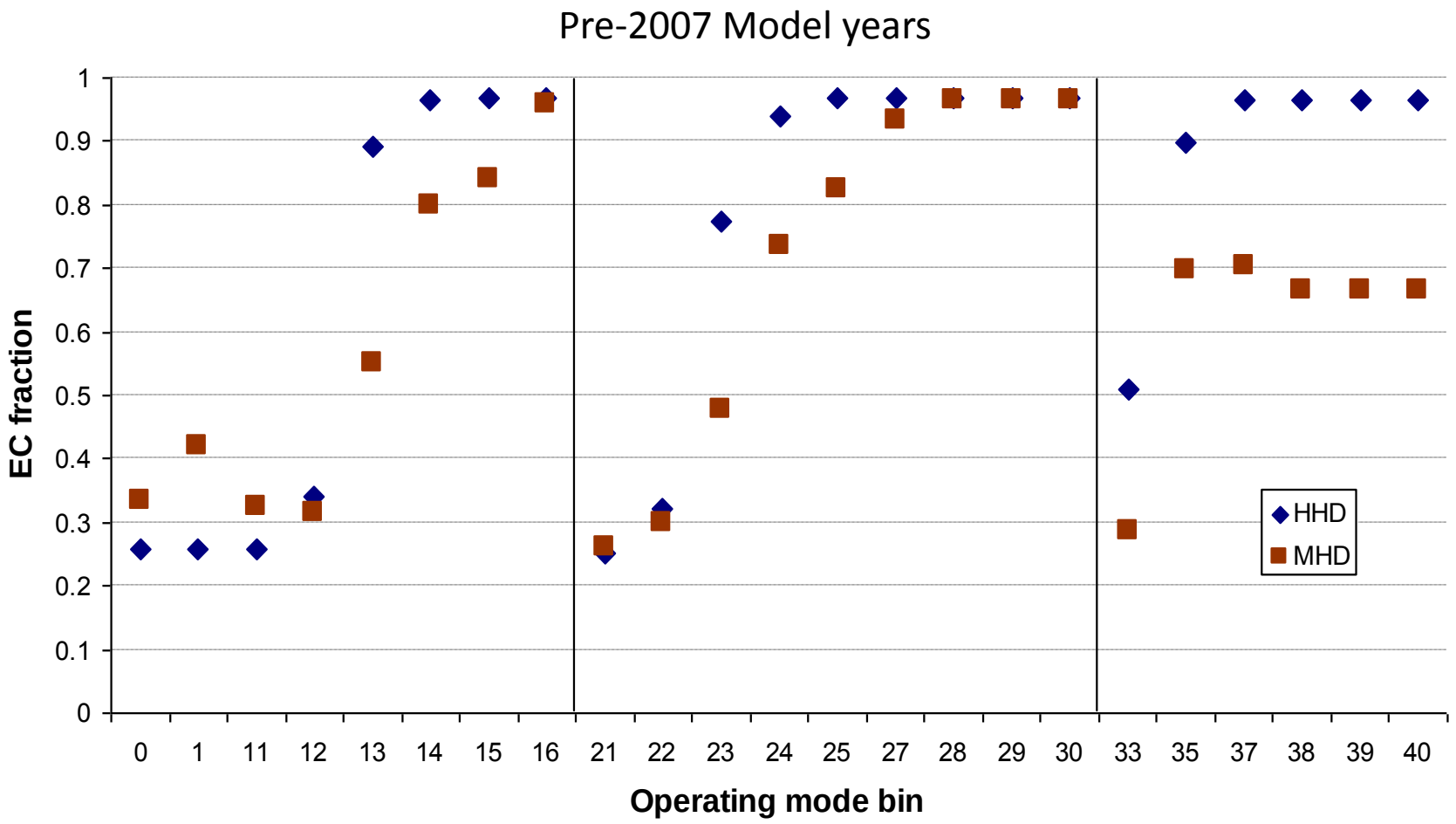
Analysis

- Normalized individual TEOM results to total cycle filter particulate results
- Calculated STP and operating modes
- Averaged rates by model year group, regulatory class, and operating mode
- Based on certification data, PM from MY 2007+ vehicles reduced by 96% from MY 2006 levels
- Tampering and malmaintenance analysis estimated 50-100% increase in PM emissions over useful life, depending on MY group

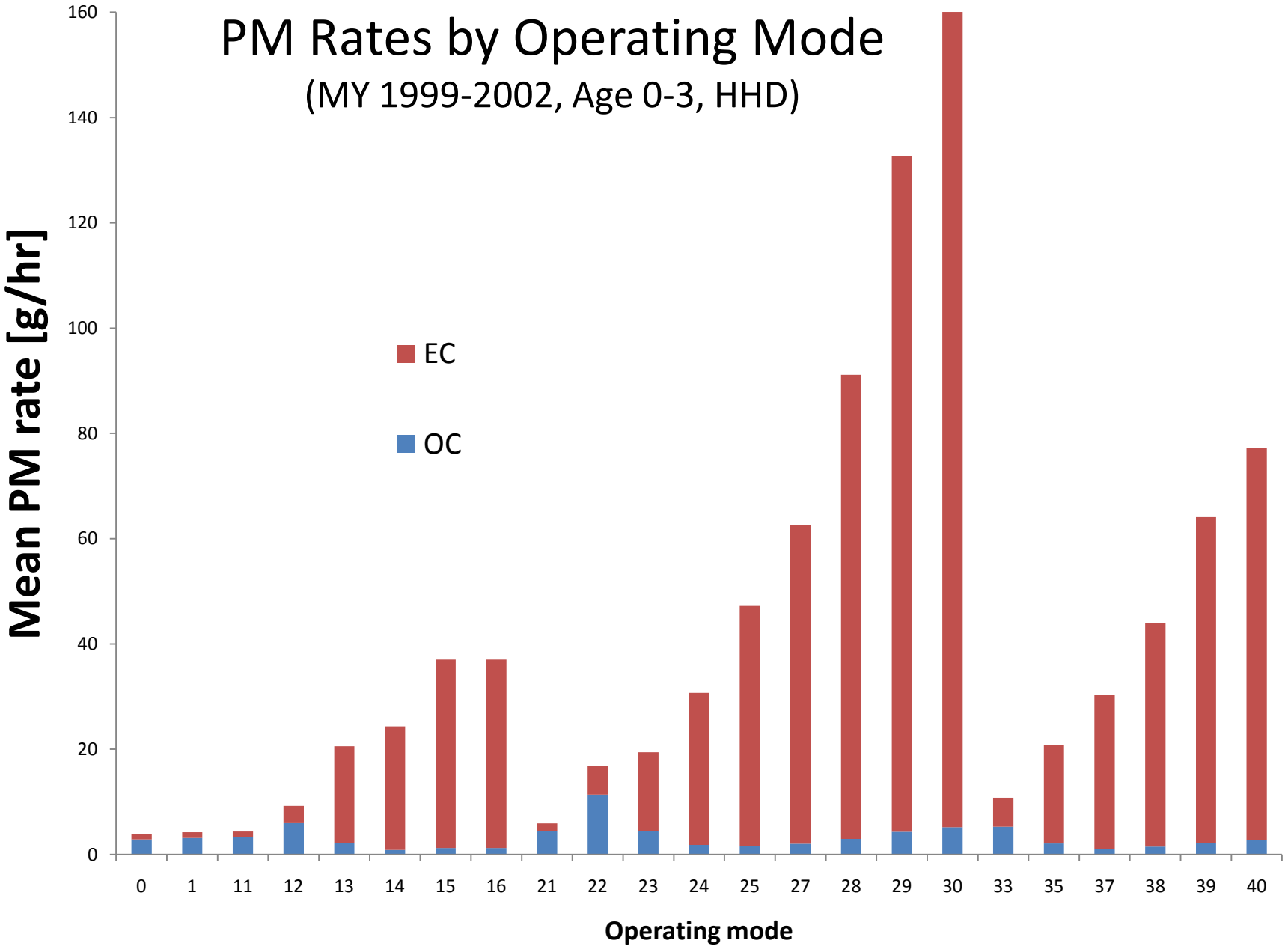
EC/OC breakdown

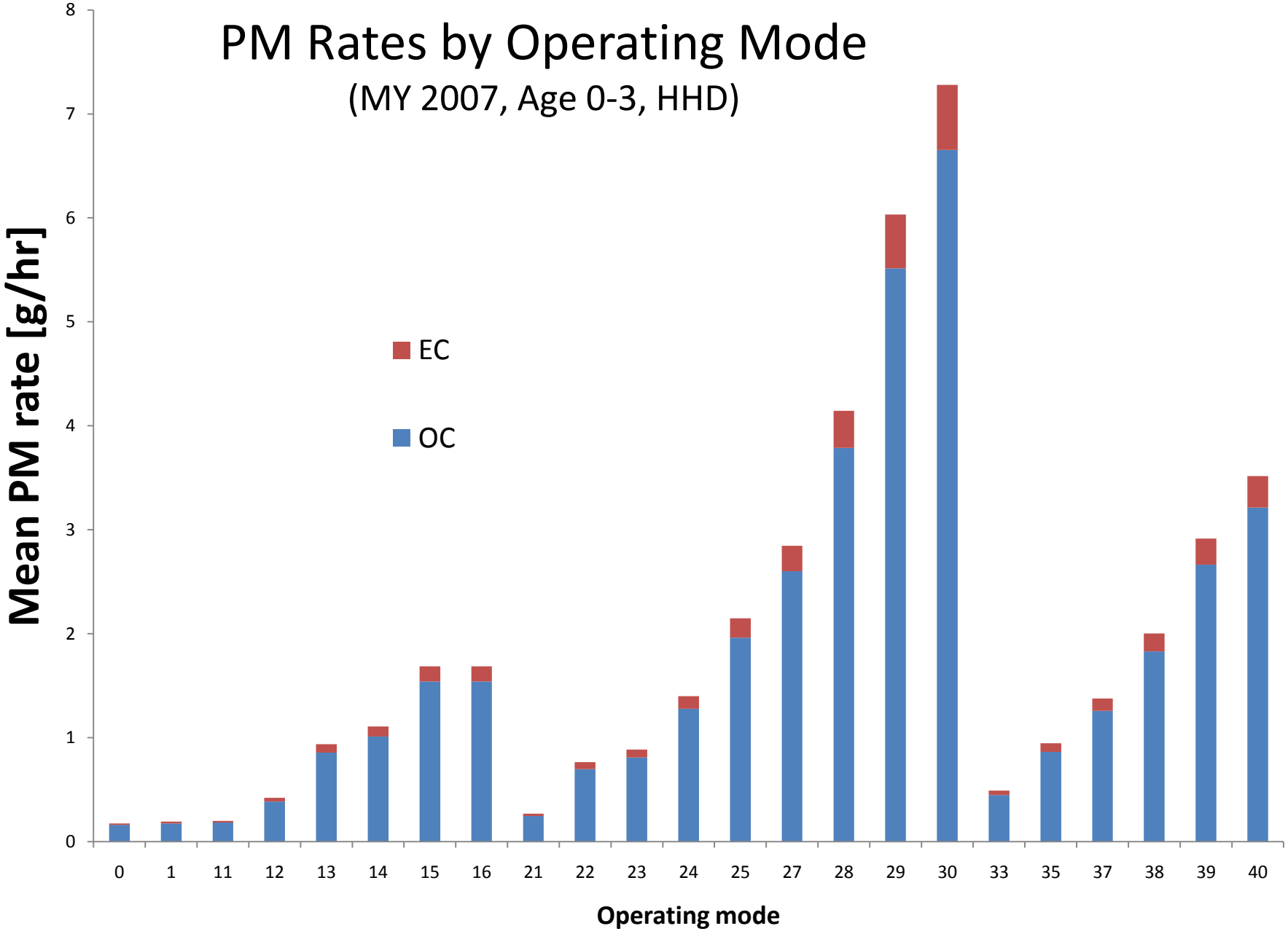
- **MOVES PM inputs are actually Elemental Carbon (EC) and Organic Carbon (OC) rates**
  - Split PM into these two components
- **Used PERE vehicle model with EC/OC data in research/literature**
- **Analyzed EC and OC fractions by operating mode**
- **Single average EC fraction for DPF-equipped trucks (MY 2007+) over all operating modes**

EC Fraction by Operating Mode



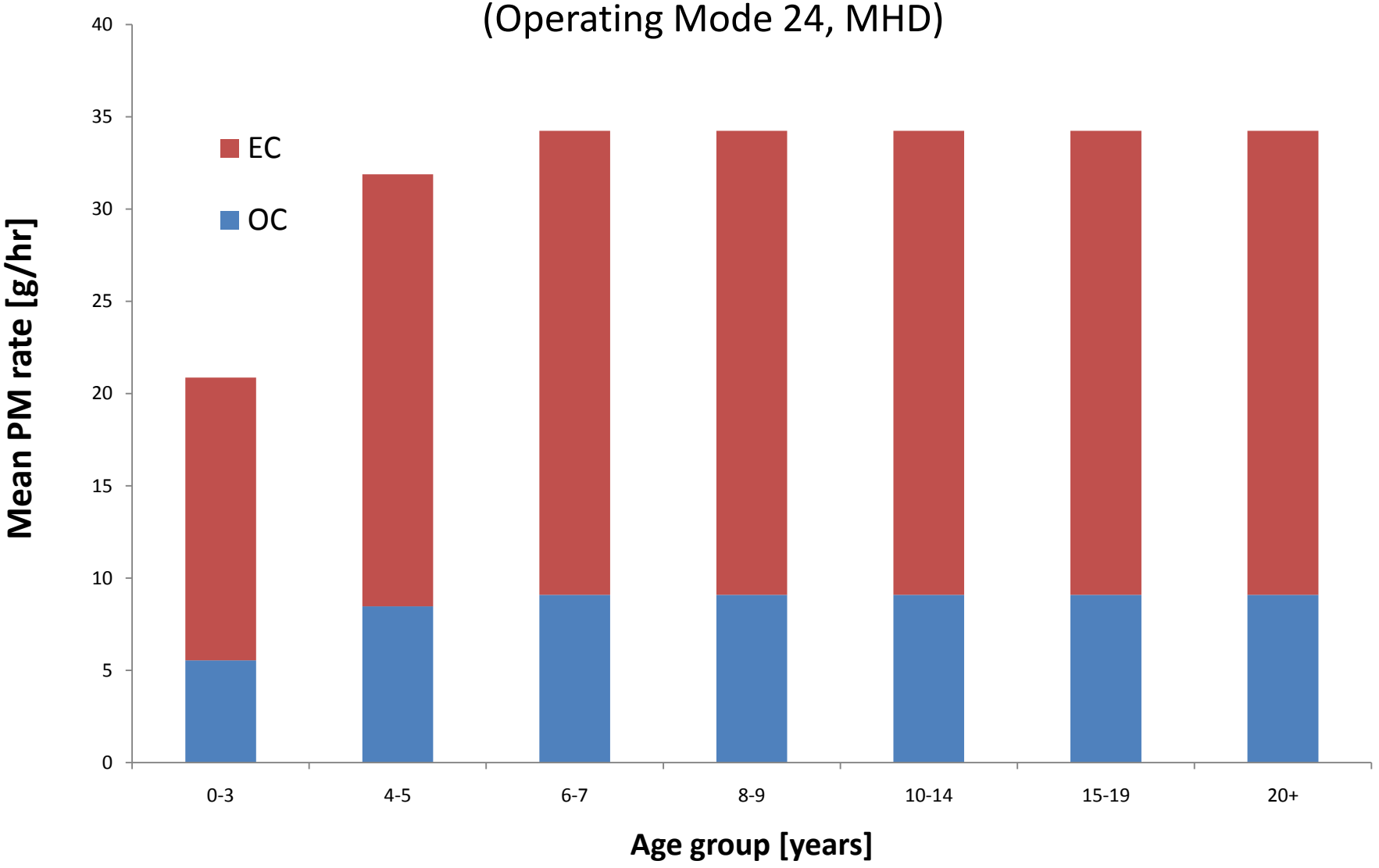
Model years 2007 and later: EC fraction = 0.0861 for all modes

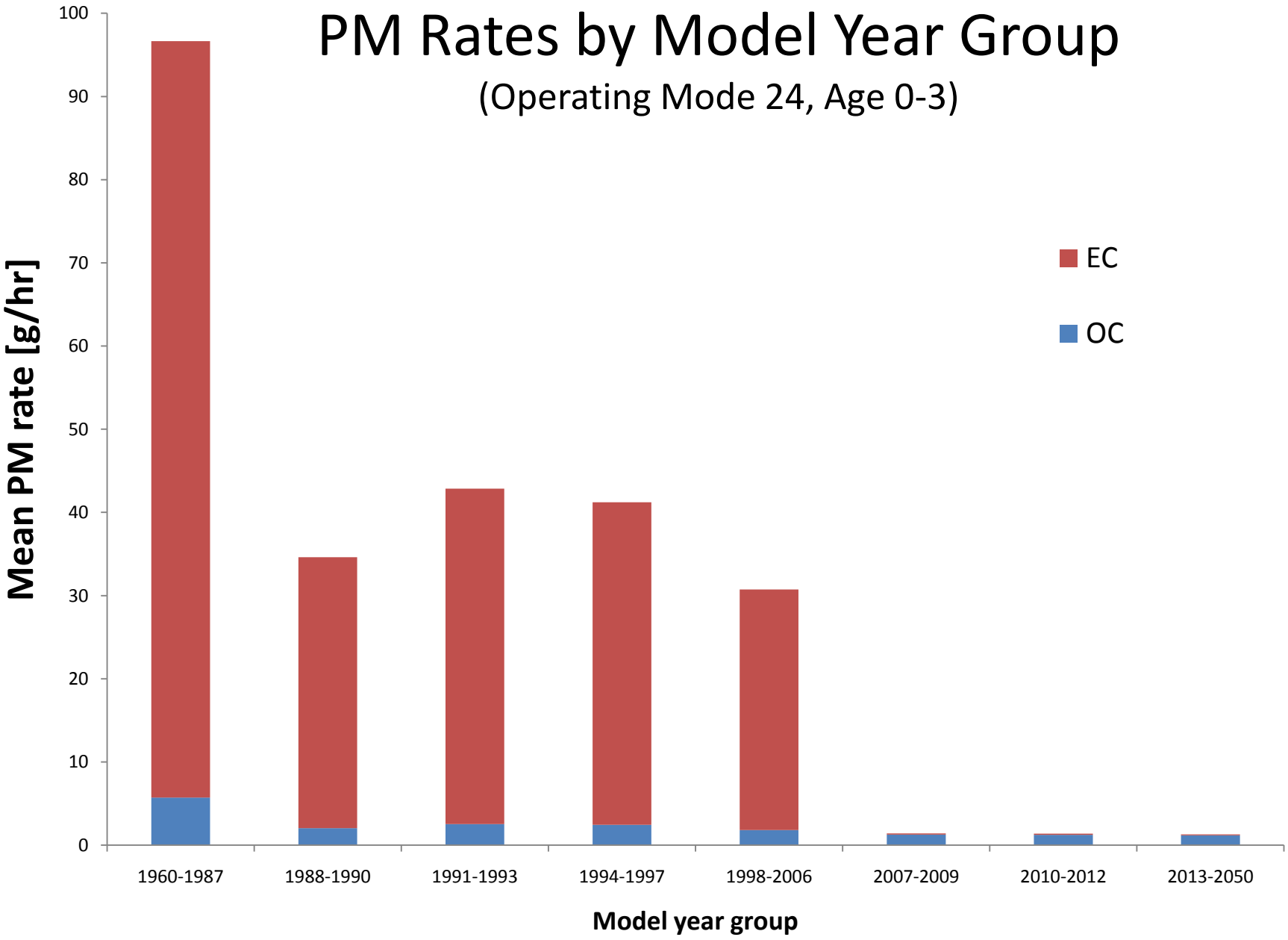

PM Rates by Operating Mode
(MY 1999-2002, Age 0-3, HHD)
Mean PM rate [g/hr]
160
140
120
100
80
60
40
20
0
EC
OC
0
1
11
12
13
14
15
16
21
22
23
24
25
27
28
29
30
33
35
37
38
39
40
Operating mode


PM Rates by Operating Mode
(MY 2007, Age 0-3, HHD)
Mean PM rate [g/hr]
EC
OC
0
1
2
3
4
5
6
7
8
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

PM Rates by Age Group

(Operating Mode 24, MHD)




PM Rates by Model Year Group
(Operating Mode 24, Age 0-3)
Mean PM rate [g/hr]
100
90
80
70
60
50
40
30
20
10
0
EC
OC
1960-1987
1988-1990
1991-1993
1994-1997
1998-2006
2007-2009
2010-2012
2013-2050
Model year group

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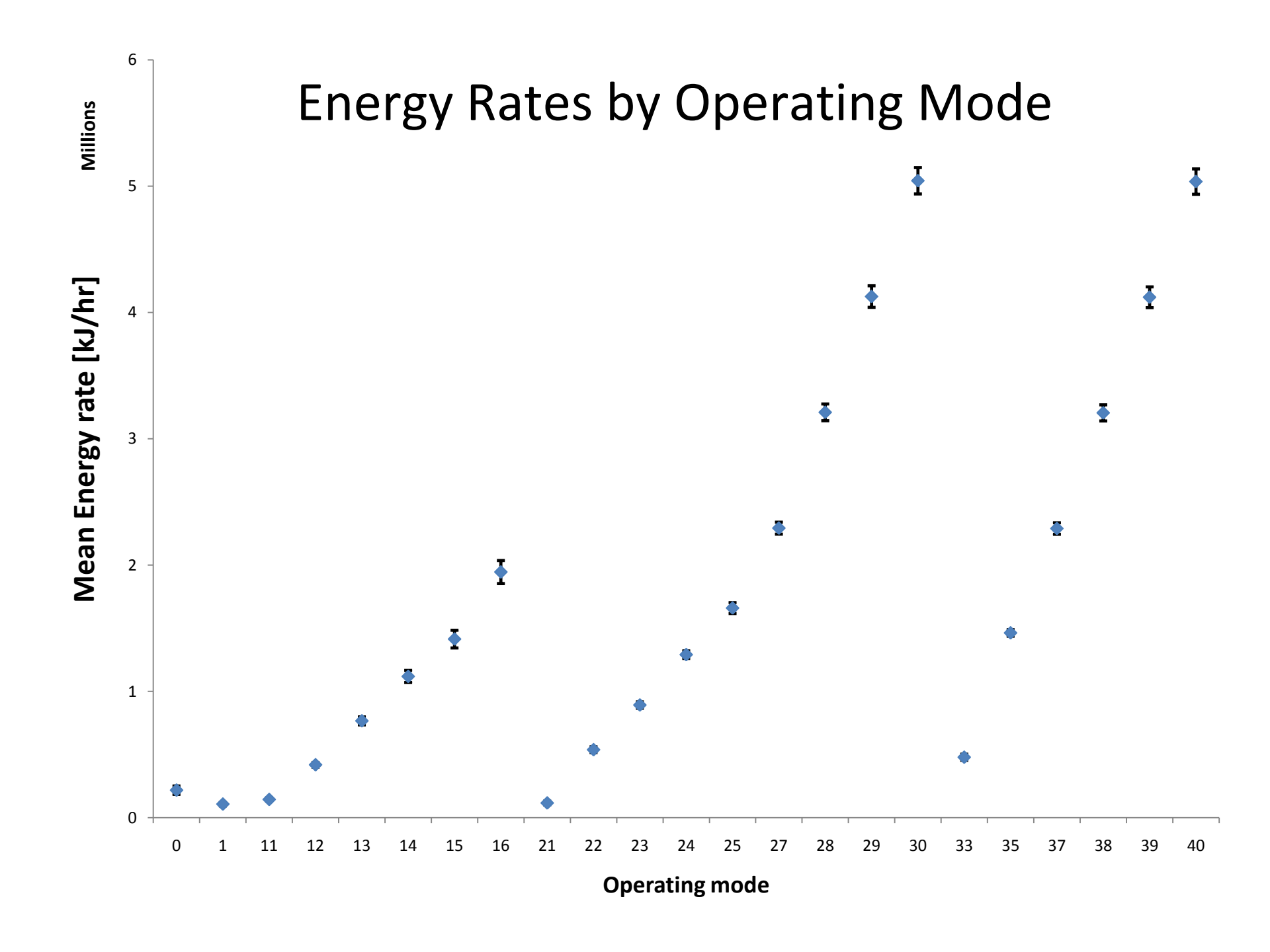
Energy Running Exhaust

Analysis

- Energy rate analysis used the same data as NOx rate analysis
- Used CO_2 g/hr emission rates and converted to energy kJ/hr rates using heating value for diesel fuel
- Calculated STP and operating modes
- Averaged rates by operating mode
- No model year effect (no GHG/fuel economy regulations in place)
- No age effect
- No regulatory class effect


Energy Rates by Operating Mode
Millions
Mean Energy rate [kJ/hr]
6
5
4
3
2
1
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

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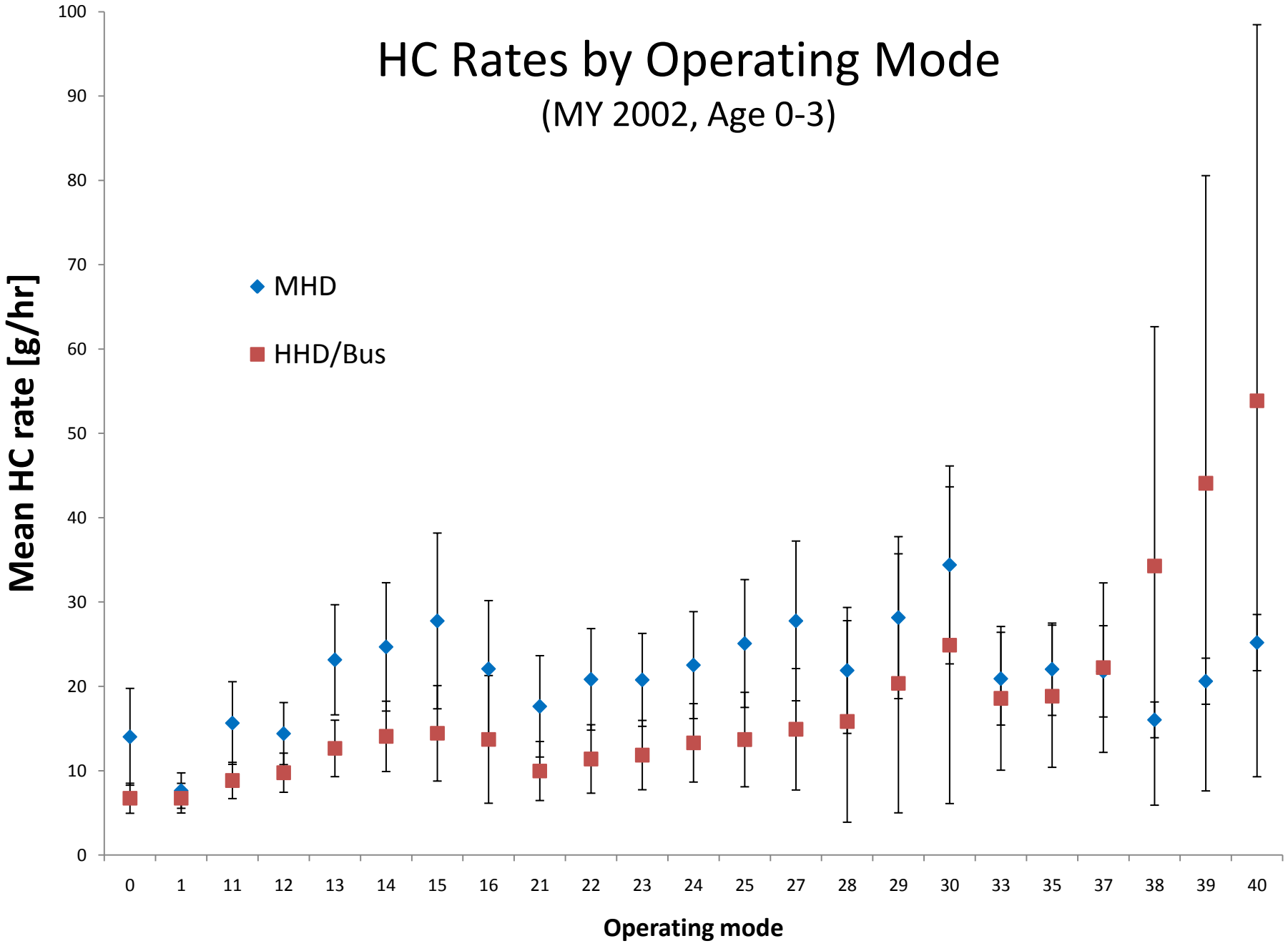
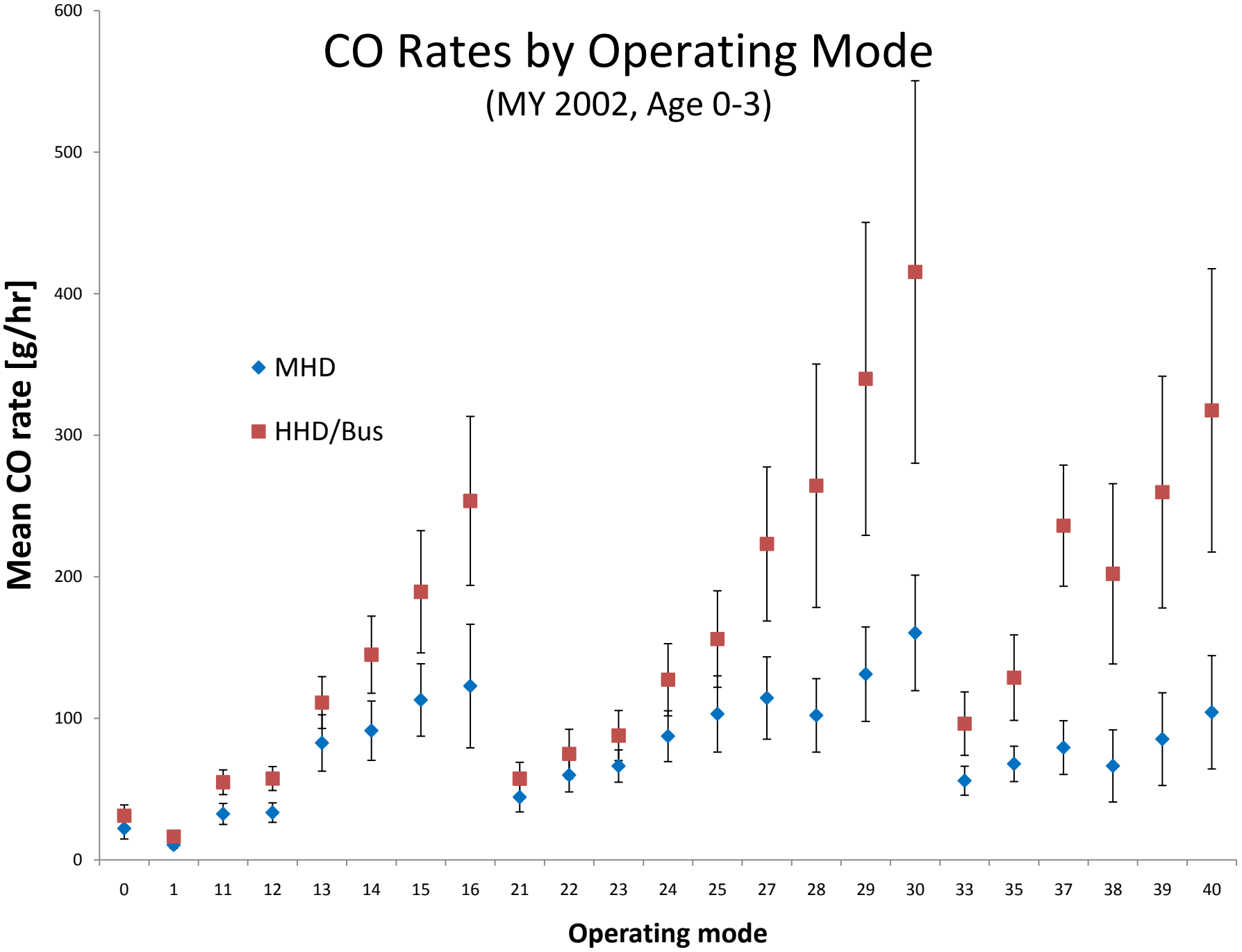
HC & CO Running Exhaust

Analysis

- Diesel vehicles not a very significant of a source HC, CO compared to gasoline vehicles
- Three model year groups based on certification data
  - 1960-1989
  - 1990-2006
  - 2007+
- Calculated STP and operating modes
- Averaged rates by model year group, regulatory class, and operating mode
- Tampering and malmaintenance analysis estimated 33-300% increase in emissions over useful life, depending on MY group


HC Rates by Operating Mode
(MY 2002, Age 0-3)
MHD
HHD/Bus
Mean HC rate [g/hr]
Operating mode
0
10
20
30
40
50
60
70
80
90
100
0
1
11
12
13
14
15
16
21
22
23
24
25
27
28
29
30
33
35
37
38
39
40


CO Rates by Operating Mode
(MY 2002, Age 0-3)
Mean CO rate [g/hr]
600
500
400
300
200
100
0
MHD
HHD/Bus
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

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Extended idle

- **Applies only to combination long haul trucks in MOVES**
- **Discretionary operation involving higher idle loads and accessories**
  - A/C, heater, TV, appliances, lamps, etc.
  - Usually involves overnight “hotelling”
- **Limited data (~30 trucks) from EPA, U of Tennessee, and UC Davis**
  - Different idle conditions, A/C settings
  - Used high idle, A/C on data
- **Extended idle emissions not regulated**
  - Modeled aftertreatment controls last only for the first hour
  - Assumed DPFs are effective during extended idling
- **Becoming a very significant portion of inventories as engines become cleaner**

Extended idle results [g/hr]

Model years		HC	CO	NOx	PM
Pre-1990	Curb Idle	21	31	47	3.8
	Extended Idle	**108**	**84**	**112**	**8.4**
1990-2006	Curb Idle	11	34	94	1.8
	Extended Idle	**56**	**91**	**227**	**4.0**
2007+	Curb Idle	3	34	9	0.2
	Extended Idle	**53**	**91**	**201**	**0.2**

Start emissions

- **Defined in MOVES as difference between warm cycle and cold cycle**
- **Data from**
  - Cold idle tests from U of Tennessee
  - In house data on a MY 2007 MHD engine
    - Idle and engine FTP tests
  - LHDDT: FTP chassis dynamometer tests
- **Results**
  - HHD/MHD/Bus – 0 NOx, 0 HC, 16g CO, 0.11g PM
  - LHD – small but nonzero
- **Adjusted rates for different soak times**
  - Similar method to LD

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HD GASOLINE

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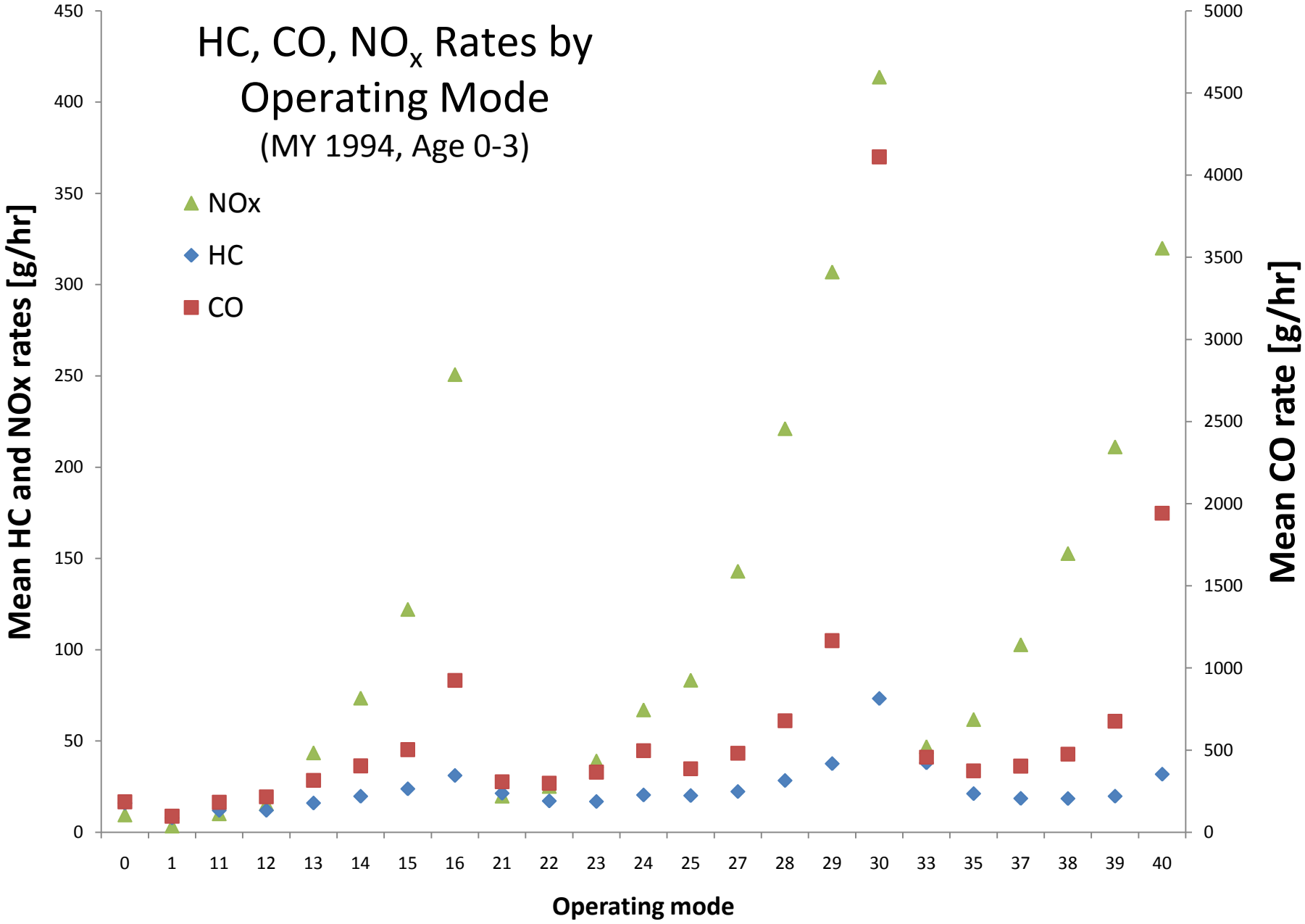
Available data

- **Limited data**
  - CRC E-55 program (4 MHD vehicles)
  - LHD data from various chassis dynamometer tests
  - Model years 1960-2002
  - ~60 vehicles
- **Five model year groups based on certification data**
  - 1960-1989
  - 1990-1997
  - 1998-2002
  - 2003-2006
  - 2007+
- **Two age groups based on data analysis**
  - 0-5 years
  - 6-9+


HC, CO, NOx Rates by Operating Mode
(MY 1994, Age 0-3)
NOx
HC
CO
Mean HC and NOx rates [g/hr]
Mean CO rate [g/hr]
Operating mode
0
50
100
150
200
250
300
350
400
450
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
0
1
11
12
13
14
15
16
21
22
23
24
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33
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39
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Questions?