MOVES

Motor Vehicle Emission Simulator

Planned Updates to Light-Duty Gaseous Emission Rates and Base Fuels in MOVES3

James Warila, Claudia Toro, Carl Fulper

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MOVES Review Work Group Meeting #11

Background

- **The current light-duty gaseous emission rates**
  - Were originally developed for MOVES2010
  - Were Updated for MOVES2014
    - To include Tier 3/LEV-III standards
- **Some studies suggested NOx is overestimated**
  - In 2011 National Emissions Inventory[1,2]
  - Suggested mobile-sources were too high
    - Particularly light-duty gasoline
- **Since 2016, we have been evaluating NOx rates in MOVES**[3,4,5,6,7]
- **Current update grown from this work**
  - Focus expanded to include THC and CO

Planned Updates to Light-Duty Emission Rates

- **Presented in April 2019**
  - Updates to emission rates at high power
  - Updates to emission rates for warm-, hot-starts
- **This presentation focuses on**
  - Updates to emissions deterioration
  - Update to Base Fuel

Issues

- **Accounting for emissions deterioration remains a challenge**
  - Broad, deep datasets necessary
    - To account for changes in average emissions with model year and age
  - Two main possibilities
    - Inspection and Maintenance Tests (I/M)
    - Remote Sensing
- **Questions:**
  - What is the shape of the long-term trend?
  - Do newer vehicles deteriorate less than older ones?
  - Is deterioration additive or multiplicative?
  - How to project deterioration for future technologies?

Assumptions

- **We have observed that**
  - Emissions distributions are highly skewed
  - Deterioration follows logarithmic patterns
    - By standard
    - By model year
- **To date, we have assumed that**
  - Logarithmic trends for Tier 2 are similar to Tier 1
- **We can evaluate these assumptions**
  - Using data covering multiple standards
    - Tier 1
    - National LEV, LEV-I,
    - Tier 2, LEV-II

Approach

- **Modify MOVES2014 rates by adjustment**
  - Datasets not ready for analysis by operating mode
    - By using adjustments, we could analyze as aggregates
- **Data Sources differ by pollutant**
  - THC and NOx: I/M tests
  - CO: remote sensing
    - Identified measurement issues with the I/M tests
- **Adjustment has two parts**
  - “Young vehicles”: ages 0-3
  - "Deterioration": ages 4-5, 6-7, 8-9, 10-14, 15-19, 20+ years
- **Use analysis of running emissions to inform start adjustments**

Running: NOx and THC

ANALYZING DETERIORATION

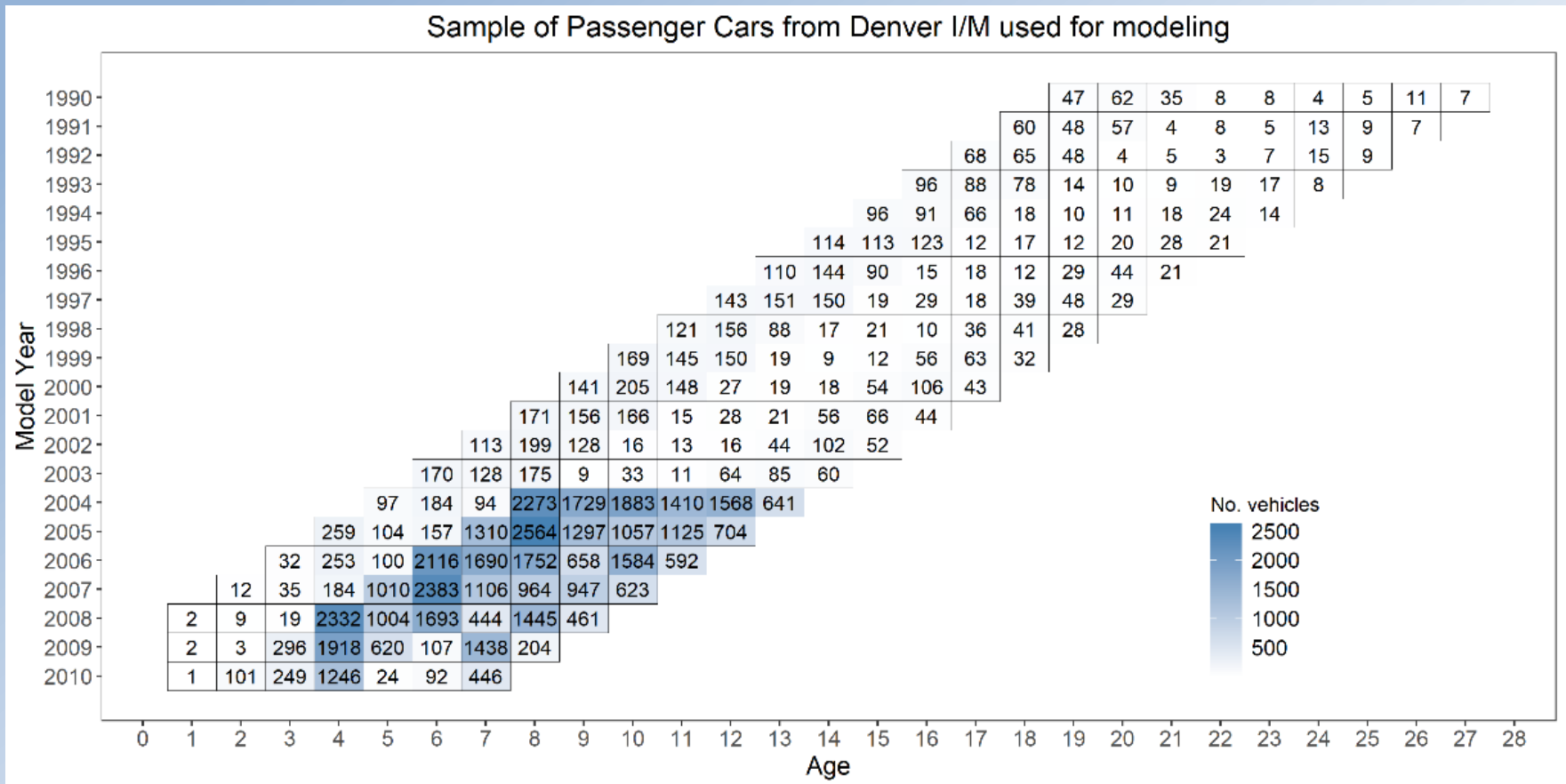
Denver Random Evaluation Sample

- **Scope**
  - CY 2009-2017
  - MY 1990-2010
- **Vehicle Classes**
  - Cars (Light-Duty Vehicle, LDV) *n* = 55,500
  - Light-Light-Duty Trucks (LLDT) *n* = 43,900
    - GVW < 6,000 lb
  - Heavy-Light-Duty Trucks (HLDT) *n* = 17,200
    - 6,000 lb <= GVW < 8,500 lb
- **IM240 Test Cycle**
  - full-duration tests
  - Used 2nd replicate (of two)
- **"Clean Screen"**
  - Potential to bias emissions high
  - Treat as "sampling" process
    - Address by weighting eligible vehicles more heavily

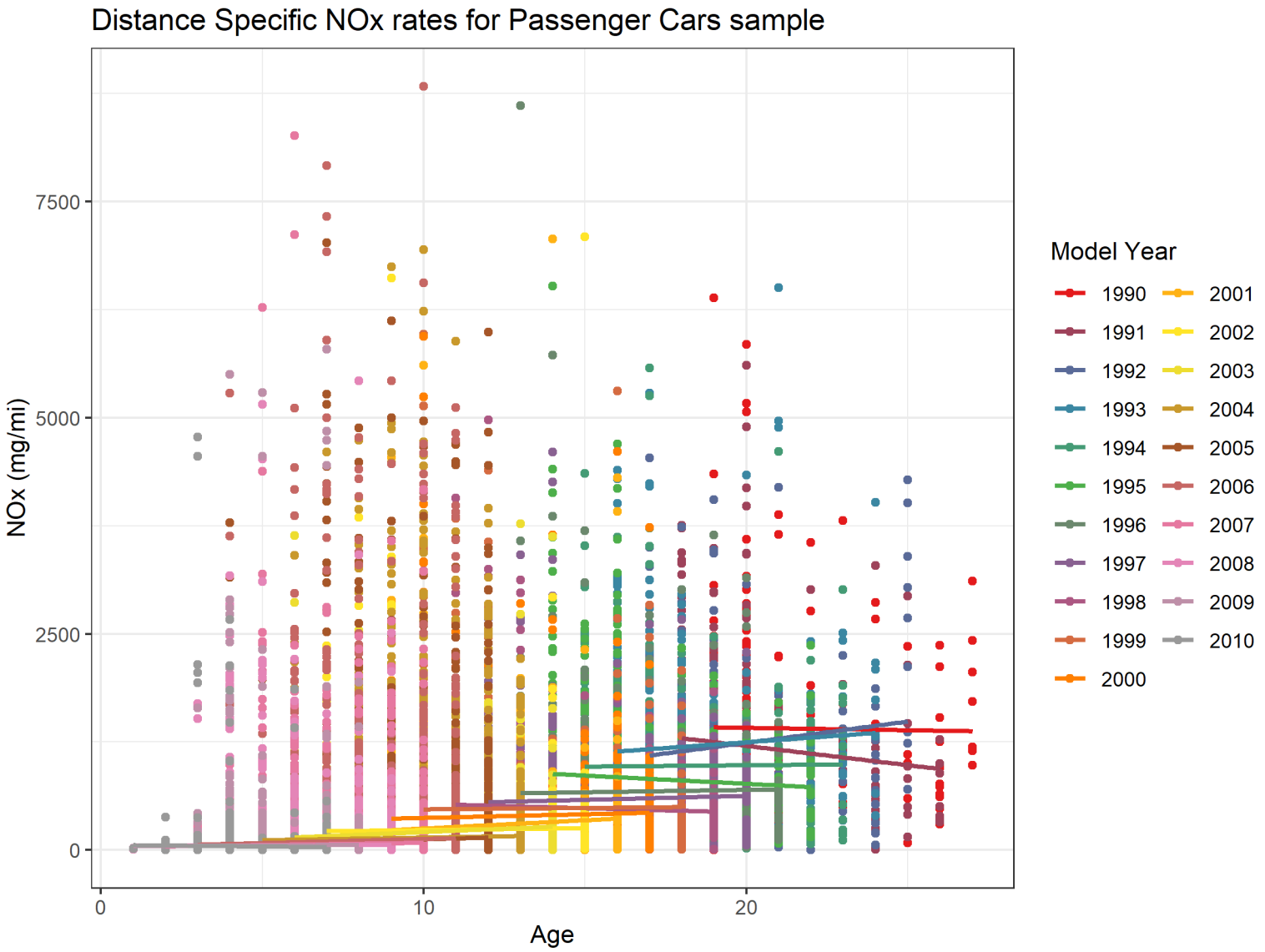
This presentation will focus on results for Cars.

Results for LLDT and HLDT are in the Appendix.

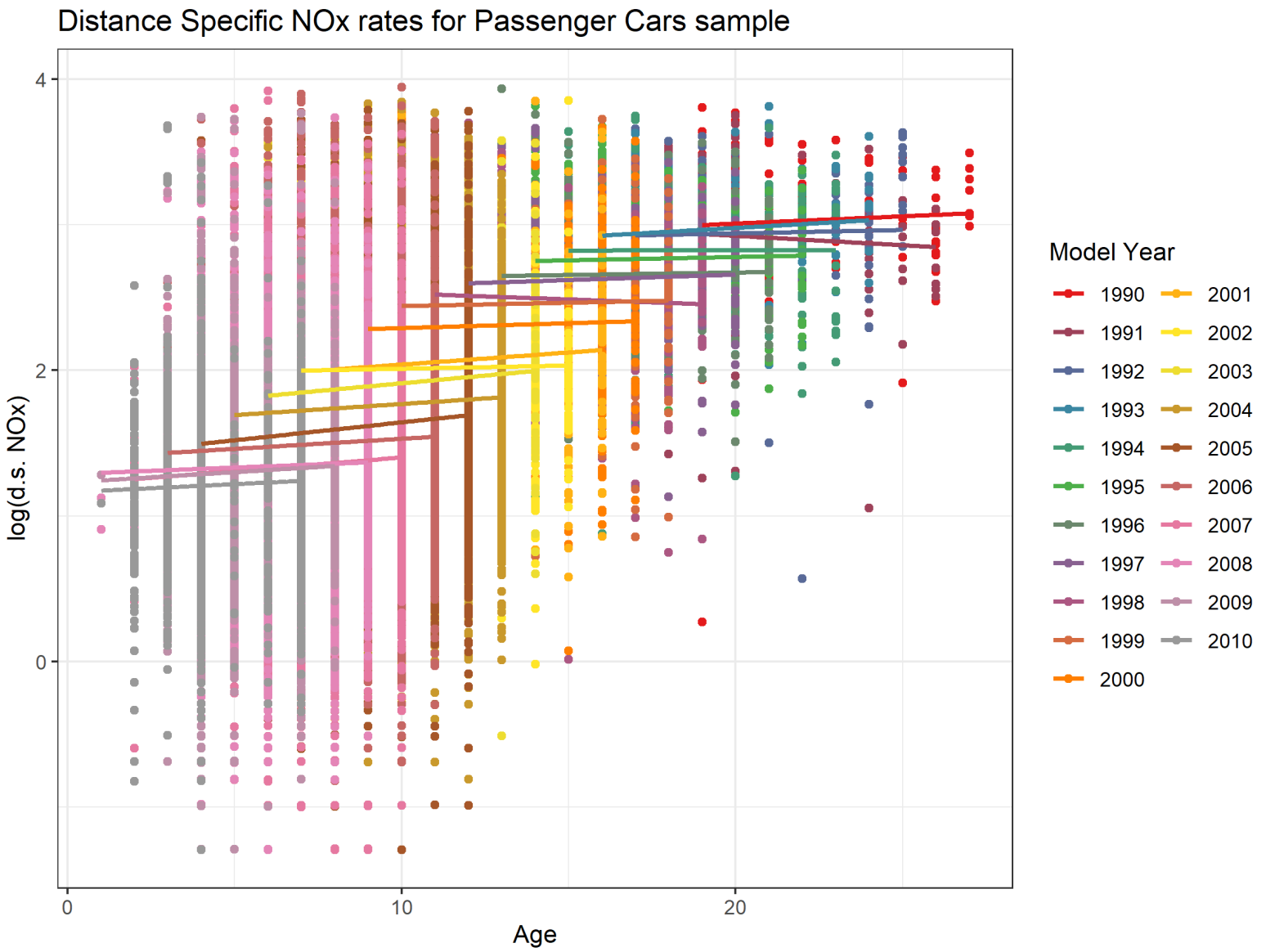
Sample Structure: Cars



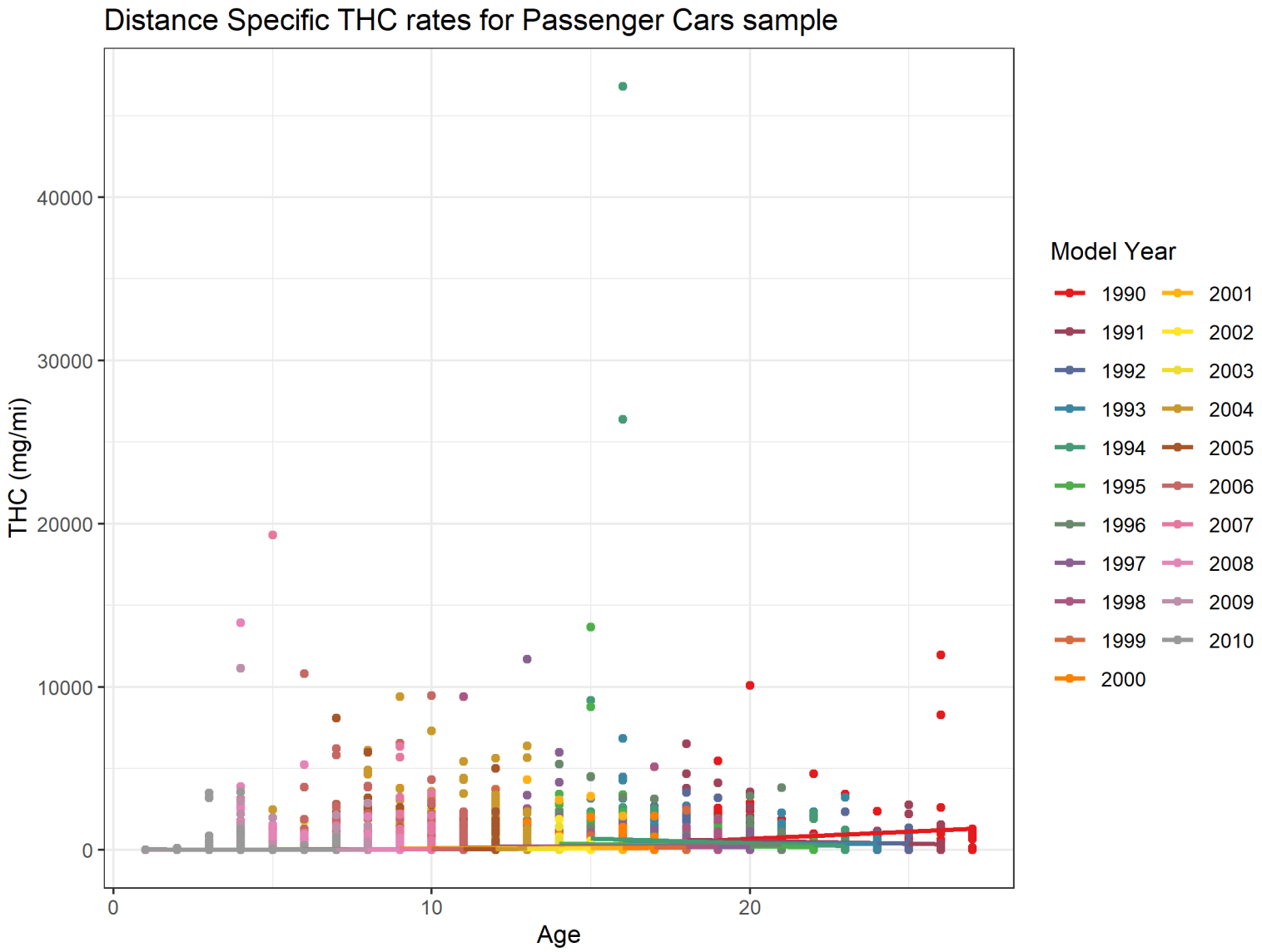
NOx: Linear Scale



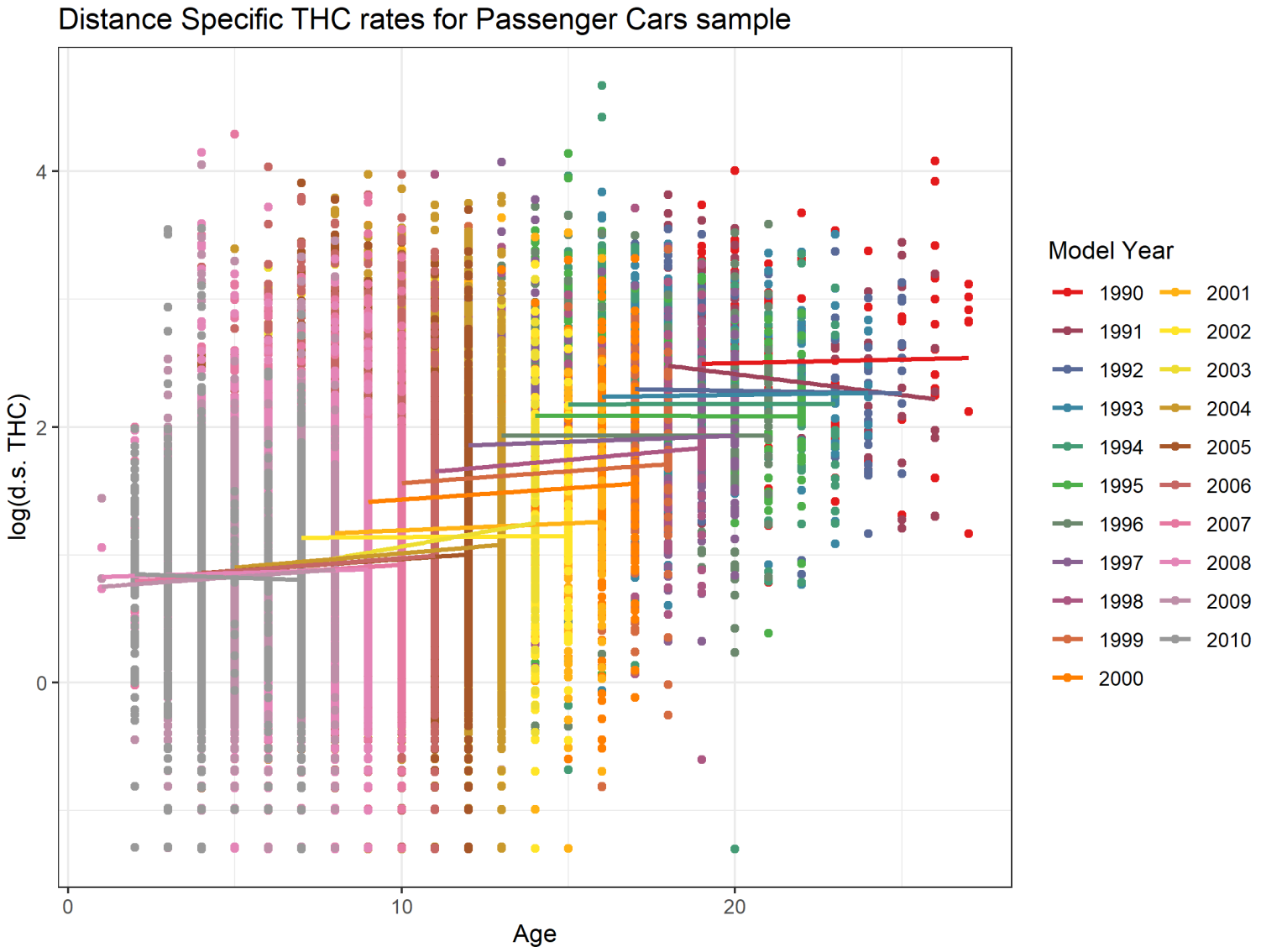
NOx: Common Log Scale



THC: Linear Scale



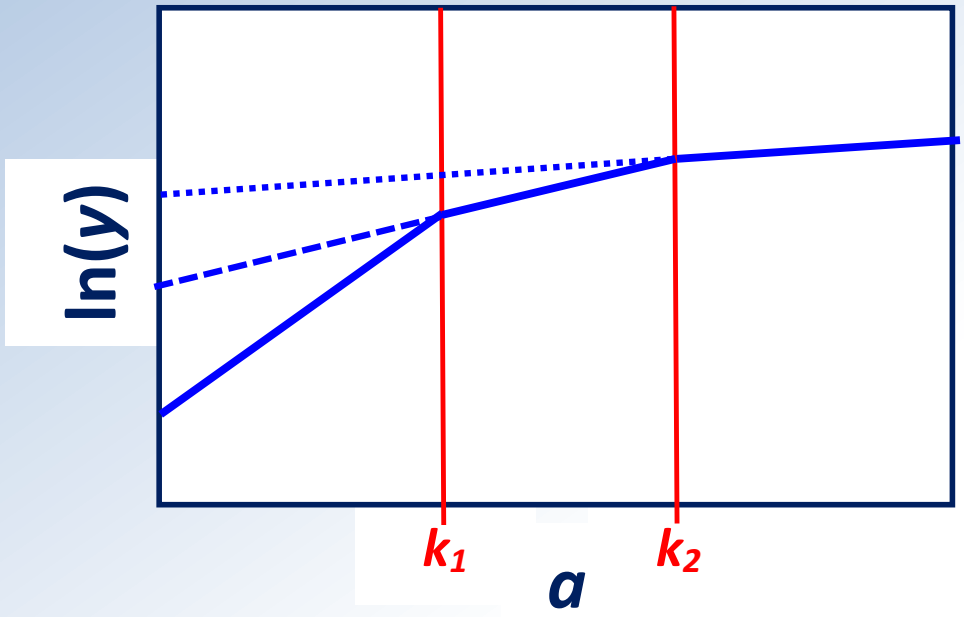
THC: Common Log Scale



The Piece-wise Statistical Model
a.k.a., "Linear Spline"

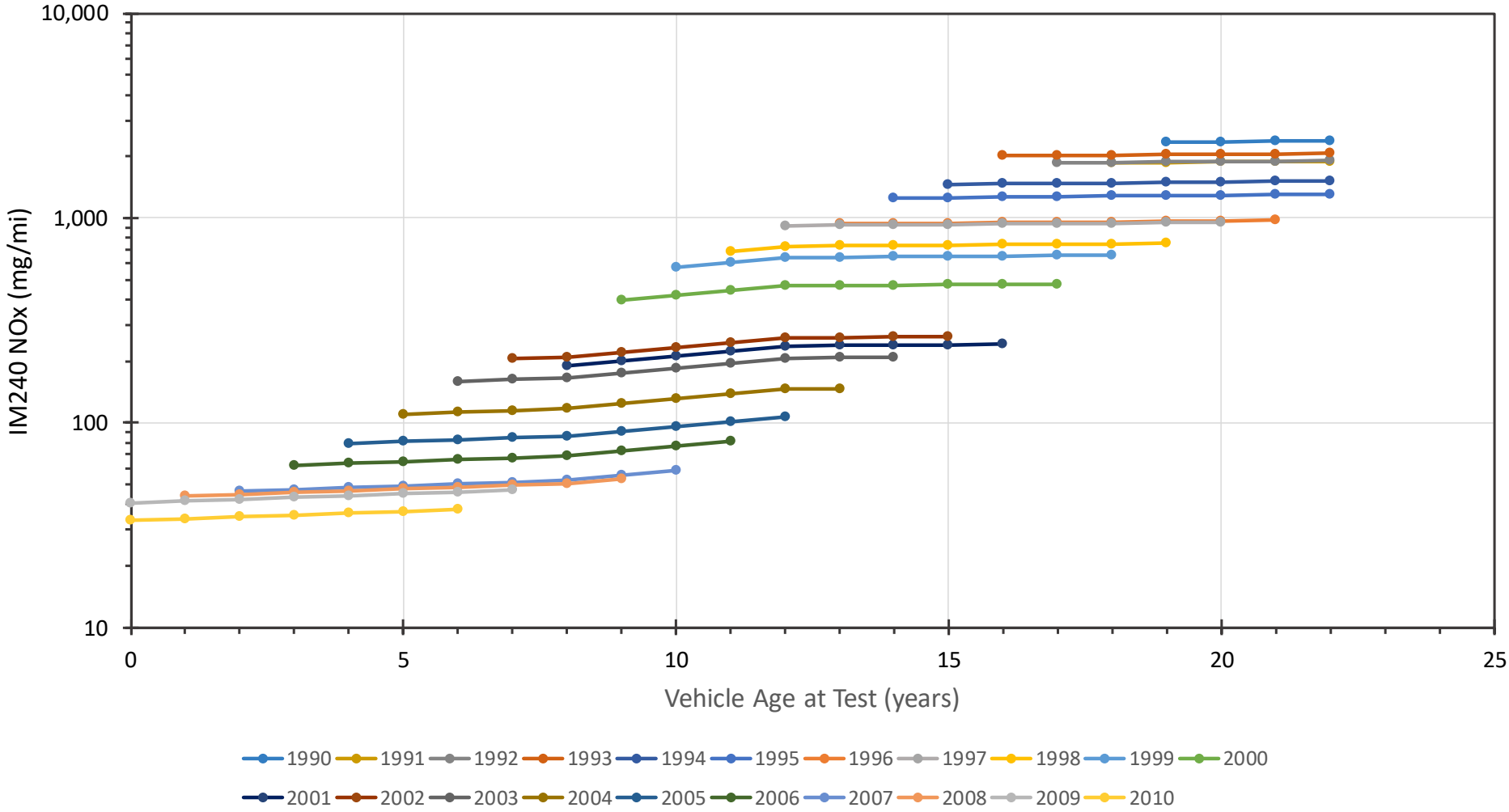
$$\ln y = b_0 + b_1 m + b_2 a + b_3 (a - k_1) d_2 + b_4 (a - k_2) d_3 + \varepsilon$$

- **Response variable (ln(*y*))**
  - lnNOx, lnTHC
  - Distance specific (mg/mi)
- **Predictors**
  - Slope term: Age (*a*, years)
  - Intercepts: Model Year
- **Segments**
  - Fit three segments
  - Defined by two "knots" (k1, k2)

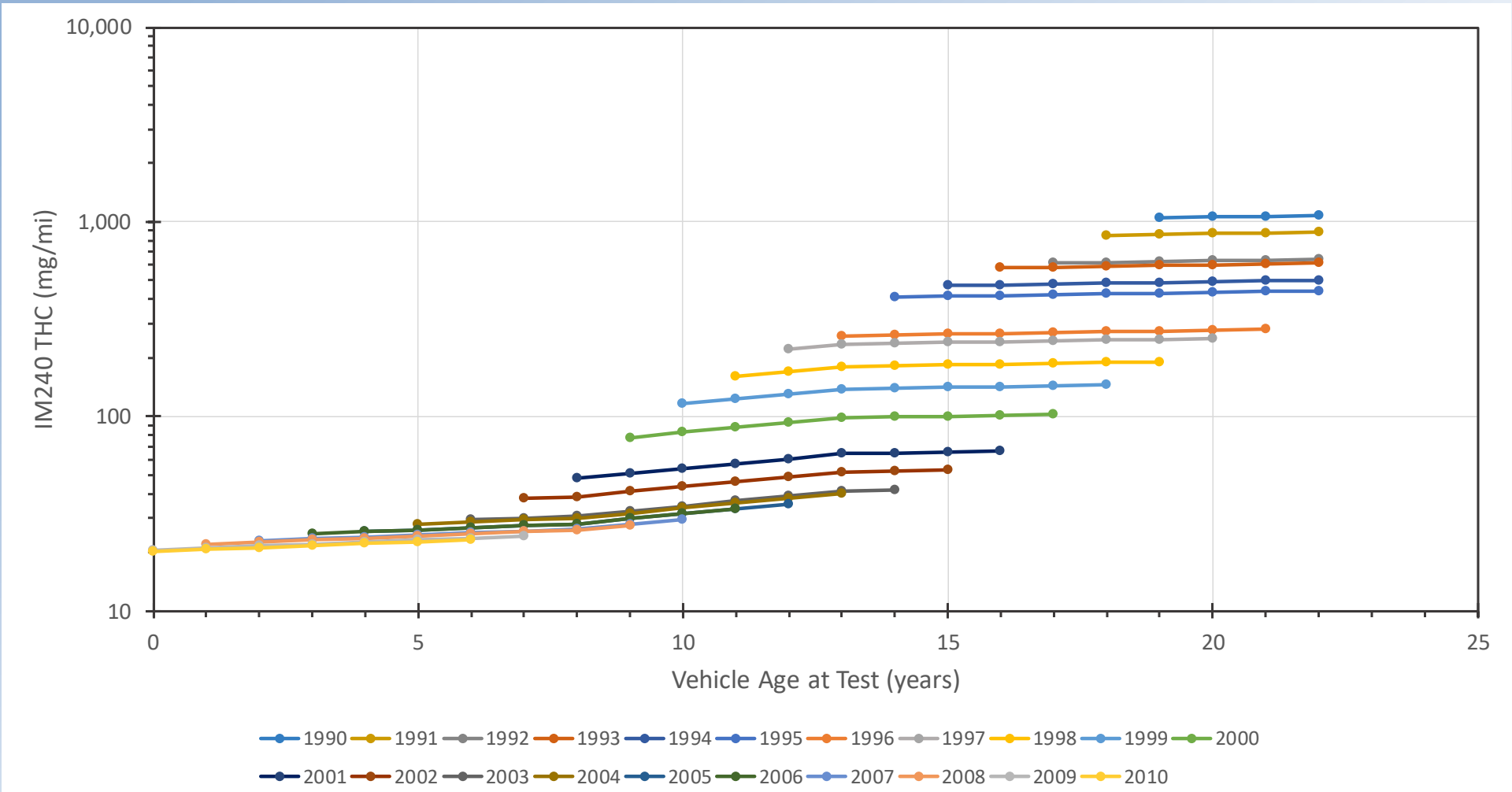


Segment	d_1	d_2	Intercept	Slope
$0 < a \leq k_1$	0	0	$b_0 + b_1$	b_2
$k_1 < a \leq k_2$	1	0	$b_0 + b_1 - b_3 k_1$	$b_2 + b_3$
$k_2 < a$	1	1	$b_0 + b_1 - b_3 k_1 - b_4 k_2$	$b_2 + b_3 + b_4$

Model Fit: NOx
Common Log Scale



Model Fit: THC
Common Log Scale



Reverse Transformation

Using NOx as an example:

The model gives $\ln \mathrm{NO}_x = b_0 + b_1 a$,

so that $\mathrm{NO}x = e^{b_0 + b_1 a}$ *, but*

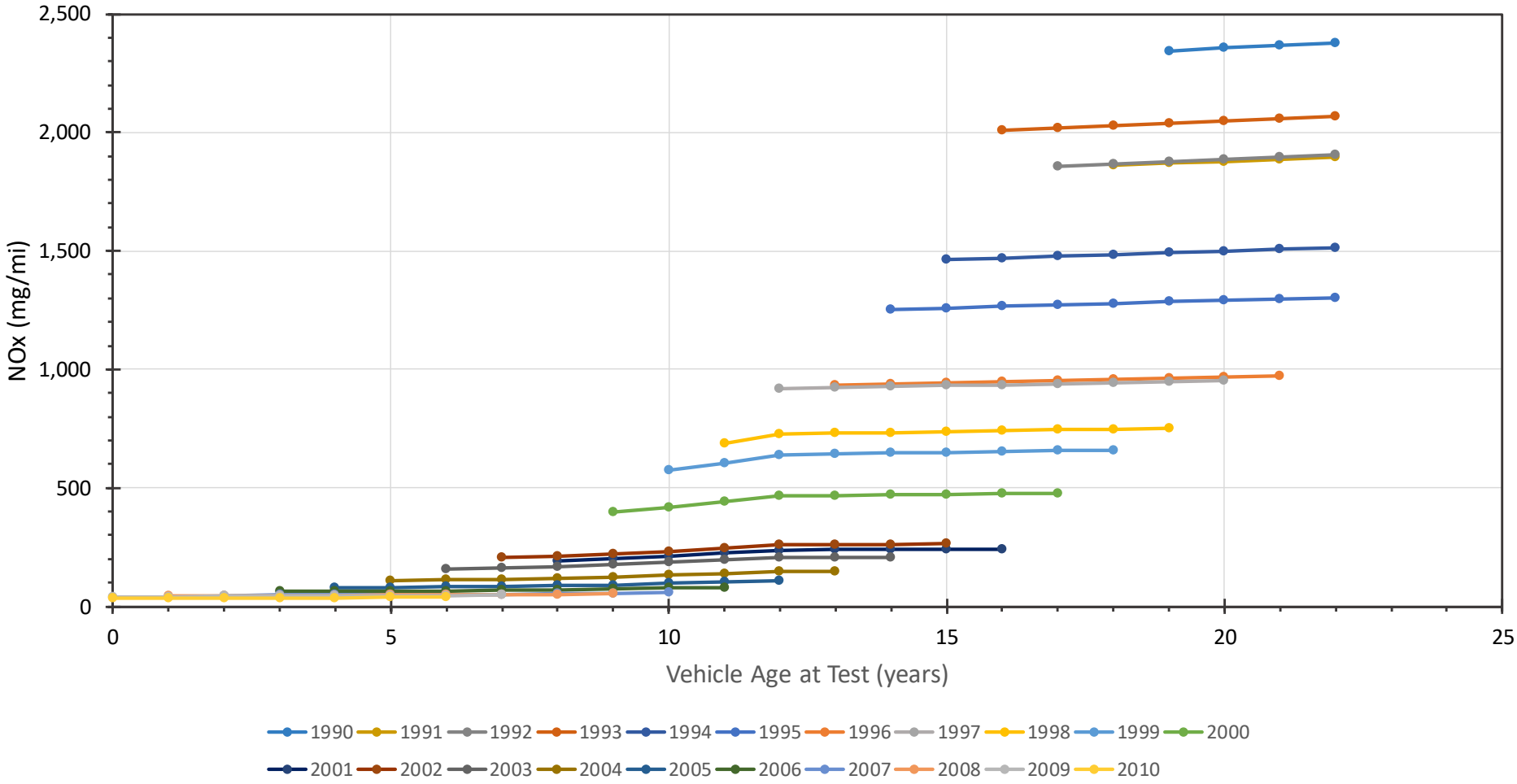
This value represents the 'median[1],' rather than the 'mean' emissions level. To get the 'mean' we need to add

$$\mathrm{NO}x = e^{b_0 + b_1 a} e^{0.5\sigma_l^2}$$

where σ_l^2 *= the variance of lnNOx*

[1]*Strictly speaking the 'geometric mean,' but effectively, the median.*

Model Fit: NOx
Linear Scale (reverse transformed)



Model Fit: THC
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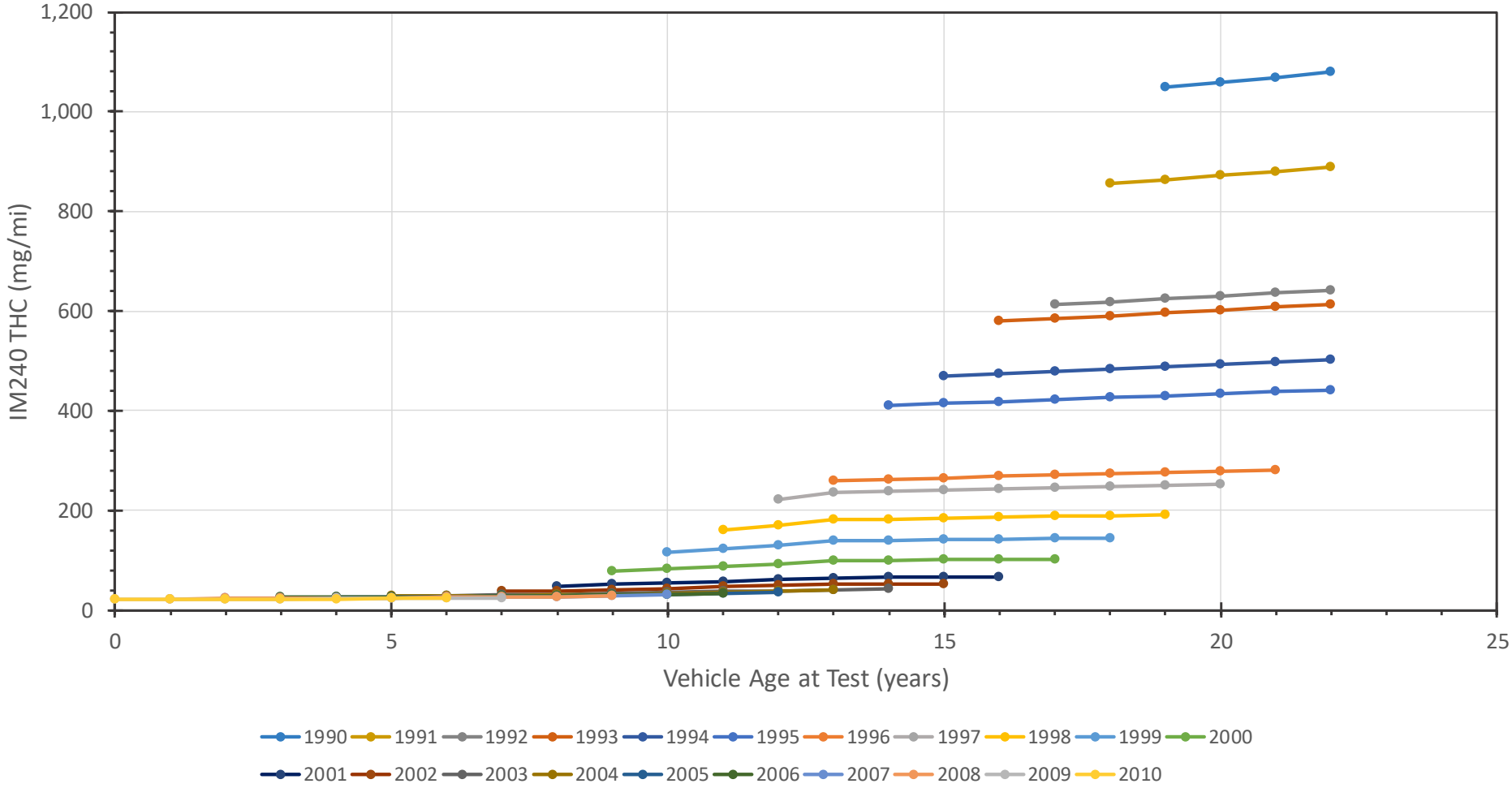


Running: CO

ANALYZING DETERIORATION

CDPHE Remote Sensing

Colorado Department of Public Health and Environment

- **Scope**
  - CY 2009-2013
  - MY 1990-2010
- **Vehicle Classes**
  - Cars (LDV)
  - Light Trucks (LDT)
- **Remote Sensing**
  - Throughout the Denver Area
  - Multiple instruments, sites
- **"Censoring"**
  - Individual measurements ≤ 0.0
    - Fractions higher for cleaner vehicles

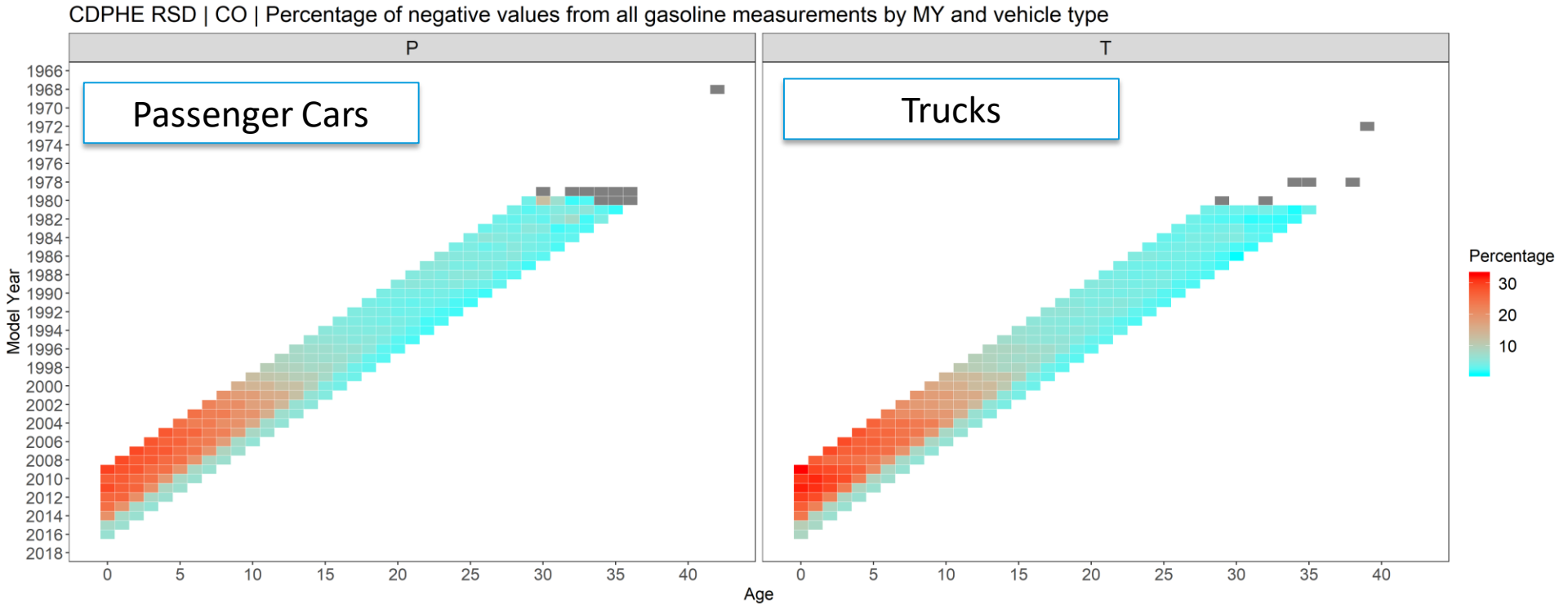
This presentation will focus on results for Cars.

Results for Trucks are in the Appendix.

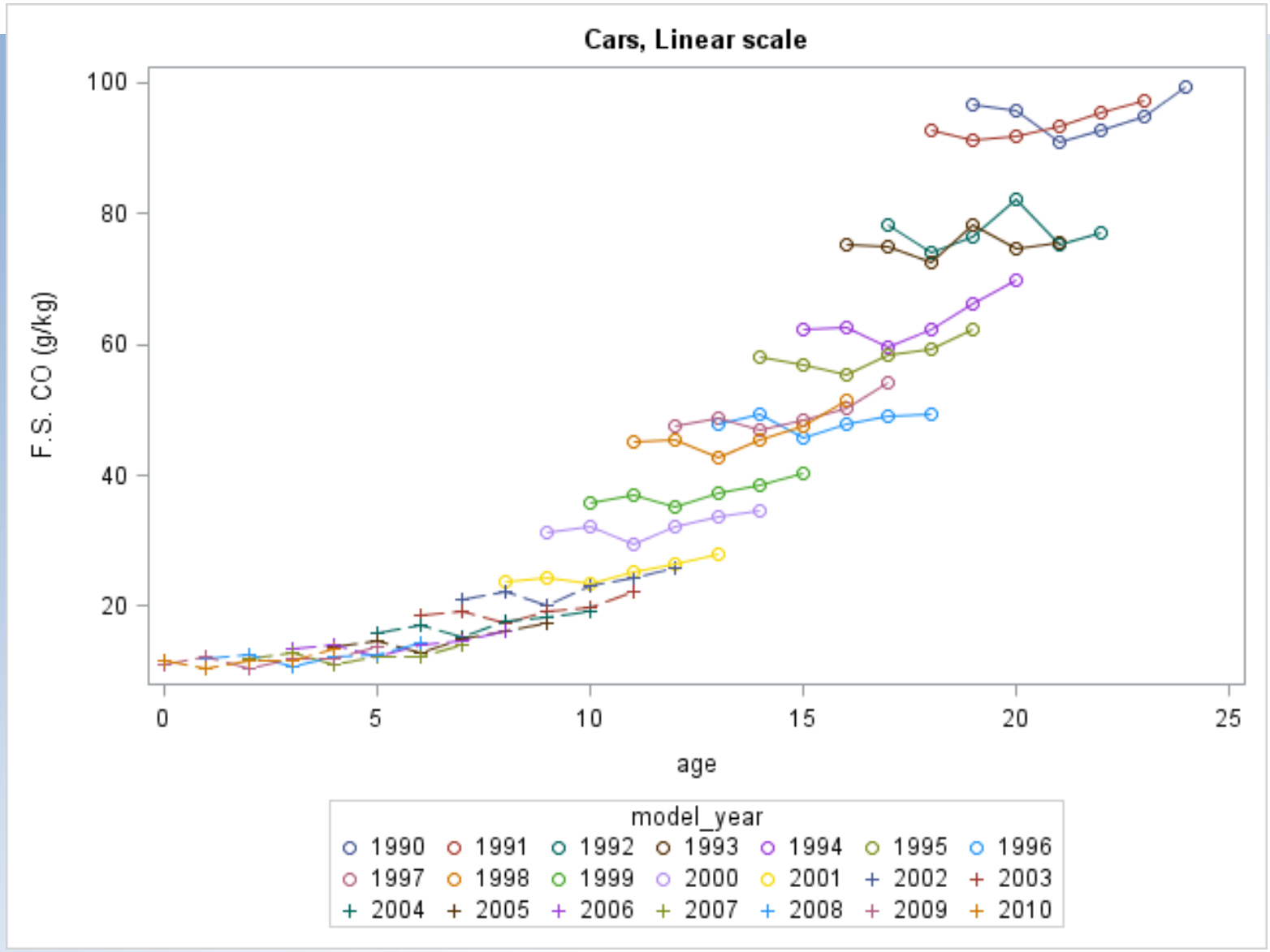
CDPHE Remote Sensing Sample Sizes

Category	Vehicle Class	No. Meas. (Incl. Negatives)	No. Meas. (Excl. Negatives)
Cars	LDV	14,965,000	13,385,000
Trucks	LDT	19,860,000	17,608,000
Total		34,825,000	30,993,000

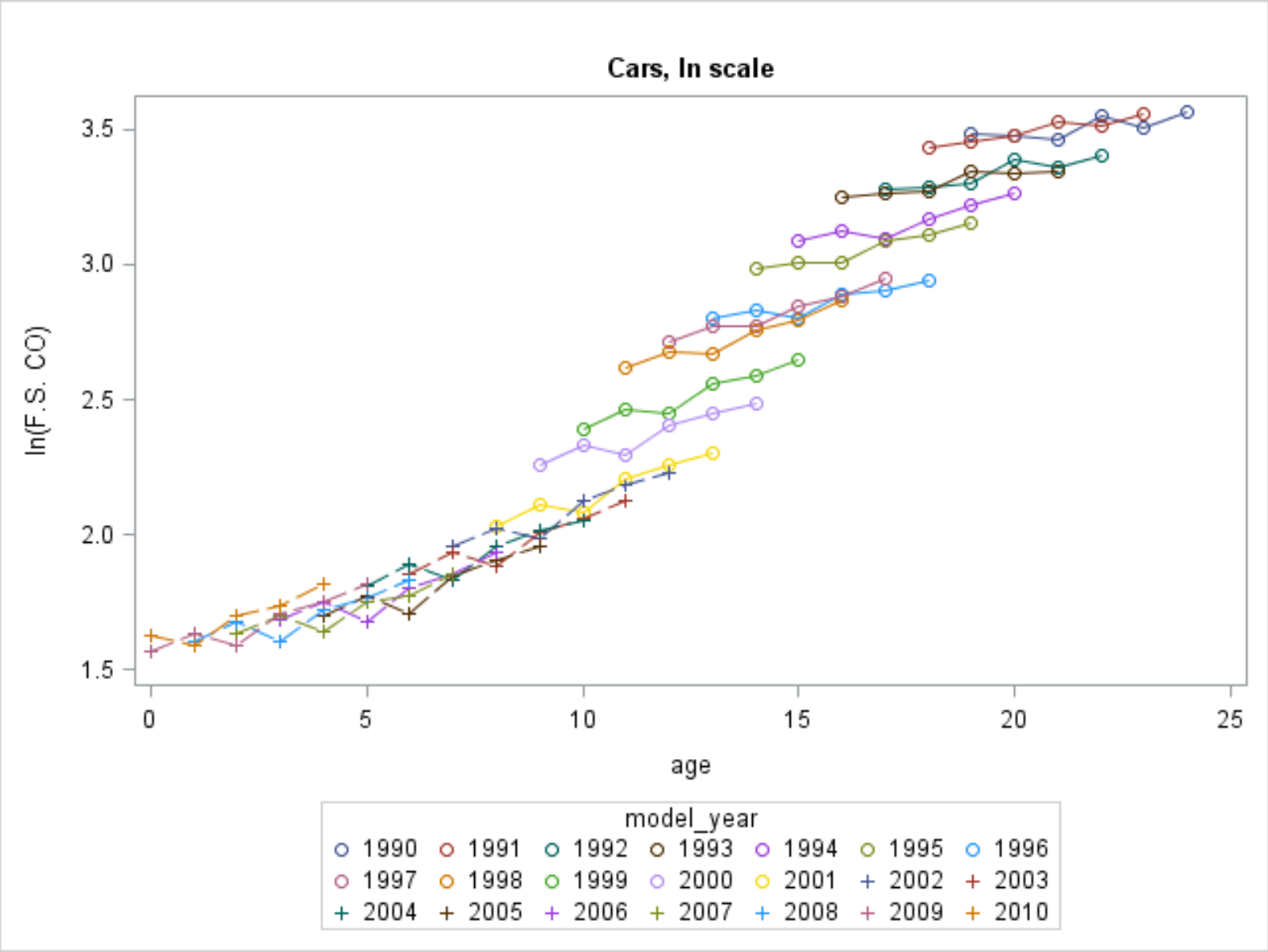
Censoring in CO datasets



CO: Linear Scale



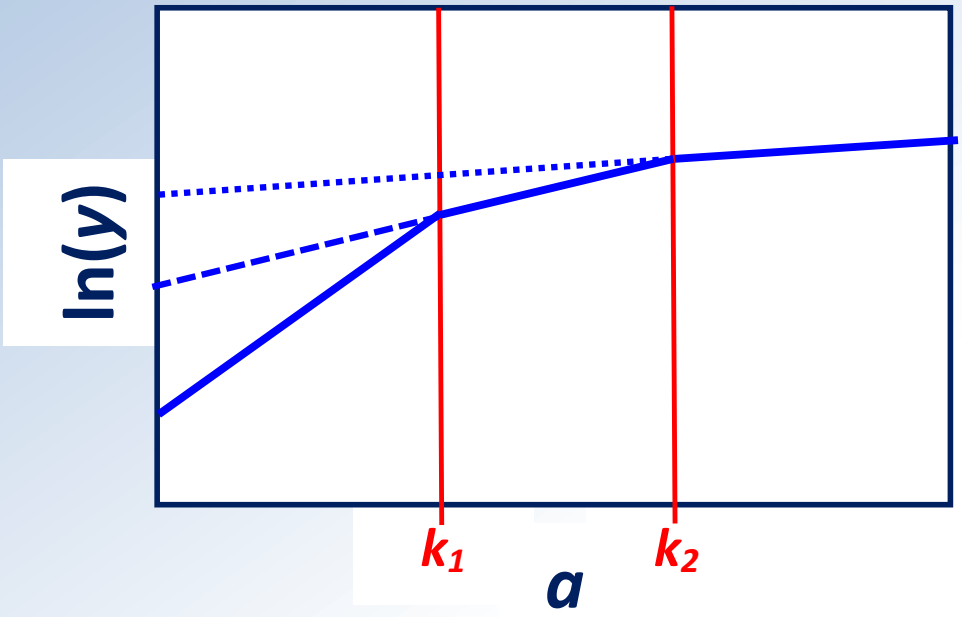
CO: Common Log Scale



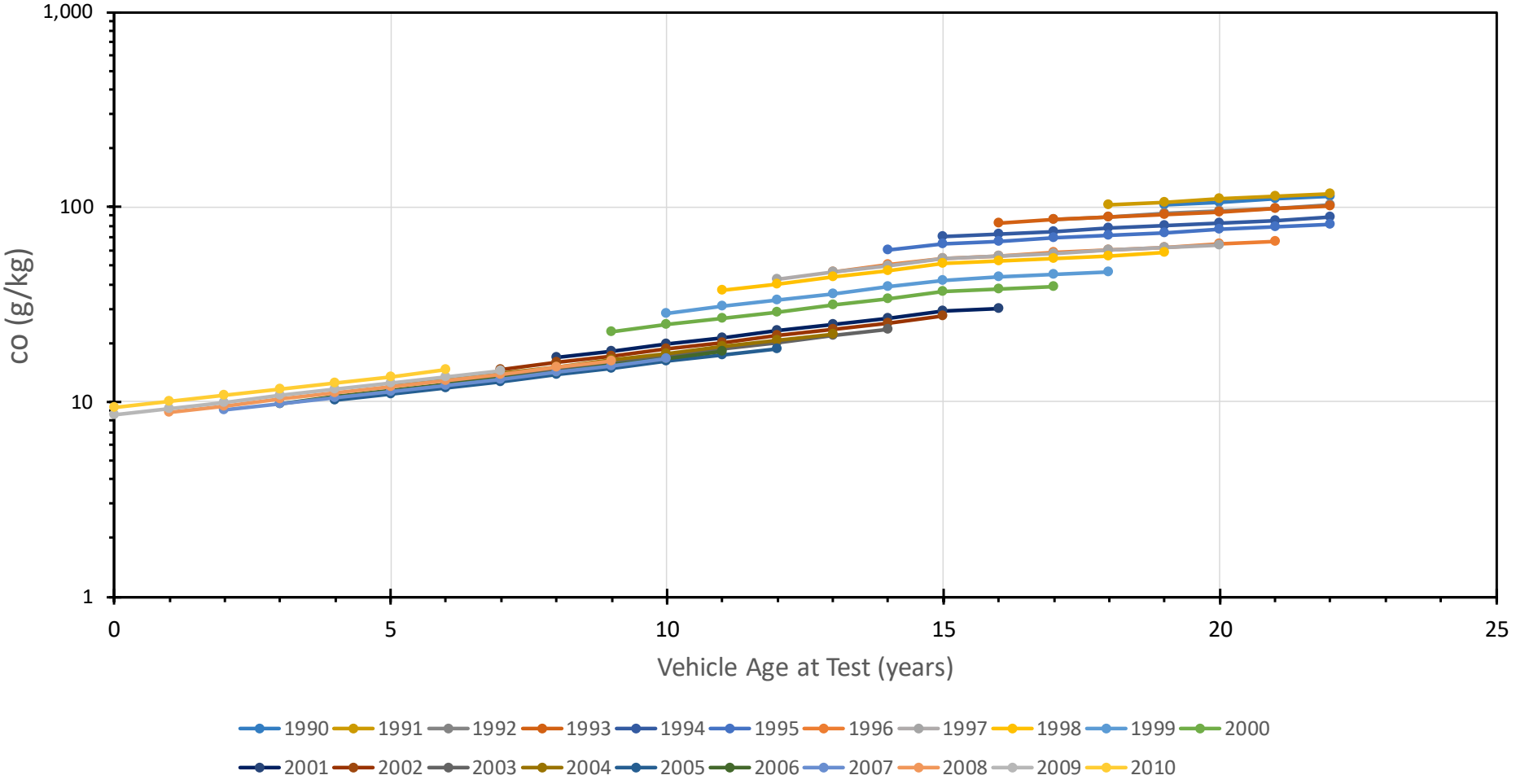
The Piece-wise Statistical Model
a.k.a., "Linear Spline"

$$\ln y = b_0 + b_1 m + b_2 a + b_3 (a - k_1) d_2 + b_4 (a - k_2) d_3 + \varepsilon$$

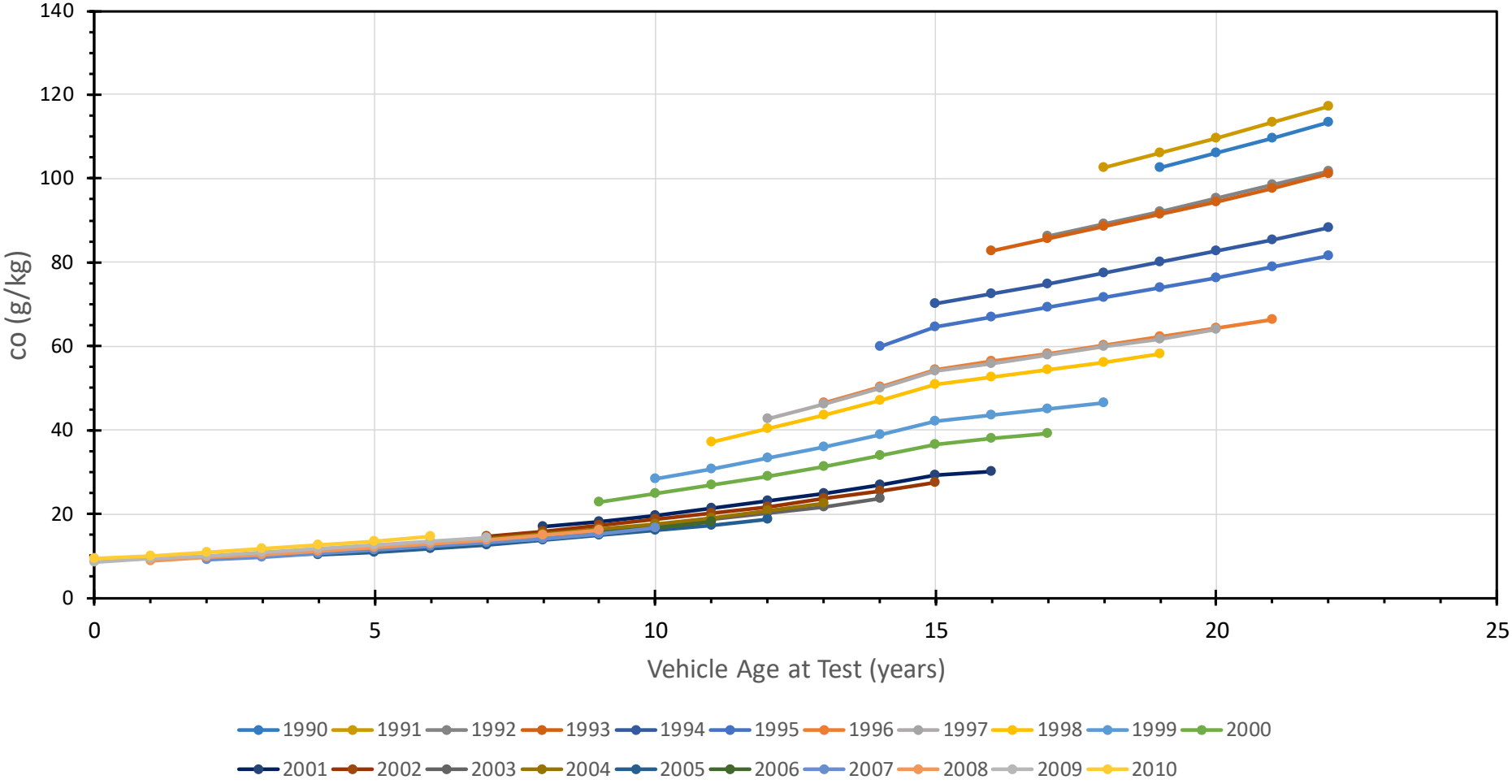
- **Response variable (ln(*y*))**
  - **lnCO**
  - Fuel-specific (g/kg)
- **Predictors**
  - Slope term: Age (*a*, years)
  - Intercepts: Model Year
- **Segments**
  - Fit three segments
  - Defined by two "knots"
- **Fitting Method**
  - "Tobit Regression"
  - For left-censored data
  - "negatives" NOT dropped, assigned as "missing"



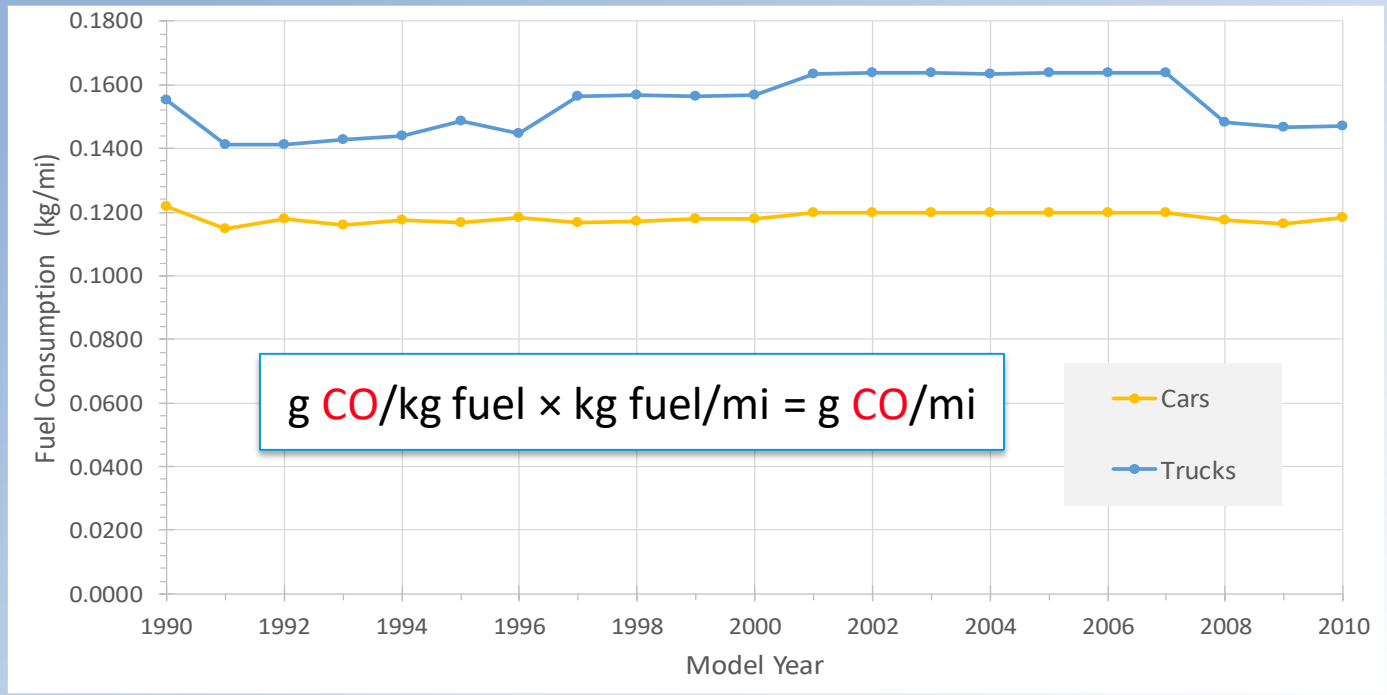
Model Fit: CO
Common Log Scale



Model Fit: CO
Linear Scale (Reverse-transformed)



Translate fuel-specific to distance-specific CO



- **Simulate fuel consumption on IM240 (kg fuel/mi)**
  - Based on MOVES Energy Consumption rates
- **Multiply by fuel-specific CO**

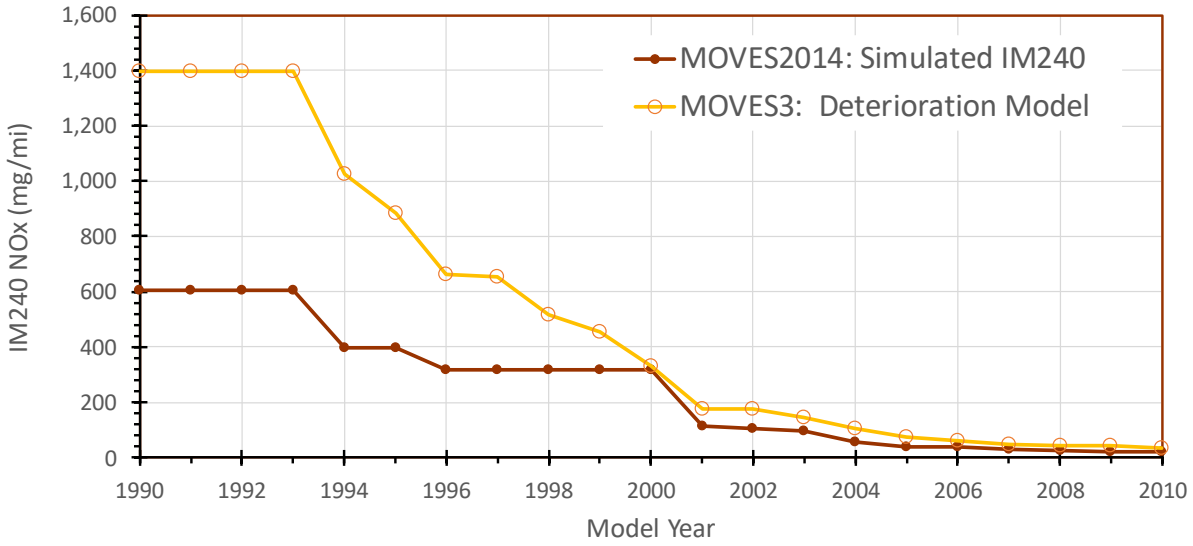
"Young-Vehicle" Adjustments for Running Process

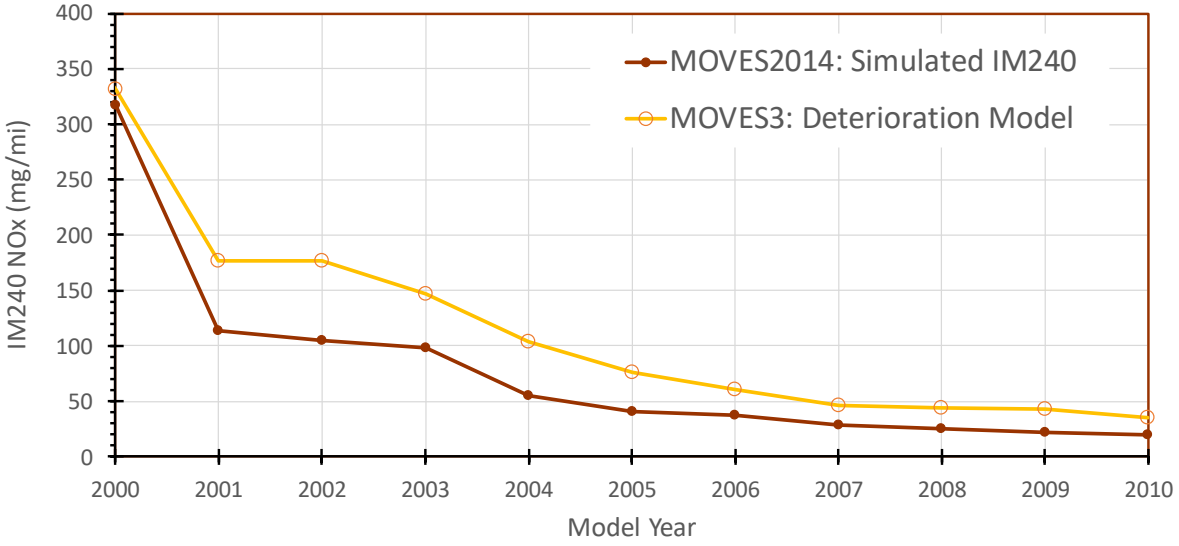
DEVELOPING REVISED RATES

"Young Vehicles"

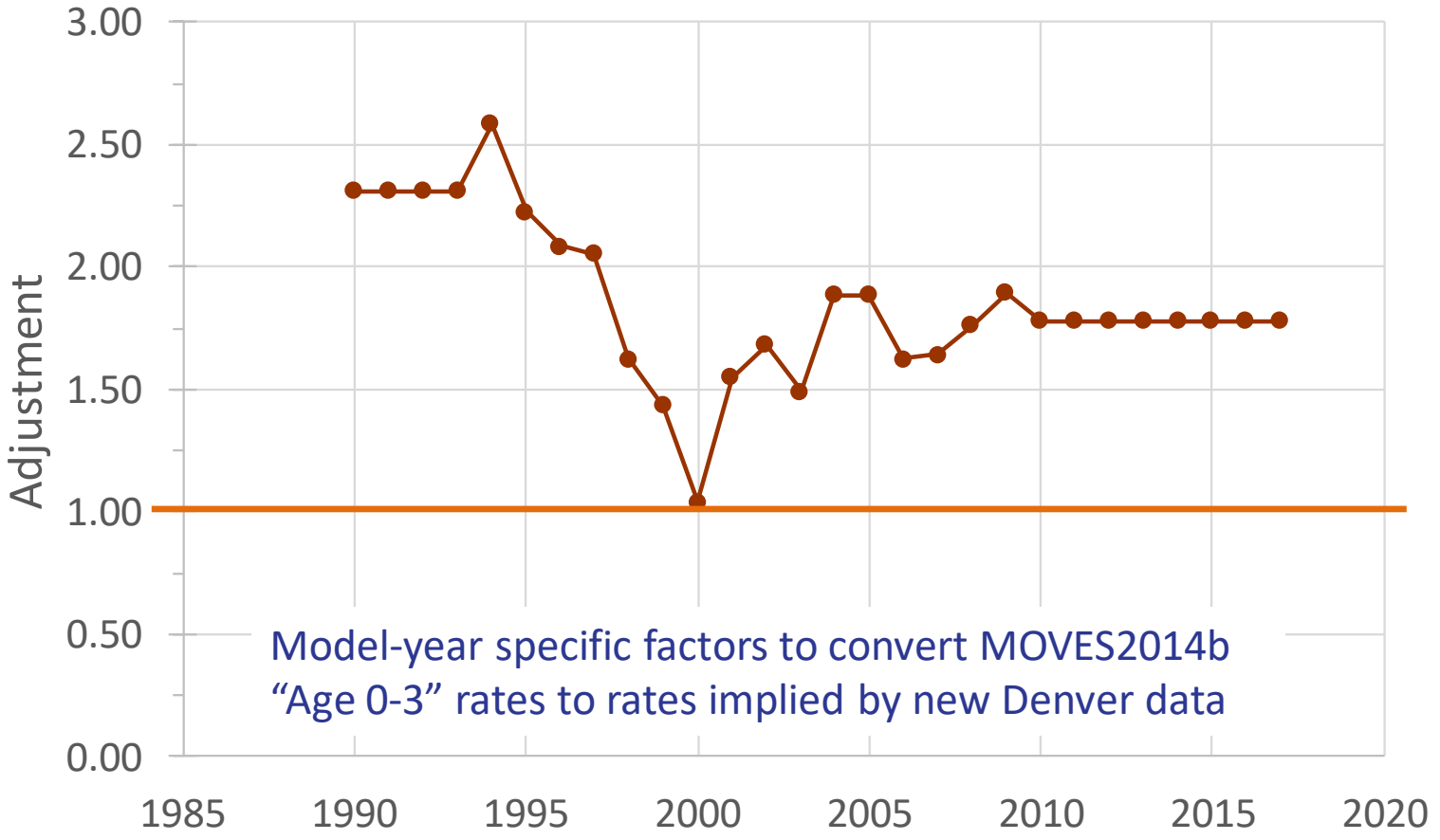
- **Definition: vehicles in the first age Group**
  - 0-3 years
- **Duration is four years (not three)**
  - Midpoint is 2 years (not 1.5)
- **Starting point**
  - Apply deterioration models
  - Examine trends vs MY
    - At age = 2 years
- **Comparison to MOVES2014**
  - Simulated IM240s
    - Combined emissions rates with operating-mode distribution

NOx: MY Trends at Age 2 MOVES2014 vs. New Analysis

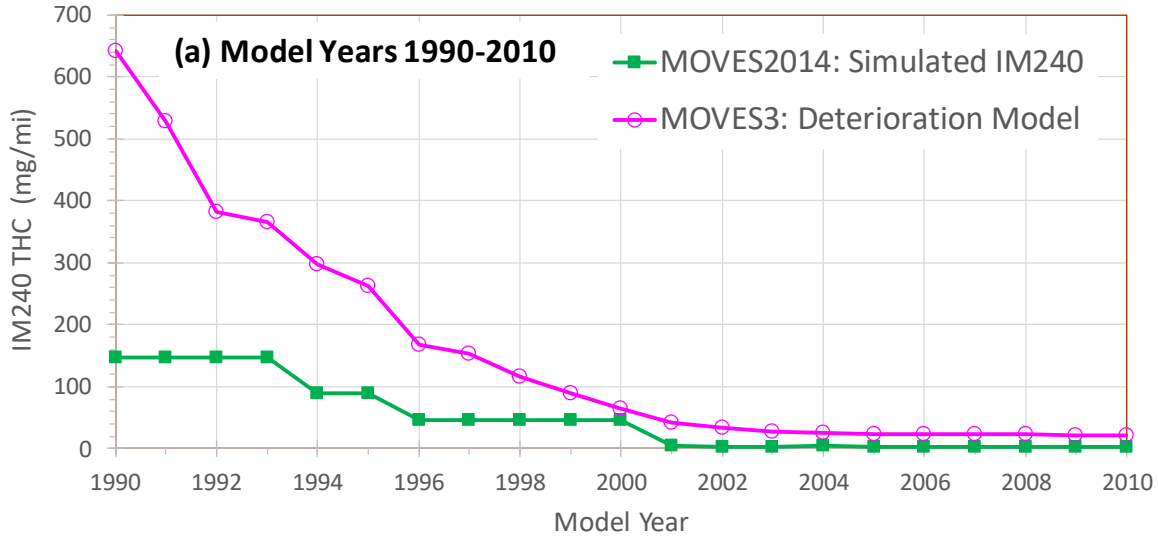


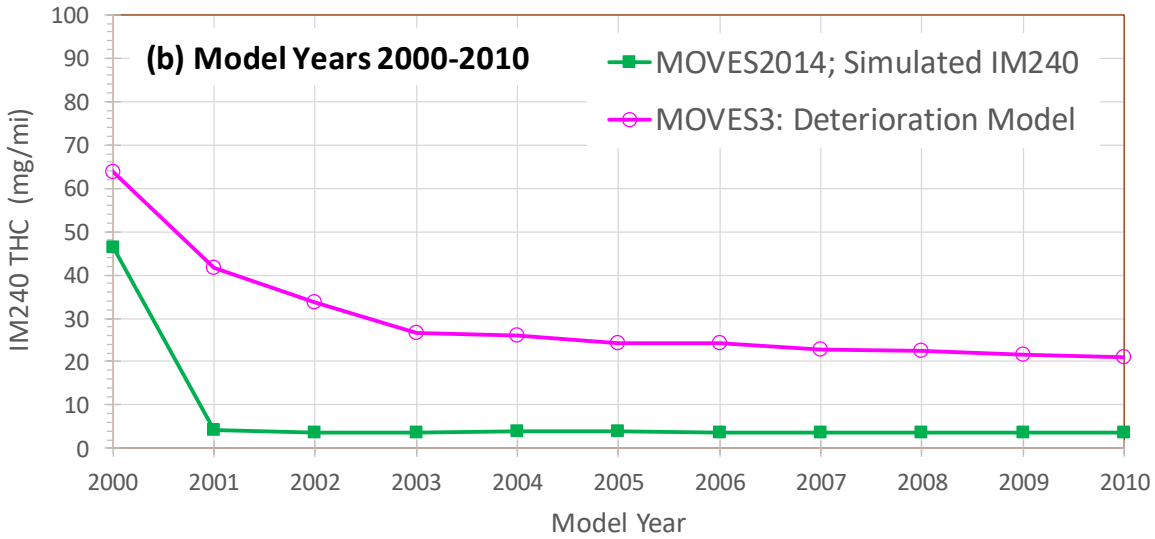


NOx: "Young-Vehicle" Adjustments

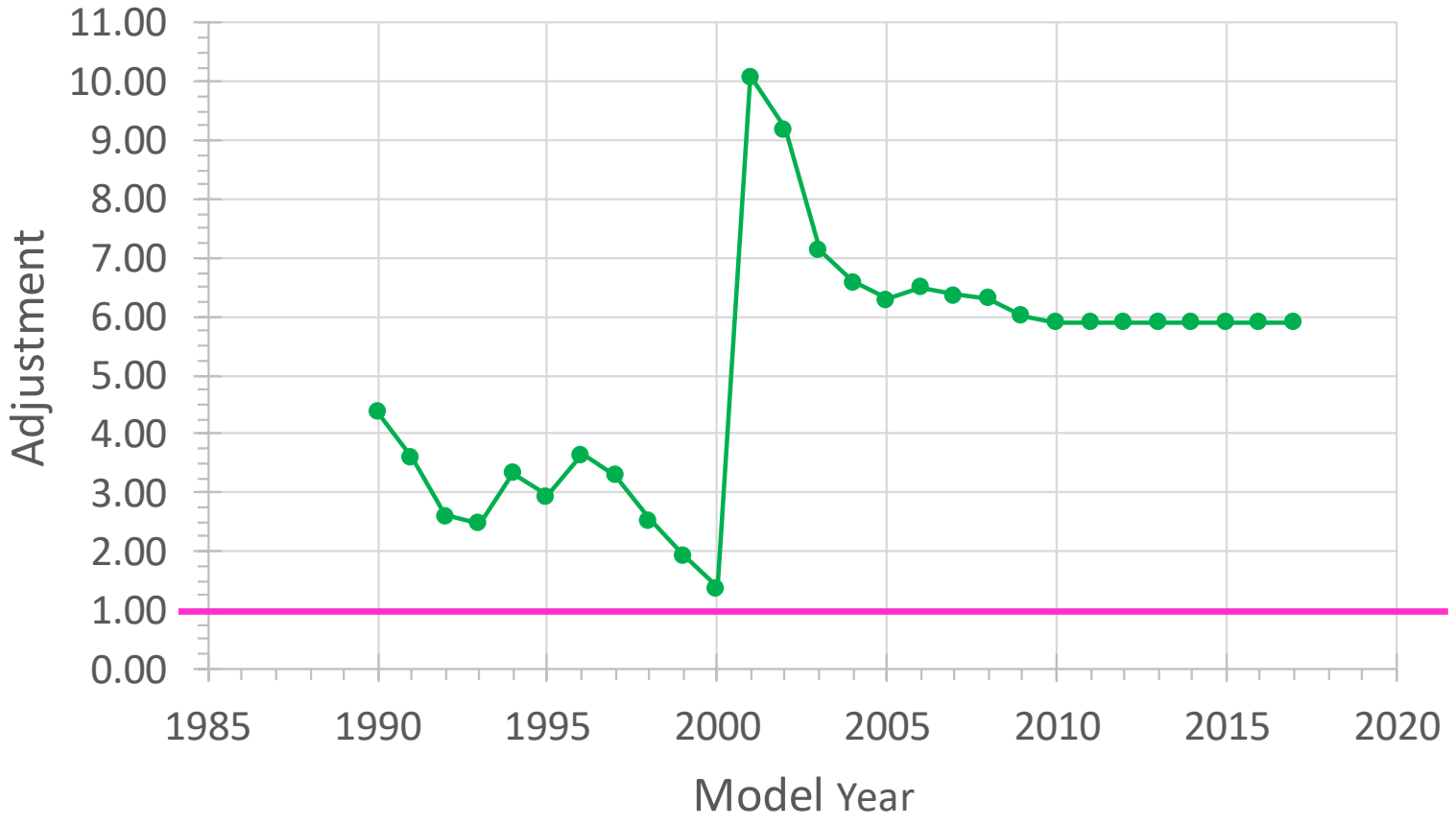


THC: MY Trends at Age 2 MOVES2014 vs. New Analysis



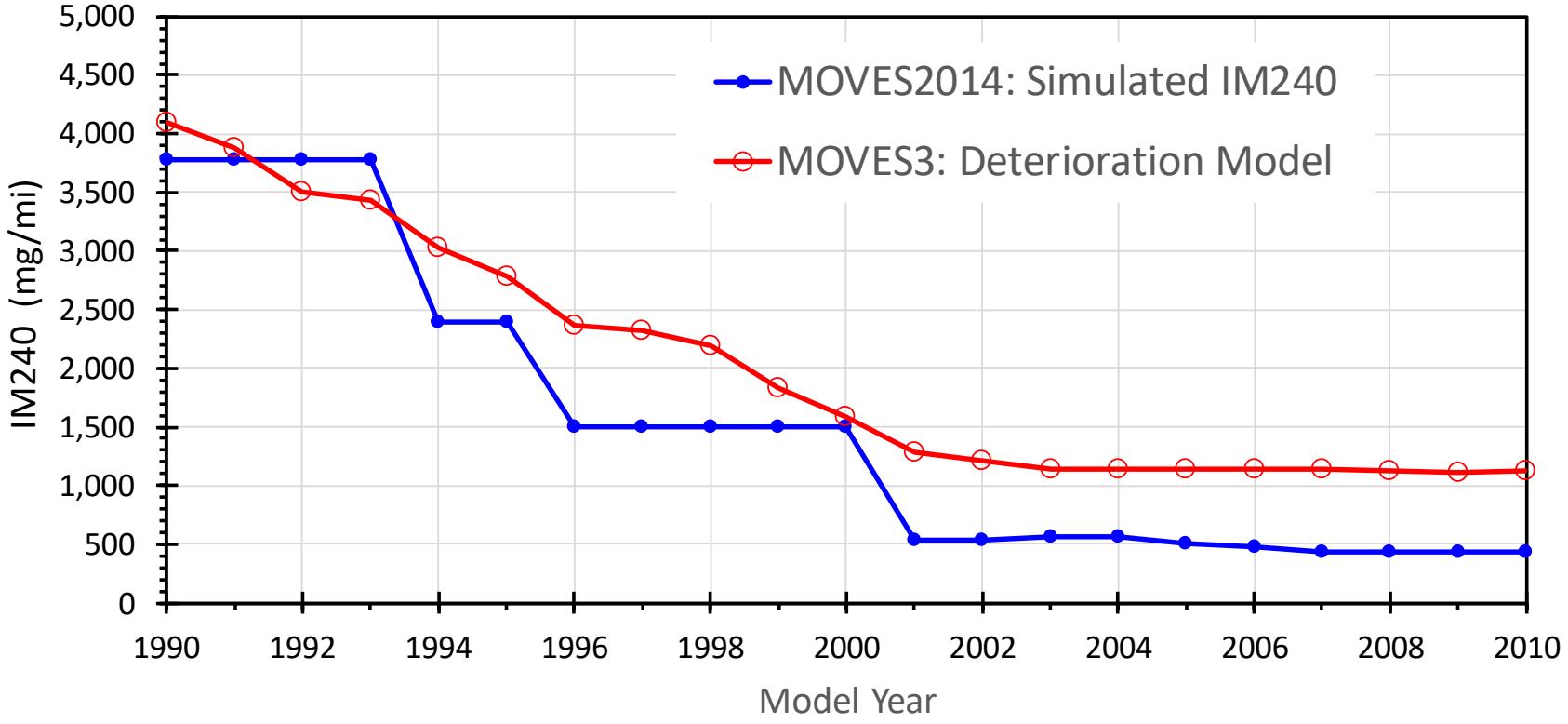


THC: "Young-Vehicle" Adjustments

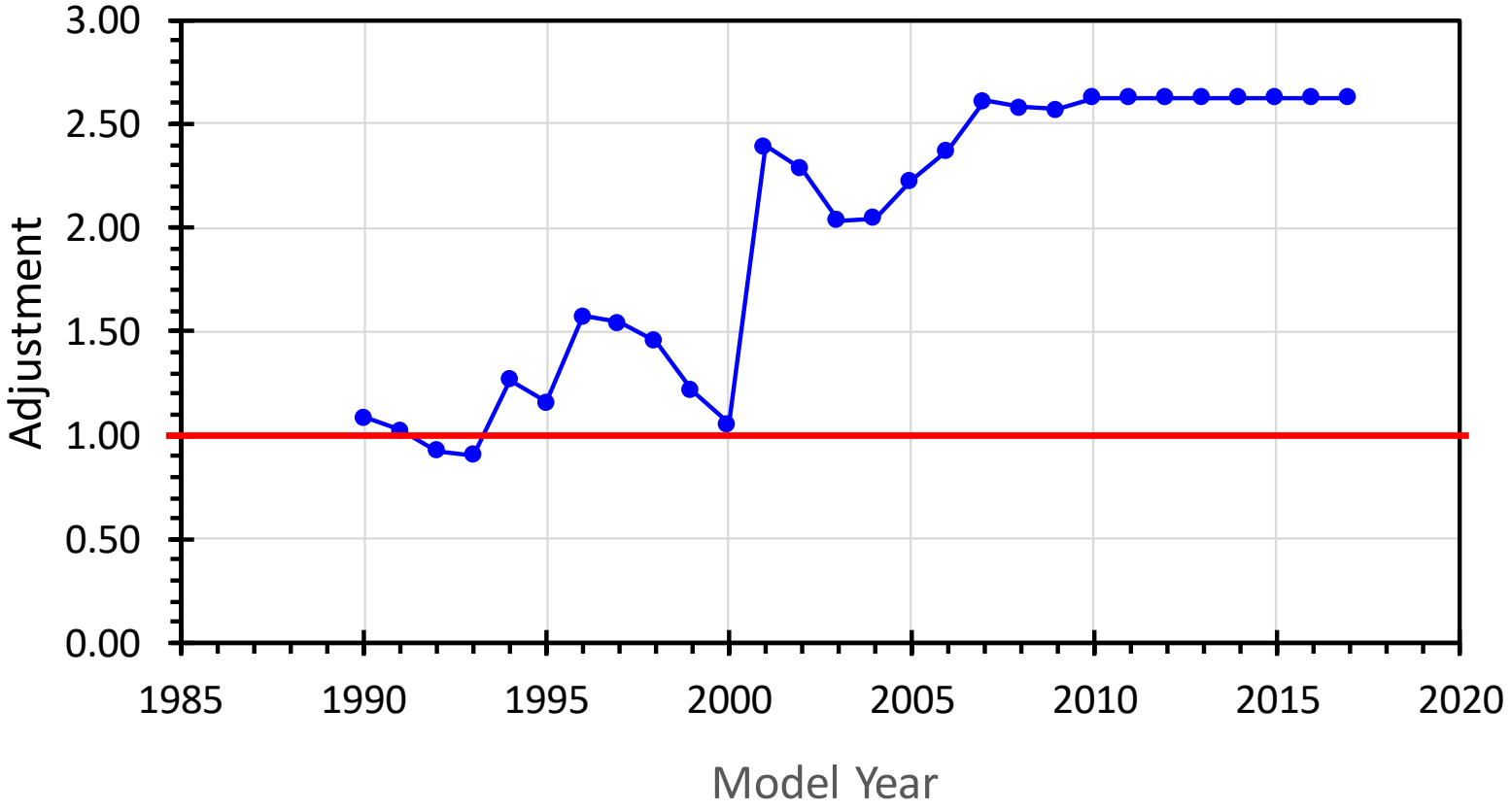


Model-year specific factors to convert MOVES2014b "Age 0-3" rates to rates implied by new Denver data

CO: MY Trends at Age 2 MOVES2014 vs. New Analysis



CO: "Young-Vehicle" Adjustments

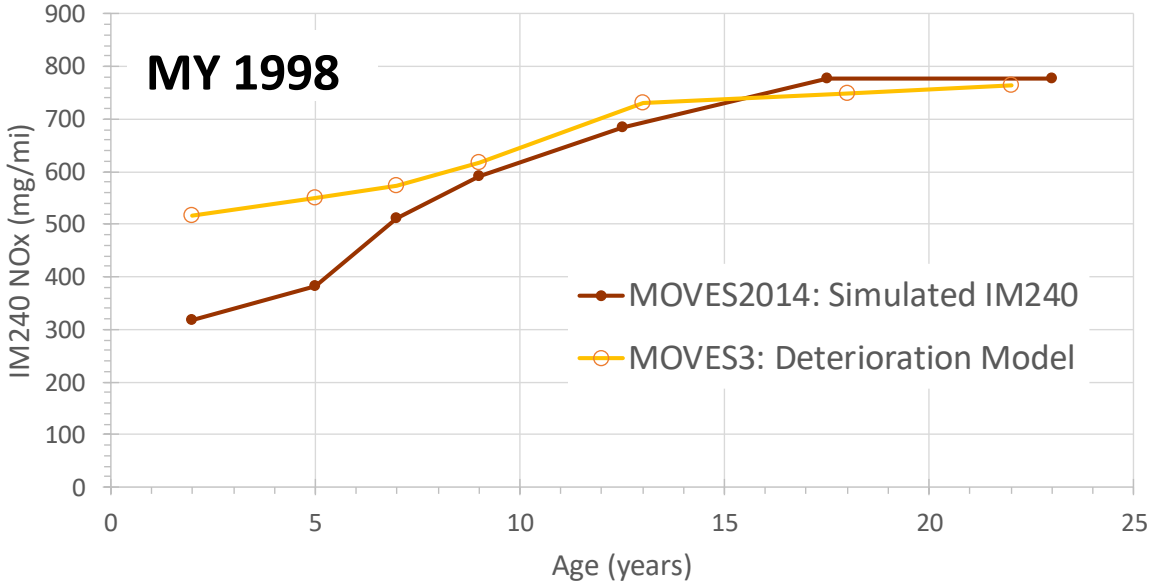


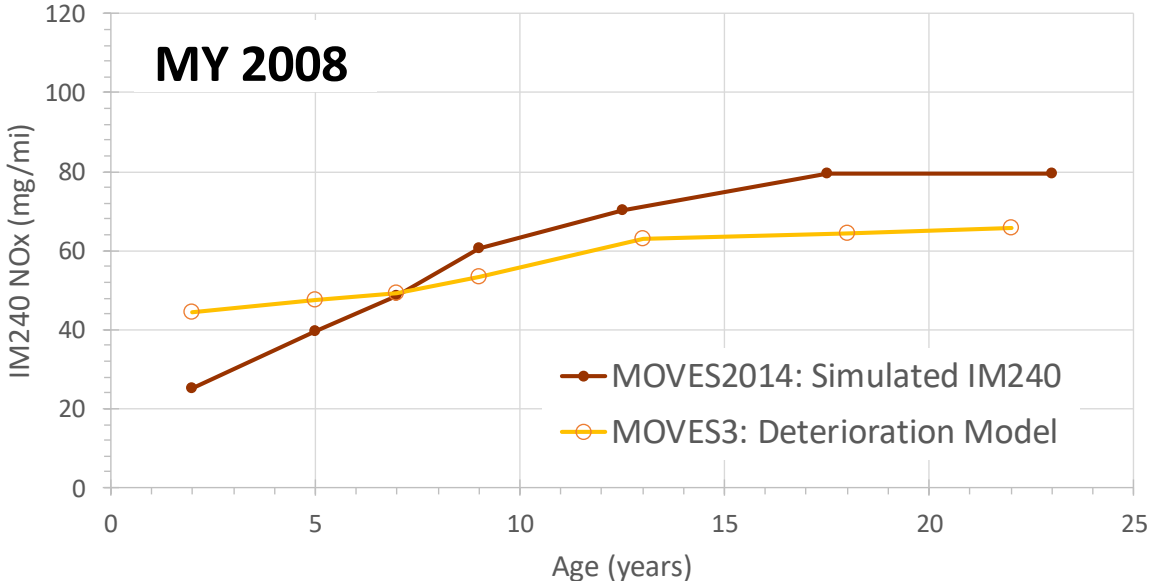
Model-year specific factors to convert MOVES2014b "Age 0-3" rates to rates implied by new Denver data

Deterioration Adjustments for Running Process

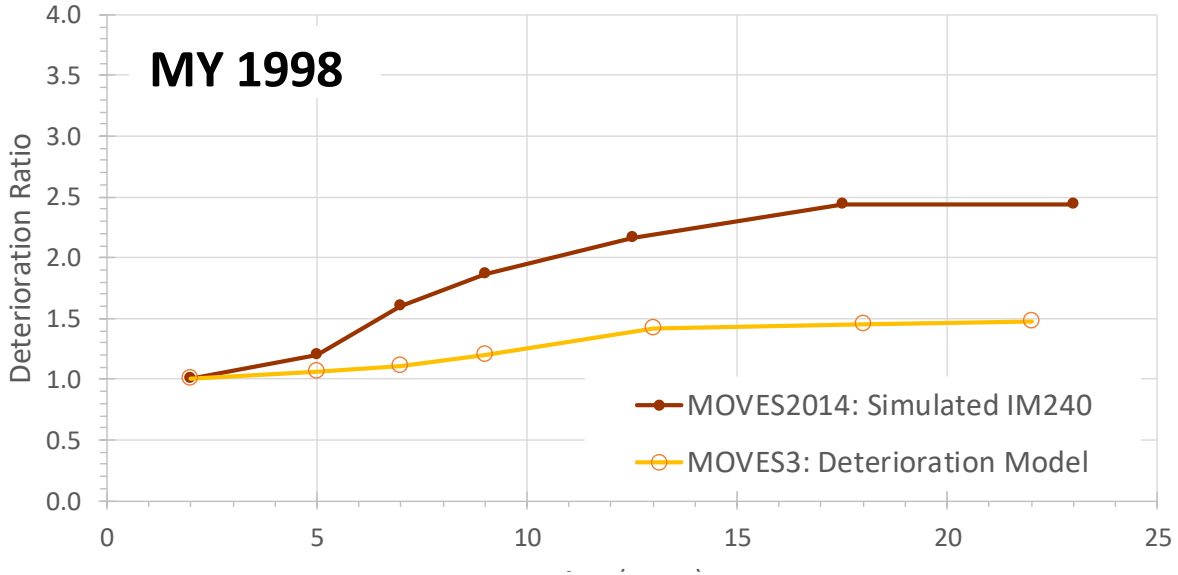
DEVELOPING REVISED RATES

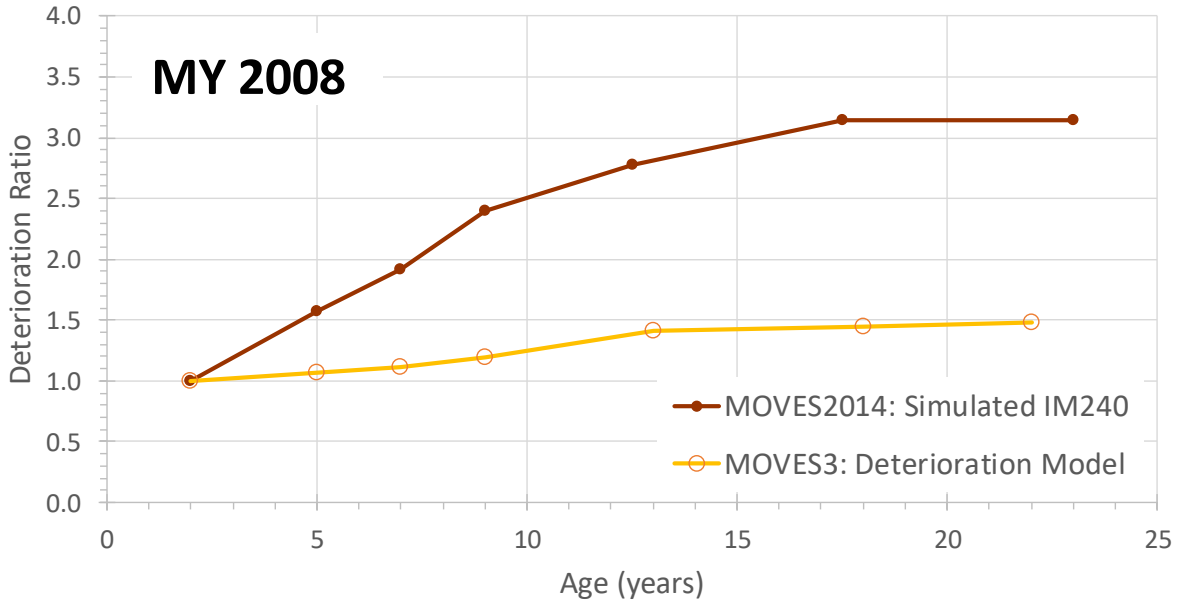
NOx: Age Trends





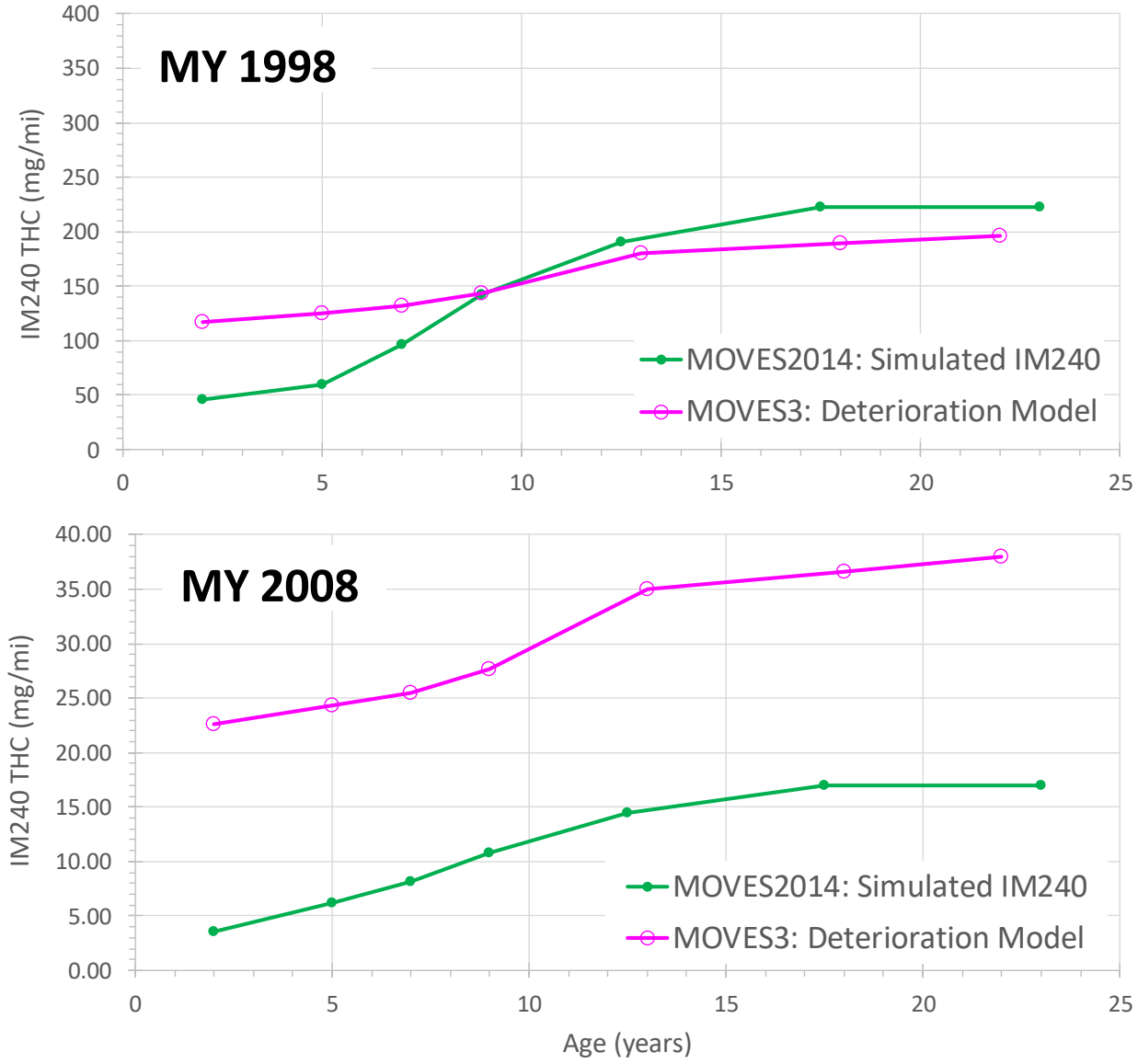
NOx: Deterioration Ratios



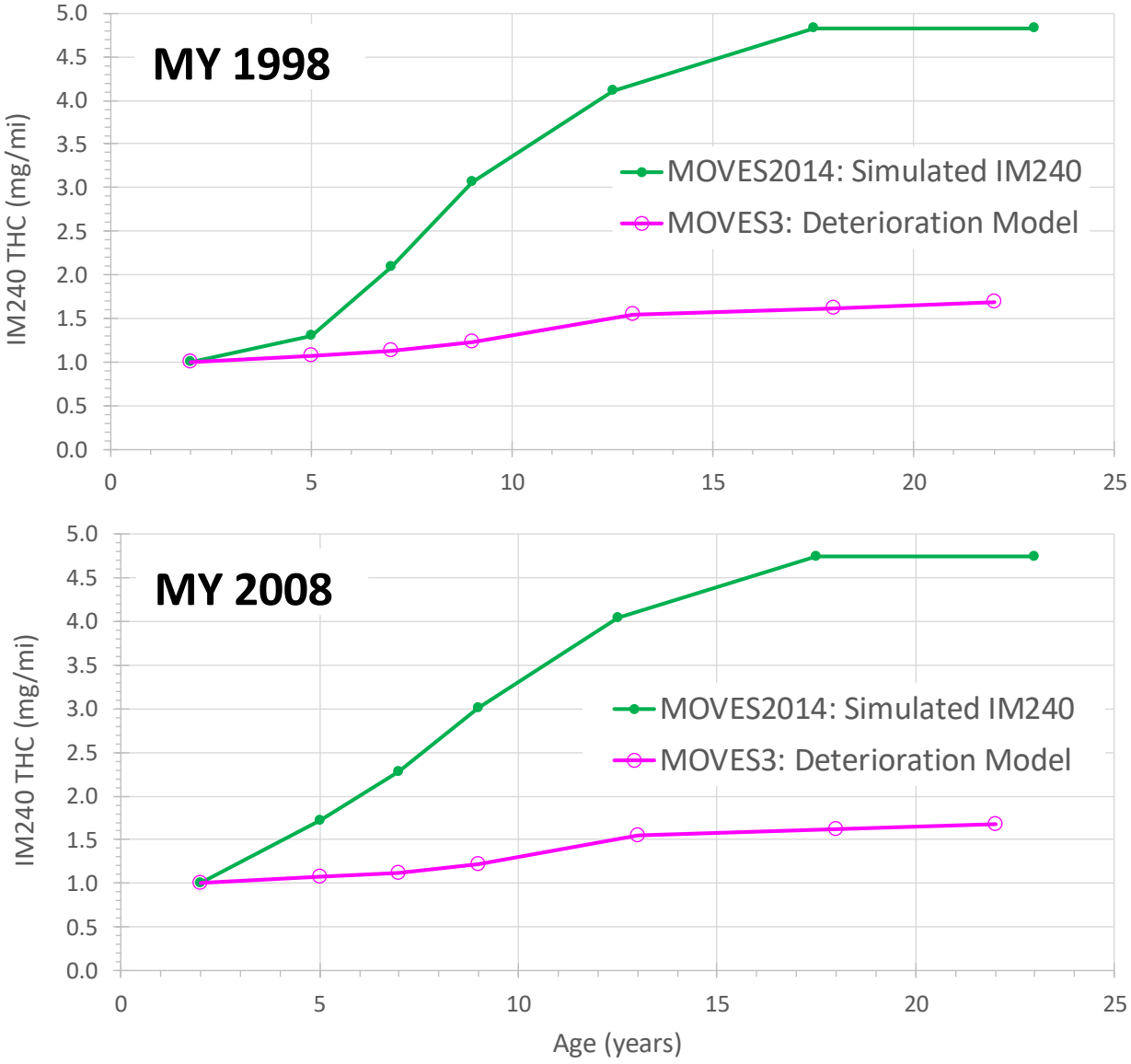


All points normalized at age 2

THC: Age Trends

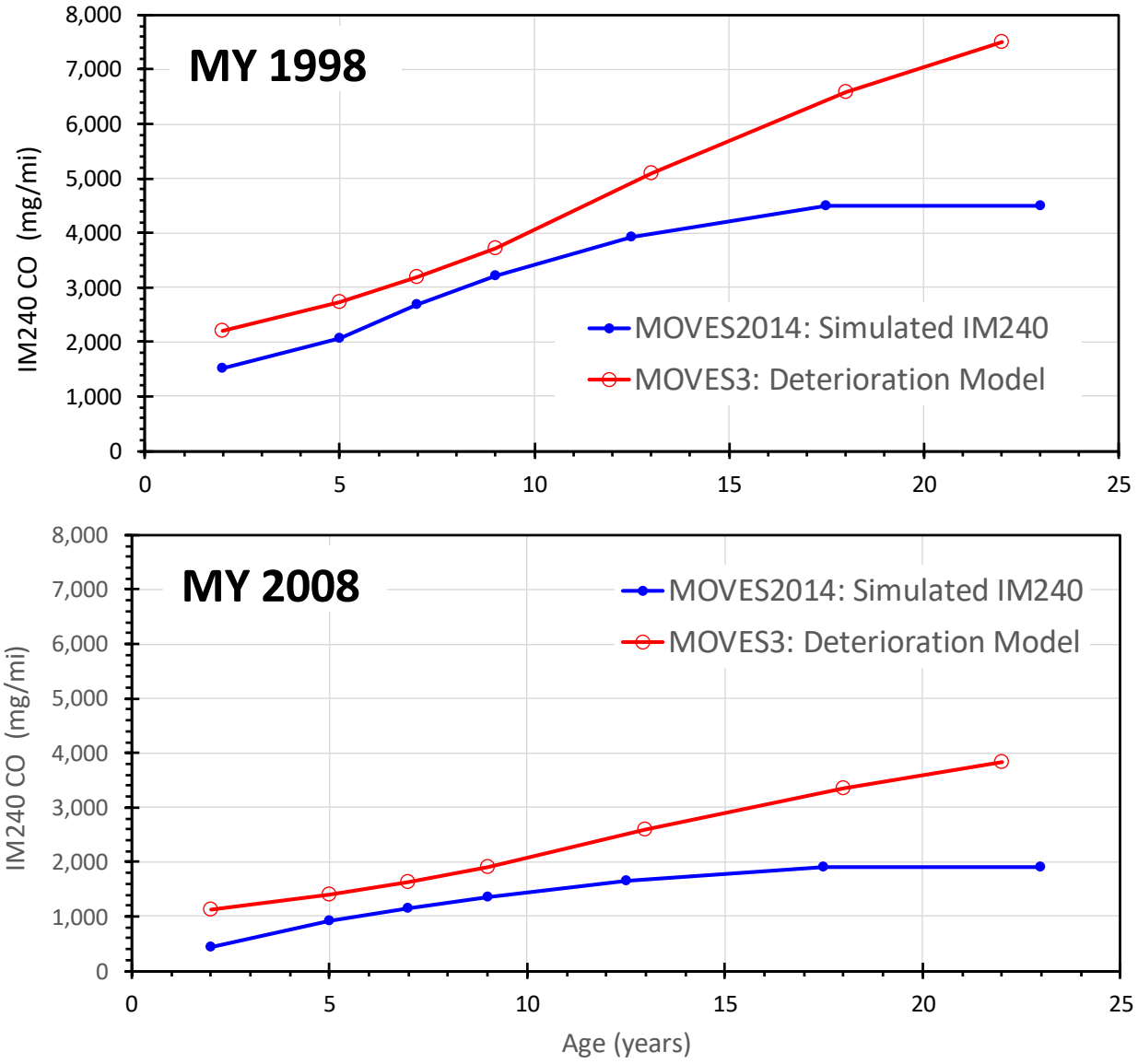


THC: Deterioration Ratios

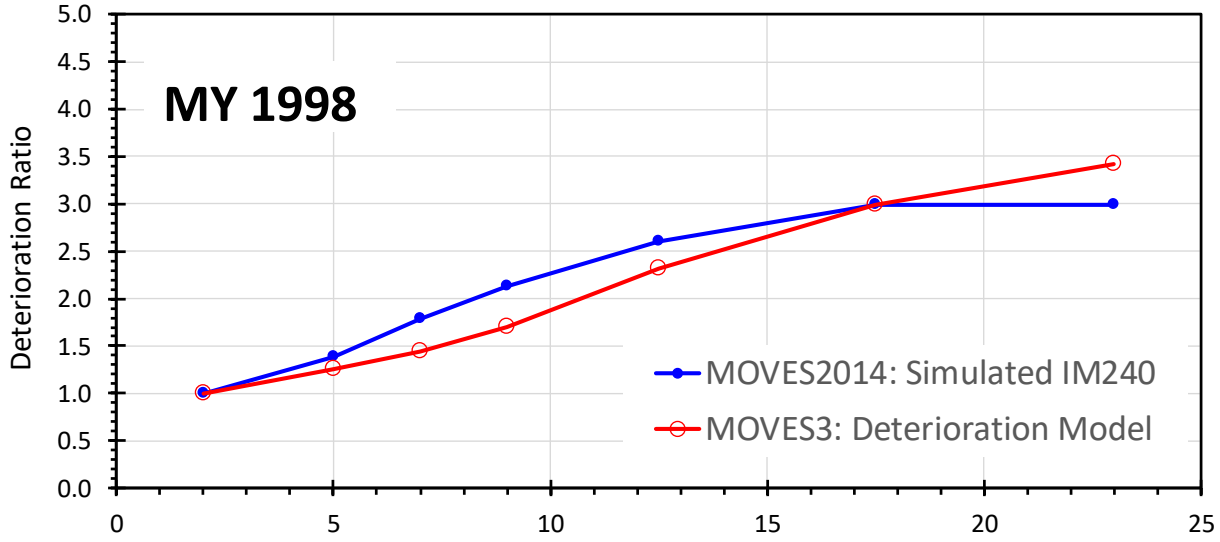


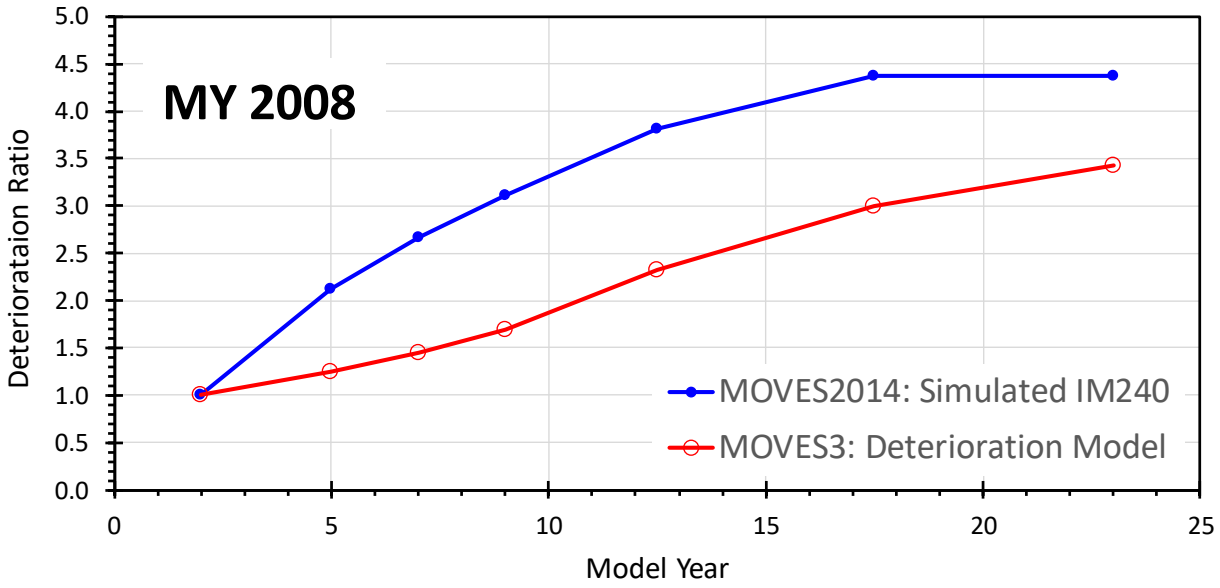
All points normalized at age 2

CO: Age Trends



CO: Deterioration Ratios





All points normalized at age 2

Deterioration Adjustments for Start Process

DEVELOPING REVISED RATES

Reexamining Deterioration for NOx Start Emissions

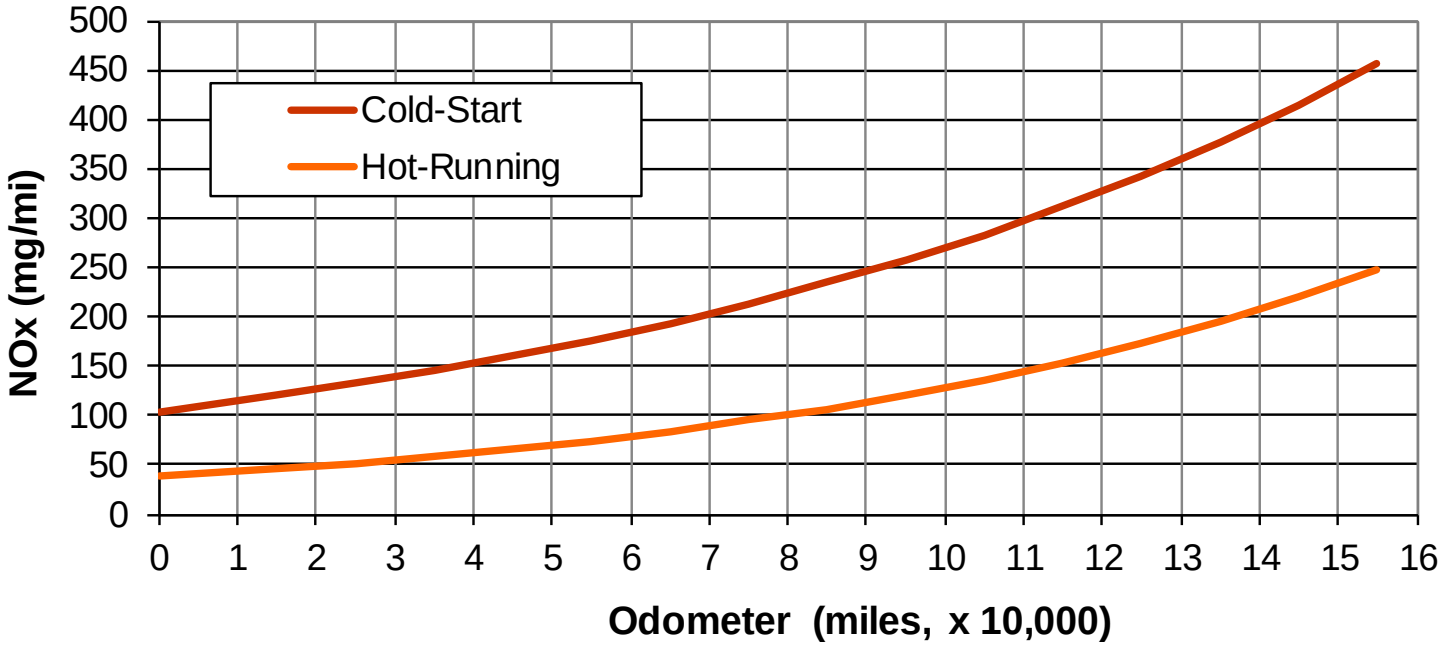
- **Starts in MOVES**
  - Incremental mass emitted (g/start)
    - During several minutes after engine start
  - Defined by Federal Test Procedure (FTP)
    - "Cold-start" = Phase 1 – Phase 3
    - "Hot-running" = Phase 2
  - Do starts deteriorate?
    - Data are sparse

Estimating NOx Start Deterioration

- **"In-use Verification Program" (IUVP)**
  - run by manufacturers
- **Goal: verify that onroad vehicles meet standards**
- **Vehicles**
  - recruited from public
  - measured at
    - 0-50,000 mi (certification standards apply)
    - 50,000-120,000 mi (useful-life standards apply)
- **Measured on certification cycles (including FTP)**
  - Results available by test phase
- **Can be used to estimate deterioration**
  - For starts as well as running
  - On absolute basis
  - On relative basis

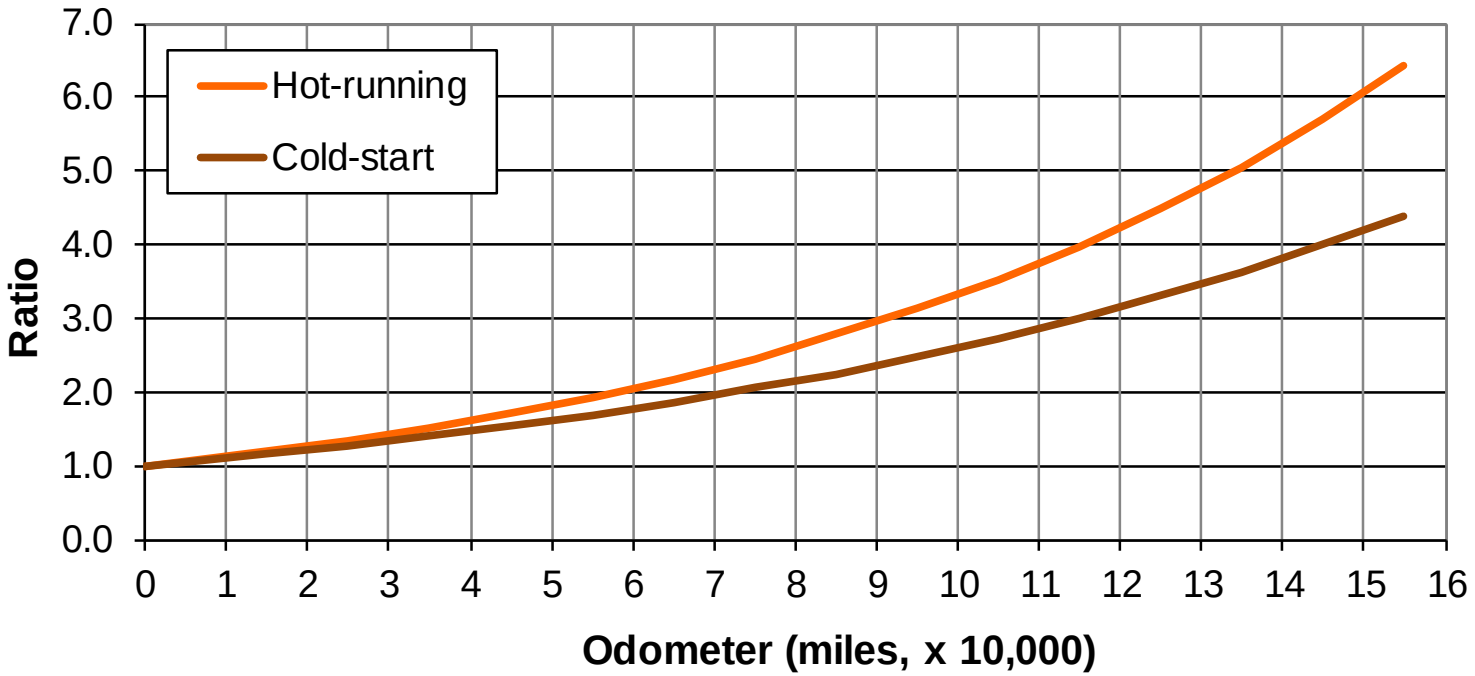
Absolute NOx Deterioration
for Cars

- **Deterioration evident for starts as well as running**
  - Based on log-linear regressions
  - Trend for starts is steeper



Relative NOx Deterioration
for Cars

- **Normalize emissions to age = 2 years**
  - Trend for running is steeper
  - Starts deteriorate, but at lower relative rate



Deterioration Ratios for Starts (R_{start})

$$R_{start} = 1 + R_{run} S_{start,run}$$

Deterioration Ratio for Running Rates

Relative Sensitivity of Start to Running

$$S_{start,run} = \frac{\frac{E_{a,start}}{E_{2,start}} - 1}{\frac{E_{a,run}}{E_{2,run}} - 1}$$

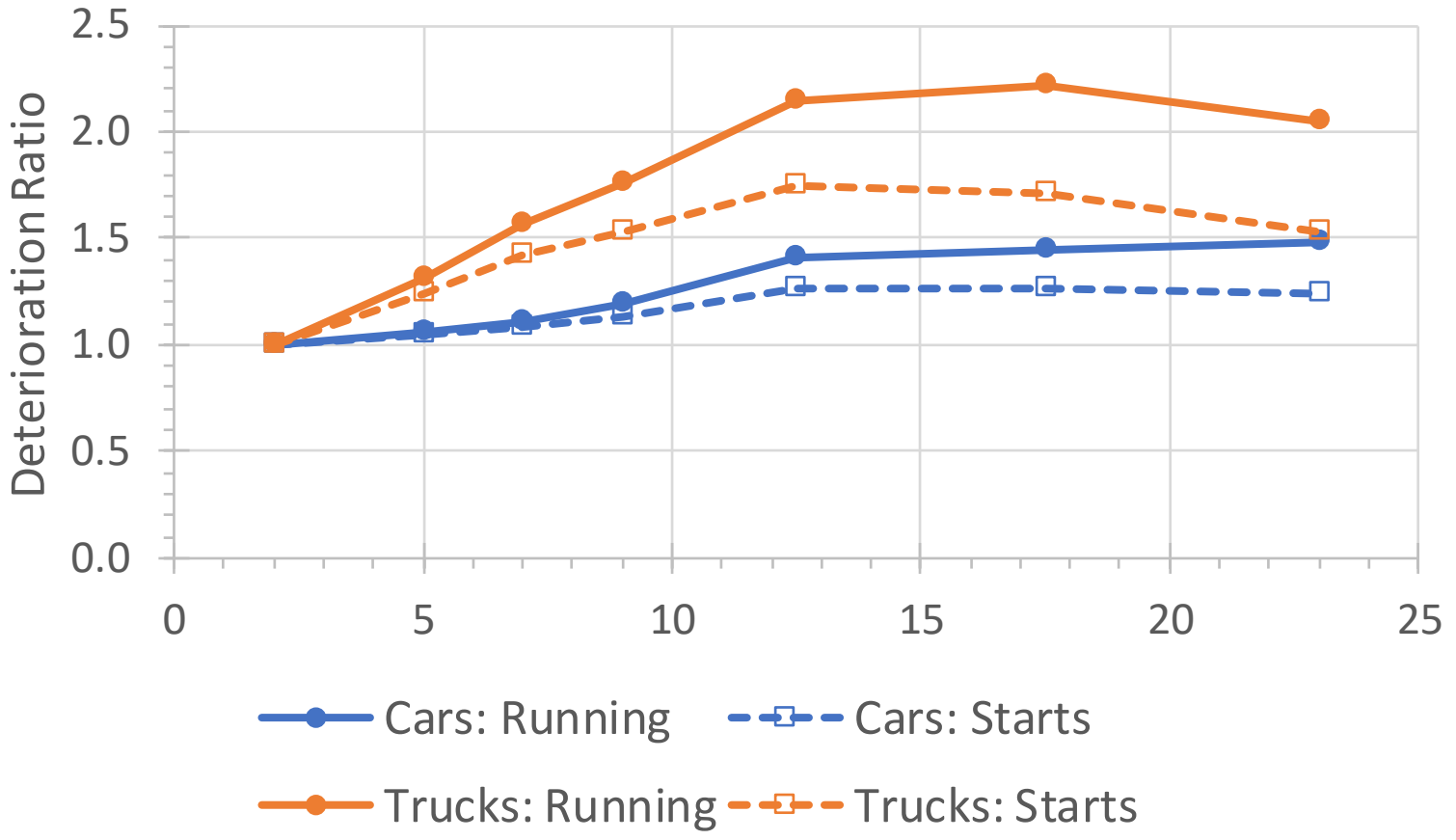
Predicted FTP Cold-start at age *a*

Predicted FTP Cold-start at age *2*

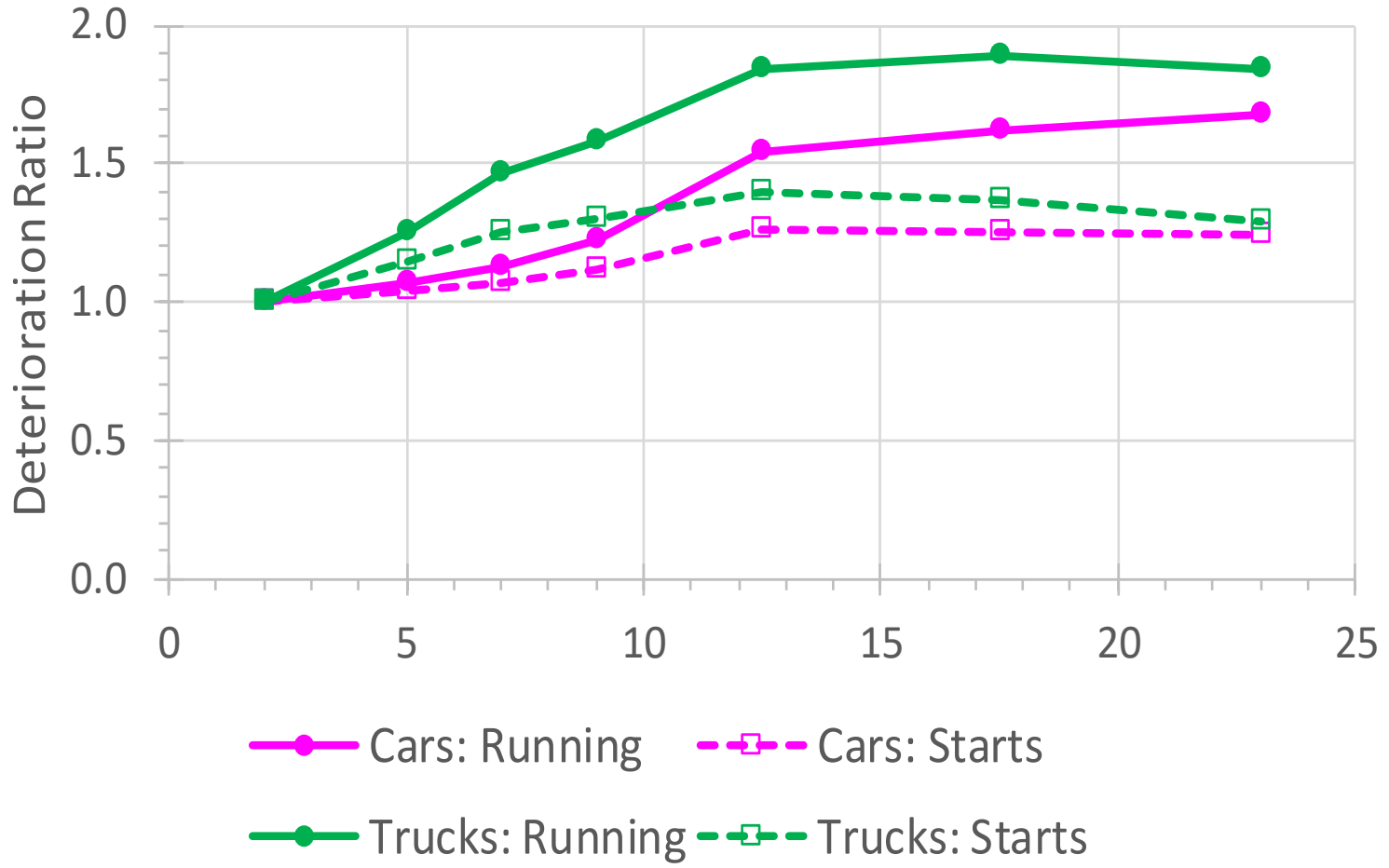
Predicted FTP hot-running at age *a*

Predicted FTP hot-running at age 2

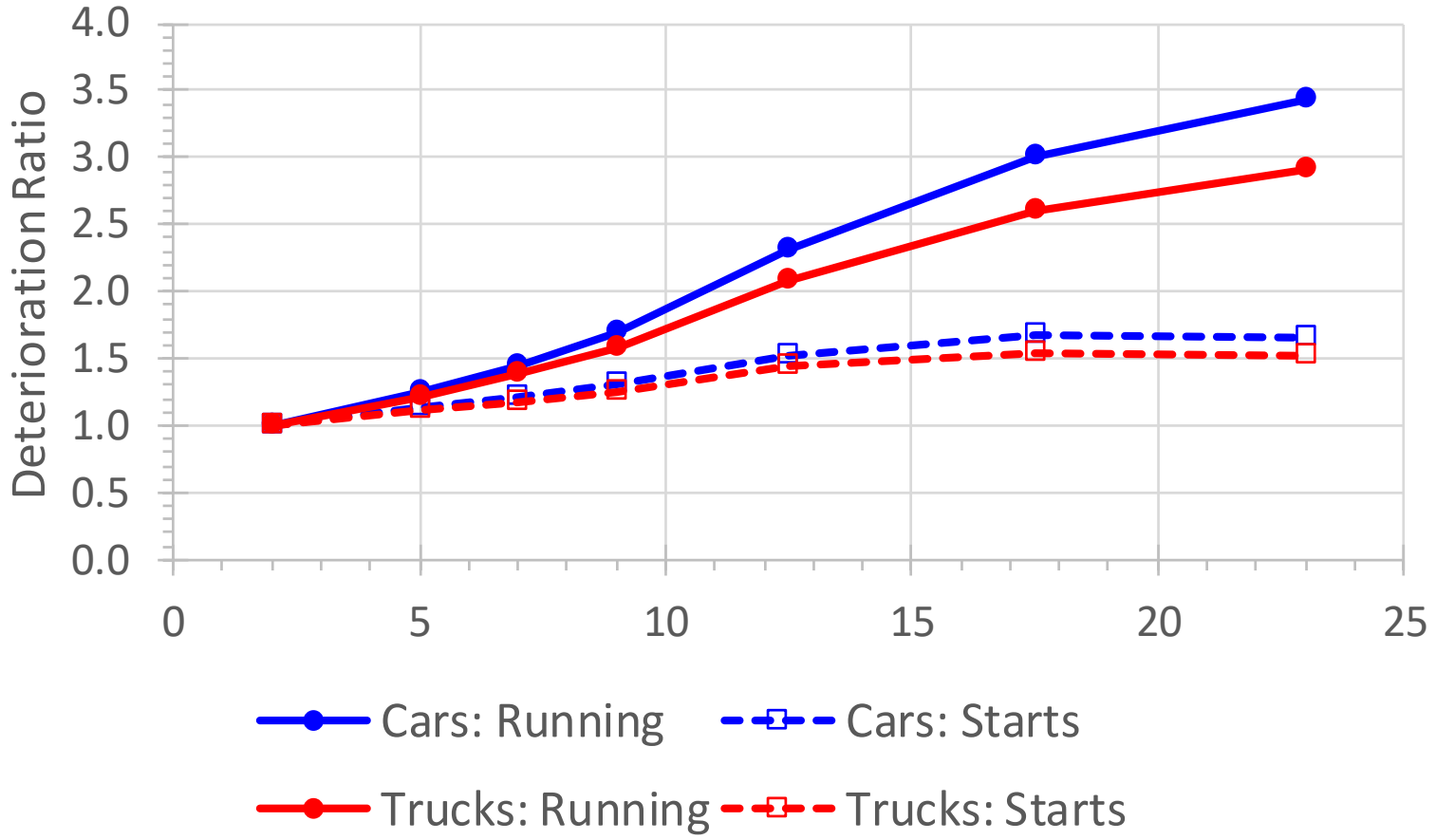
Deterioration Ratios for Starts (NOx)



Deterioration Ratios for Starts (THC)



Deterioration Ratios for Starts (CO)



Update to Base Fuel

- **Definition:**
  - Fuel assumed to be associated with the "base rates"
    - meanBaseRate
    - meanBaseRateIM
- **Used in calculation of "fuel adjustments"**
    - Ratio, representing difference in emissions
    - Between "base" and "target" fuels
    - For MY 2001 and later
      - Based on EPAct models, for THC, CO, NOx, PM
    - For MY 2000 and earlier
      - Based on Complex Model, for THC, CO, NOx

Update to Base Fuel

- **In MOVES2010, MOVES2014**
  - Represented fuel in Phoenix area
  - Gaseous rates based on Phoenix I/M data
- **In MOVES3**
  - Represents fuel in Denver area
    - Is an E10 fuel, as are most market fuels
  - Summer fuel, CY 2013
    - Based primarily on refinery batch data
    - Adjustments equal 1.0 in fuel region
  - "Centroid" of Denver Evaluation data

Selected Base Fuel Properties

Property	MOVES2014	MOVES3
fuelFormulationID	98/99	99
Sulfur Level (ppm)	90/30	30/10
Ethanol (v.%)	0.0	10.0
Aromatics (v.%)	26.1	25.77
Benzene (v.%)	1.0	0.65
RVP (psi)	6.9	8.8
T50 (◦F)	218	212.3
T90 (◦F)	329	321.7

Steps for Developing Revised Rates

- **Extract Rates from current database**
- **Apply "Young-vehicle" adjustments**
  - Running process only
  - Uniformly and multiplicatively across all operating modes
- **Apply Deterioration adjustments**
  - Running process
  - Start process
  - Uniformly and multiplicatively across all operating modes
- **Apply non-I/M ratios**
  - Estimate meanBaseRate from meanBaseRateIM
- **Replicate rates for alternate fuels**
  - Diesel
  - E85

RESULTS

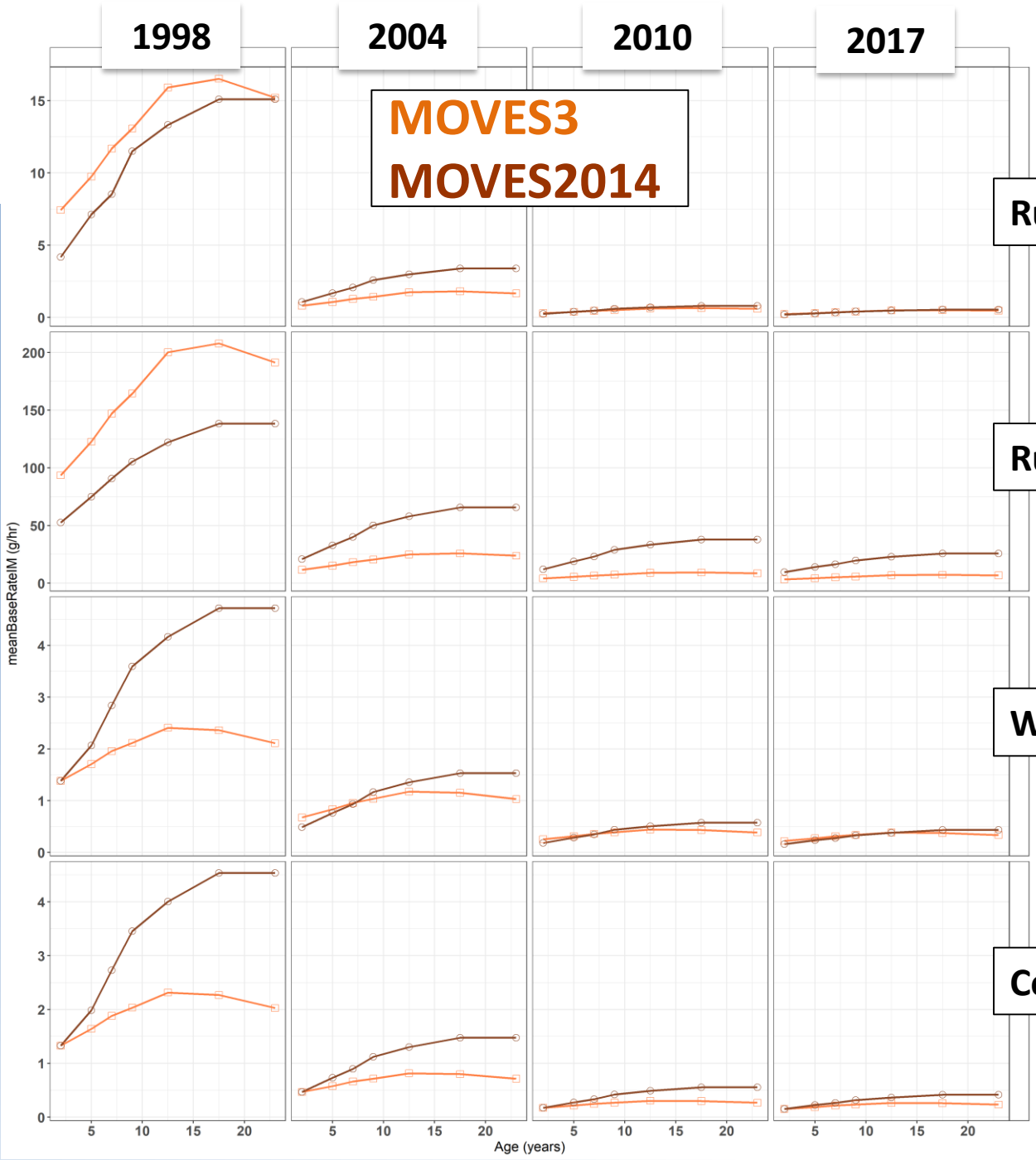
Reviewing Results

- **Trends vs. Age**
  - Deterioration
- **Trends vs. Vehicle-specific power**
  - Operating mode for running process
  - Modes (21-30) at 25-50 mph
- **Trends vs. Soak-time**
  - Operating mode for start process

Deterioration Trends vs. Age, by Model Year and Operating Mode

RESULTS

NOx:
Trends vs. Age



Running, Coasting (21)

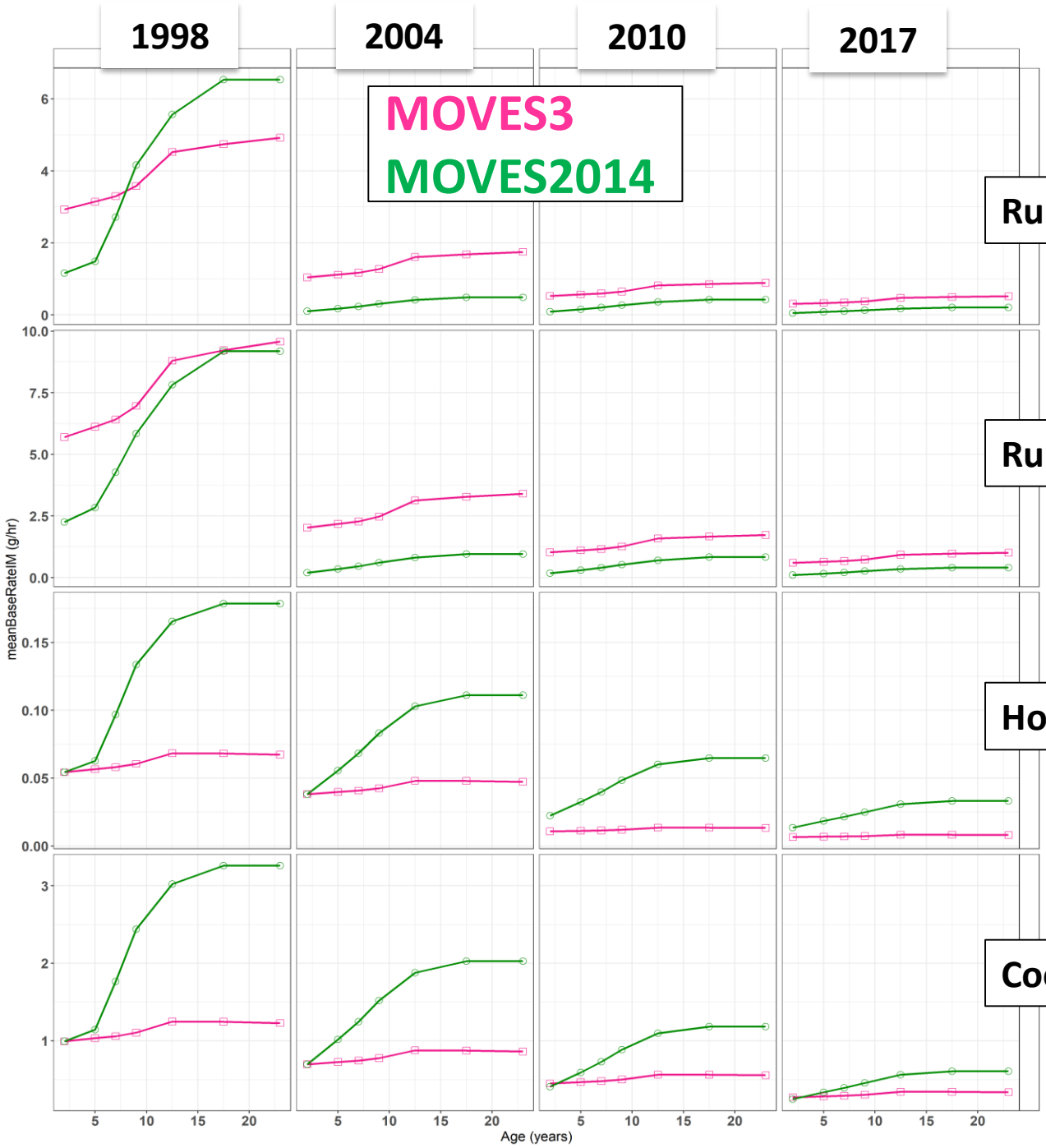
Running, High Power (28)

Warm Start (103)

Cold Start (108)

NOTE: Axes free by row!

THC:
Trends vs. Age



Running, Low Power (13)

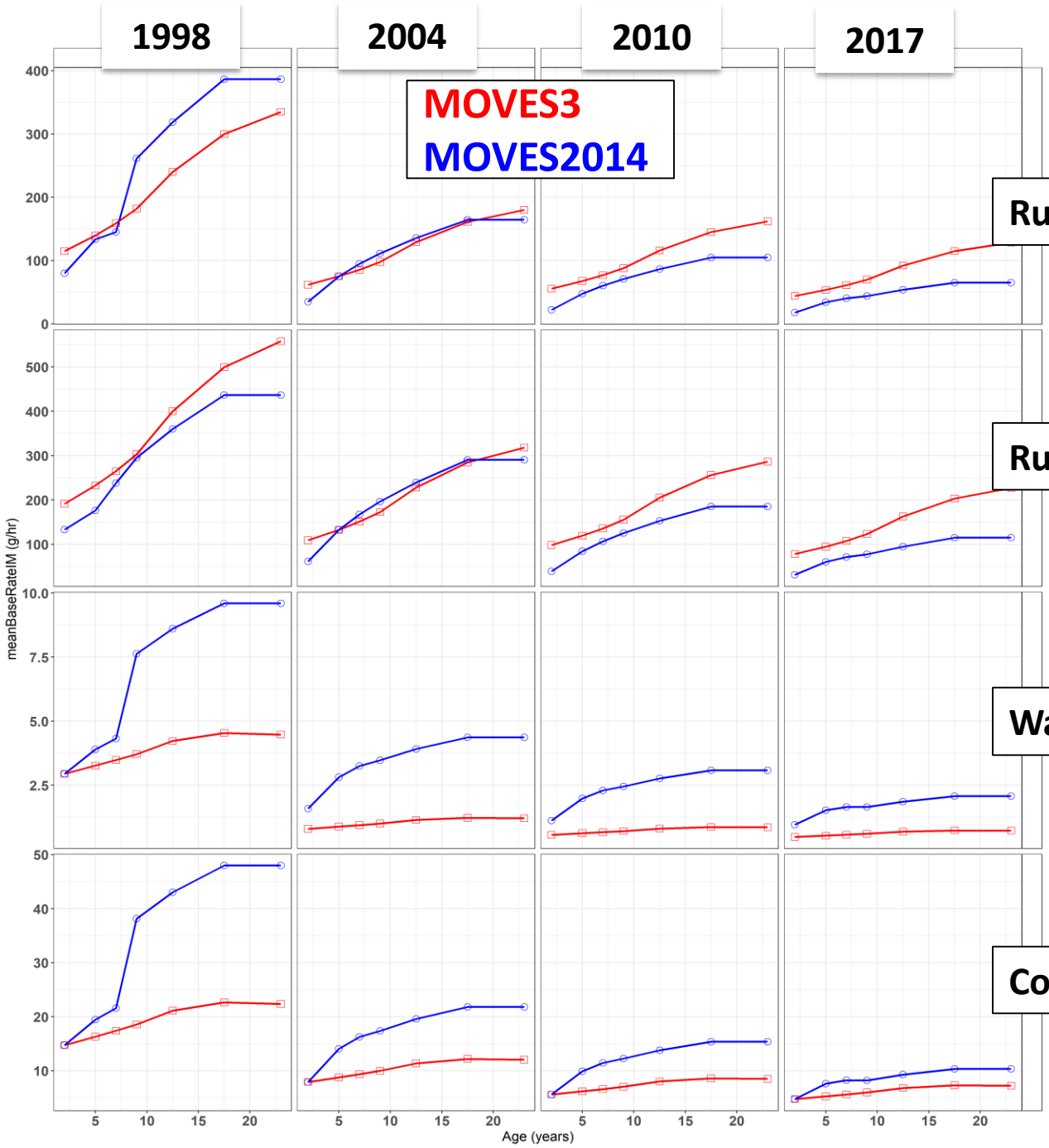
Running, Moderate Power (25)

Hot Start (101)

Cool Start (106)

NOTE: Axes free by row!

CO:
Trends vs. Age



Running, Medium Power (15)

Running, Moderate Power (27)

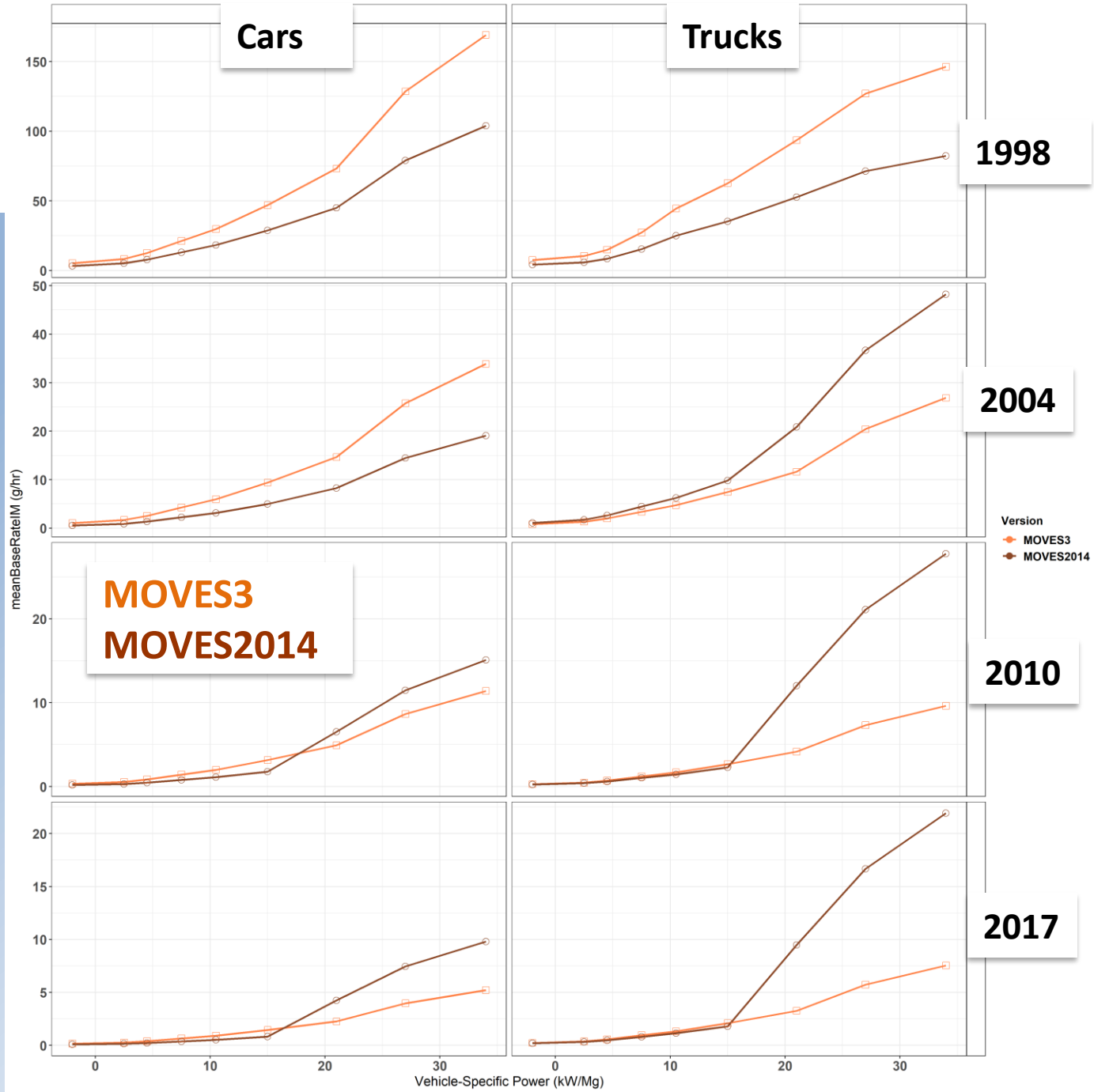
Warm Start (102)

Cold Start (108)

NOTE: Axes free by row!

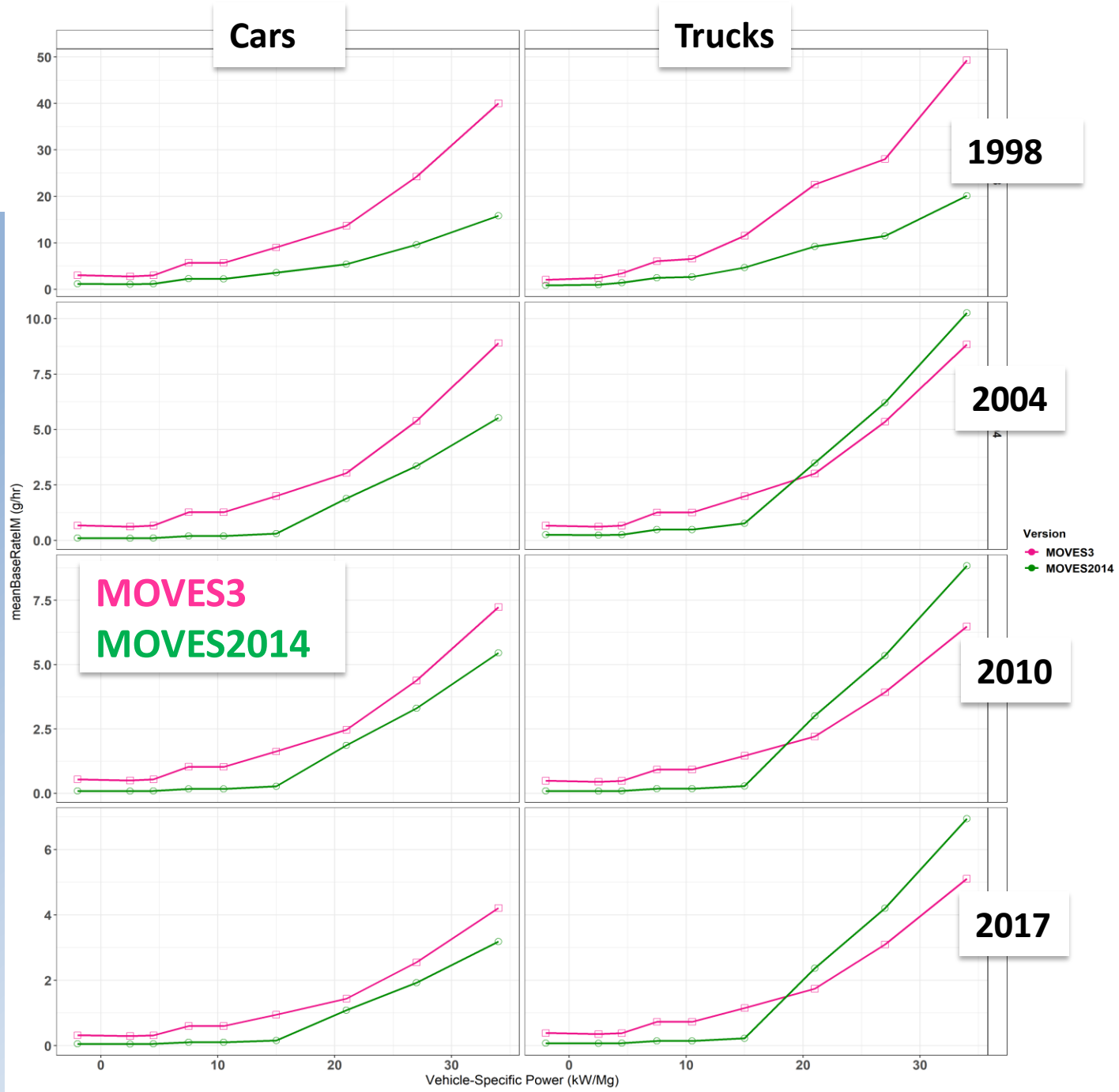
Running Rates vs. VSP by Regulatory Class and Model Year (age Group = 0-3 years)

RESULTS



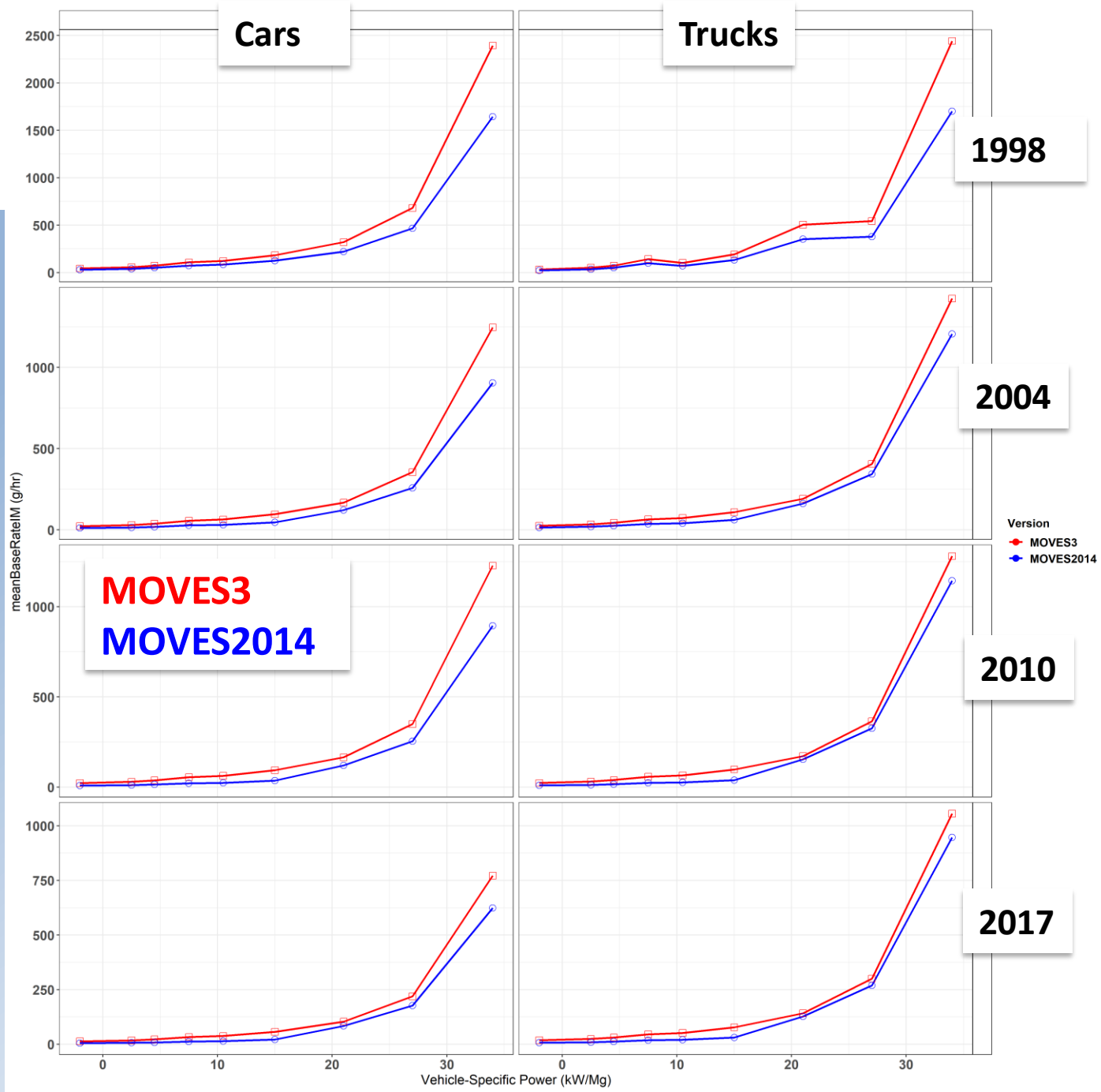
NOx:
Trends vs. VSP, four MY

NOTE: Axes free by row!



THC:
Trends vs. VSP, four MY

NOTE: Axes free by row!



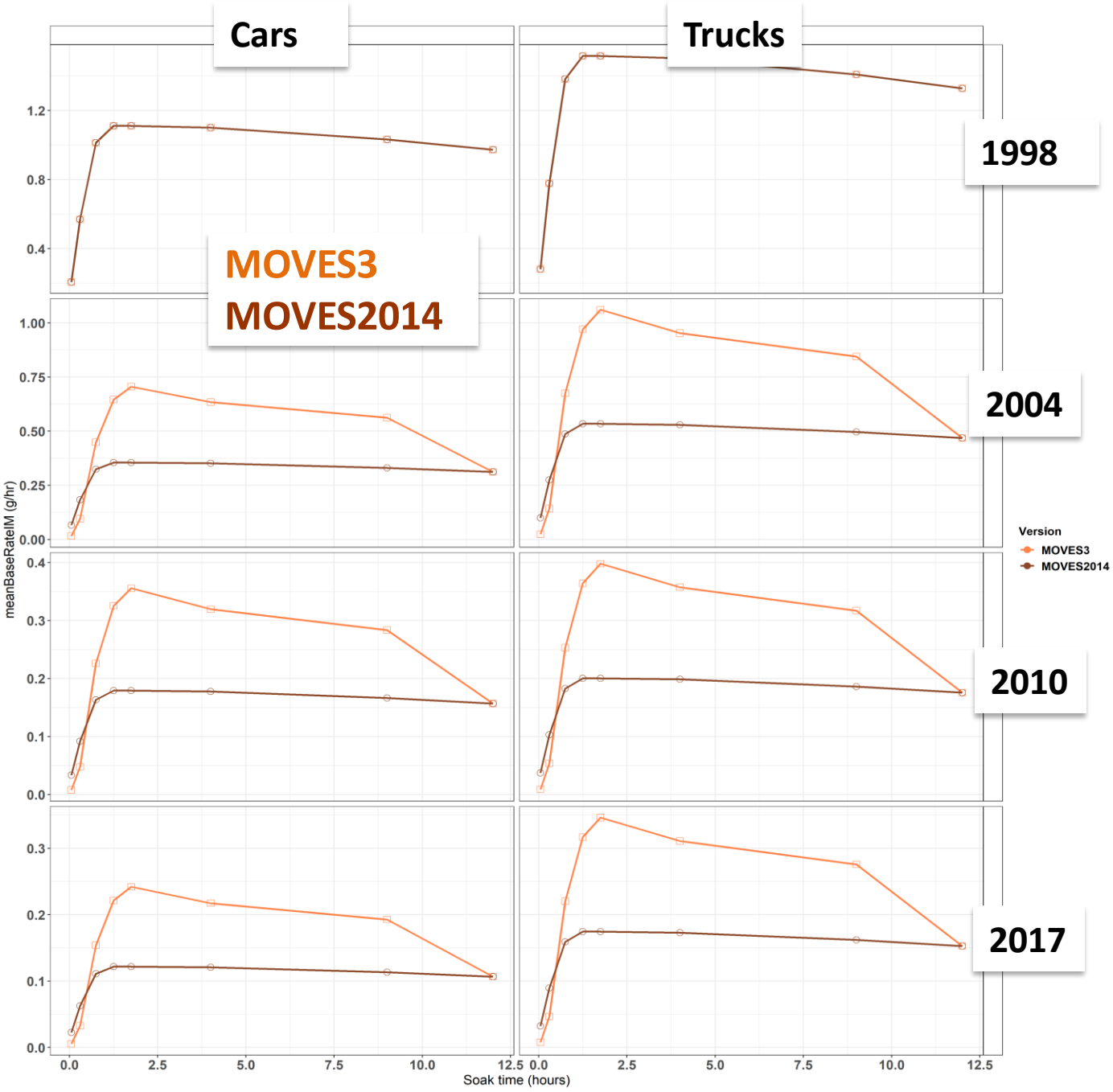
CO: Trends vs. VSP, four MY

NOTE: Axes free by row!

Start Rates vs. Soak time by Regulatory Class and Model Year

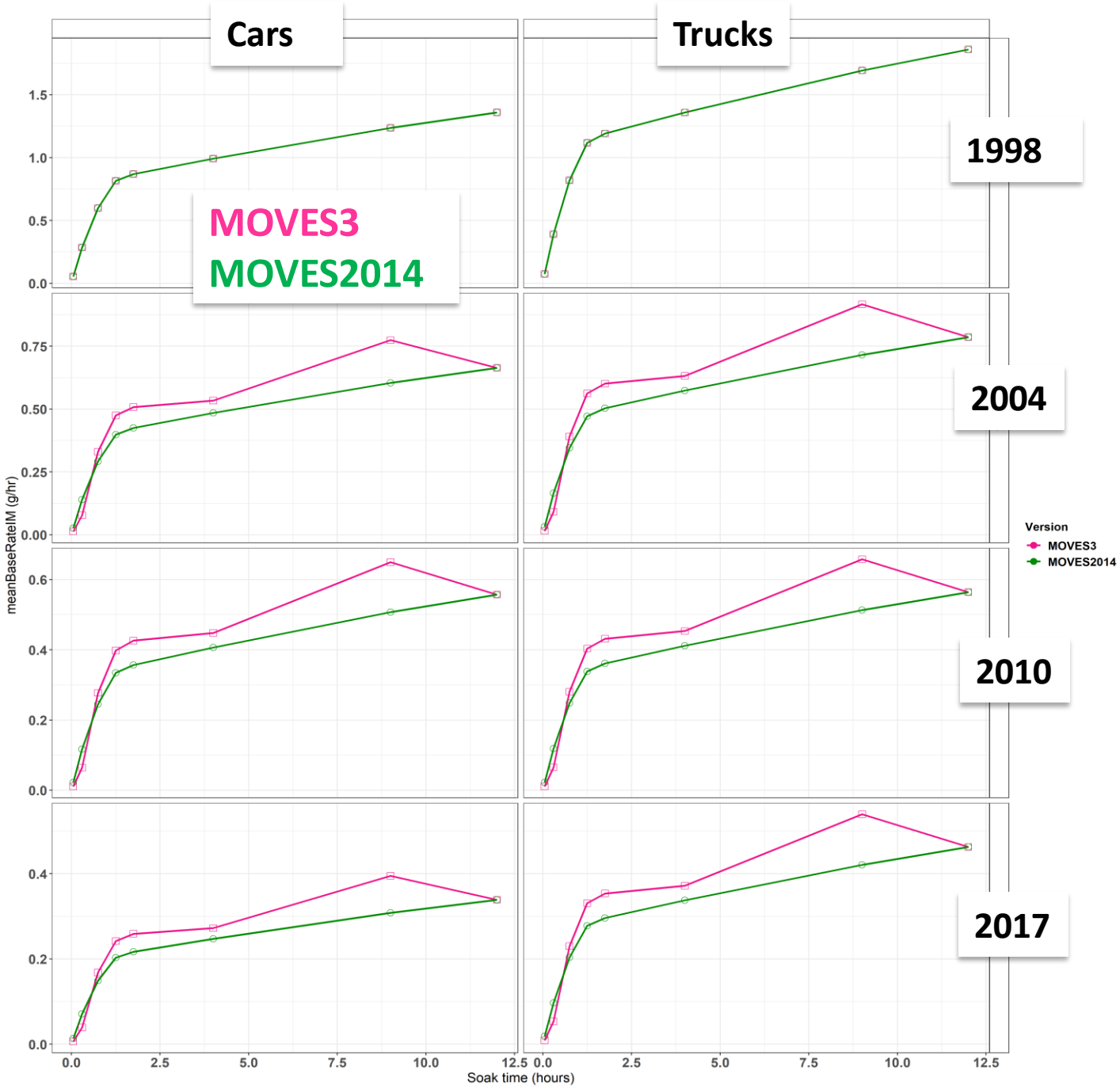
(age Group = 0-3 years)

RESULTS



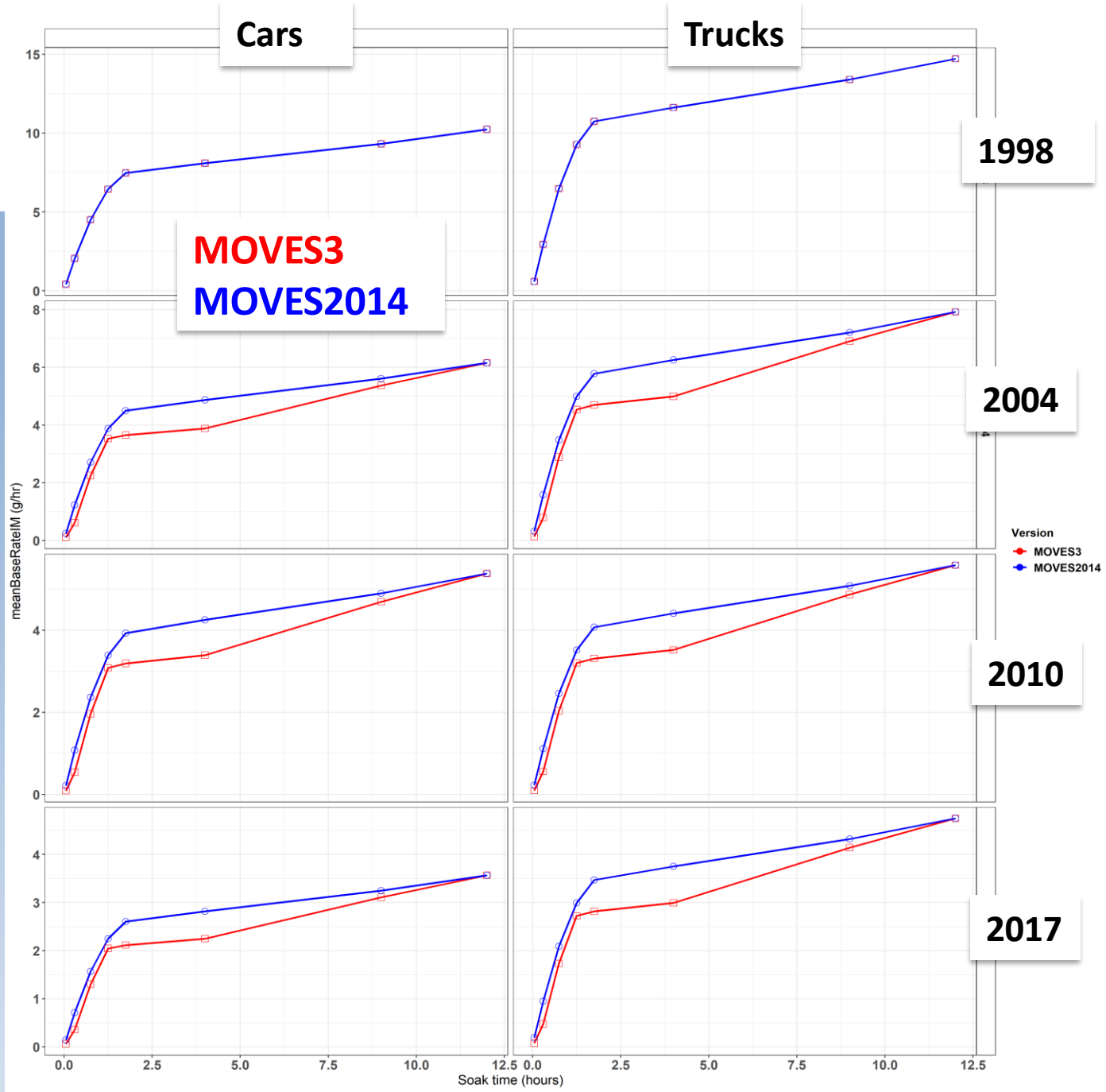
NOx:
Trends vs. soak time, four MY

NOTE: Axes free by row!



THC:
Trends vs. Soak time, four MY

NOTE: Axes free by row!



CO:
Trends vs. soak time, four MY

NOTE: Axes free by row!

Peer Review

- **All planned updates to MOVES3 light-duty emission rates have been peer-reviewed**
- **Responses**
  - Both reviewers considered data selection and approaches reasonable and appropriate
  - Both reviewers asked clarifying questions
  - Neither suggested revisions needed
    - Neither major nor minor

Summary

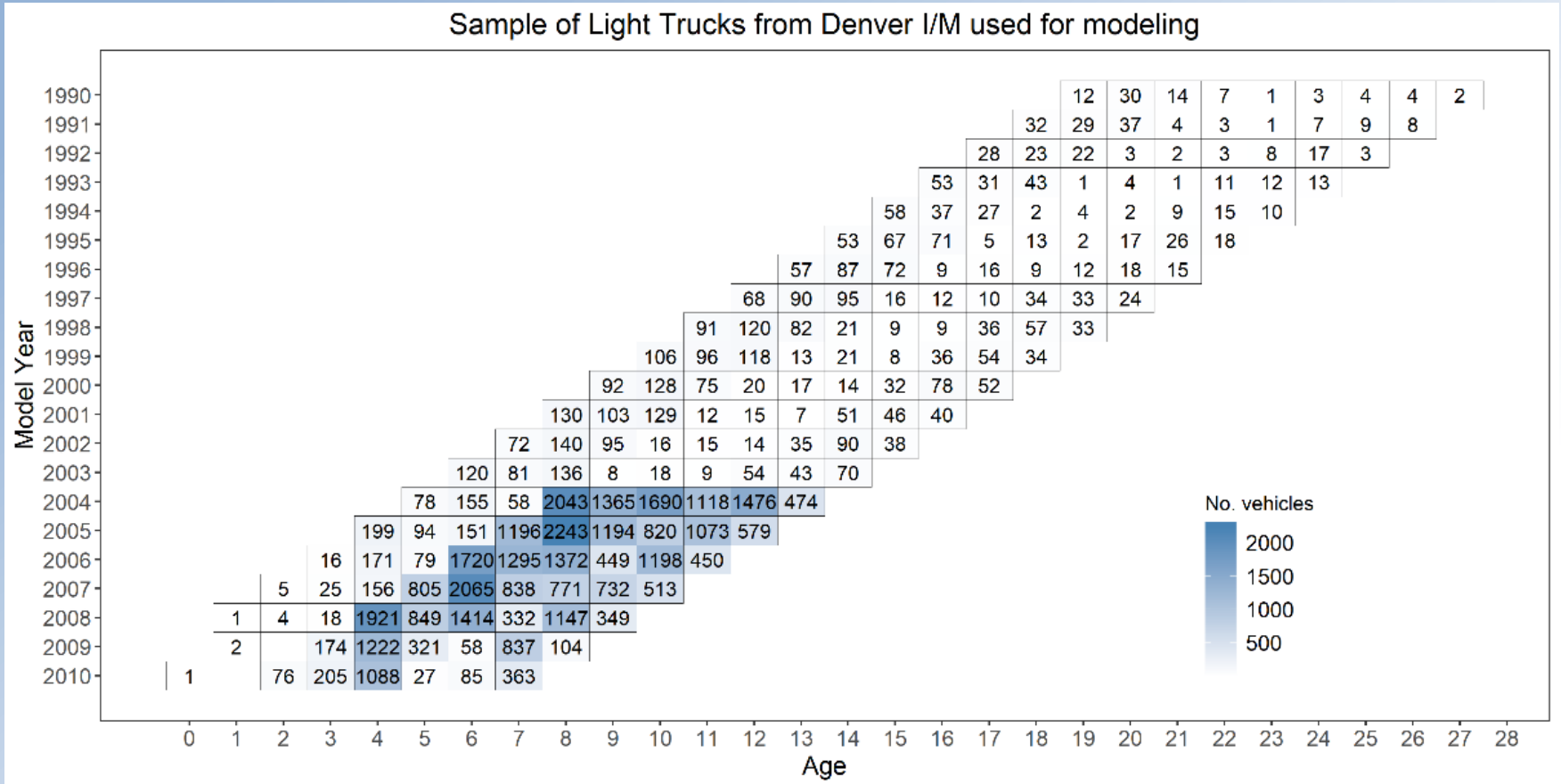
- **Running Emissions**
  - Emission rates in "high-power" modes reduced
    - Relative to those at lower power
  - Emissions rates for "young" vehicles increased
  - Relation between cars and trucks changes
    - Emissions from cars and trucks closer when "young"
    - Deterioration steeper for trucks
      - Implies truck emissions still greater than cars on inventory basis
- **Start Emissions**
  - "Cold-start" emissions unchanged
  - "Hot- and warm-start" emissions to increase
  - Deterioration substantially reduced
- **We will continue to evaluate/update MOVES light-duty emission rates as more data become available**

References

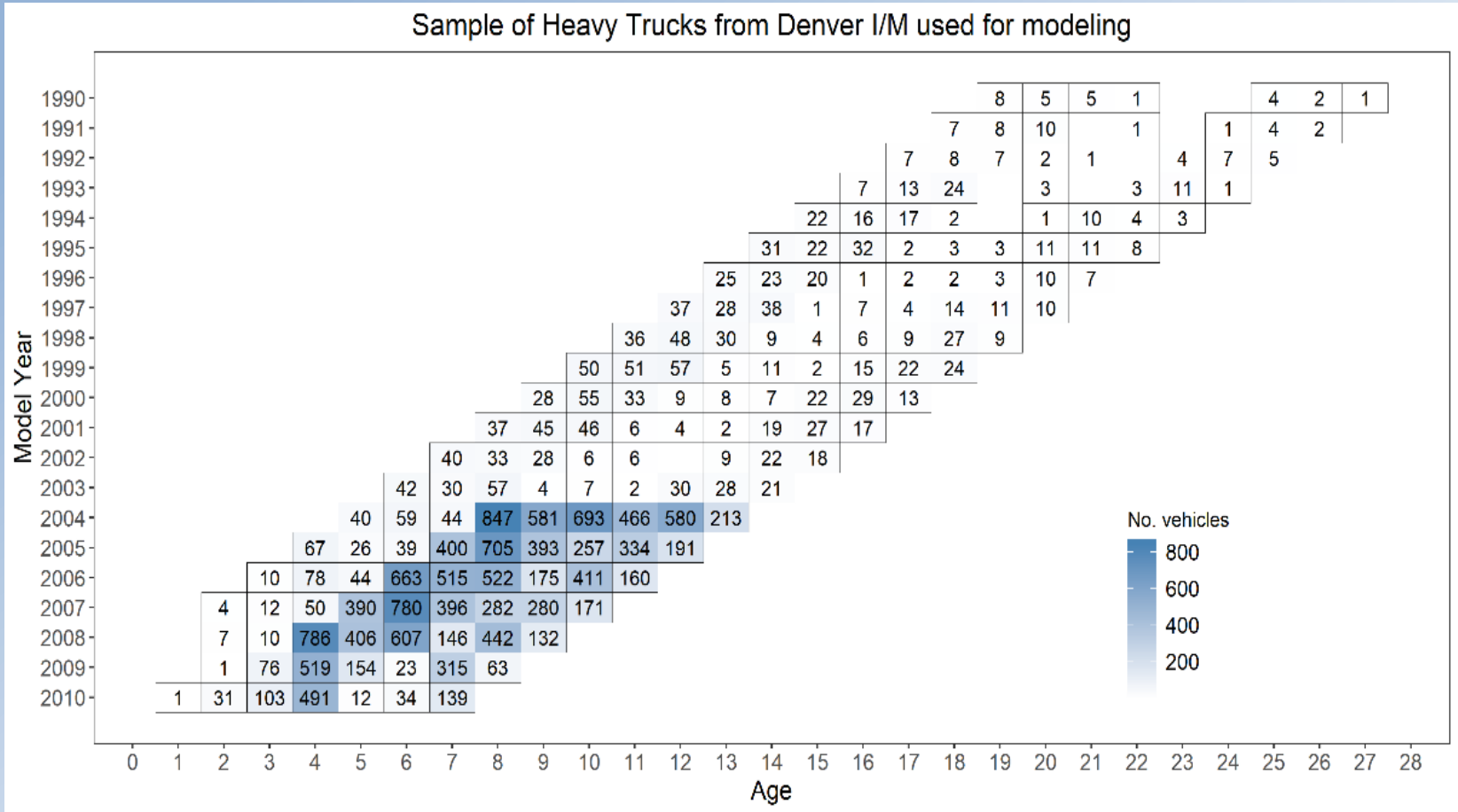
1. Anderson DC, et al. (2014) *Measured and modeled CO and NOy in DISCOVER-AQ: An evaluation of emissions and chemistry over the eastern US*. Atmos Environ 96:78–87.
2. Travis KR, et al. (2016) *Why do models overestimate surface ozone in the Southeast United States?* Atmos Chem Phys 16(21):13561–13577.
3. Choi et al., (2017) *Comparisons of MOVES Light-duty Gasoline NOx Emission Rates with Real-world Measurements*, American Geophysical Union Fall Meeting, New Orleans, LA.
4. Warila et al. (2017) *Evaluation of NOx Emissions Projected by MOVES2014 Using Dynamometer, Remote-Sensing and Tunnel Data*, 27th CRC Real World Emissions Workshop, Long Beach, CA.
5. Sonntag et al., (2018) *Updated Evaluation of MOVES Light-duty Gasoline NOx Emission Rates with Real World Measurements*, 28th CRC Real World Emissions Workshop, Garden Grove, CA.
6. Toro et al., (2019) *Updates to high-power emission rates and start deterioration for light-duty vehicles*, MOVES Review Workgroup, Ann Arbor, MI.
7. Toro et al., (2019) MOVES Light-duty Emisison Rate Evaluation in the context of Reconciling Modeled and Ambient NOx. 2019 International Emissions Inventory Conference, Dallas, TX.

APPENDIX

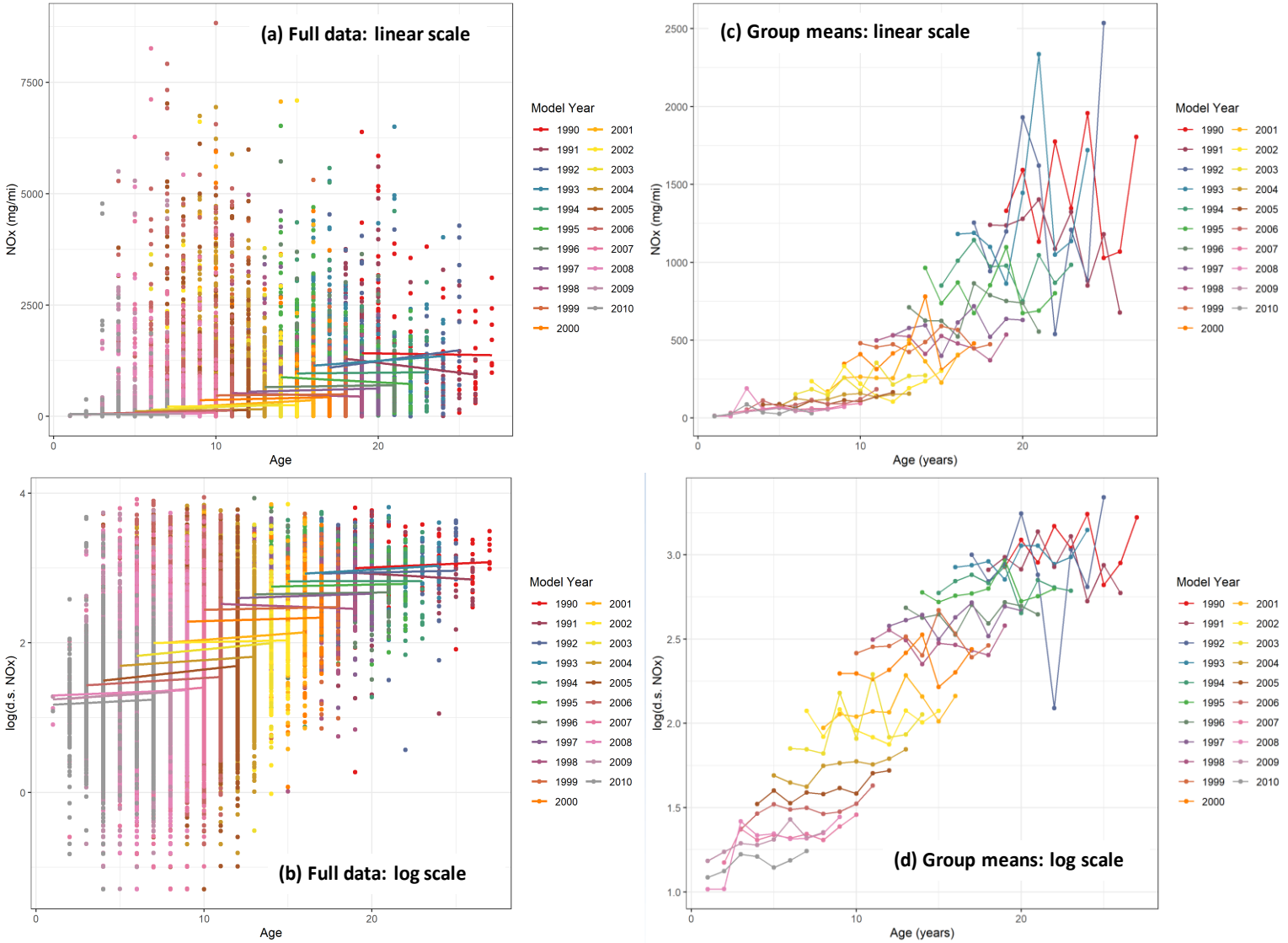
Sample Structure: LLDT



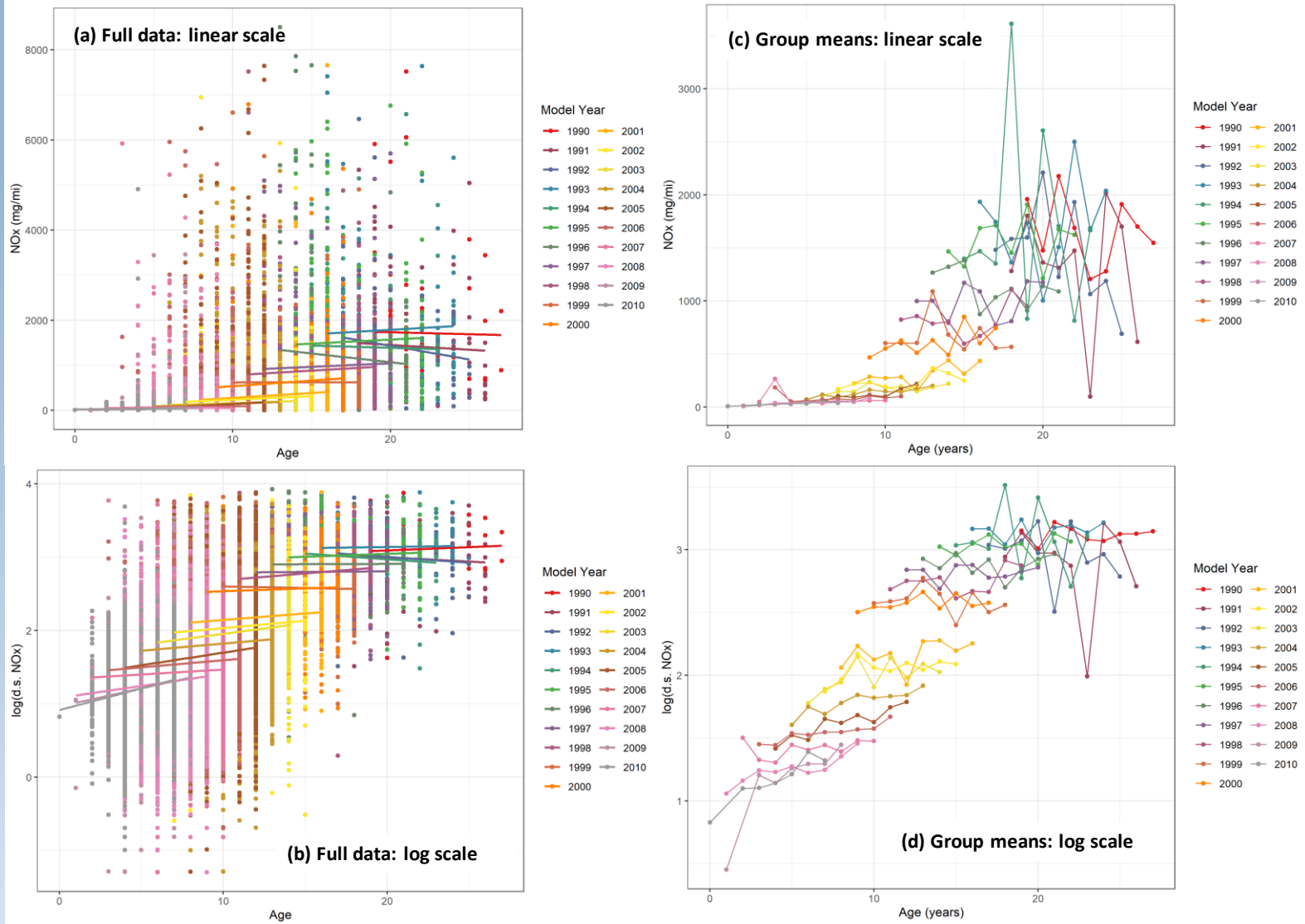
Sample Structure: HLDT



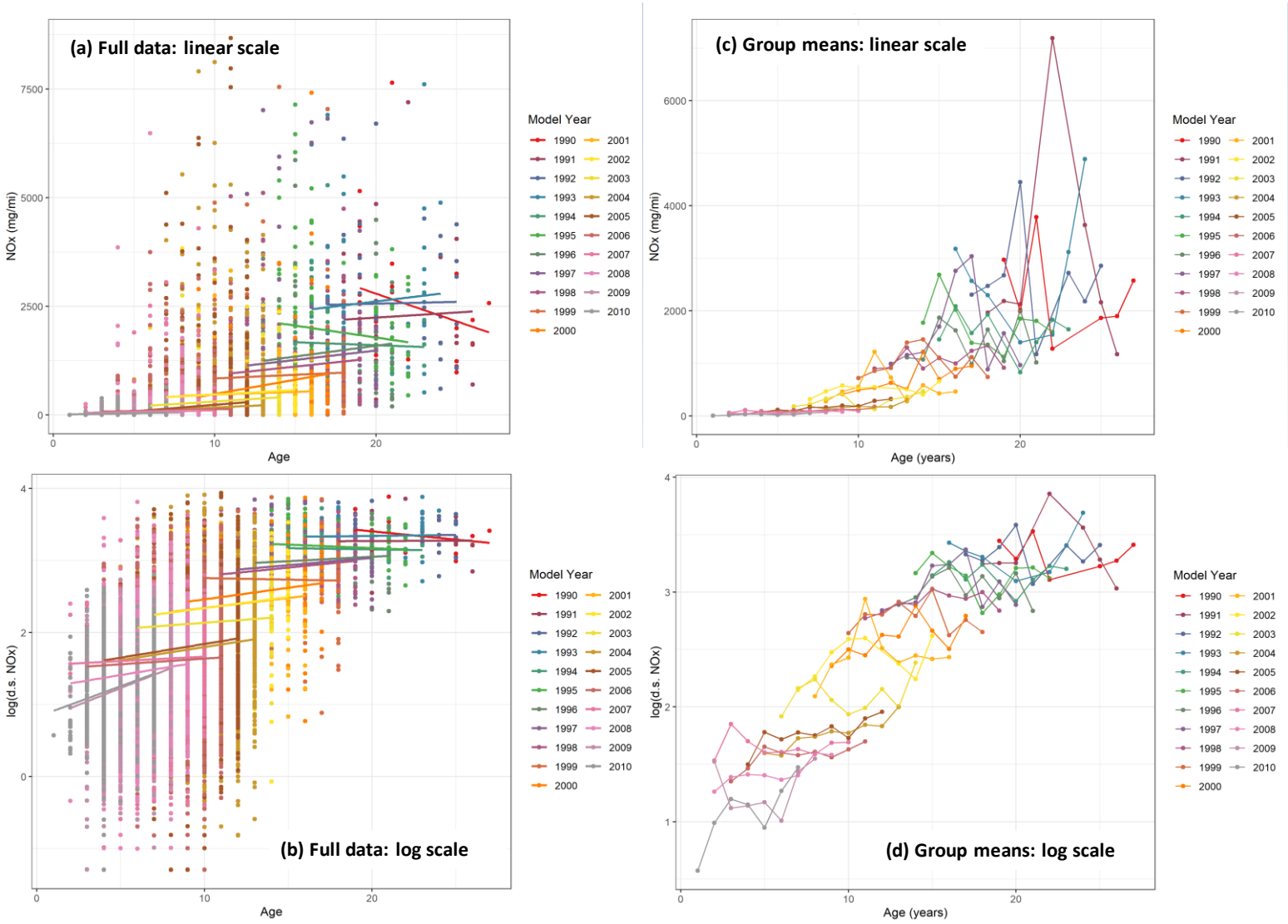
Data Review: NOx, Cars



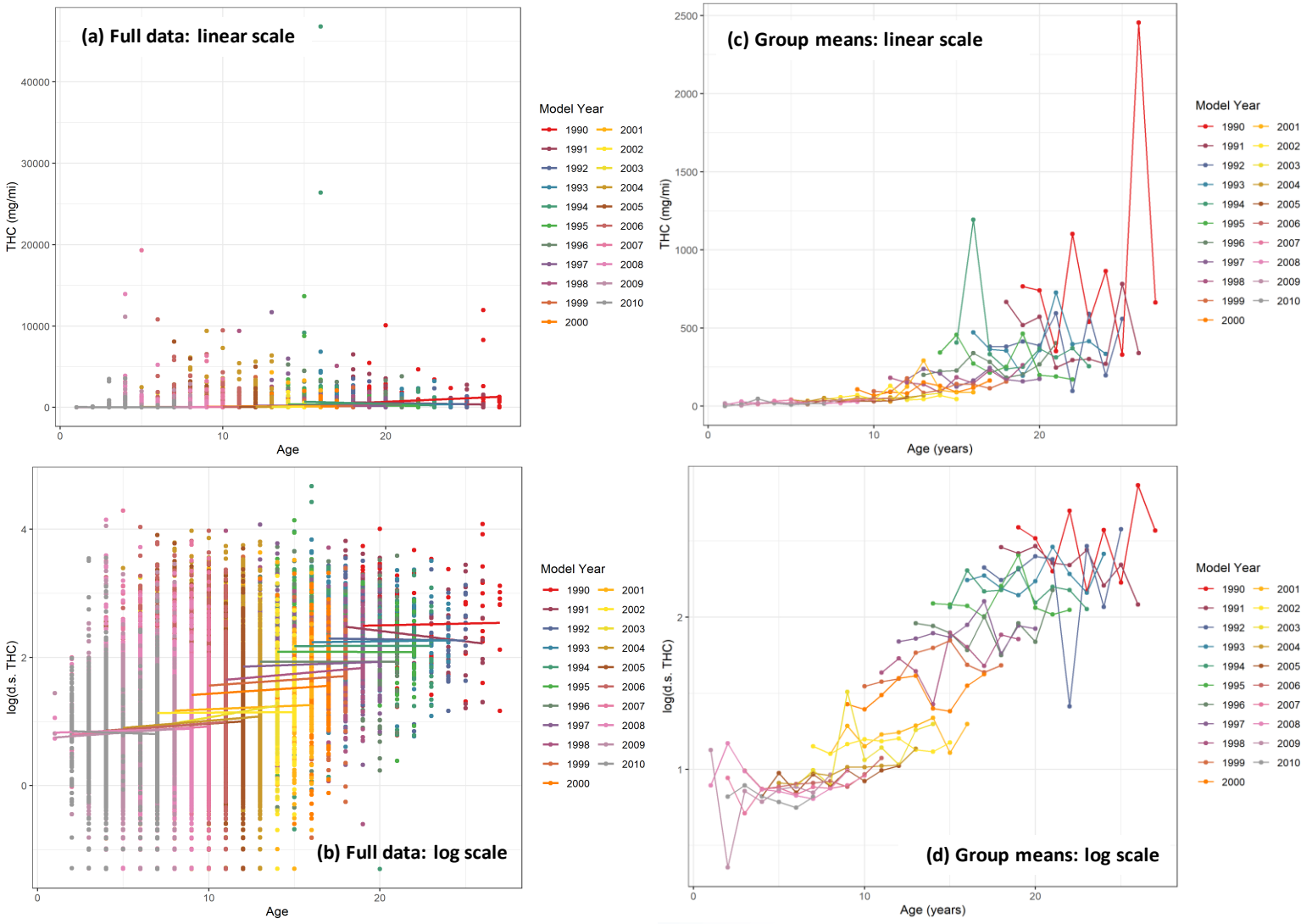
Data Review: NOx, LLDT



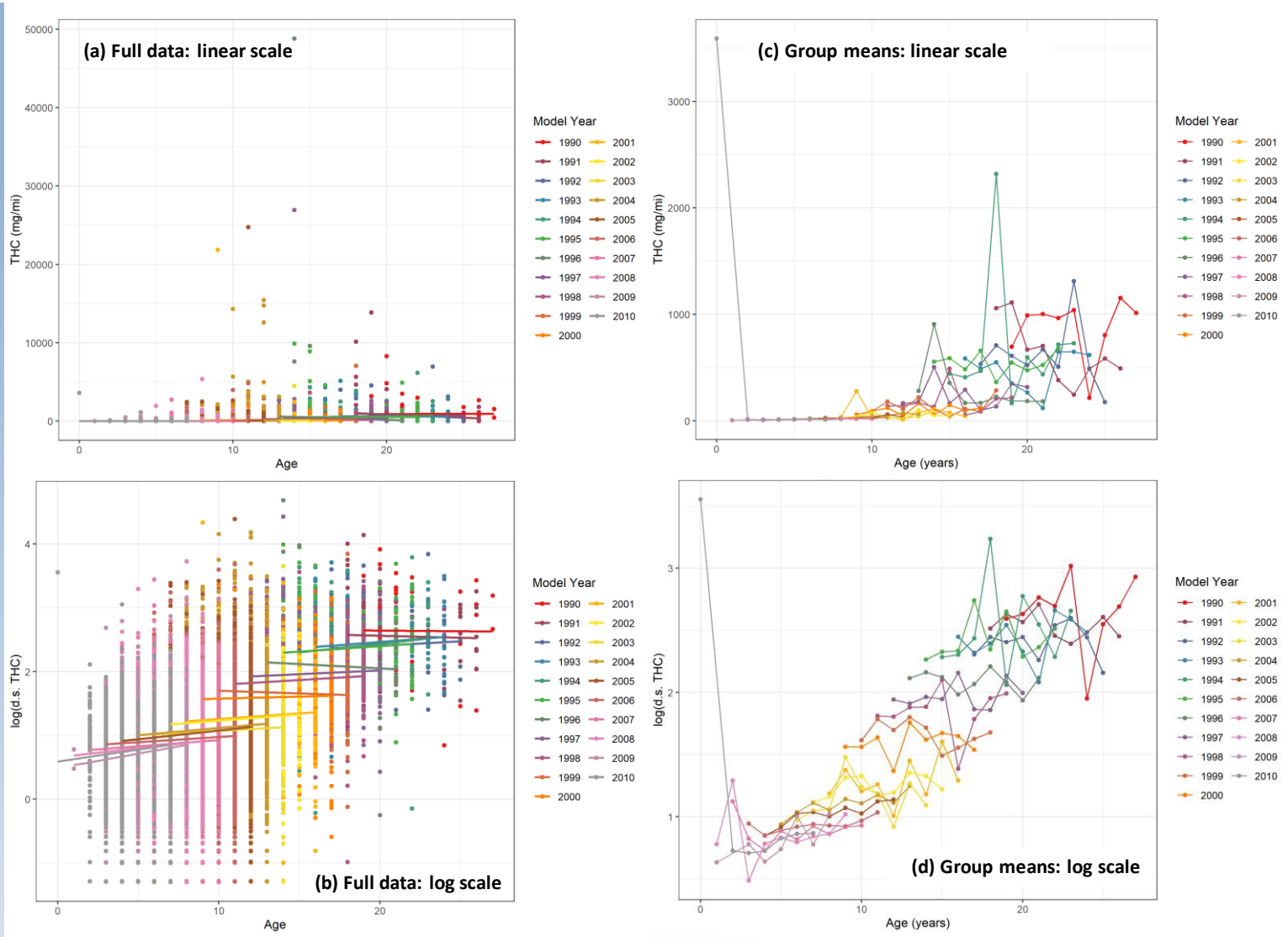
Data Review: NOx, HLDT



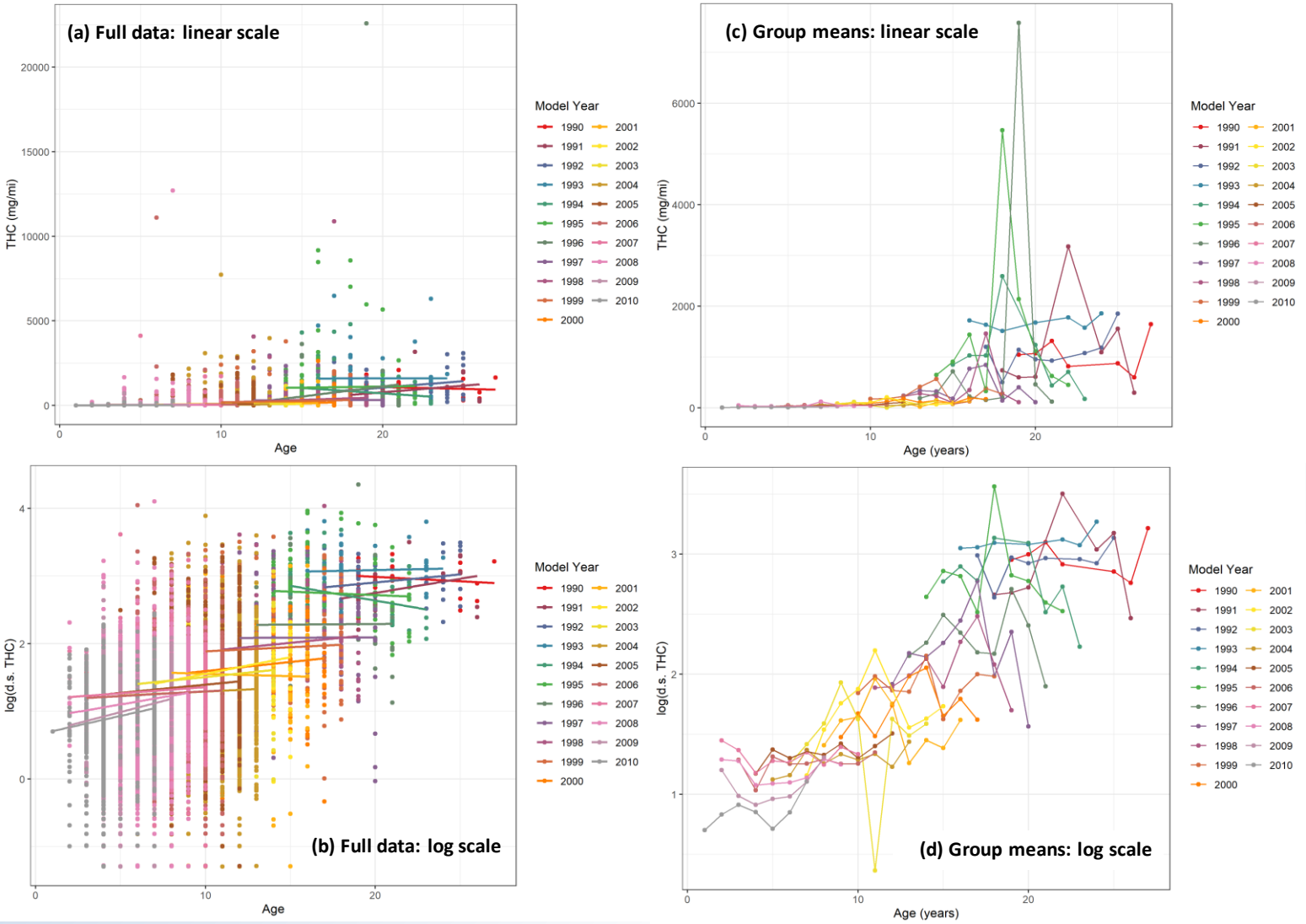
Data Review: THC, Cars

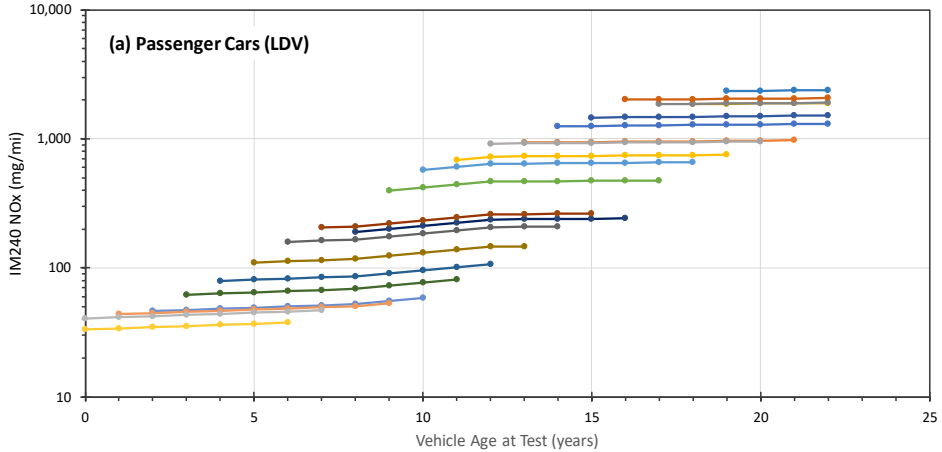


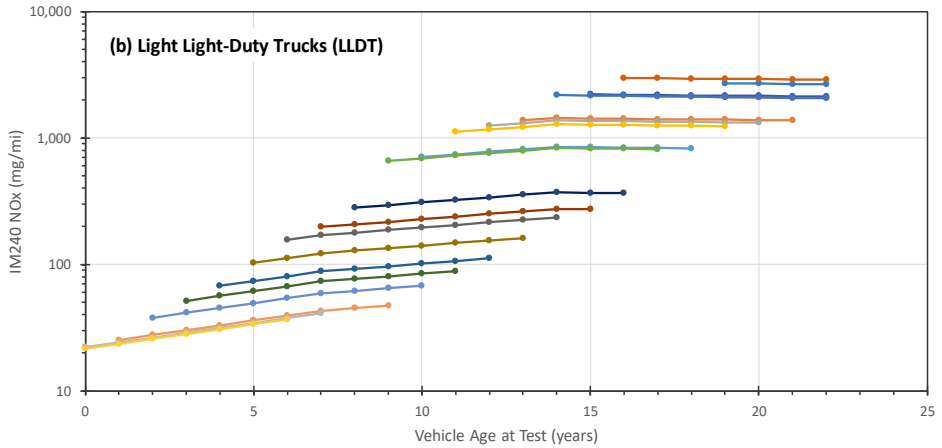
Data Review: THC, LLDT

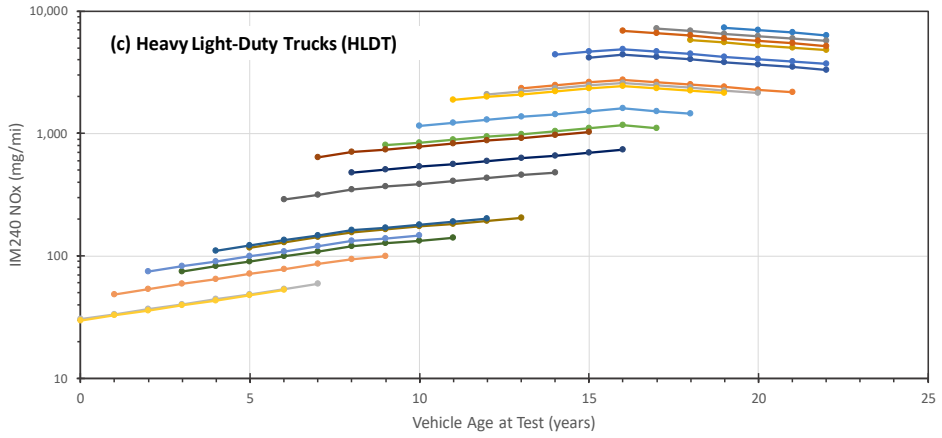


Data Review: THC, HLDT



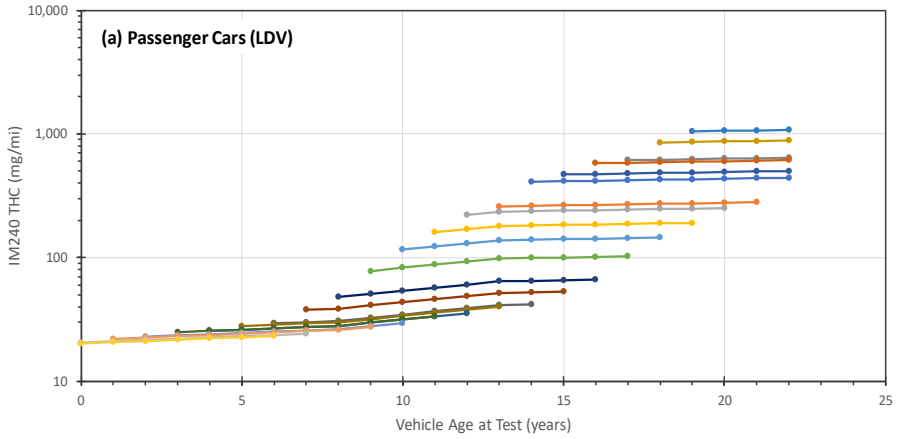


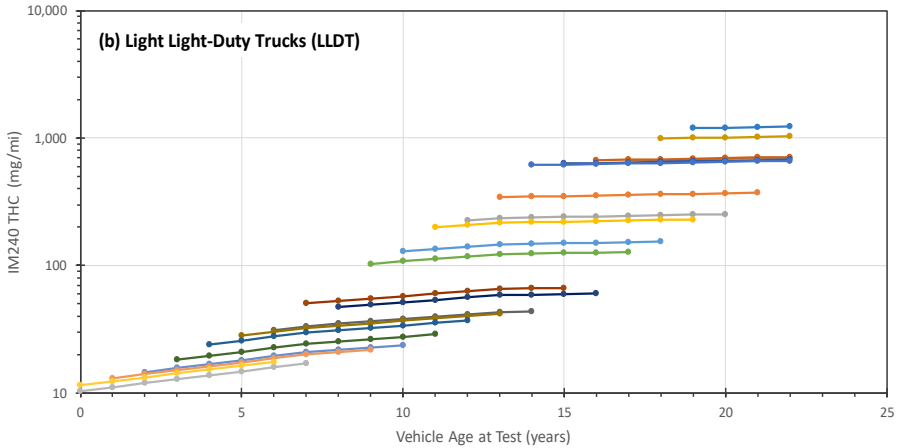


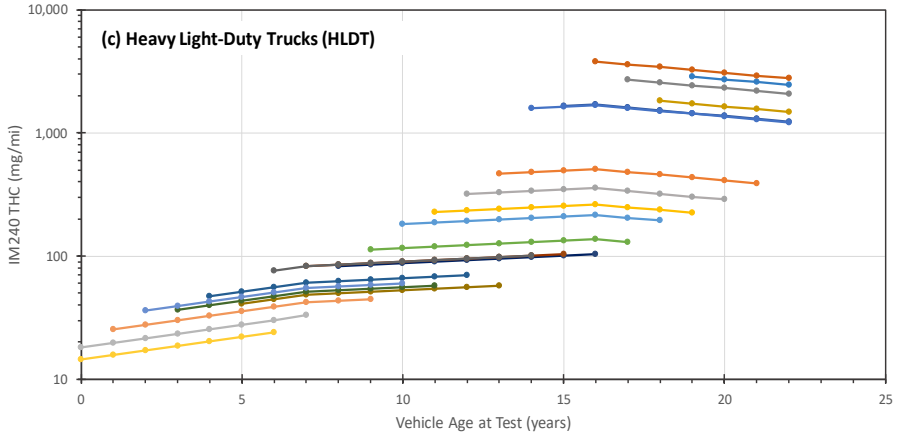


Model Fits: NOx,

Common Log Scale

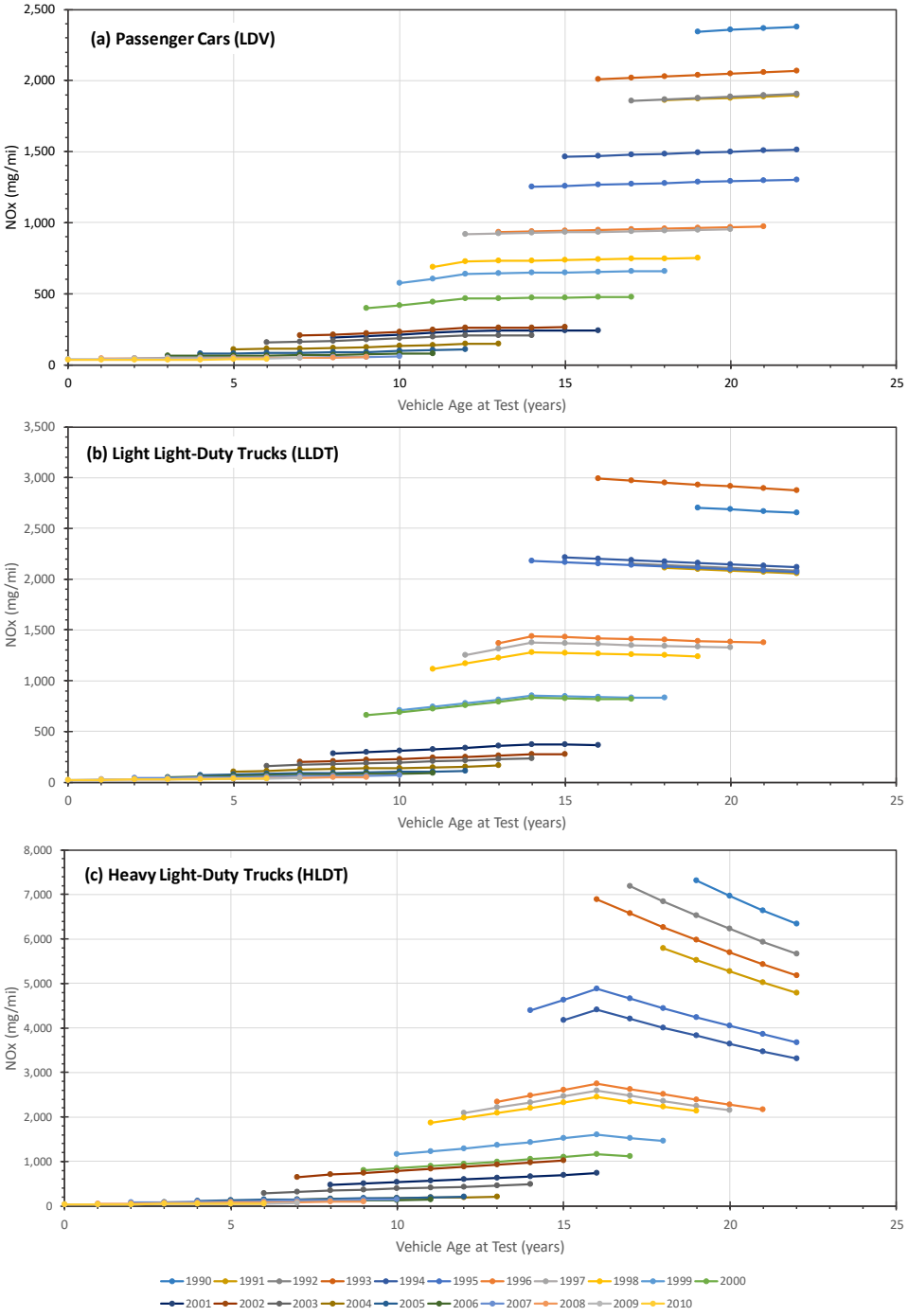






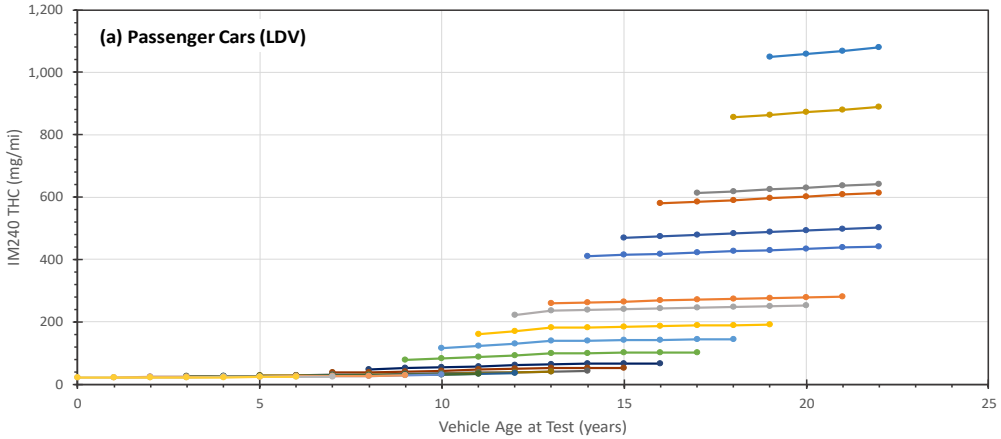
Model Fits: THC,

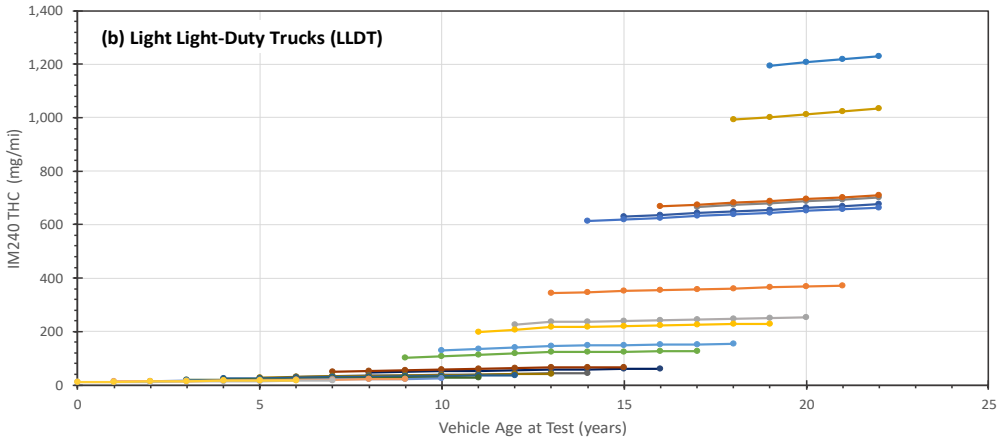
Common Log Scale

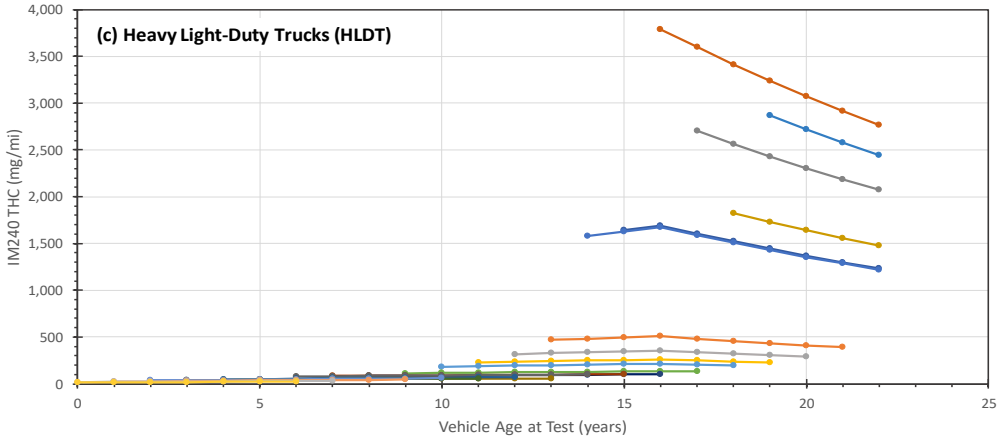


Model Fits: NOx,

Linear Scale (Reverse-transformed)



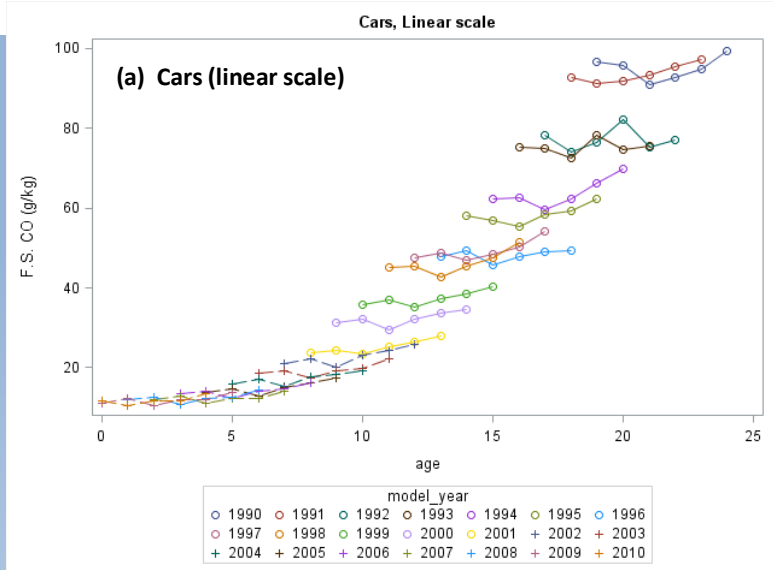


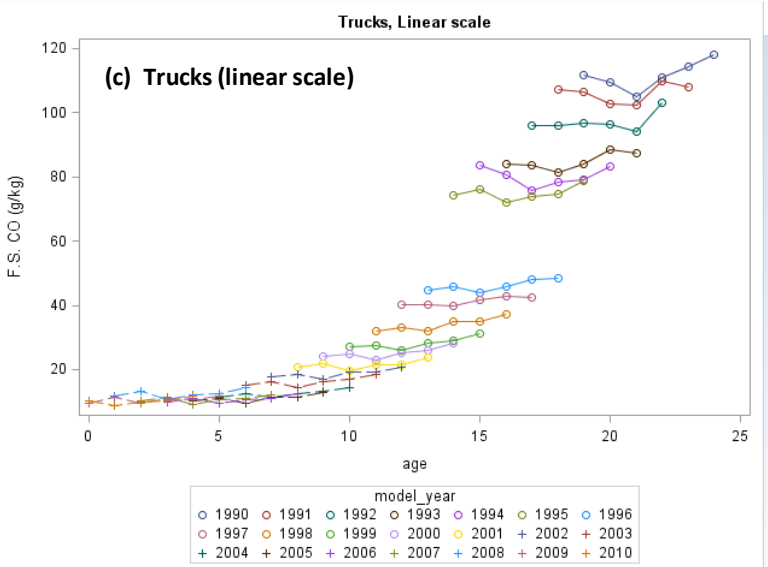


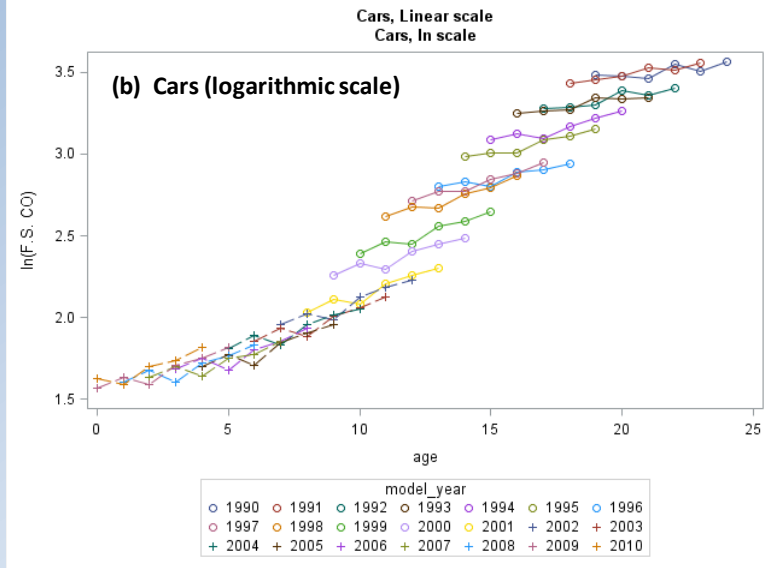
Model Fits: THC,

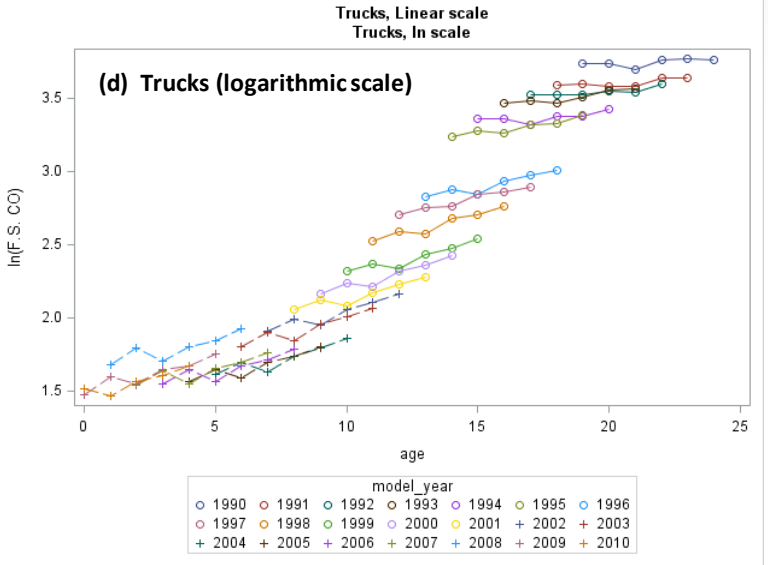
Linear Scale (Reverse-transformed)

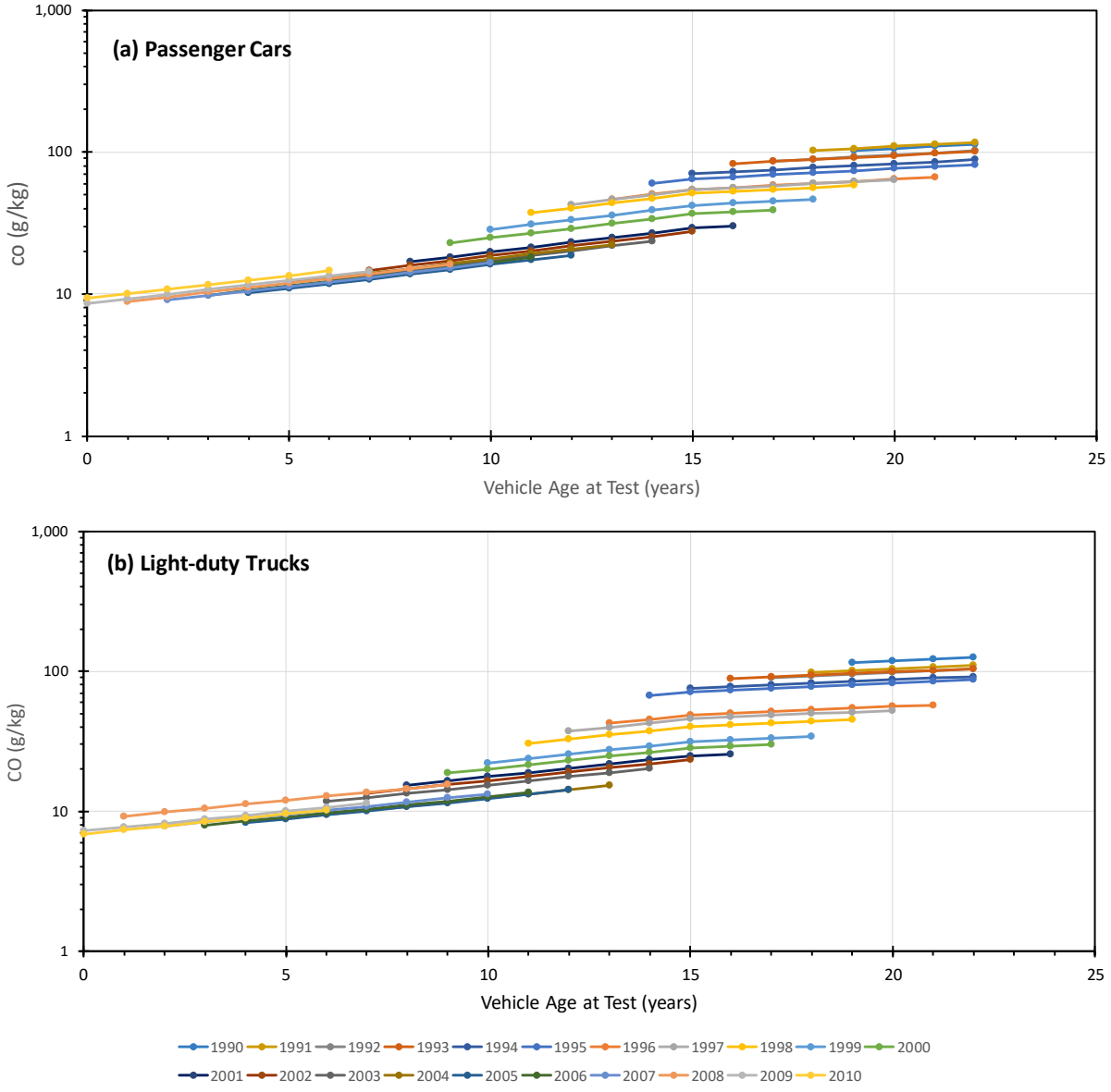
Data Review: CO



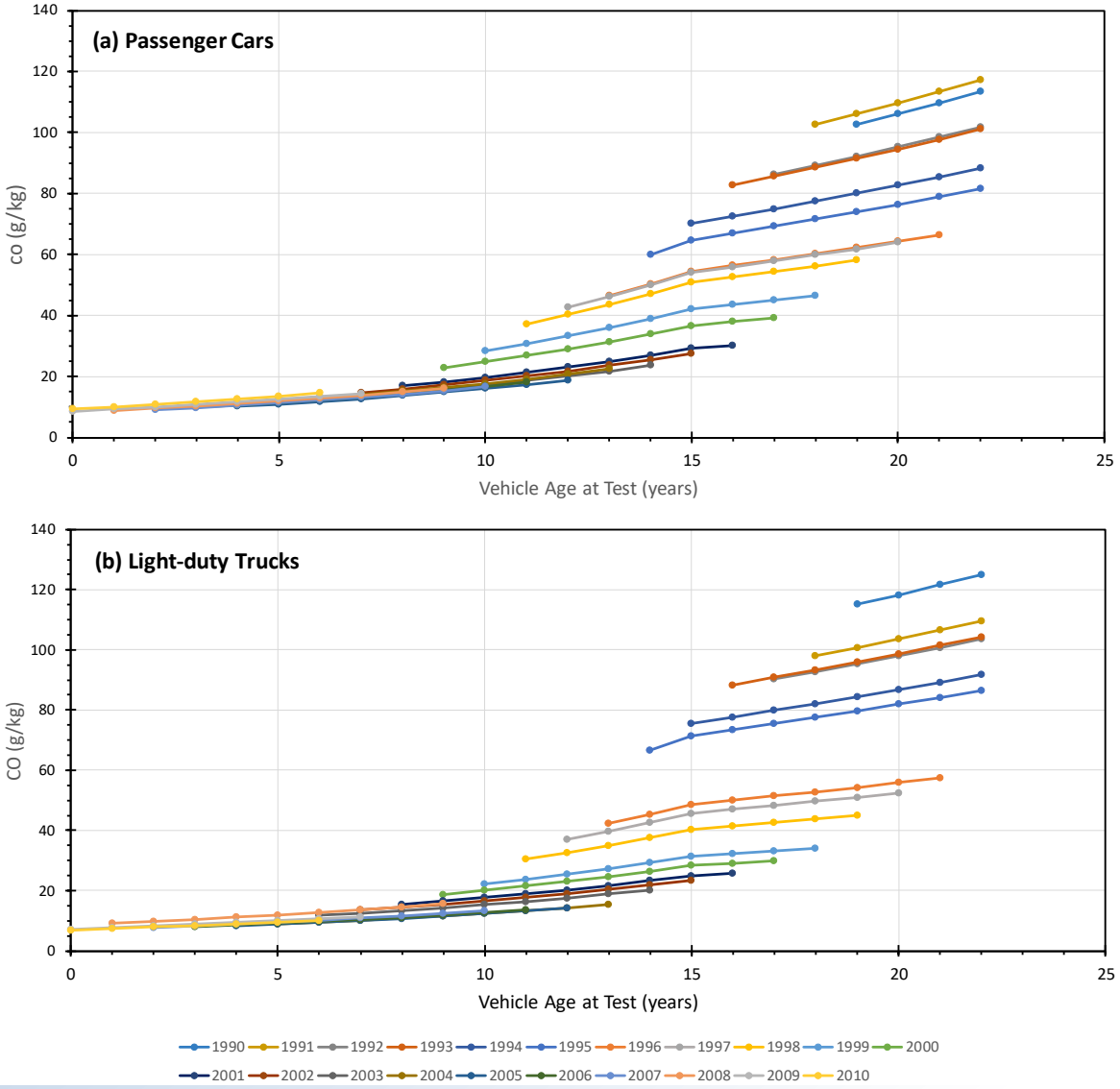




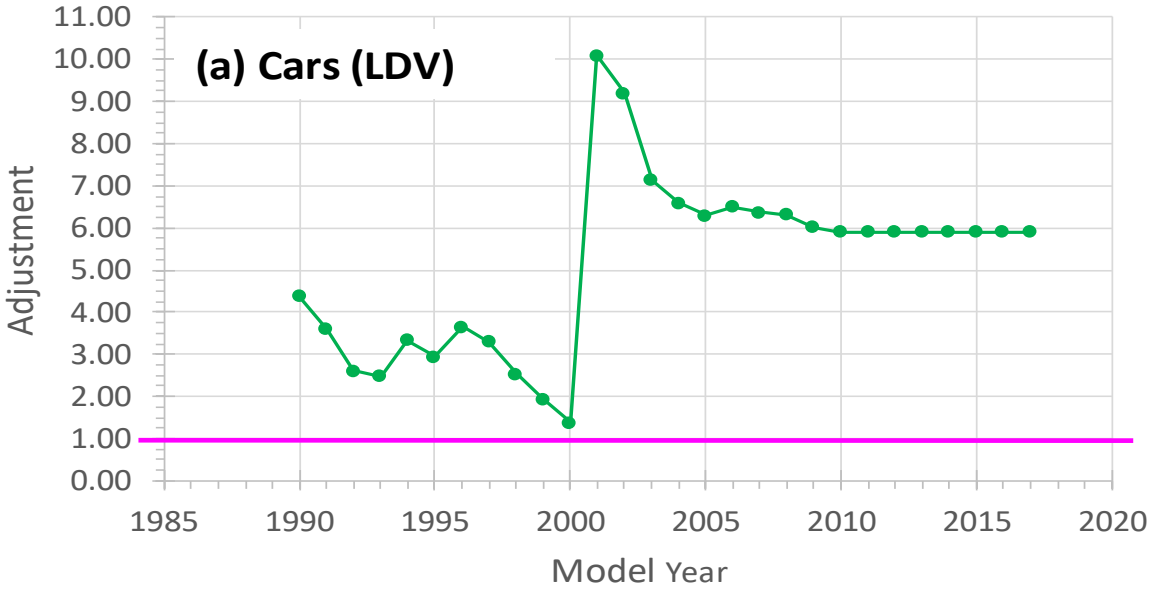


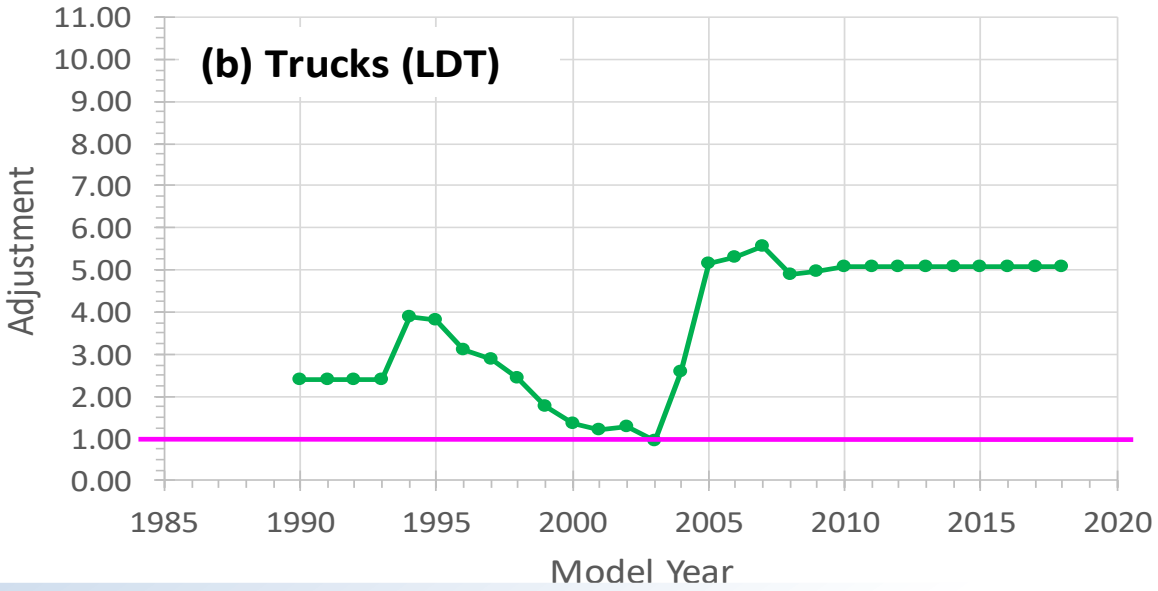


Model Fits: CO, Common Log Scale



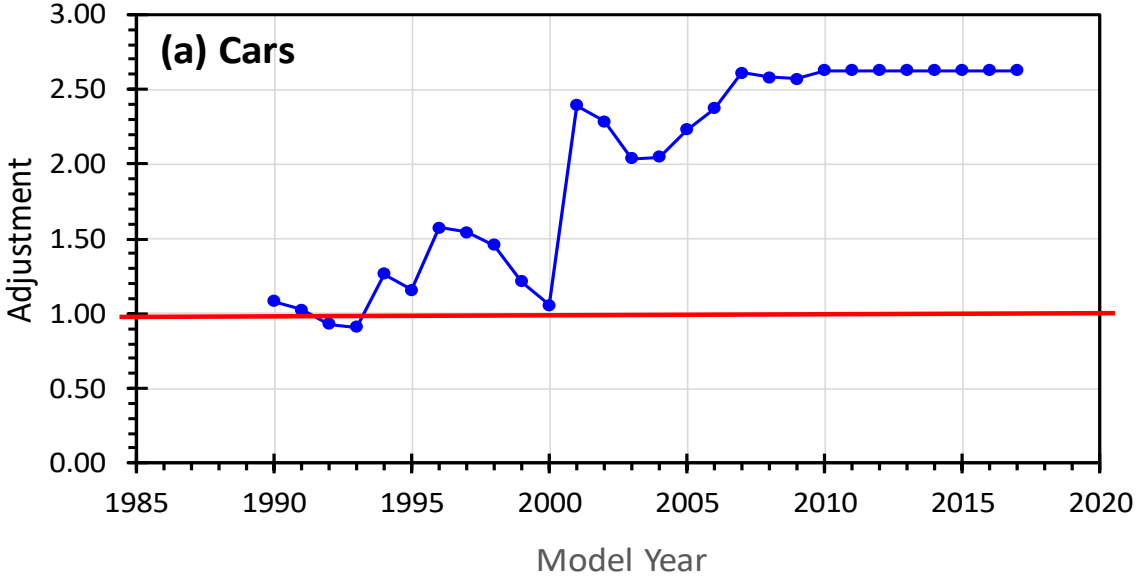
Model Fits: CO, Linear Scale (Reverse-transformed)

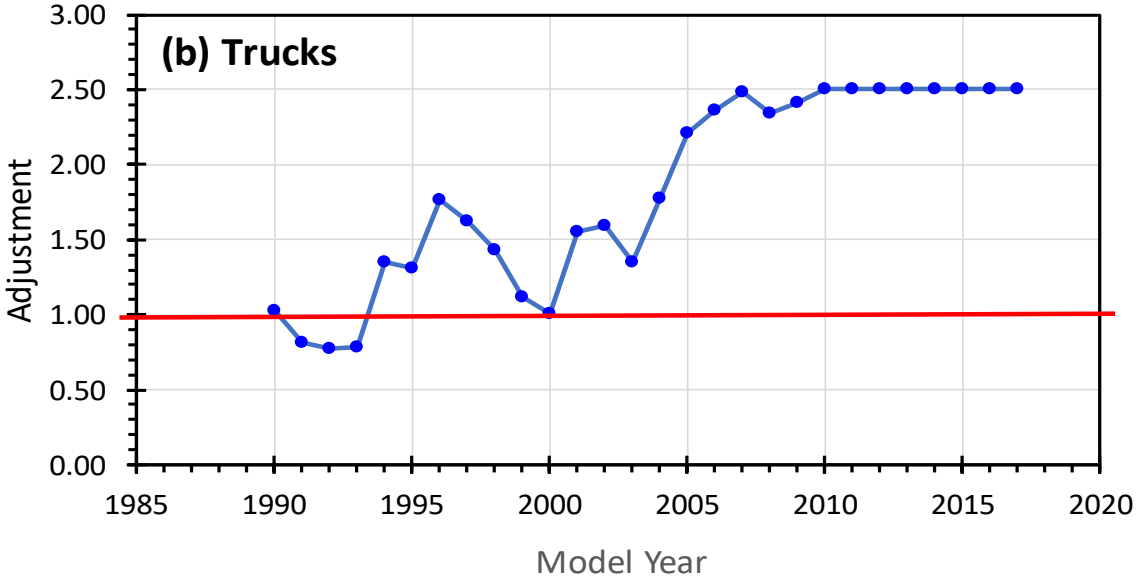




THC
"Young-Vehicle" Adjustments

Model-year specific factors to convert MOVES2014b "Age 0-3" rates to rates implied by new Denver data





CO
"Young-Vehicle" Adjustments

Model-year specific factors to convert MOVES2014b "Age 0-3" rates to rates implied by new Denver data