Light-Duty Exhaust Emission Rates in MOVES2010

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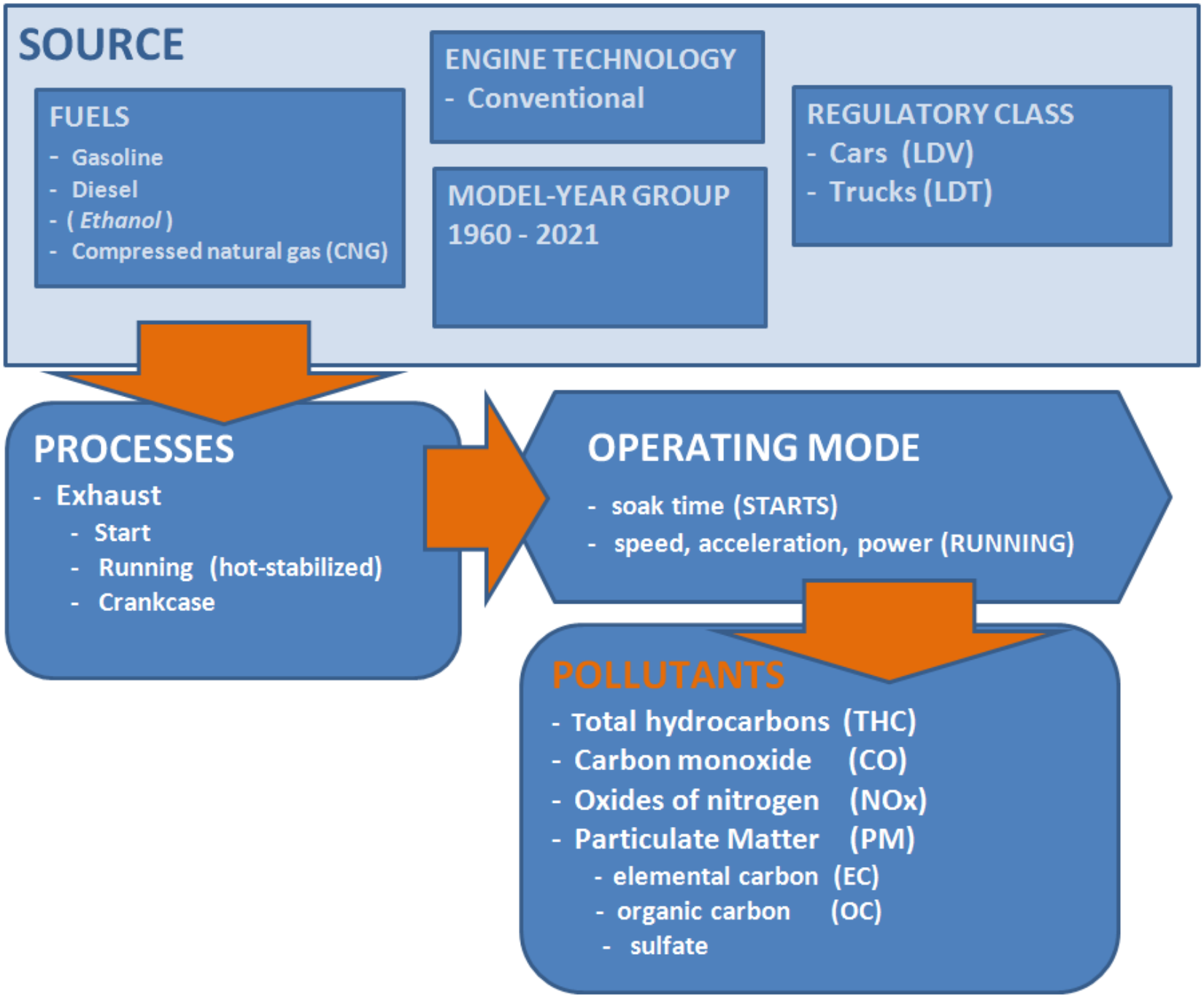

SOURCE
FUELS
- Gasoline
- Diesel
- (Ethanol)
- Compressed natural gas (CNG)
ENGINE TECHNOLOGY
- Conventional
MODEL-YEAR GROUP
1960 - 2021
REGULATORY CLASS
- Cars (LDV)
- Trucks (LDT)
PROCESSES
- Exhaust
- Start
- Running (hot-stabilized)
- Crankcase
OPERATING MODE
- soak time (STARTS)
- speed, acceleration, power (RUNNING)
POLLUTANTS
- Total hydrocarbons (THC)
- Carbon monoxide (CO)
- Oxides of nitrogen (NOx)
- Particulate Matter (PM)
- elemental carbon (EC)
- organic carbon (OC)
- sulfate

MOVES

The emissionRateByAge Table in MOVES DB

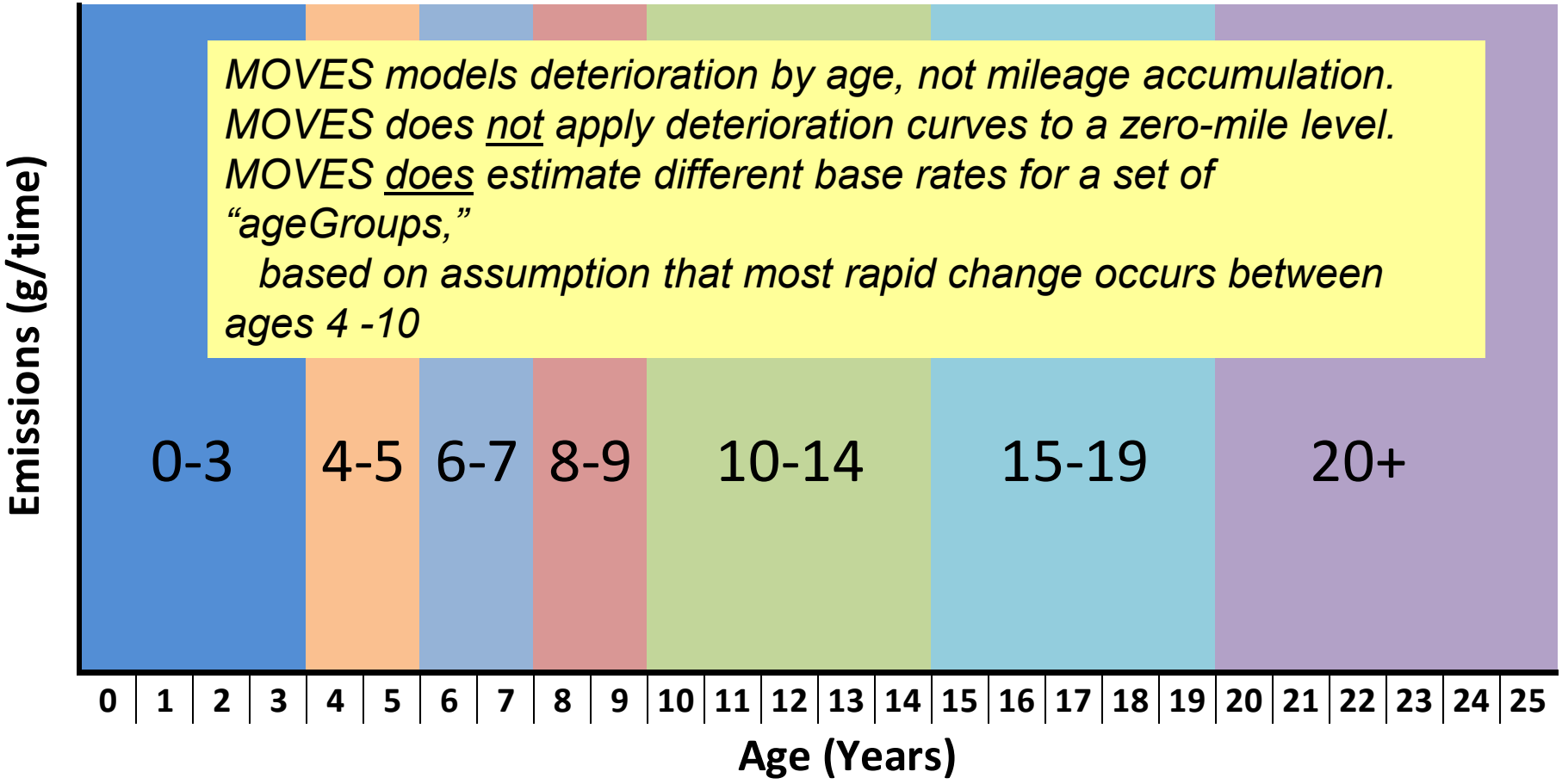
- "*Emissions Source*" (SourceBinID)
  - Fueltype
  - Engine technology
  - Regulatory class
  - Model-year group
- "*Pollutant and Process*" (polProcessID)
- "*operating Mode*" (opModeID)
- "*Deterioration*" (ageGroupID)
- "*Base Emission Rates*" (meanBaseRate, meanBaseRateIM)
- "*Uncertainty*" (meanBaseRateCV, meanBaseRateCVIM)
- "*Sources and Methods*" (dataSourceID)

"Base Rates"

- **Definition: default rates under a set of defined conditions:**
- **For light-duty exhaust, defined as emissions :**
  - On MOVES "Base fuel" (gasoline),
  - On temperature range of 68-86 °F,
  - At 75% specific humidity,
  - Without inspection-and-maintenance program, OR
  - Under parameters of a specific program
    - Phoenix, AZ (CY 1995 – 2005)

Deterioration

ageGroups in emissionRateByAge



Operating Modes
for Running Emissions

Operating modes for running emissions are based primarily (but not entirely) on "vehicle specific power" **(VSP, kW/Mg)**.
VSP represents a vehicle's tractive power normalized to its own weight.

$$VSP_t = \frac{Av_t + Bv_t^2 + Cv_t^3 + mv_t a_t}{m}$$

VSP is calculated as a function of velocity, acceleration, weight and the vehicles' road-load coefficients (A,B,C)

v = velocity, m/sec
a = acceleration m/sec2
m = weight (metric ton)
A = rolling resistance (kW-sec/m)
B = rotating resistance (kW-sec^2/m^2)
C = aerodynamic drag (kW-sec^3/m^3)

Operating Modes for Running Exhaust Emissions

VSP Class (kW/tonne)	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	

21 modes representing "cruise & acceleration" (VSP>0)

PLUS

2 modes representing "coasting" (VSP<=0)

PLUS

One mode each for
idle, and
decel/braking

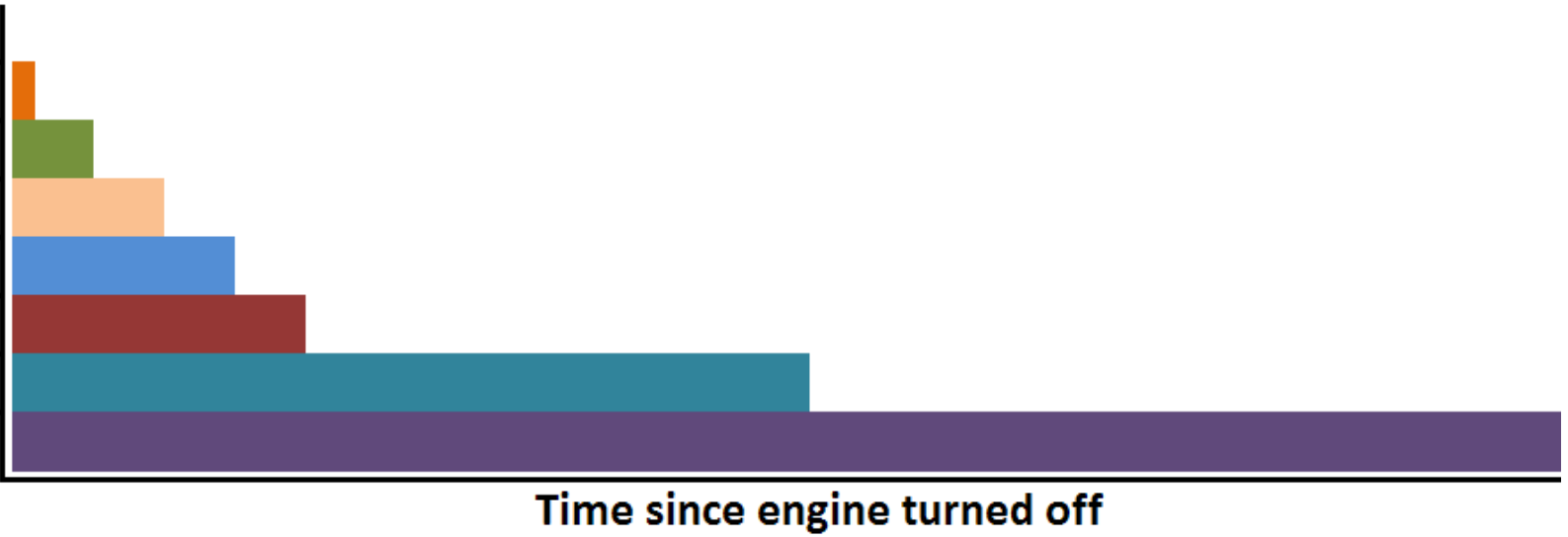
Gives a total of

23 opModes

Operating Modes
Start Emissions

Operating modes for start emissions are defined in terms of "soak time,"
representing a period of time since the engine was turned off, before being restarted

Minutes	Hours
6	0.1
30	0.5
60	1.0
90	1.5
120	2.0
360	6.0
720	12.0



Light-duty Gaseous Emissions (HC/CO/NOx)

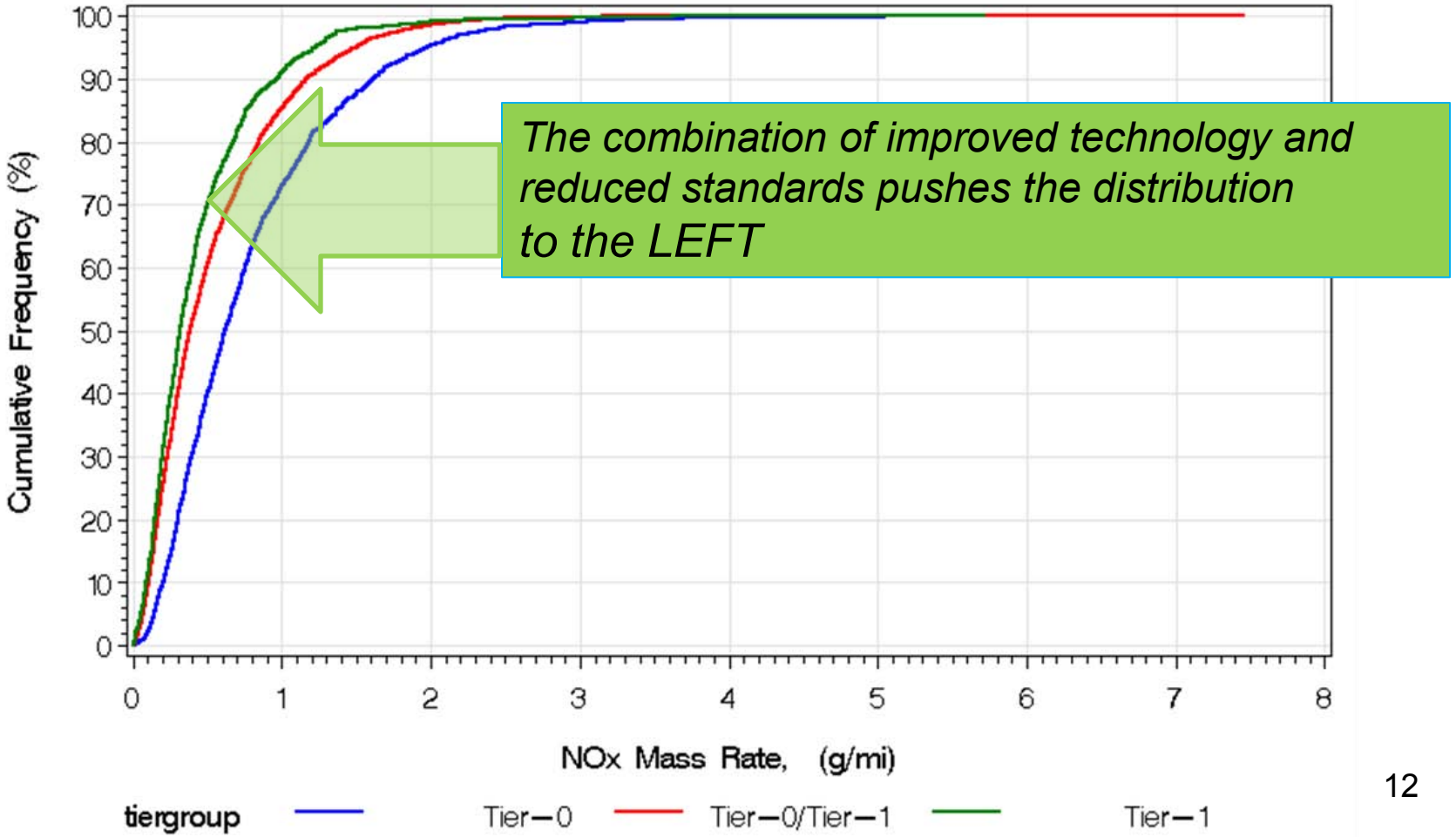
Sub-group 1 , MY 2000 and earlier

RUNNING EXHAUST EMISSIONS

"High Emissions," not "High Emitters"

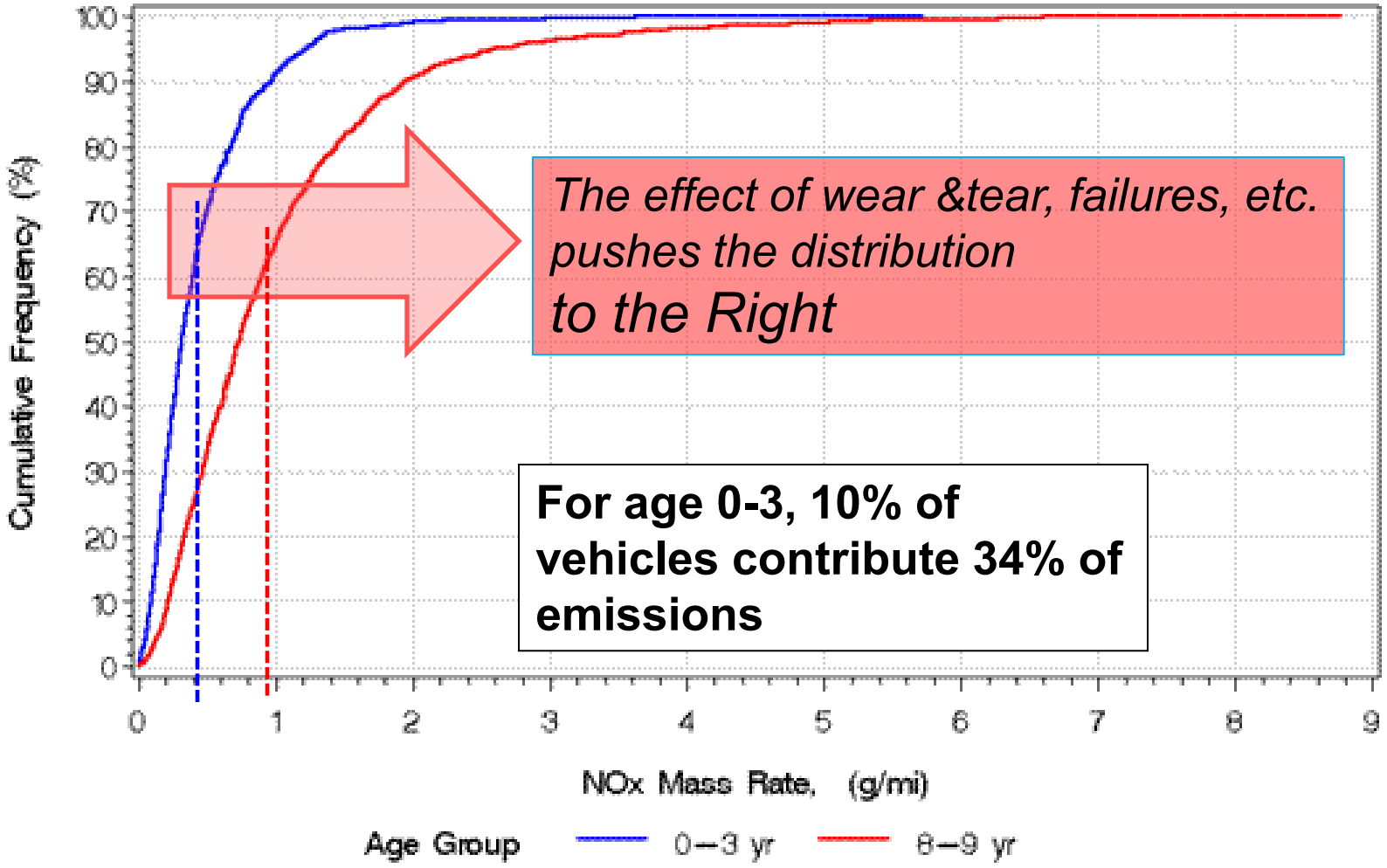
- **In MOBILE:**
  - used discrete "high emitter" category
    - Defined as multiple of FTP standard
    - Assigned separate fuel effects, etc.
- **In MOVES:**
  - Focus on "*high emissions*" (not "*high emitters*")
  - Don't see evidence of distinct "high emitter" group
  - Emissions distributions not discrete, but continuous
    - With looooooong tails
  - Emphasis on capturing mean of whole distribution
    - Including the tail

NOx, Cars, Ages 0-3
Effect of standard/technology
Phoenix I/M (IM147)



The combination of improved technology and reduced standards pushes the distribution to the LEFT

NOx, Cars, MY 96-97 (Tier-1)
Effect of Age
Phoenix I/M (IM147)



logNOx, Cars, MY 96-97 (Tier-1)
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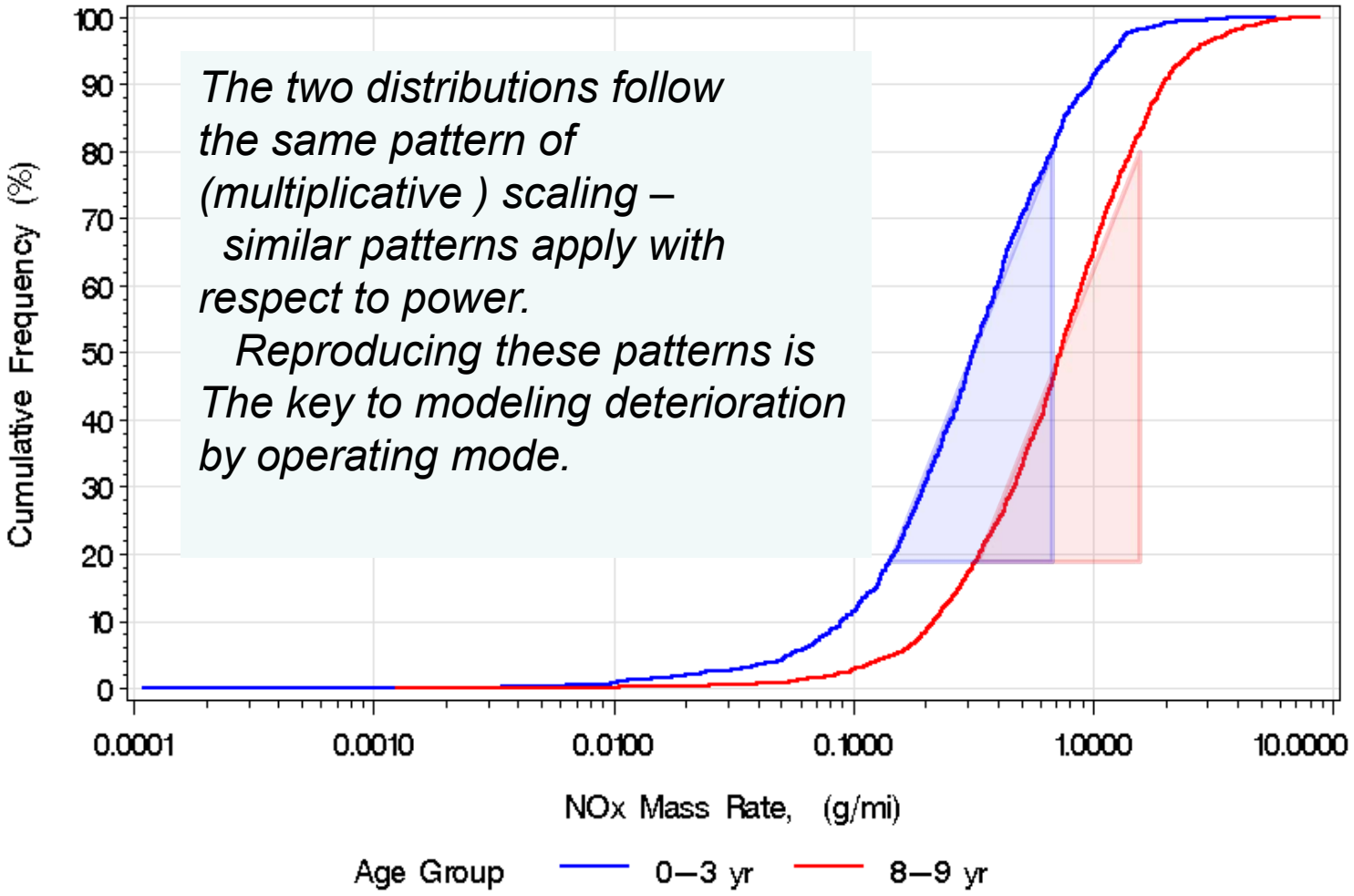

THC, Cars, MY 96-97 (Tier-1)

Effect of Age

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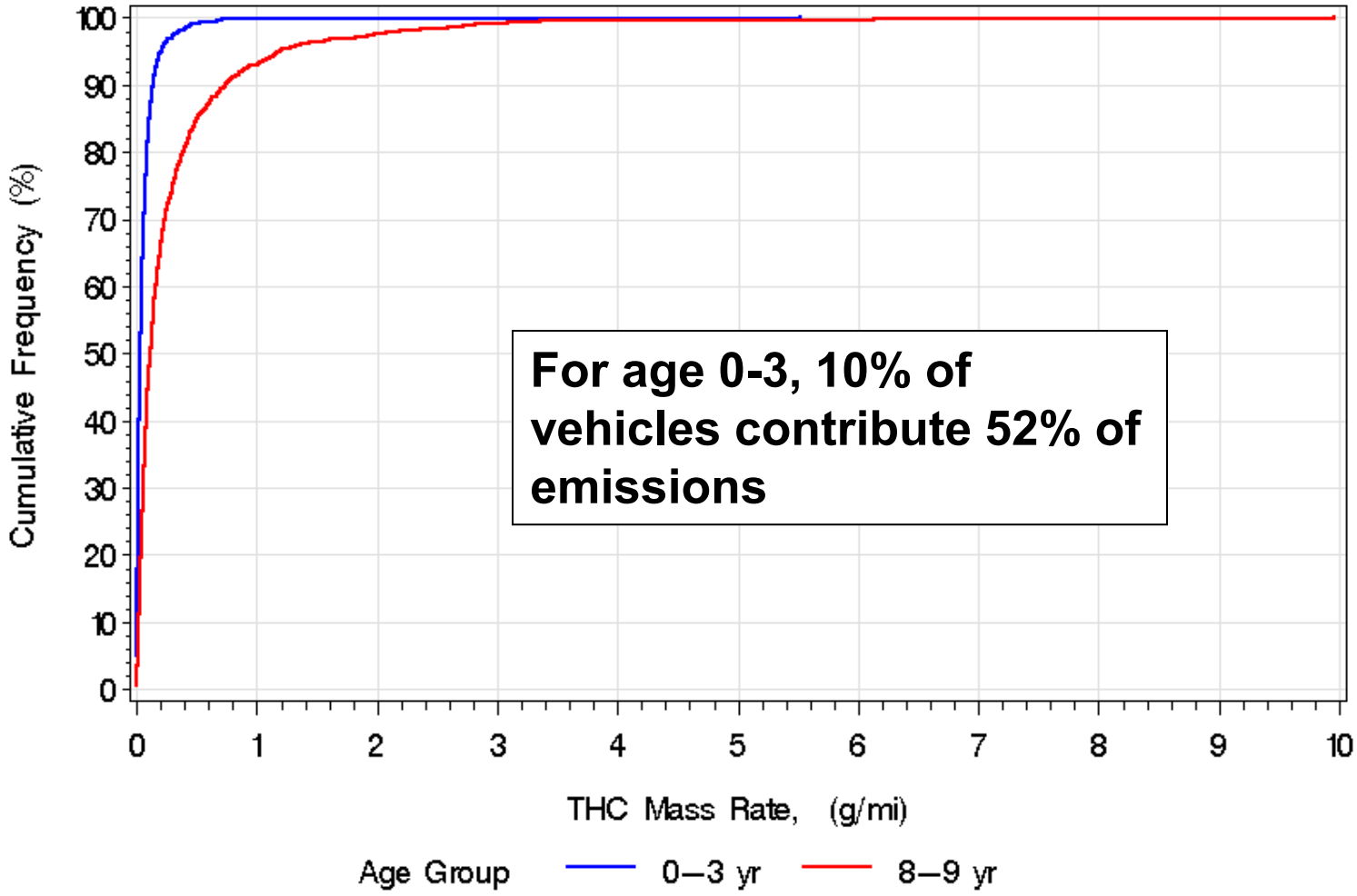


Data Sources

- **Measured on transient tests**
  - Need changes in speed, acceleration
- **Measured on continuous basis**
  - To get modal rates
  - “second-by-second”
- **Known temperature**
  - at time of test
- **Subject to I/M requirements**
  - at time of test
- **Meets quality-assurance criteria**

Emission Rates for I/M Conditions

- **Invert previous approach**
  - MOBILE: I/M in reference to non-I/M
  - MOVES: non-I/M in reference to I/M
- **Simplified Approach**
  - Develop two sets of “Reference” or “Default” Rates
    - One set to representing vehicles under “I/M conditions”
    - One set representing vehicles under “non I/M conditions”
  - Modify by IMAdjustmentFactor
    - To allow for differences among programs

Source Selection

- **Decision: rely on:**
  - Phoenix I/M evaluation sample
  - CY 1995 - 2005
- **Rationale:**
  - Historic depth
    - Can estimate deterioration directly
    - Other datasets far more limited
  - Avoid technical issues
    - Difference in size/influence
    - Need for sample-weighting
      - Phoenix sample stratified (Pass/Fail)
      - Others not
  - Uniformity in Fuels
    - Fuels in Phoenix relatively stable
    - Provide basis for Fuel effects

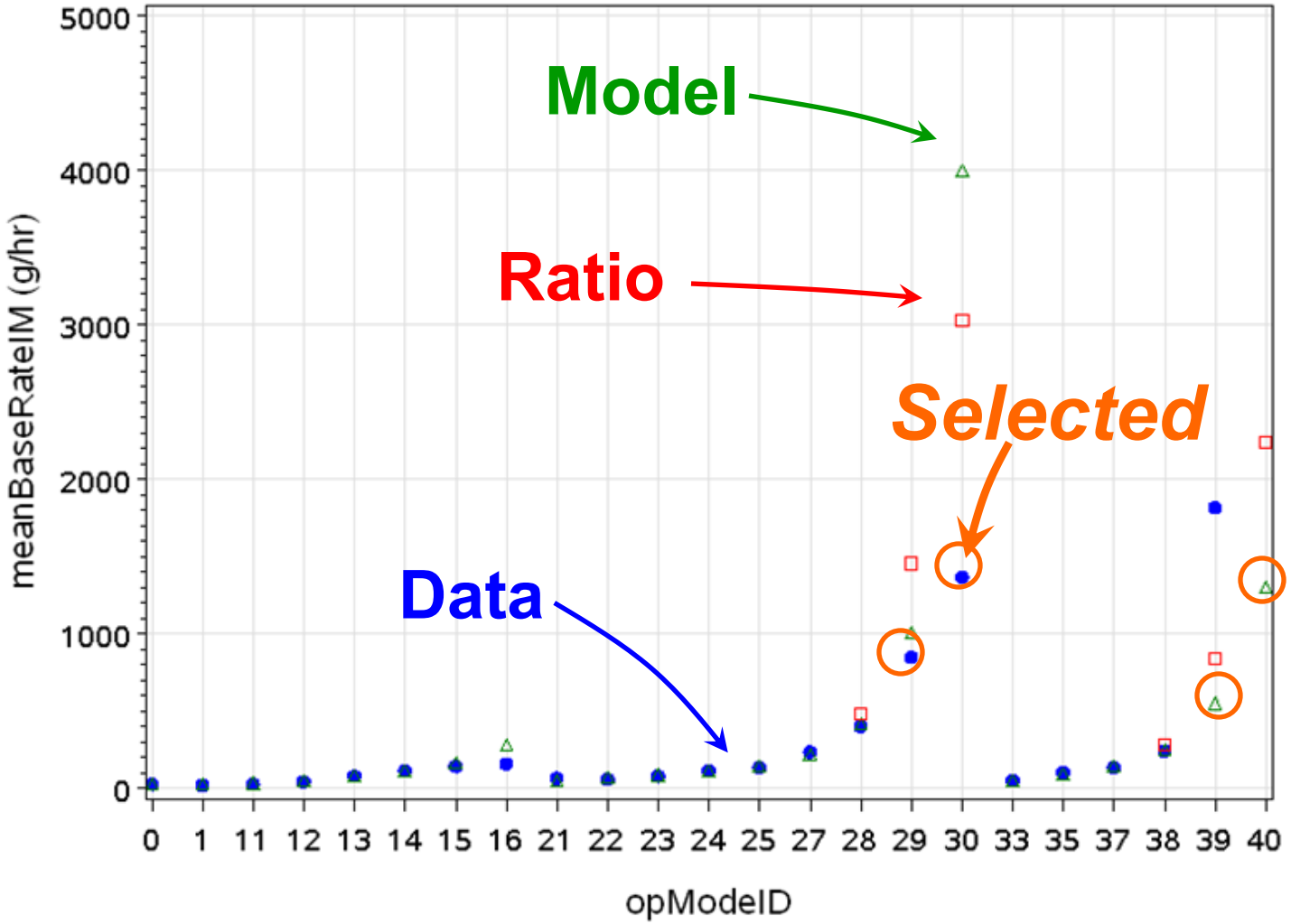
Methods: Developing Rates

- **Where we have data**
  - Calculate means
    - By SourceBin, AgeGroup, and operating mode
    - May be weighted
  - Calculate associated variances
    - By SourceBin, AgeGroup and Operating Mode
    - May be weighted
- **Where we don't have data (filling the holes)**
  - Extrapolate VSP trends (filling missing opModes)
  - Extrapolate Age trends (deterioration)
    - Forecasting
    - Backcasting
  - Method: statistical models

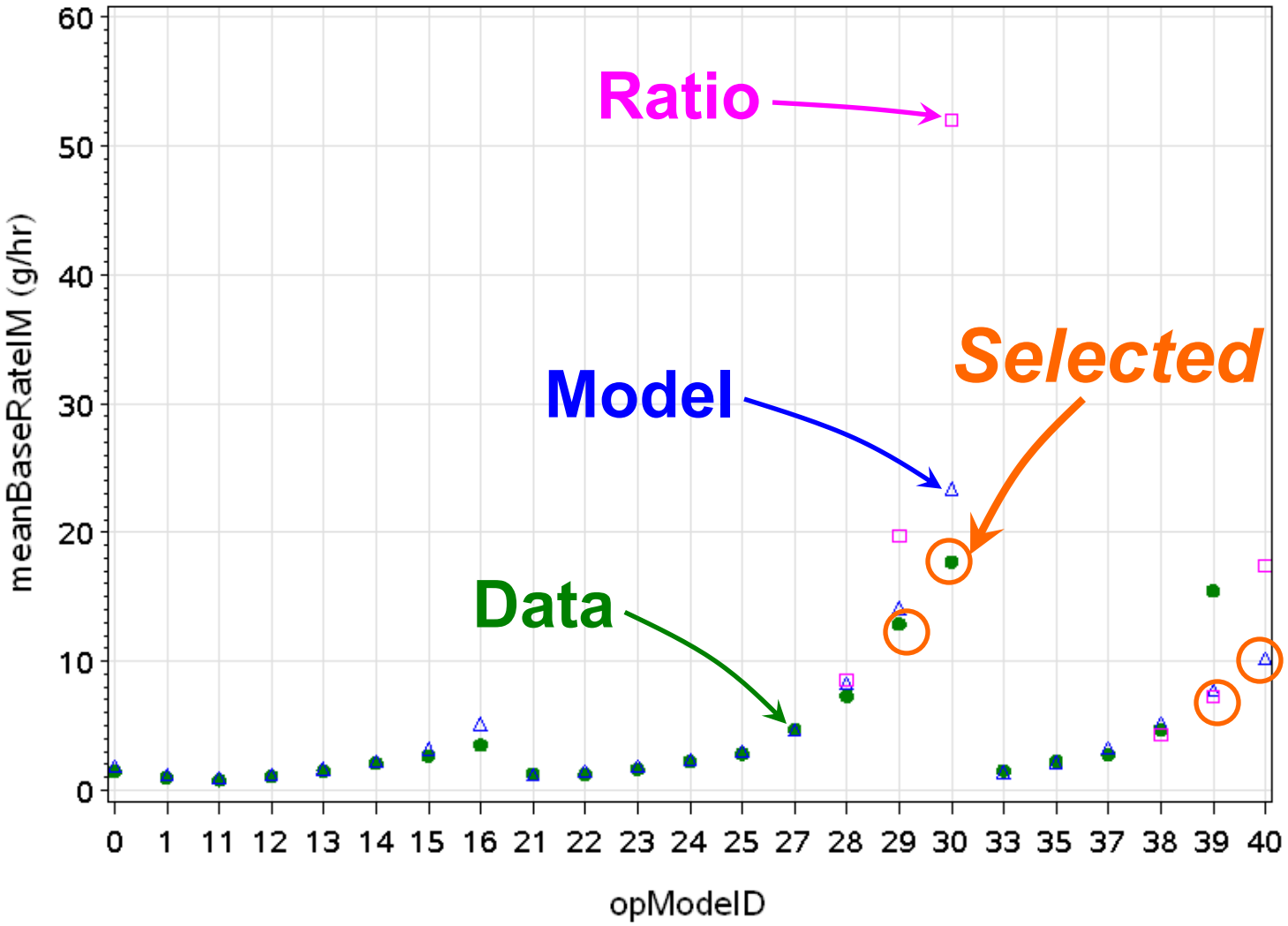
High-Opmode Adjustments

- **Rates developed from data measured on IM147/IM240**
  - Moderate cycles
    - speed < 50 mph
    - VSP <= 24 kW/Mg
- **Several opModes outside this range**
  - The “high-power” opModes
  - Used statistical models to extrapolate to 34 kW/Mg
- **Gave extrapolation extra scrutiny**
  - Analyzed independent data on aggressive cycles
    - Speed over 70 mph
    - VSP over 30 kW/Mg
  - Estimated alternative rates (by ratio)
- **Adjusted rates on case-by-case basis**
  - **Concern**: avoid gross overestimation
  - Selected minimum of (original, alternate)
  - Giving non-declining trend with power

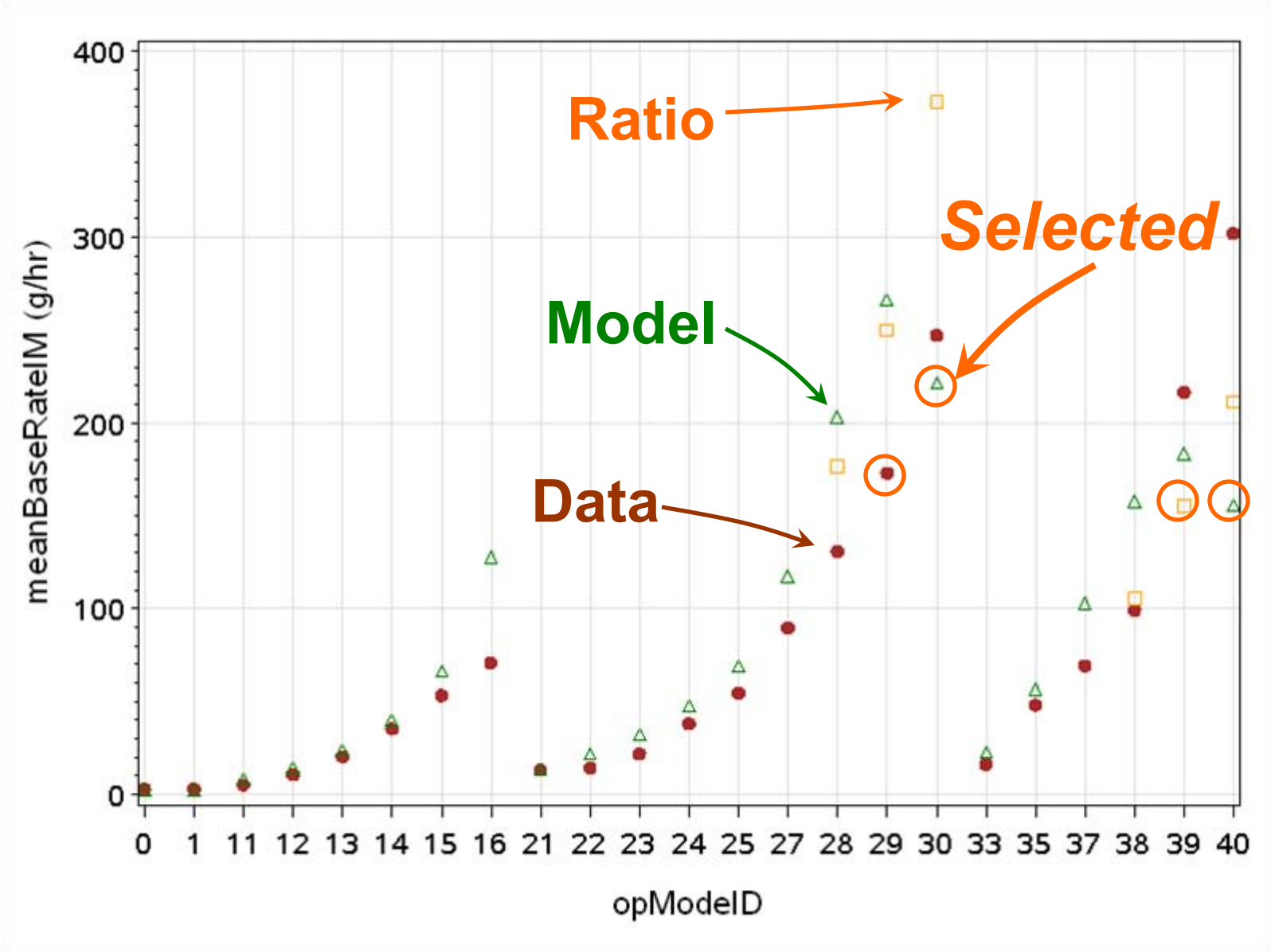
Ex: CO, Trucks, MY1998, Age 6-7



Ex: THC, Cars, MY1998, Age 4-5



Ex: NOx, Cars, MY95, Age 8-9



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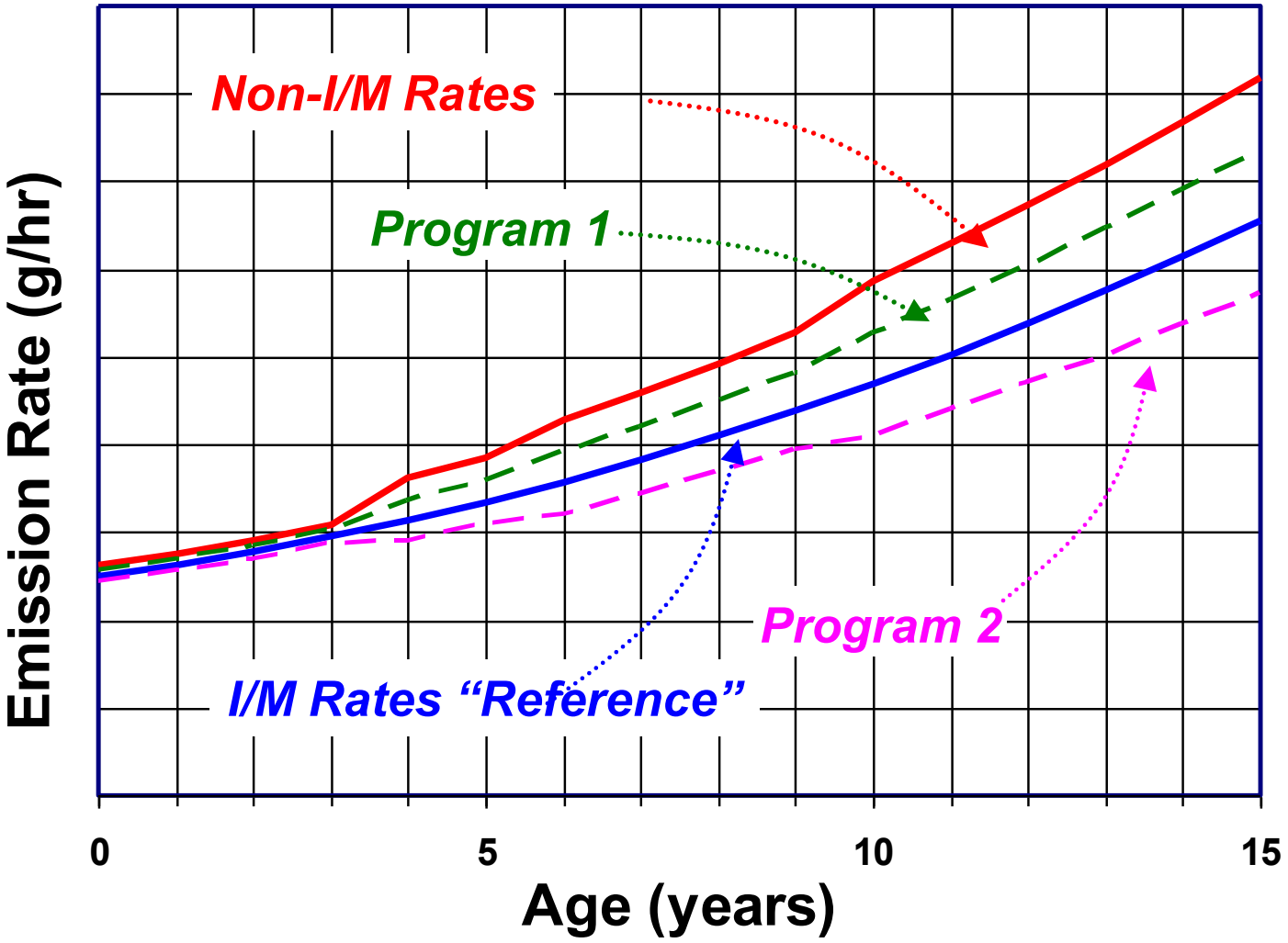
Modeling Inspection and Maintenance for Exhaust Emissions

- **In MOBILE …**
  - Emission rates represent “non-I/M”
  - Specific programs modeled relative to “non-I/M”
- **In MOVES**
  - Use two sets of Rates
    - representing vehicles under “I/M conditions”
      - **Phoenix (CY 1995-2005)**
    - representing vehicles under “non I/M conditions”
  - Modify rates during MOVES run
    - accounting for differences among programs
    - discounting for avoidance, non-compliance, etc.

Example: Reference Rates by Age



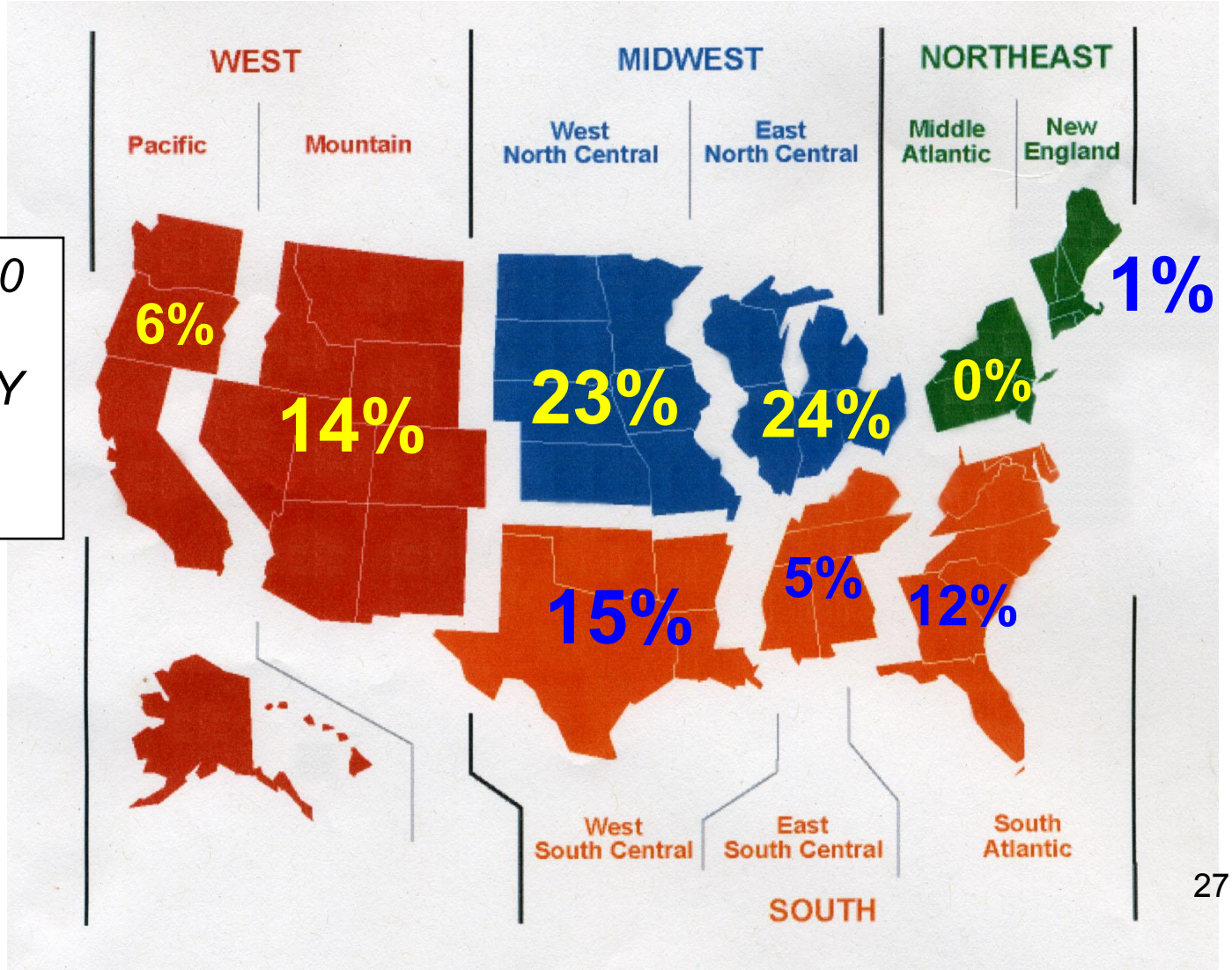
Non-I/M Reference Rates

- **Approach** :
  - Derive by adjustment relative to I/M references
- **Method: "migrating vehicles"**
  - vehicles migrating into Phoenix
  - Criteria
    - from out of state
    - OR from non-I/M counties in AZ
    - NOT from other I/M areas
    - AND Receiving very first test
    - AND selected for inclusion in random sample
- **Result**
  - Sample of ~1,400 vehicles

Geographic Distribution

of migrating vehicles (*by Census Region*)

Out of 1,400 vehicles, between CY 1995 and 2005 …



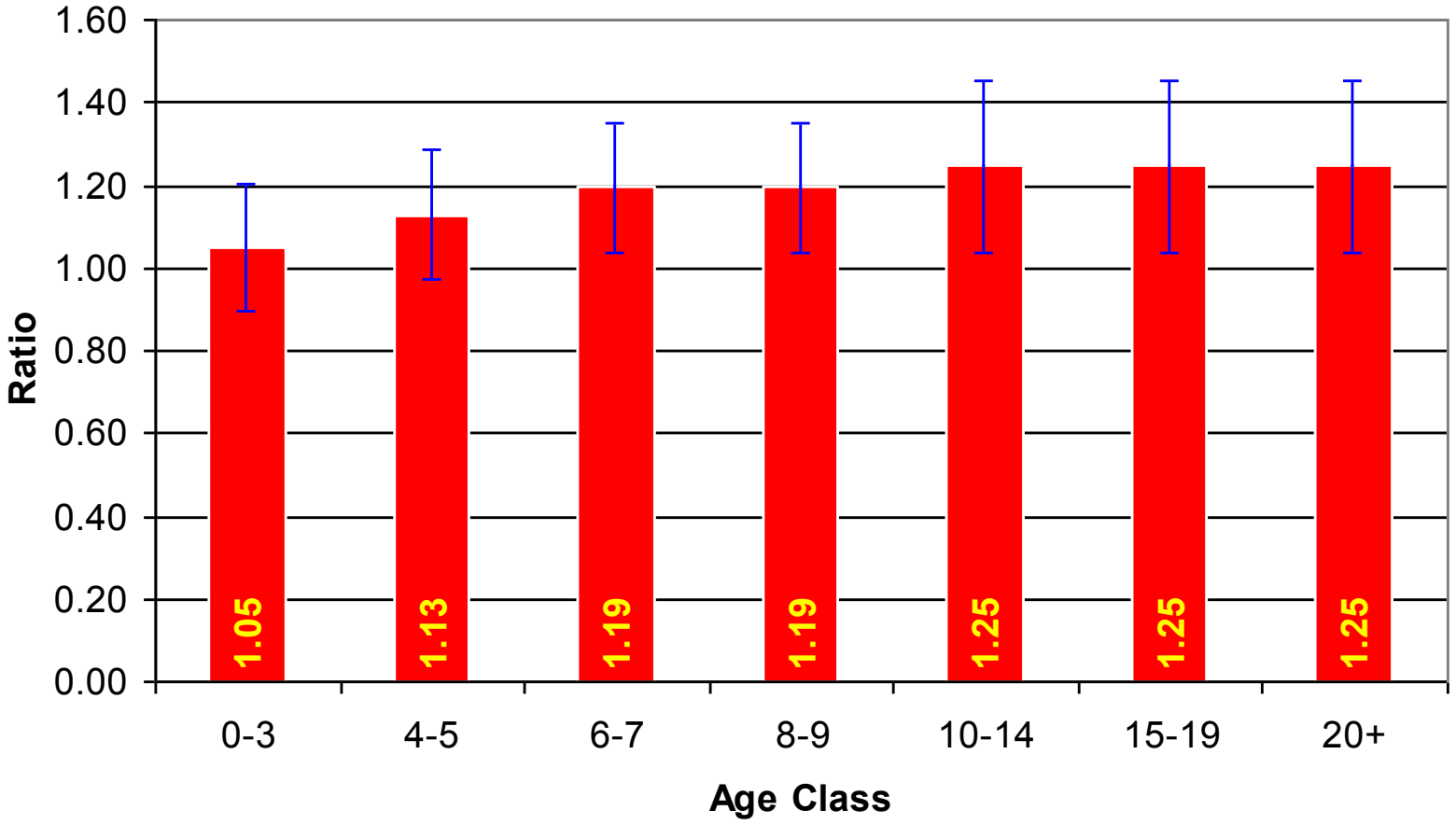
Methods: Calculations

calculate the ratio of the means of emissions for "Non-IM" tests to those for IM tests (in g/time)…

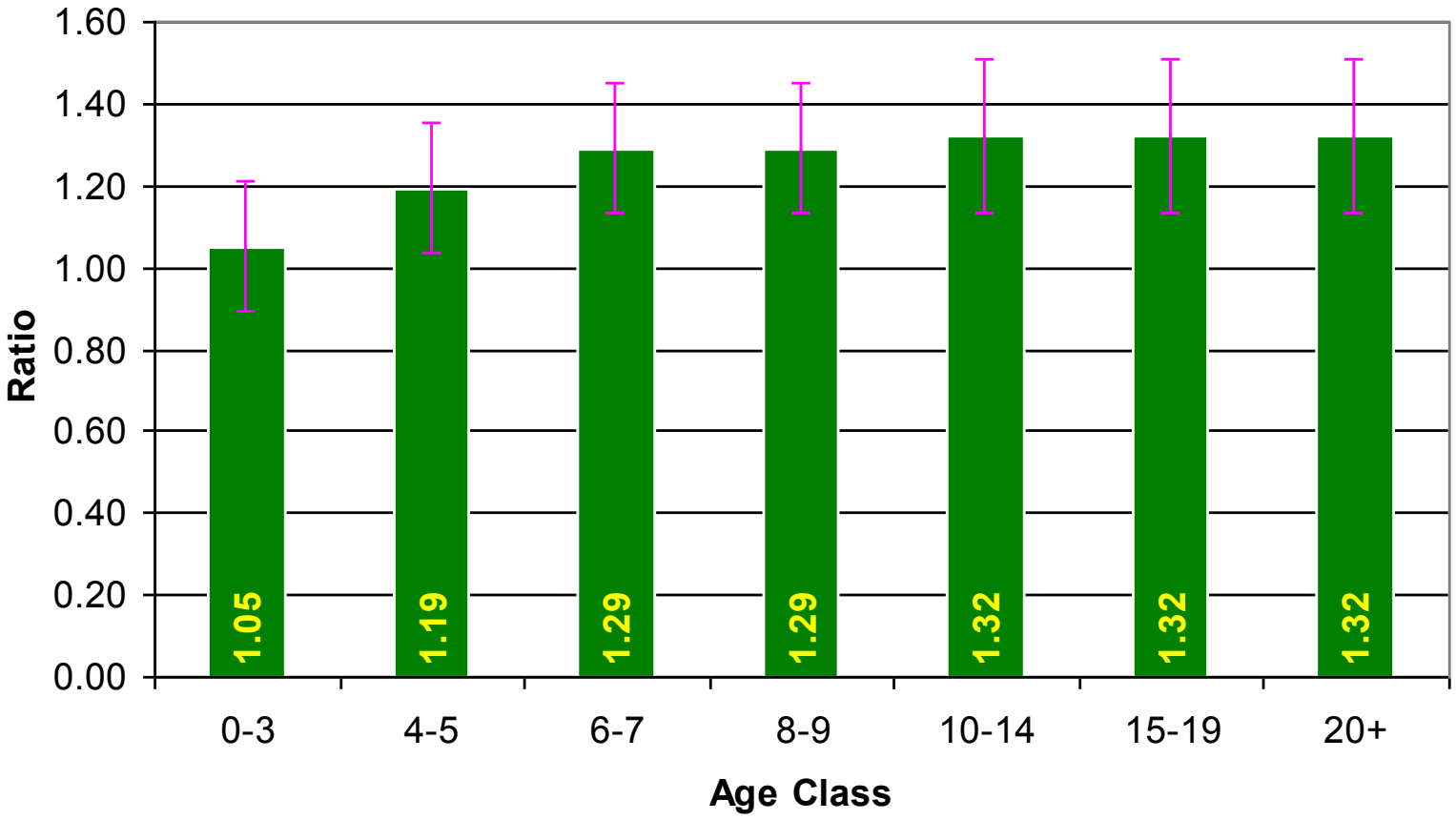
$$Ratio = \frac{\overline{E}_{\text{nonIM}}}{\overline{E}_{\text{IM}}} = \frac{N}{I}$$

Aggregate:
no VSP
cars + trucks
across MYG

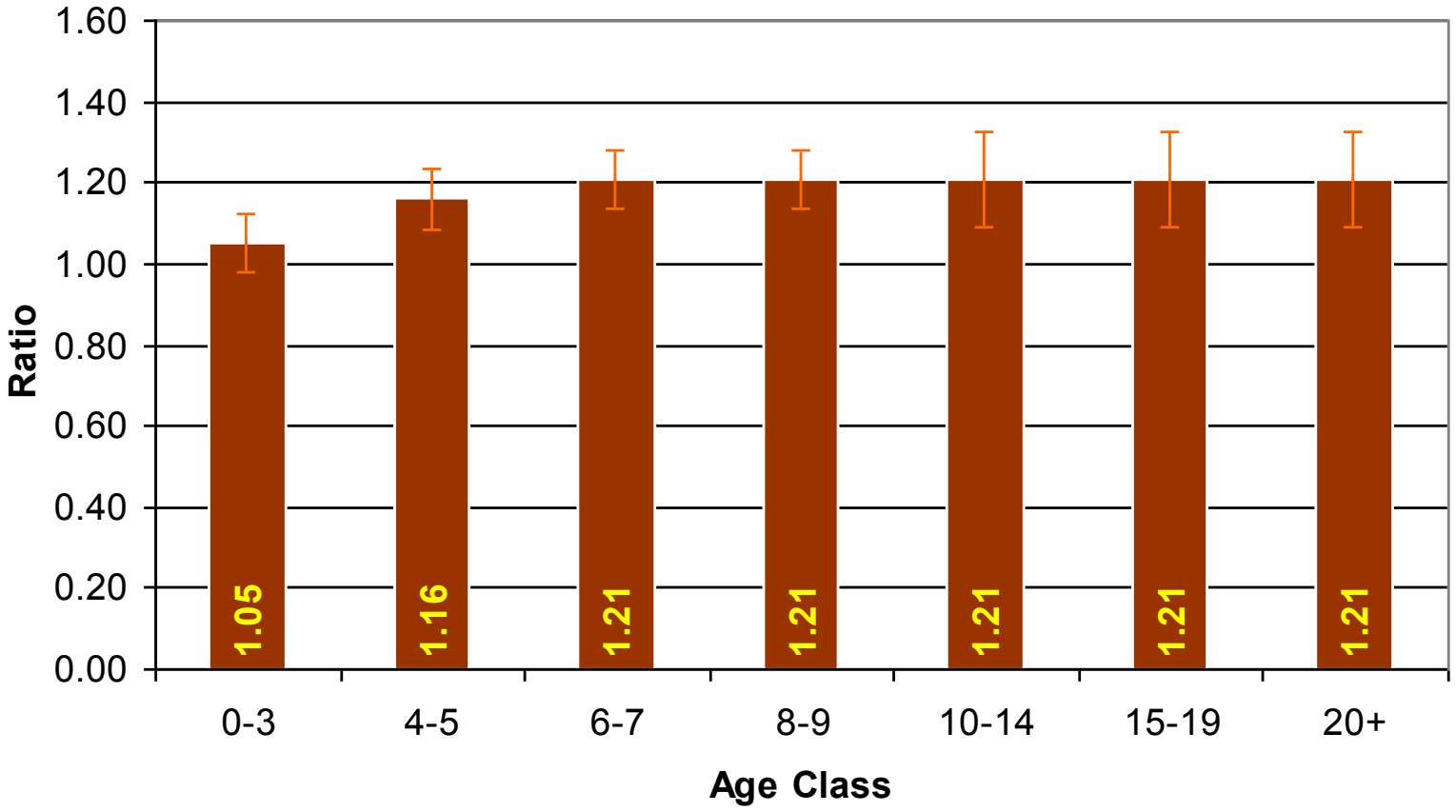
Non-I/M : I/M Reference Ratios for CO



Non-I/M : I/M Reference Ratios for THC



Non-I/M : I/M Reference Ratios for NO_x



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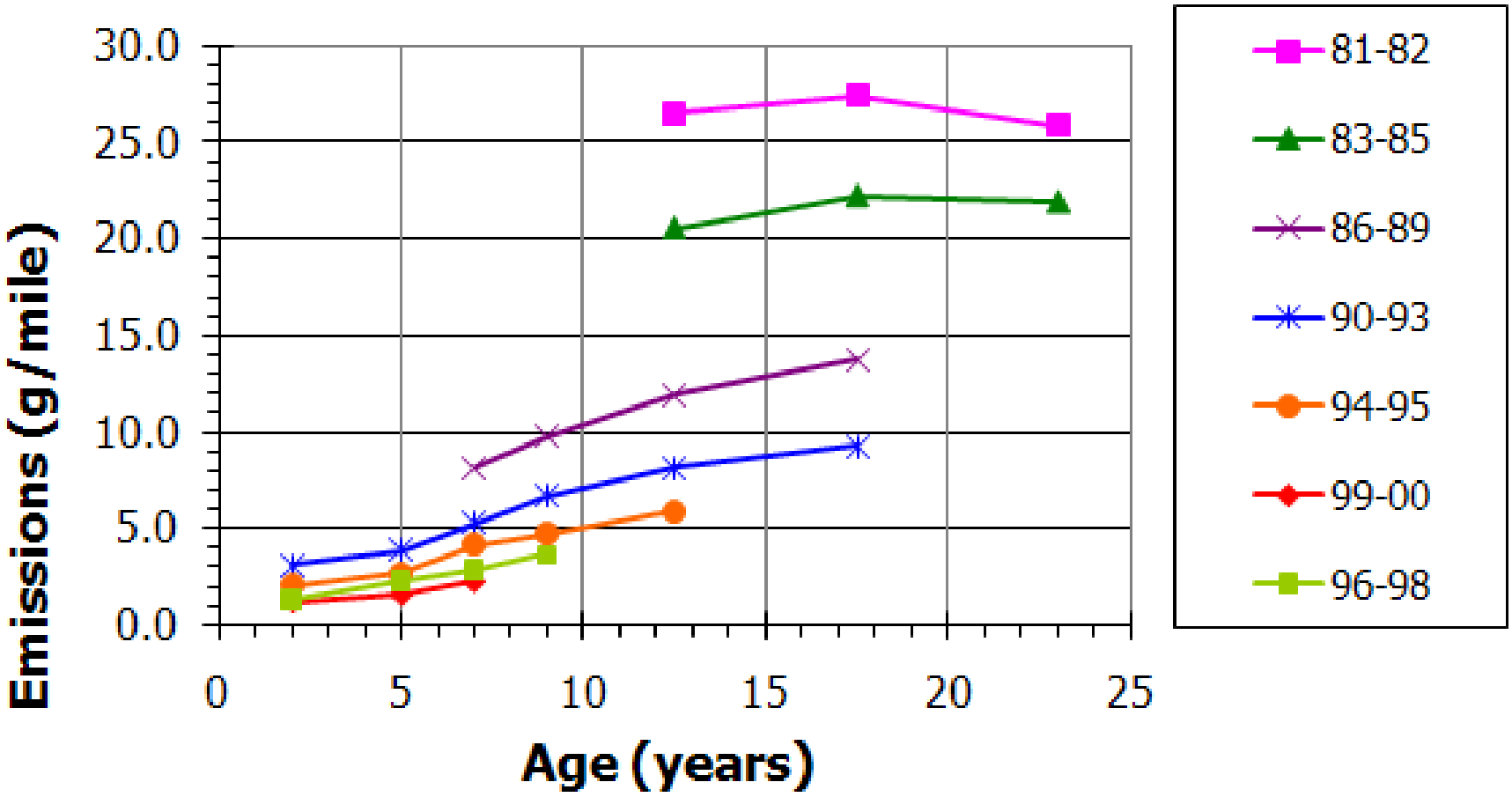
Emissions Stabilization
a.k.a. "survival of the fittest"

- **Analysis has changed our notions about how deterioration occurs**
- **Deterioration slows or stops at 12-15 years**
  - In I/M areas (at least)
  - Dirtier vehicles get scrapped or leave fleet?
    - Perhaps moving to non-I/M areas (?)
  - What happens in non-I/M areas?
- **MOBILE assumed rates just kept increasing**

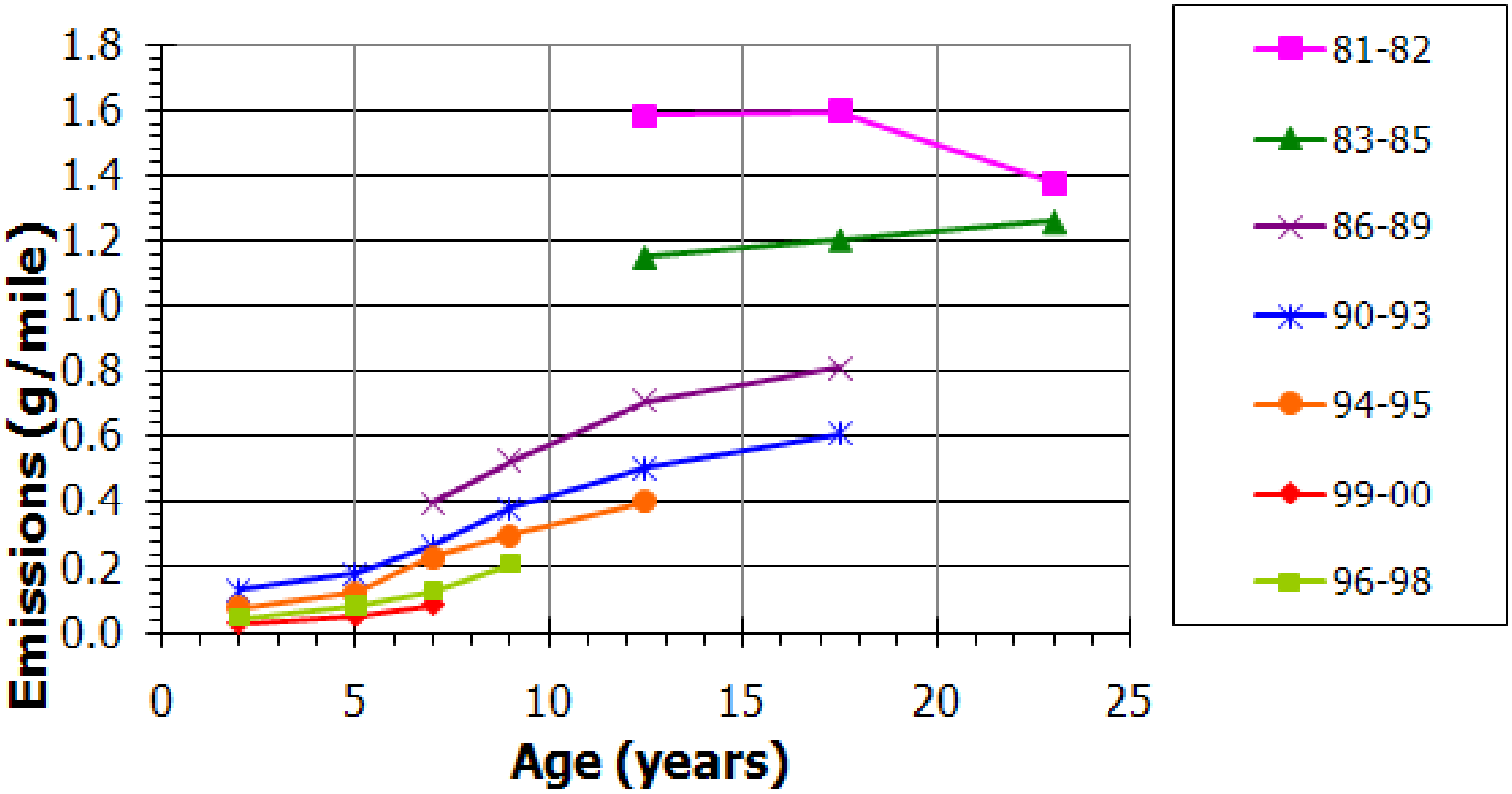
Aggregate CO IM147 Emissions

by model-year group and age group



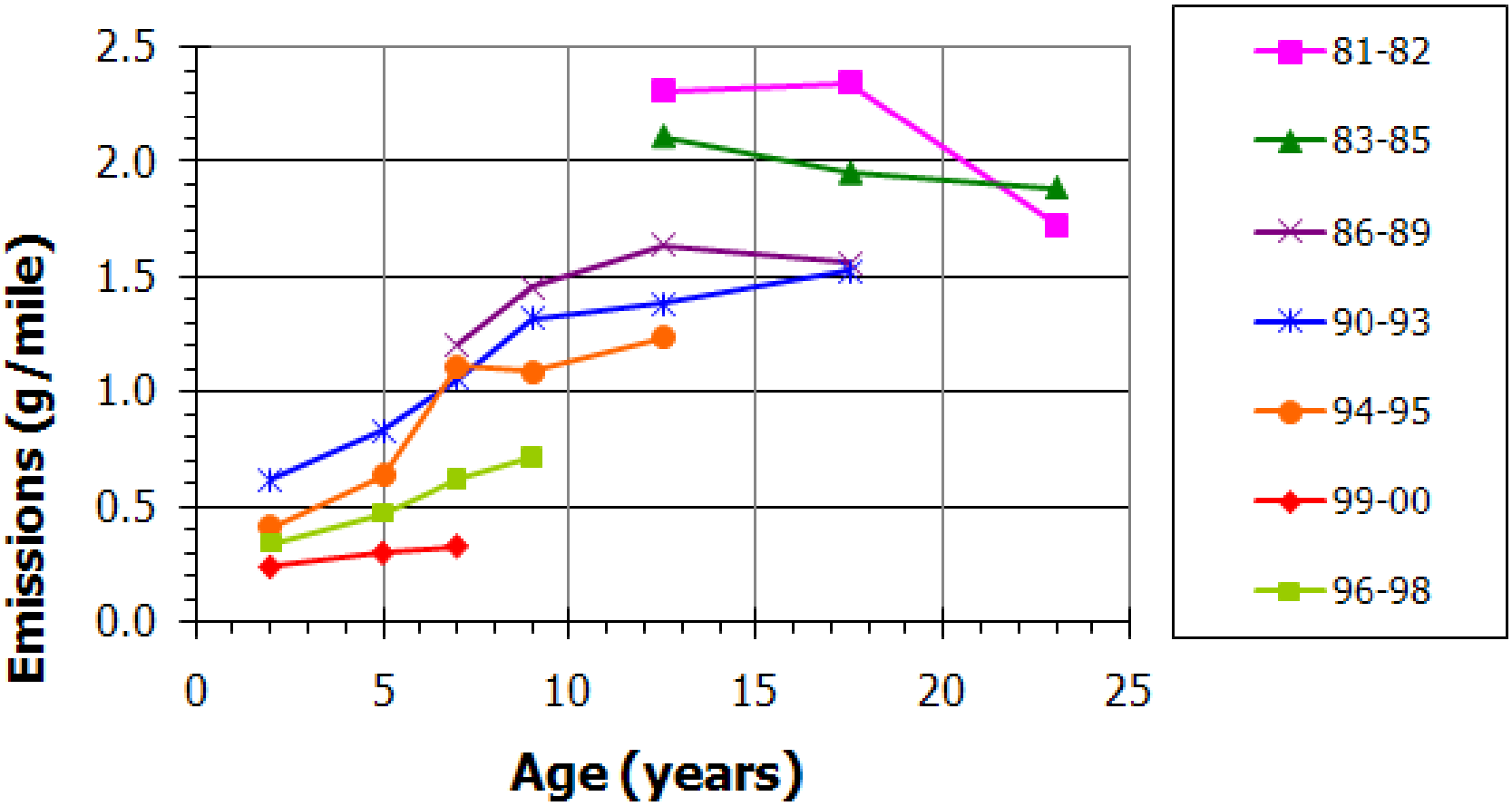
Aggregate THC IM147 Emissions

by model-year group and age group



Aggregate NOx IM147 Emissions

by model-year group and age group

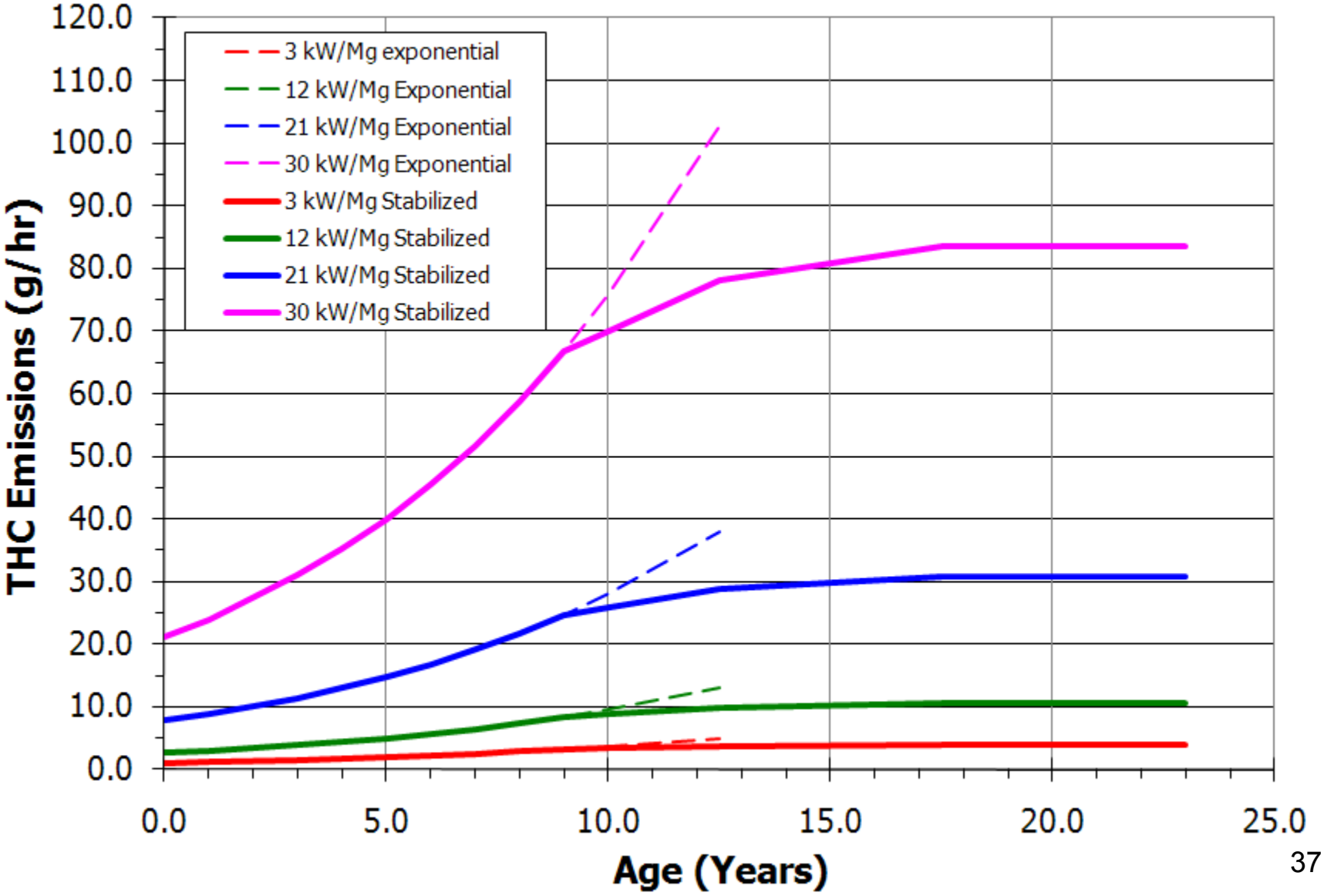


Assumptions

- **Deterioration exponential from age 0 to 9 years**
- **Inflection point at 9 years**
  - From increasing to declining trends,
  - Emissions stable by 12.5 years (10-14 year ageGroup)
- **Rates for ages > 9 years calculated relative to rate at 9 years**
  - Using ratios derived from Phoenix I/M data
    - As aggregate cycle averages
  - Proportional relationships applied across operating Modes
- **For I/M Reference rates**
  - No increase after 17.5 years (15-19 year ageGroup)
- **For non-I/M Reference rates**
  - Rates increase after 17.5 years (in 20+ yr ageGroup)
    - By same rate as between 10-14 and 15-19 year ageGroups

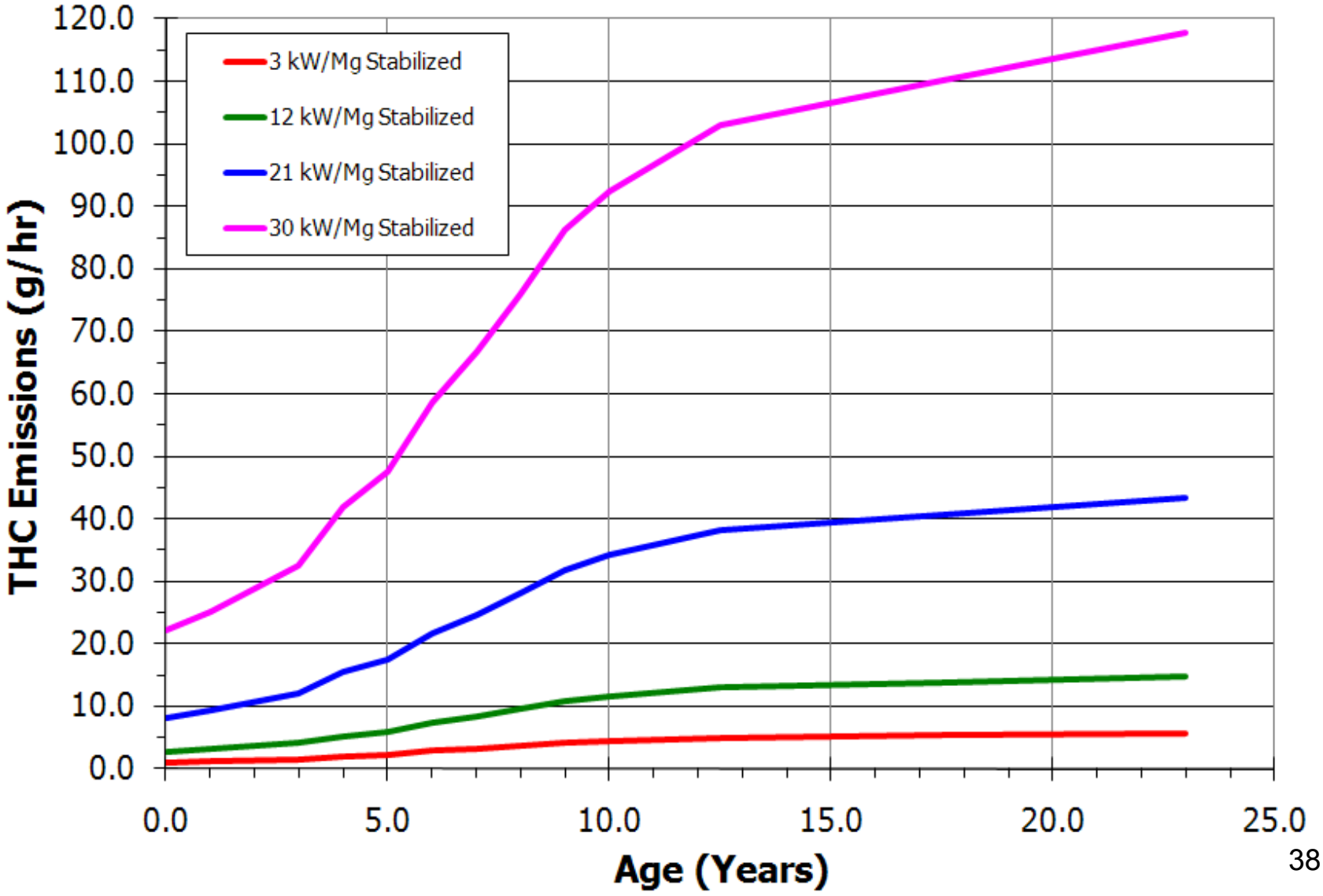
Emissions Stabilization by Operating Mode

in I/M area



Emissions Stabilization by Operating Mode

in non-I/M area



Sub-group 2 , MY 2001 and later

RUNNING EXHAUST EMISSIONS

Emission Rate Data Sources

- **MY through 2000**
  - Generated from AZ I/M program data
    - "second-by-second" data
- **MY 2001 and later**
  - Needed additional data source
    - To assess emission declines beyond Tier 1
  - To consider distinctions between standards
    - Federal: Tier 1, NLEV, Tier 2, CA LEV / LEV-II
    - California: LEV-I, LEV-II
  - Selected : In-use Verification Program (IUVP)
    - Aggregate "bag" data
    - On Federal Test Procedure, US06 cycles

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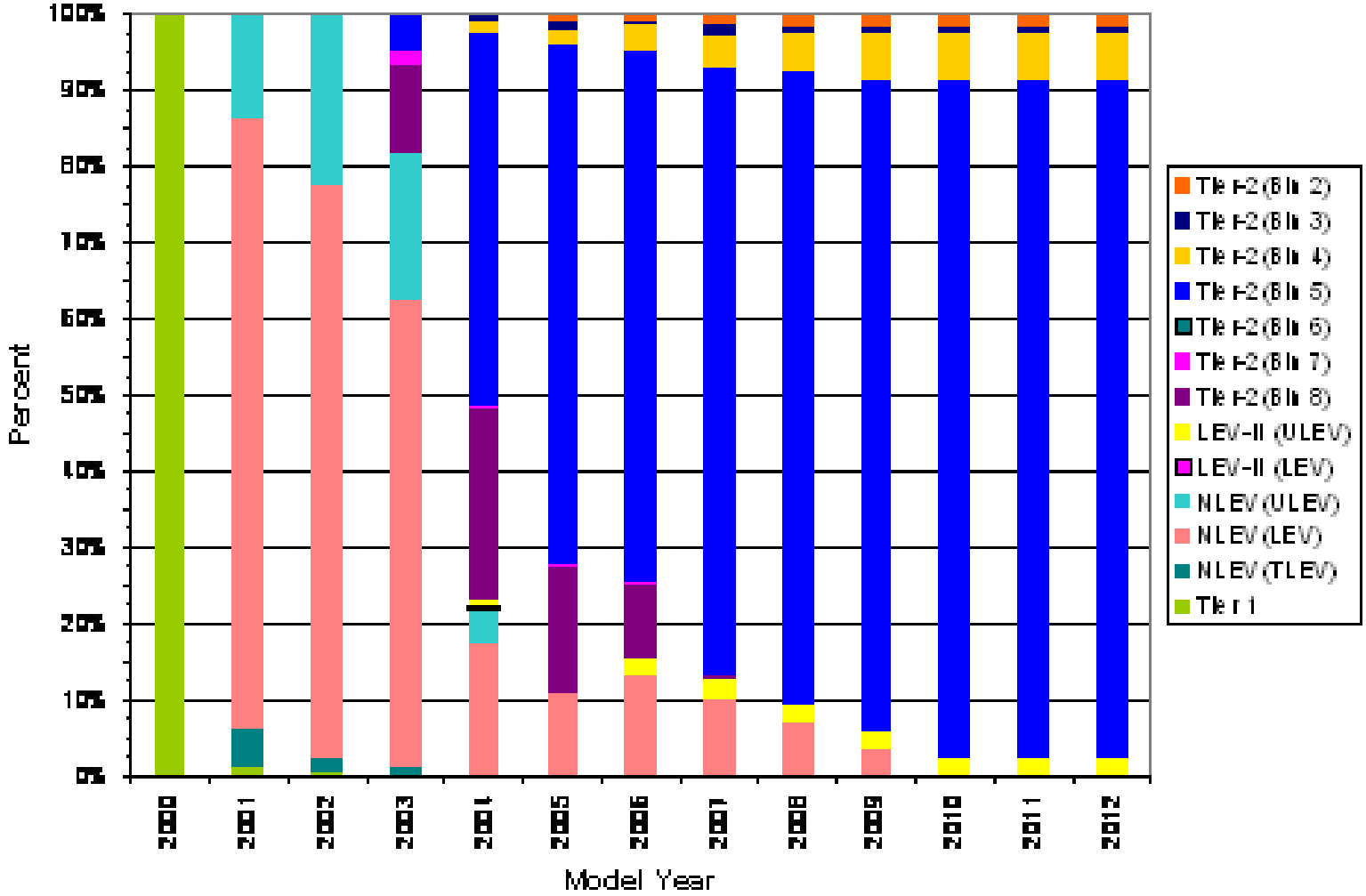
Estimating Emission Rates for MY 2001+

- **1. Average IUVP data by standard level**
  - By standard-level, vehicle class
  - Running: = Bag 2
  - Start: = Bag 1 – Bag 3
- **2. Develop Phase-In Assumptions**
  - By standard level, Model-year, vehicle class
- **3. Weight FTP results by Phase-In Assumptions**
  - Running: calculate ratios to Tier 1
  - Start: use weighted averages directly
    - Apply soak fractions
- **4. Apply Deterioration**
  - Apply "Survival of the Fittest"
- **5. Estimate non-I/M**
  - Apply non-I/M : I/M ratios

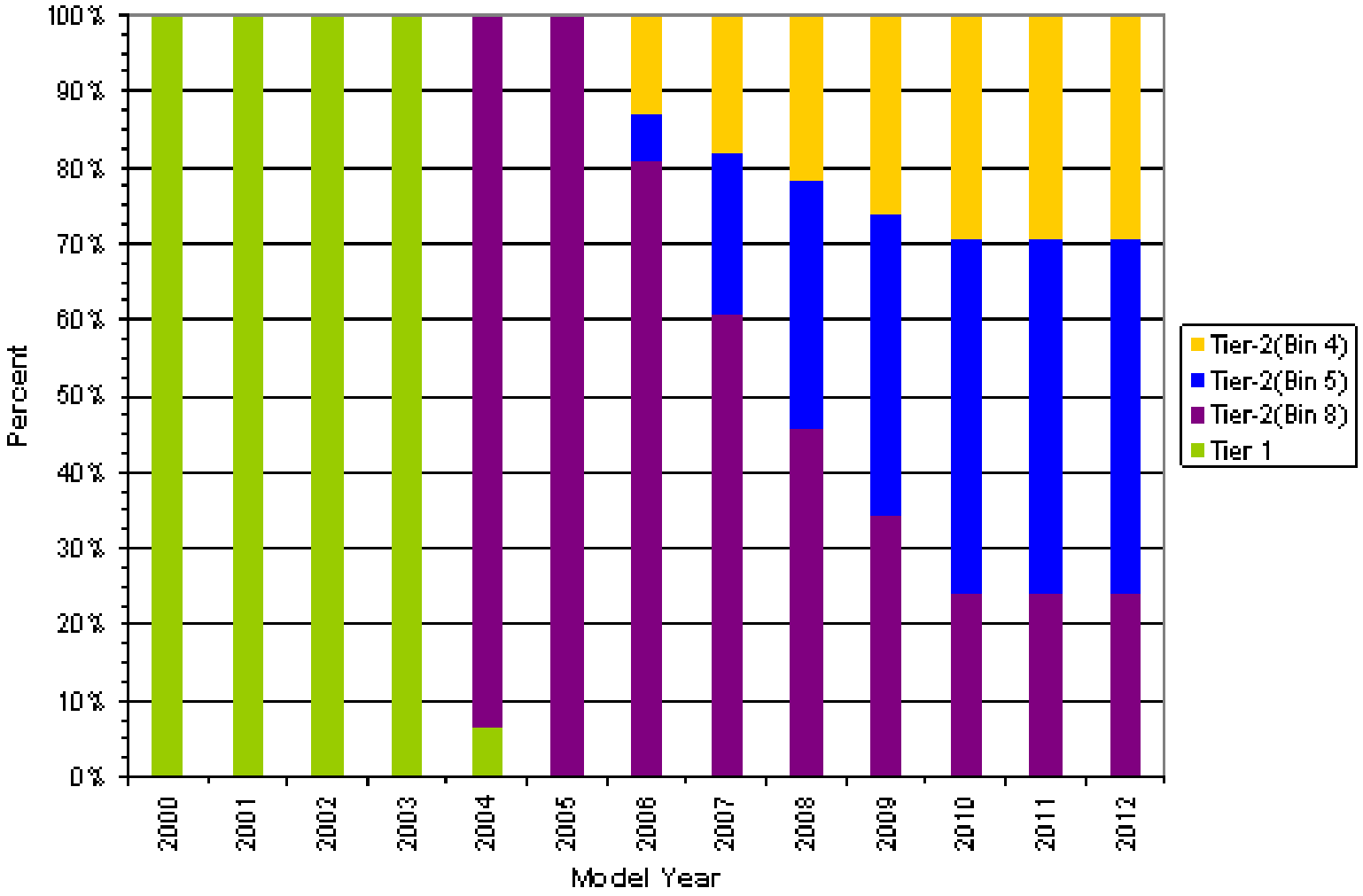
Phase-In Assumptions

- **After MY 2000, things get complicated**
  - Multiple standards phasing in and out
- **"National-Federal" scenario,**
  - Applies to all states except
    - The "Northeast Trading Region" (NTR)
    - California
    - States adopting California LEV
  - National Low Emissions Vehicle Program (NLEV)
    - Phases in between T1 and T2
    - MY 2001 – 2004
  - Federal Tier 2
    - Phases in starting in 2004
- **"CA/Section 177" scenario**
  - Have different phase-in (not pictured)

Phase-In (default Fed)
ex: LDV-T1

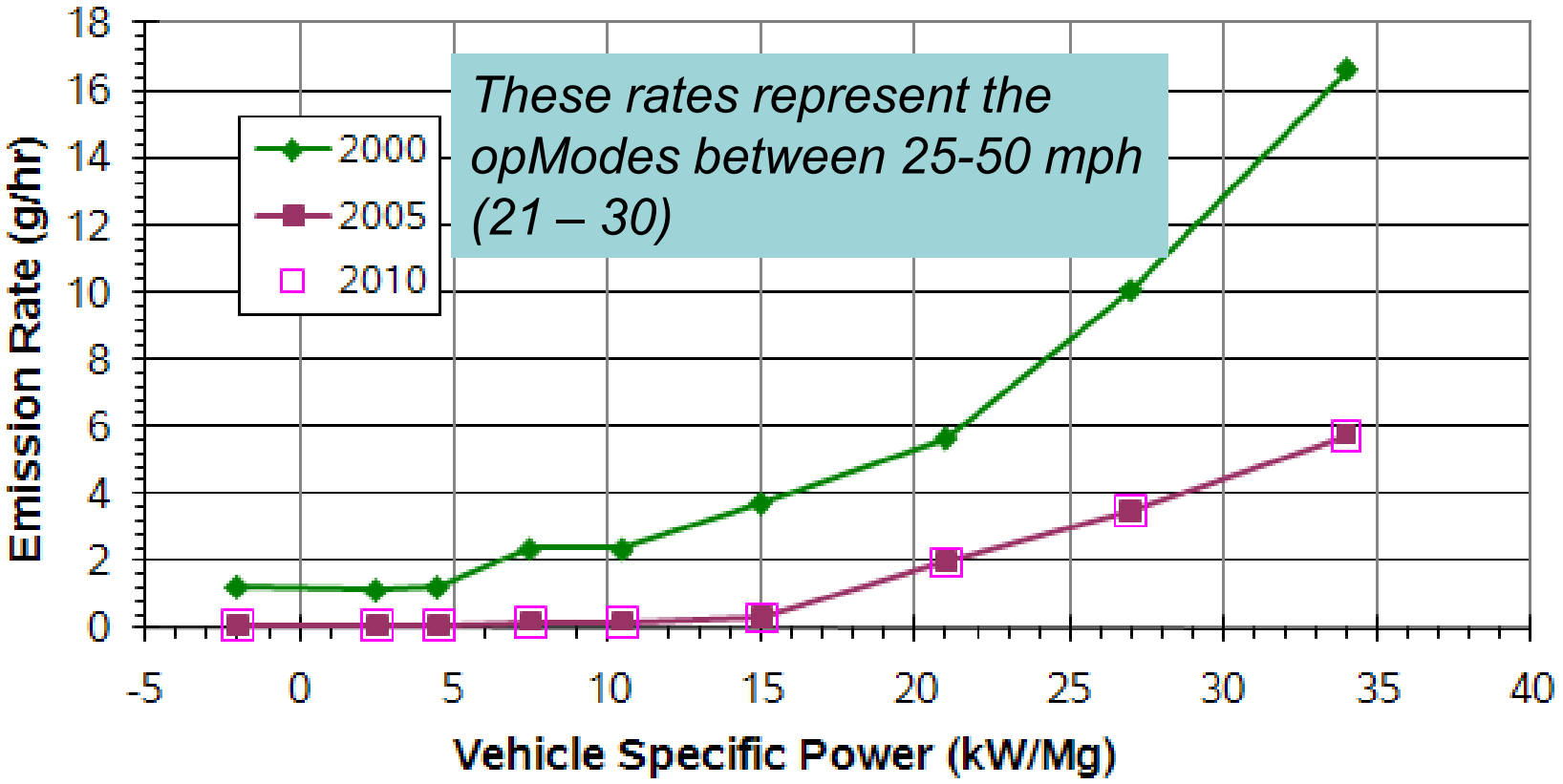


Phase-In (default Fed)
ex: LDT3



Running Emission Rates in Three Model Years

THC, Cars, Age 0-3 (LINEAR SCALE)



The rates in MY2000 (representing Tier 1) are scaled down proportionally, representing the mix of standards in
MY2005 (NLEV phasing out, T2 phasing in) AND
MY2010 (T2 phase-in complete)

Running Emission Rates in Three Model Years

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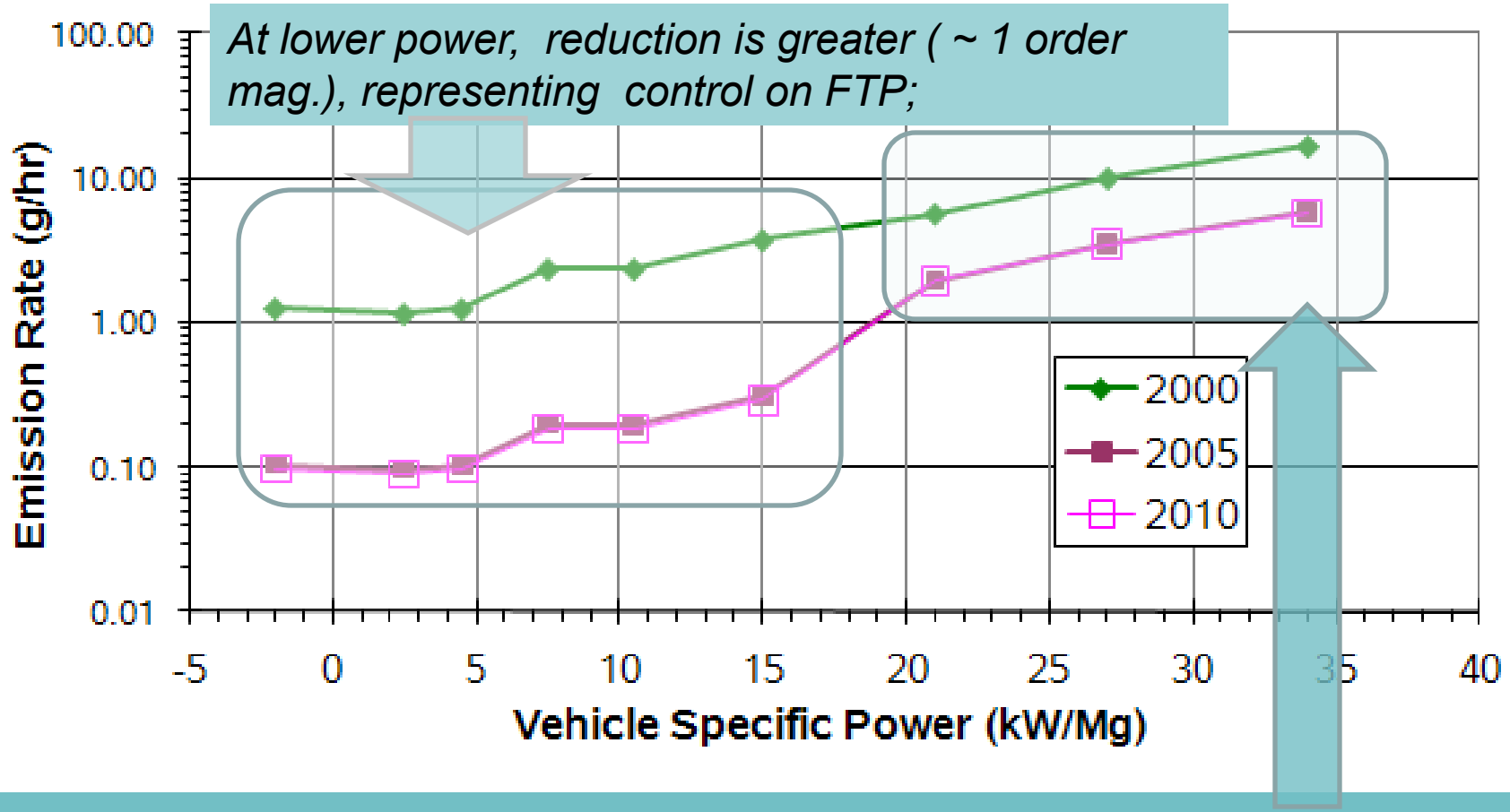

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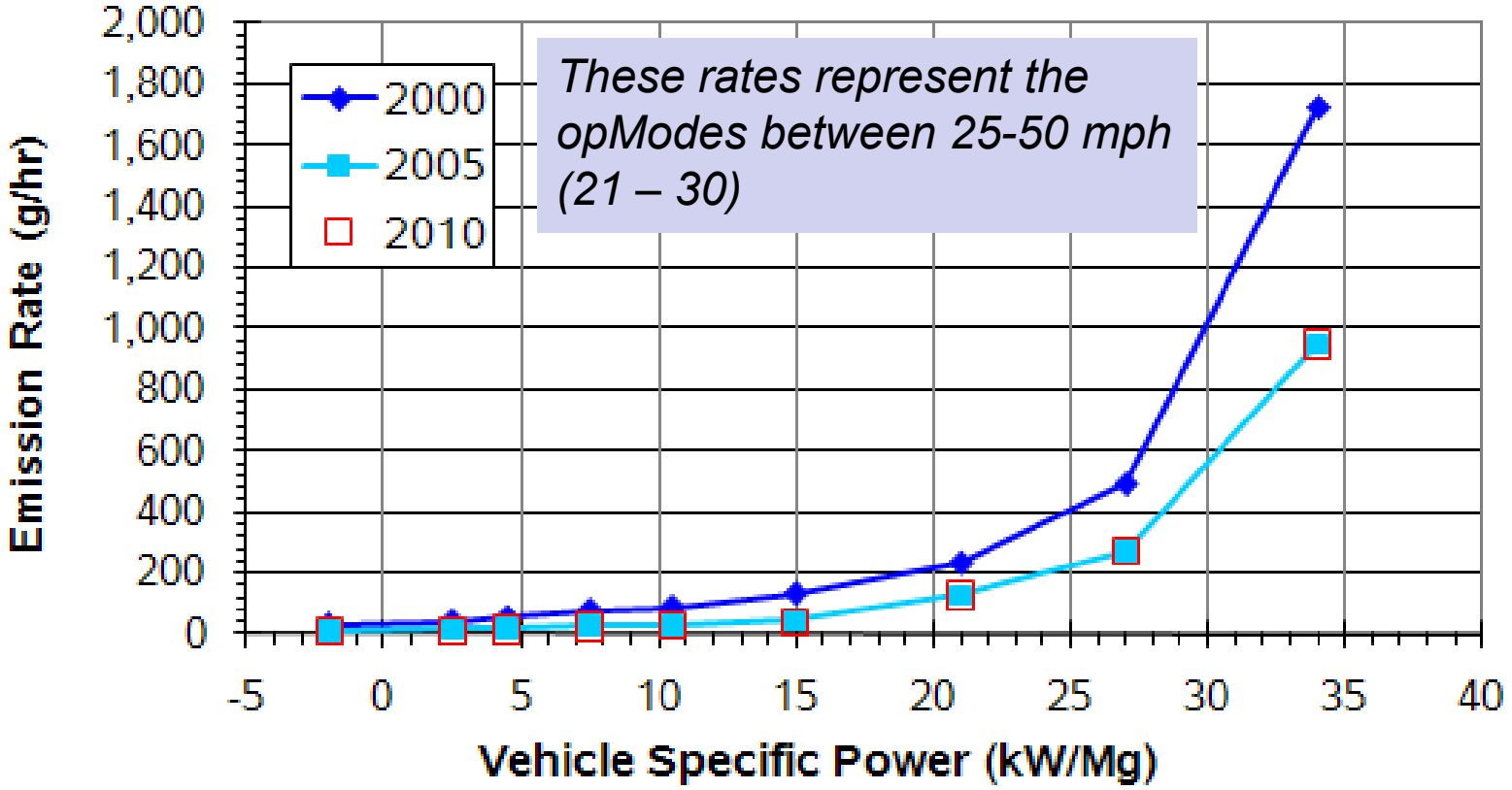

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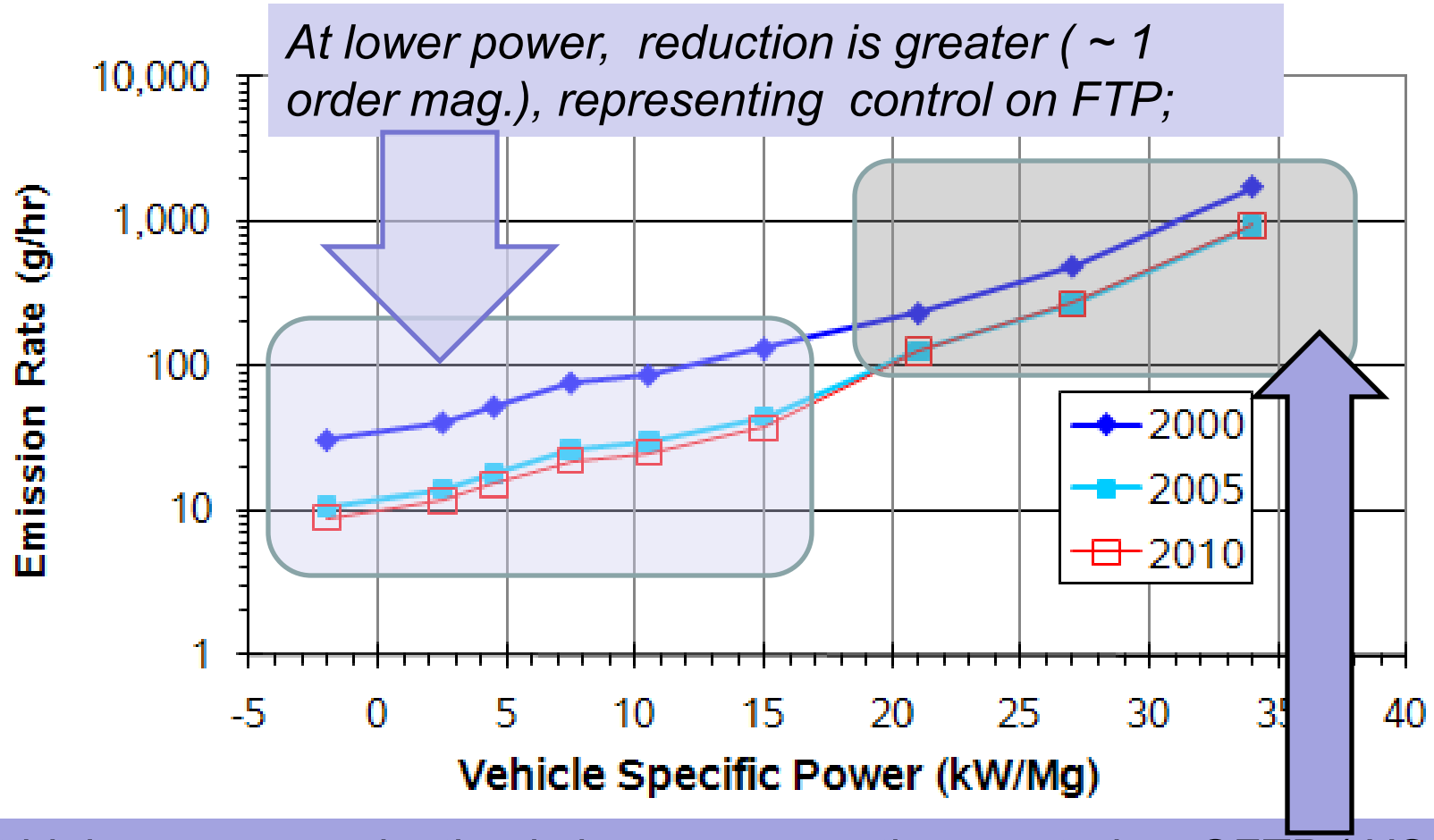

Running Emission Rates in Three Model Years

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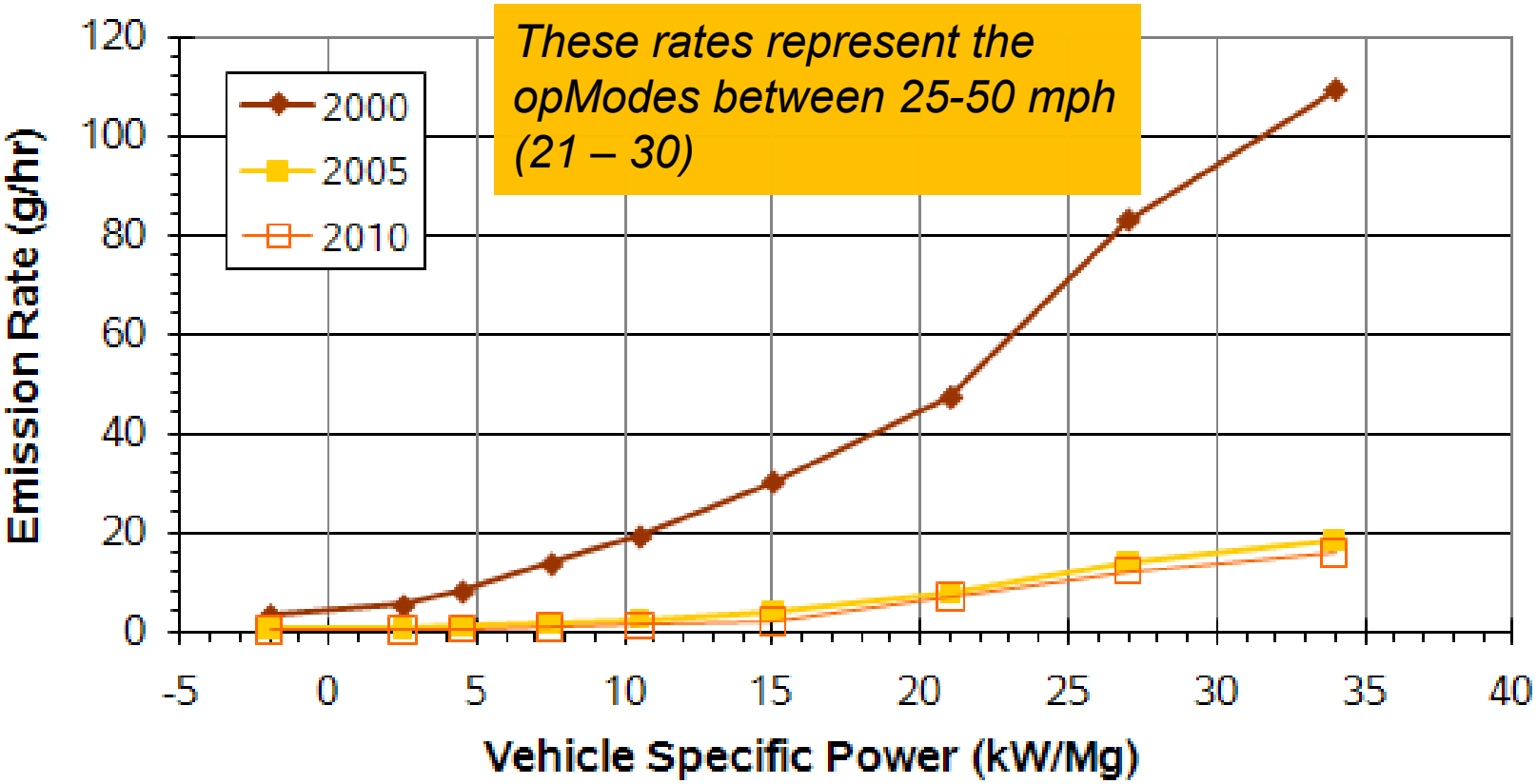

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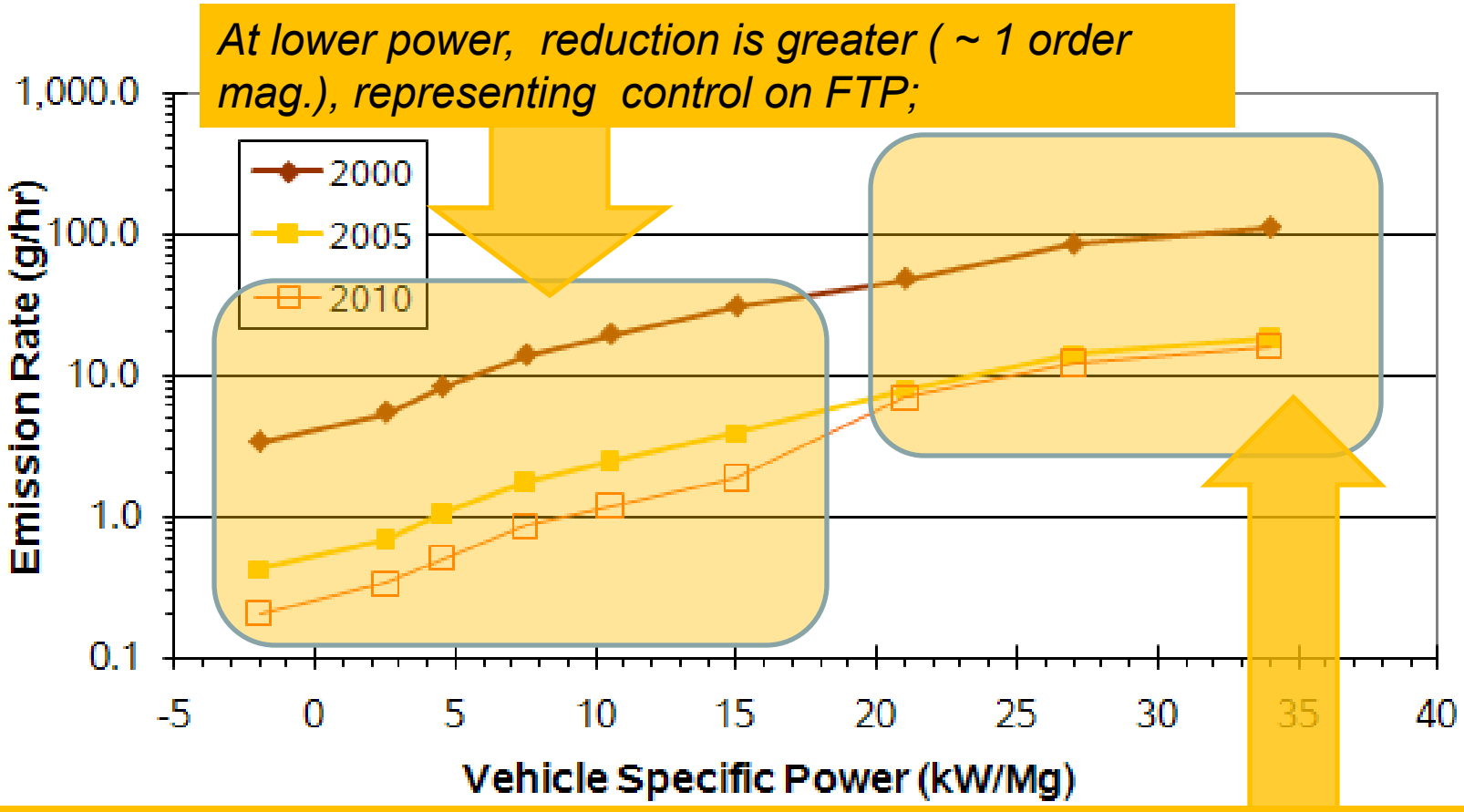

START EXHAUST EMISSIONS

Start Emissions
MY 1995 and Earlier

- **Used selected FTP results**
  - Archived in Mobile-Source Observation Database
- **Estimate Cold starts**
  - Cold start = Bag 1 – Bag 3
  - Average by model-year group
- **Estimate Warm to hot starts**
  - By applying soak-start relationships
- **Estimate deterioration**
  - Relative to running
    - In I/M and non-I/M areas

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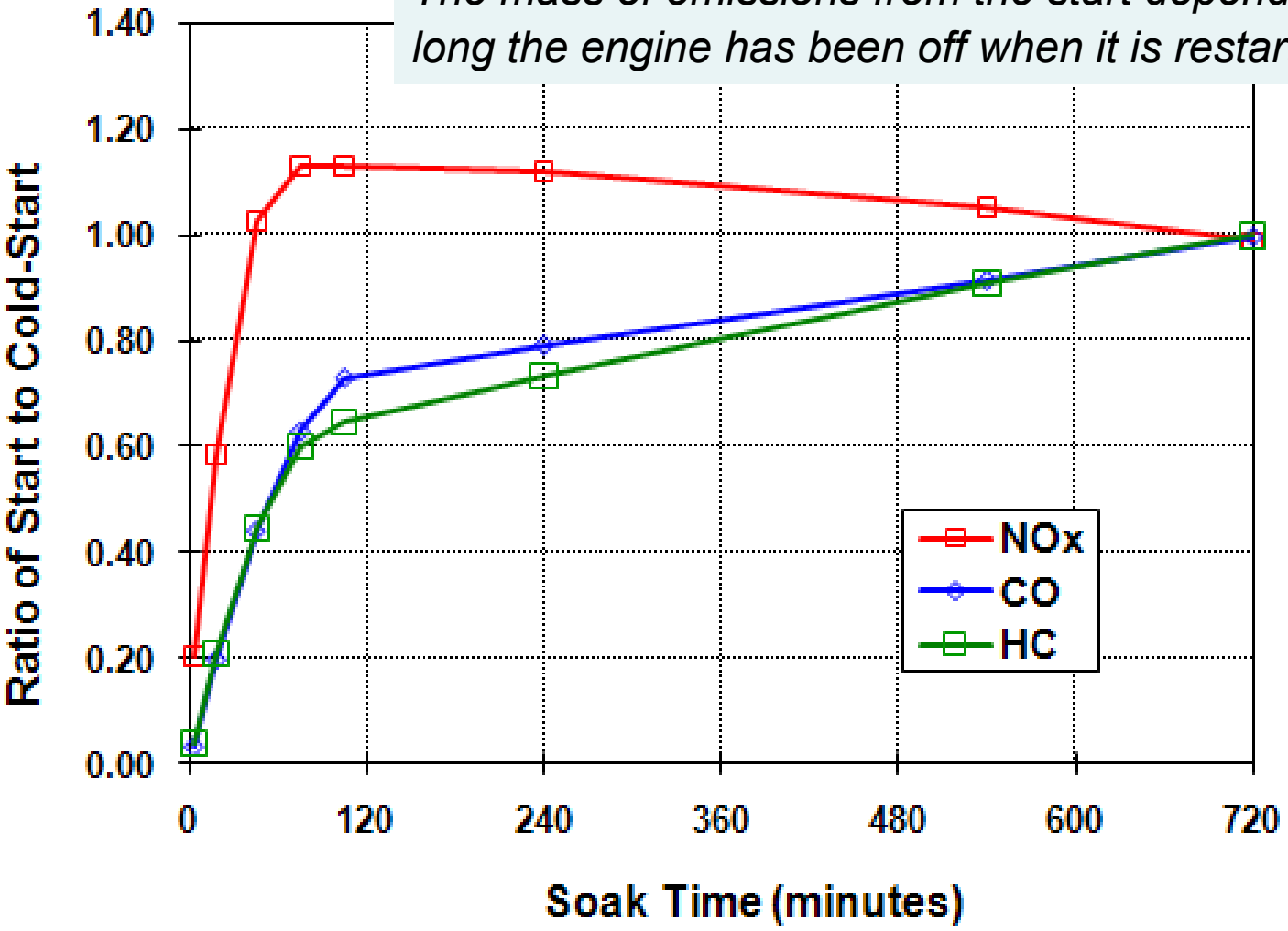
Start Emissions

MY 1996 and Later

- **Average IUVP data by**
  - By standard level, vehicle class
- **Develop Phase-In Assumptions**
  - By standard level, Model-year, vehicle class
- **Combine FTP results and Phase-In Assumptions**
  - Use Bag 1 – Bag 3 as “cold start”
    - Estimate warm to hot starts using soak-start
- **Apply Deterioration**
  - Based on IUVP data
  - Relative to running
    - HC, CO less than running
    - NOx equal to running
    - In I/M and non-I/M areas

Soak-Start Relationships

The mass of emissions from the start depends on how long the engine has been off when it is restarted.



Start Deterioration

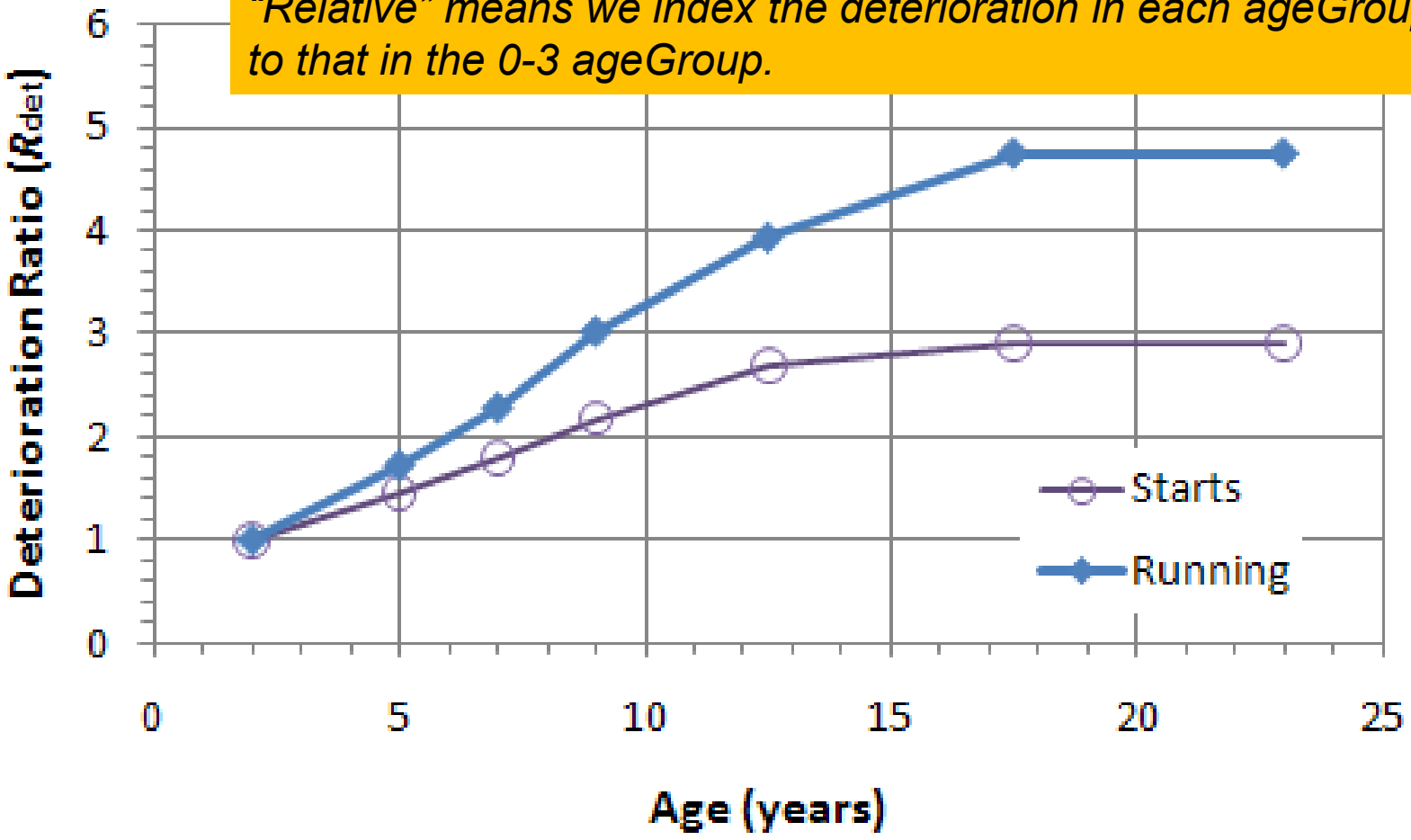
- **For running emissions,**
  - Have much data on deterioration
- **For start emissions,**
  - Much less
- **Based on available data (IUVP), we conclude**
  - Starts do deteriorate, BUT
  - For HC, CO, at LOWER relative rate than running,
  - For NOx, at same relative rate as running
- **We calculate start deterioration relative to running deterioration**

Relative Deterioration (HC,CO)

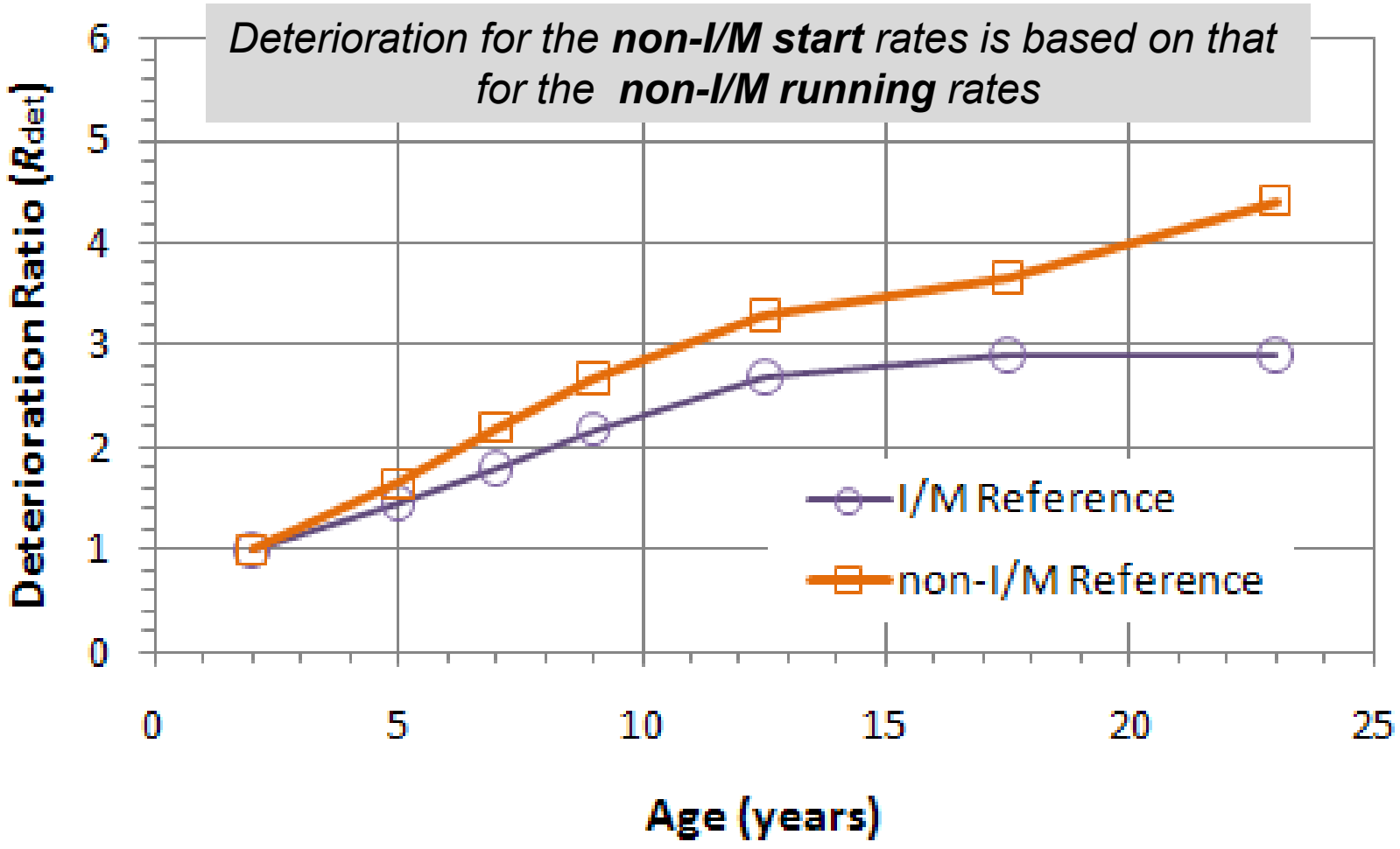
Start and Running, Cars, MY2010

I/M areas

"Relative" means we index the deterioration in each ageGroup to that in the 0-3 ageGroup.

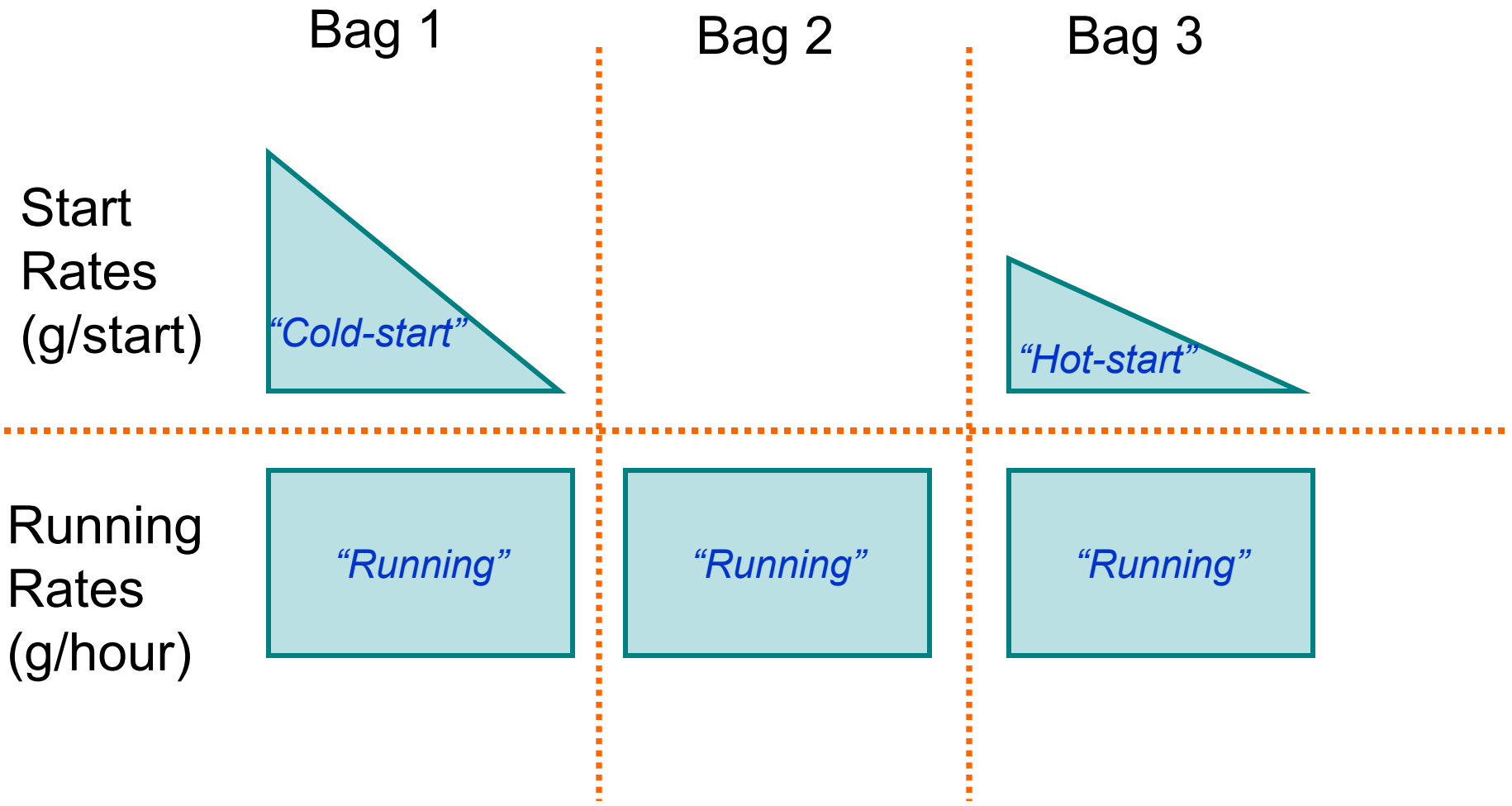


Relative Start Deterioration (HC, CO) for I/M and non-I/M References

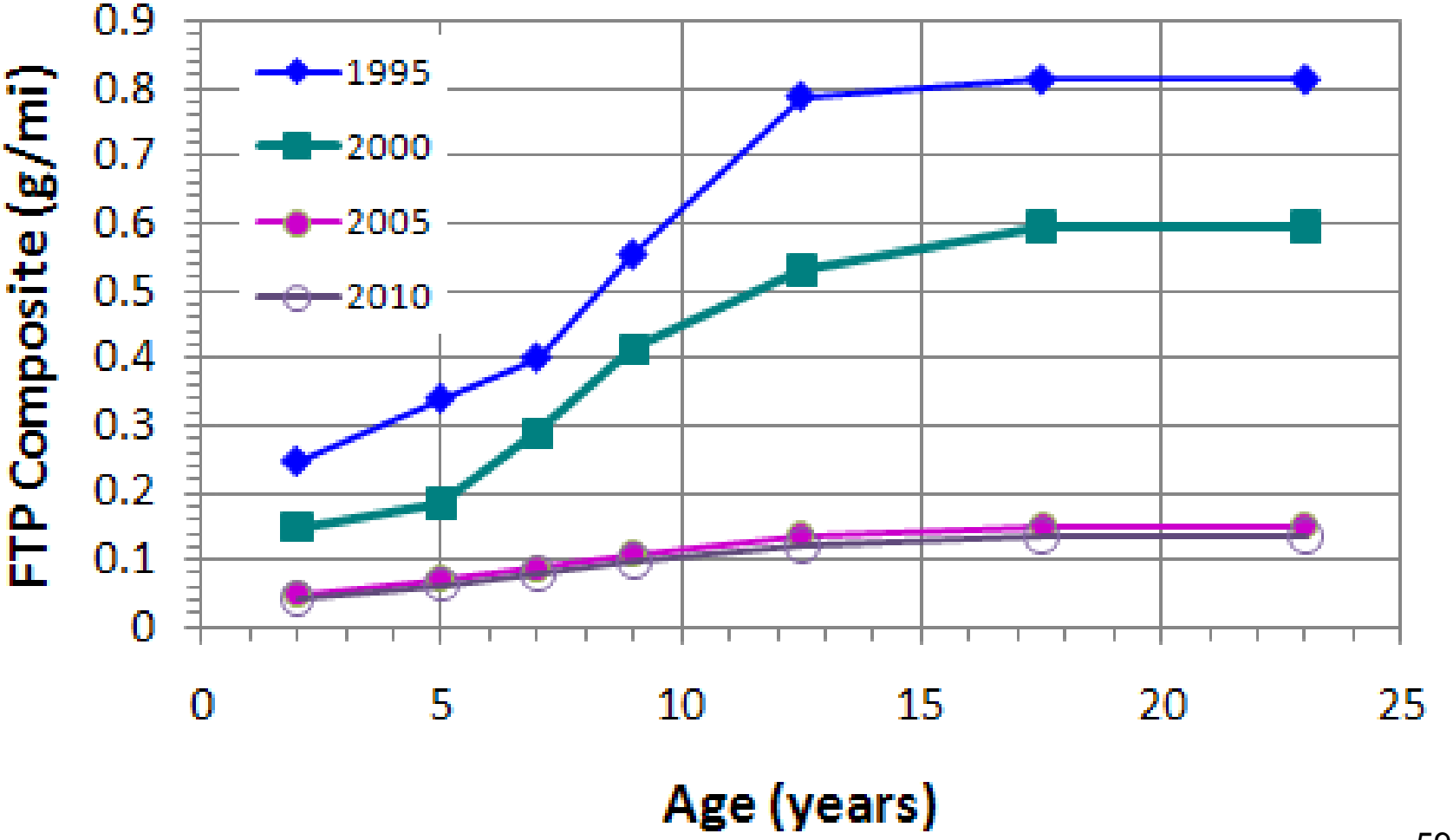


*Deterioration for the **I/M start** rates is based on that for the **I/M running** rates*

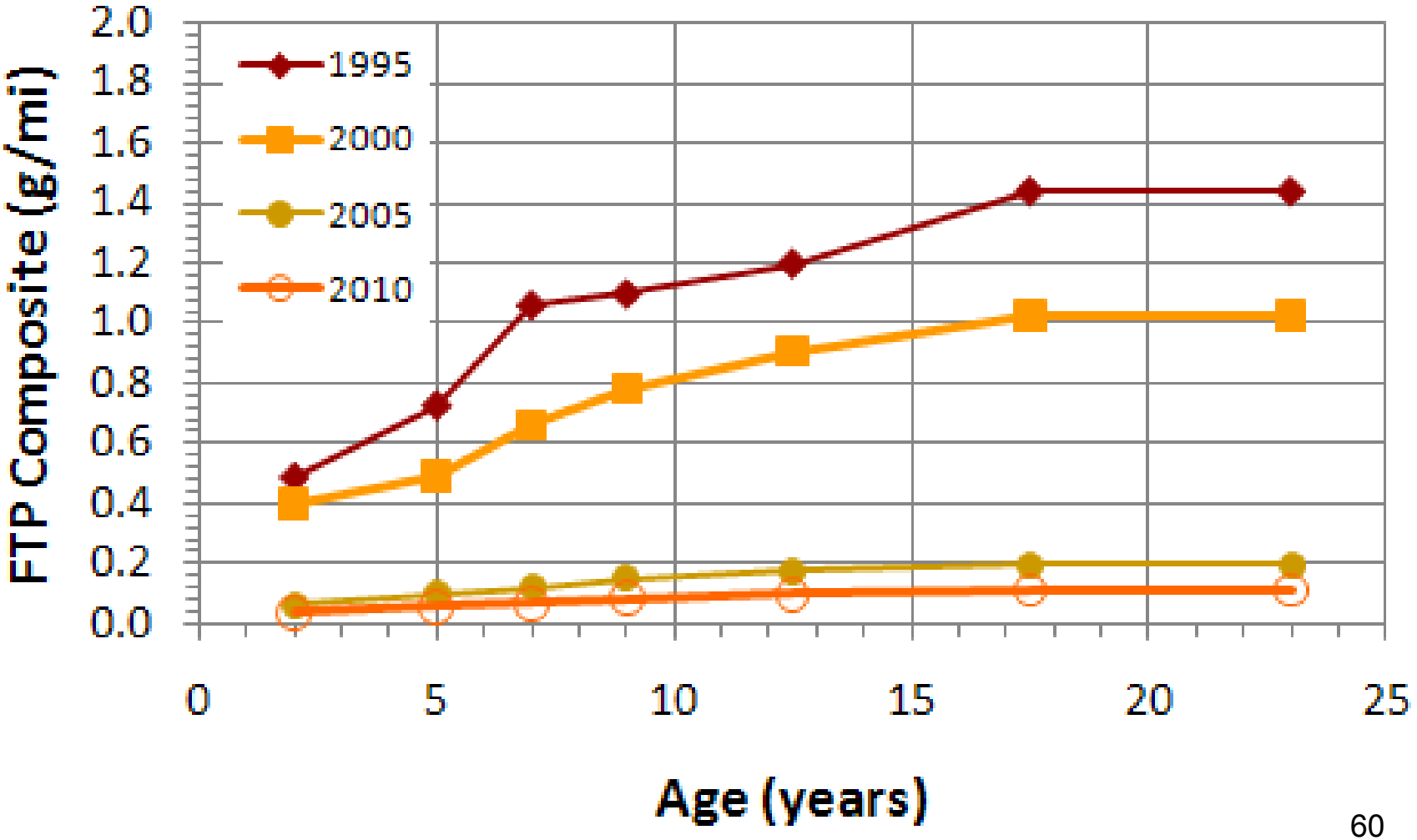
Simulating the FTP



Simulated FTP Composites, THC
I/M References, Cars



Simulated FTP Composites, NOx
I/M References, Cars



Particulate Emissions

Kansas-City Study

- **Sponsored by EPA and partners**
- **Performed during CY2004-2005**
- **Made strenuous efforts to get representative sample**
  - Using stratified sampling design
- **Used LA92 cycle**
- **At ambient temperatures**
  - During summer , winter
  - Used for temp adjustments
- **Measured Particulate (PM2.5)**
  - On aggregate basis (using filters)
  - on continuous basis
    - Quartz-crystal microbalance
    - Nephelometer
    - Dustrak
    - photoacoustic

Major Steps

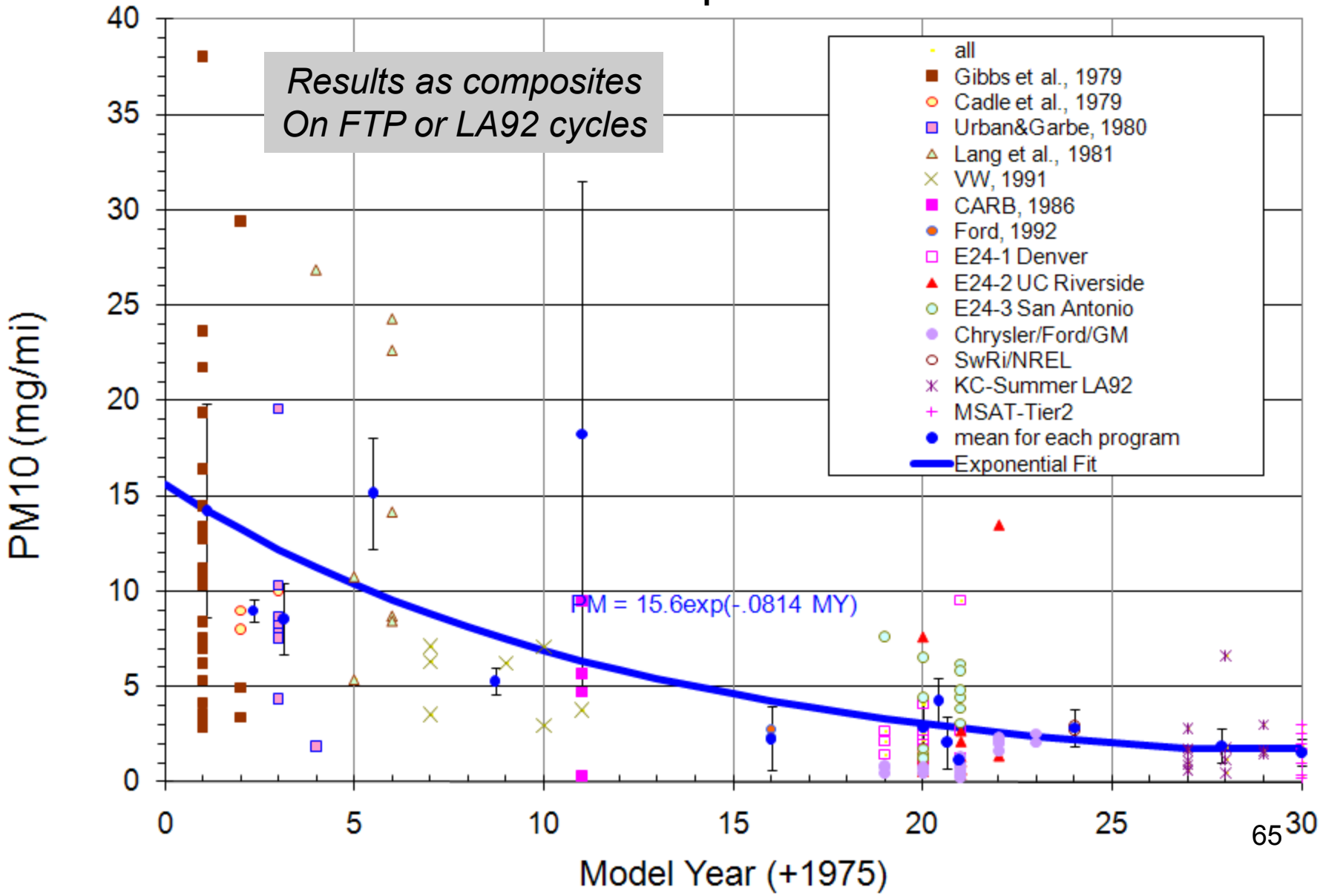
- **Develop deterioration model**
  - Using aggregate emissions
- **Develop modal rates**
  - Using continuous measurements
  - Running emissions (by opMode)
  - Start emissions (by opMode)
    - Using soak curve for HC
- **Partition into components**
  - Elemental carbon (EC)
  - Organic carbon (OC)

Develop Deterioration Model

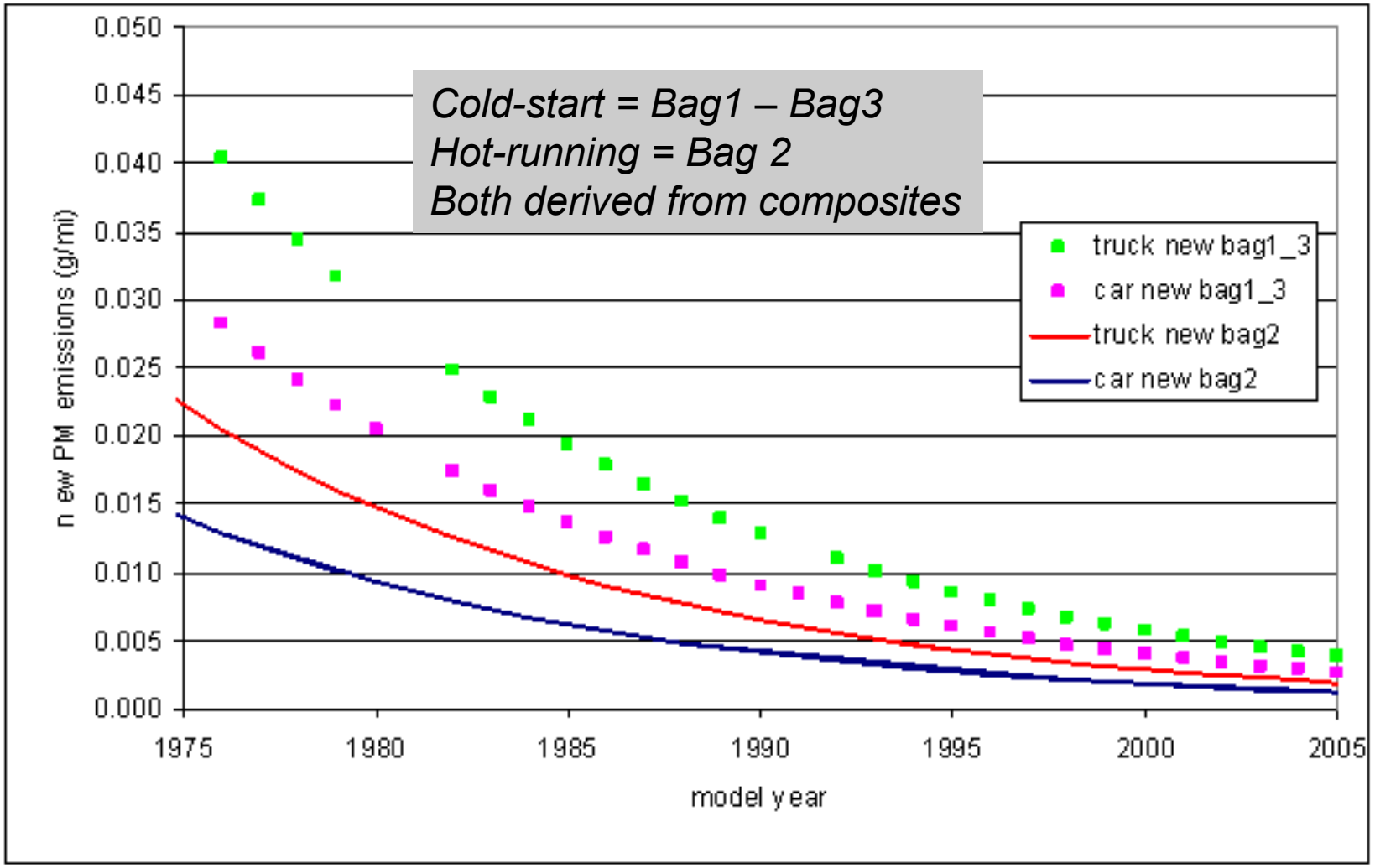
- **Estimate rates for "young vehicles" (ages 0-3)**
  - Using data from KC study
    - Adjusted from ambient to 72 F
  - Using data from historical studies
  - Based on cycle composites
    - Combining start and running
  - developed exponential model
    - Showing declining trend with MY
  - distinguish composites by emissions process
    - Cold start
    - Hot-running
- **Estimate age slopes**
  - As ratio of "aged" to "young" vehicles (or ln diffs)
  - Multiplicative model analogous to that for (HC/CO/NOx)

PM Emissions for "Young" Vehicles (age 0-3)

from selected independent studies

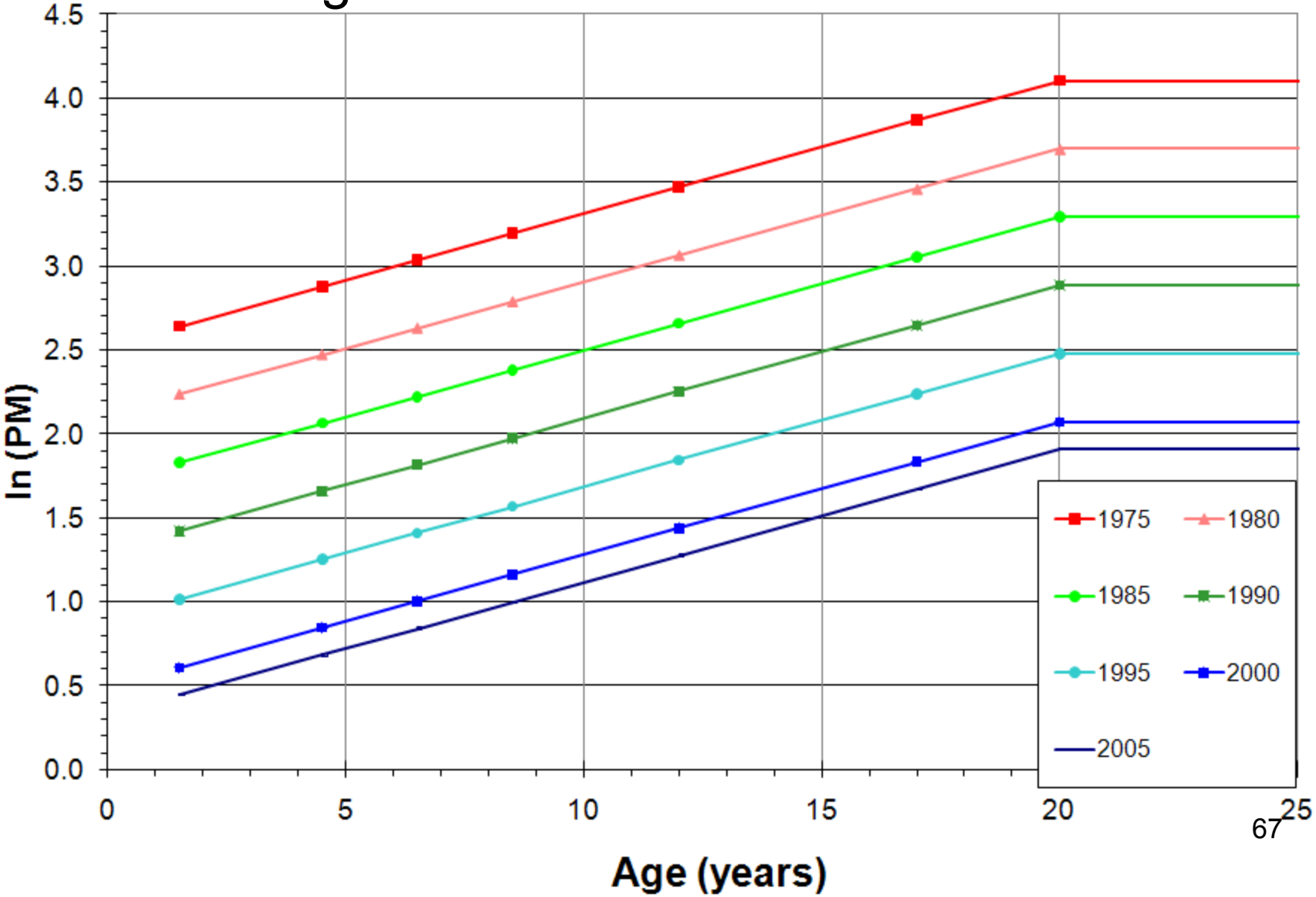


Cold-start and Hot-running PM Emissions
for “young” cars and trucks (age 0-3)



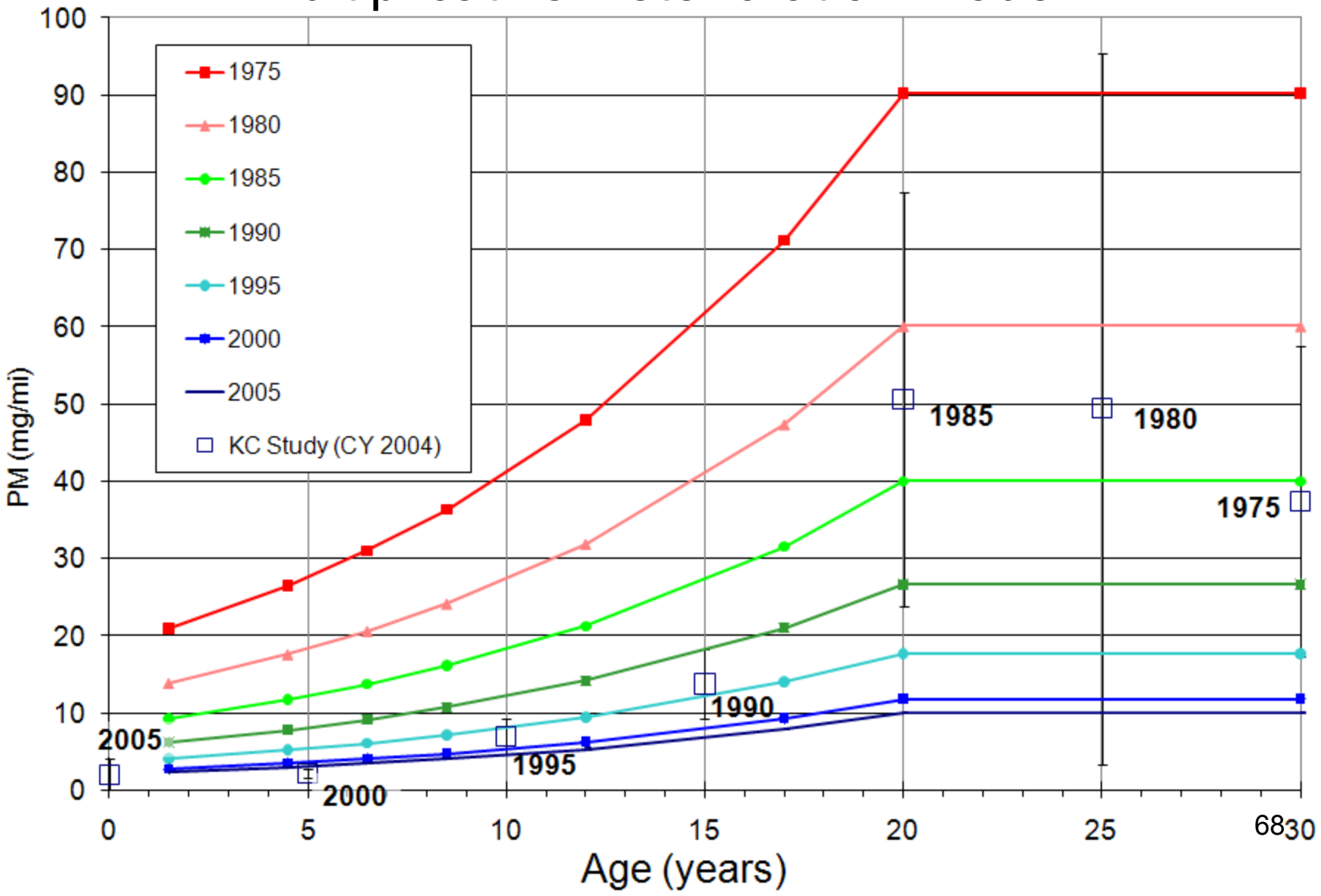
Estimating Age trends

Logarithmic Deterioration Model



Estimating Age Trends

Multiplicative Deterioration Model



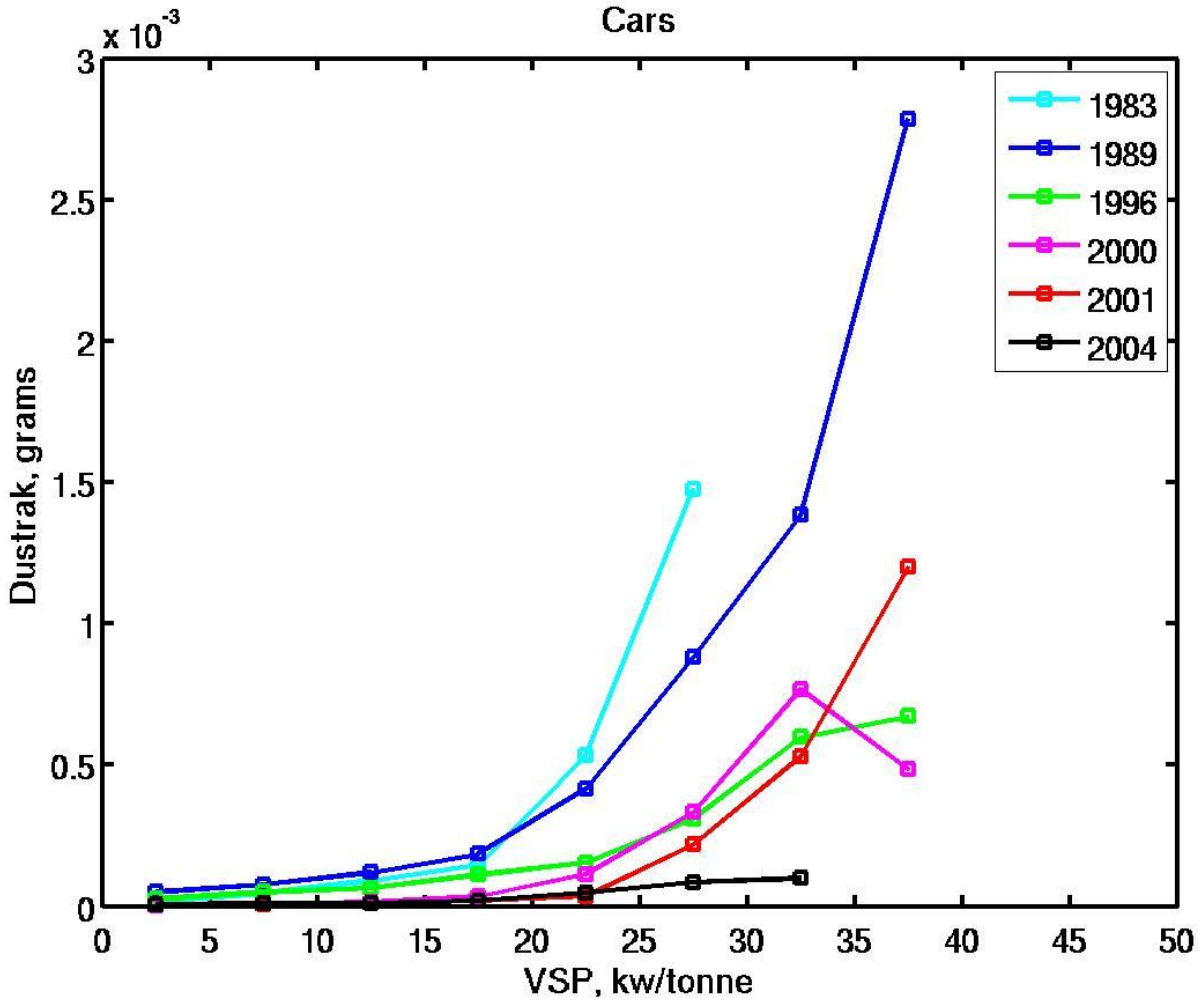
Develop Modal Rates

- **Developed modal rates**
  - Based on continuous PM emissions
    - "Dustrak"
    - in relation to VSP (same opModes as for gaseous)
  - Simulated aggregate LA92 (Hot-running phase (Bag 2))
    - Using modal rates
    - Based on opMode distribution
  - Normalized modal LA92 to aggregate LA92
    - "aggregate" estimated by deterioration model
    - Treated as "gold standard"
  - Repeat
    - For all model-year groups
    - And all age Groups

Continuous PM measurements

from the Kansas-City Study

averaged by vehicle-specific power



Values for running Emissions on the LA92 cycle –

Provide basis for Rates by operating Mode

Normalized to LA92 estimates From deterioration Model (continuous optical Normalized to Aggregate filter)

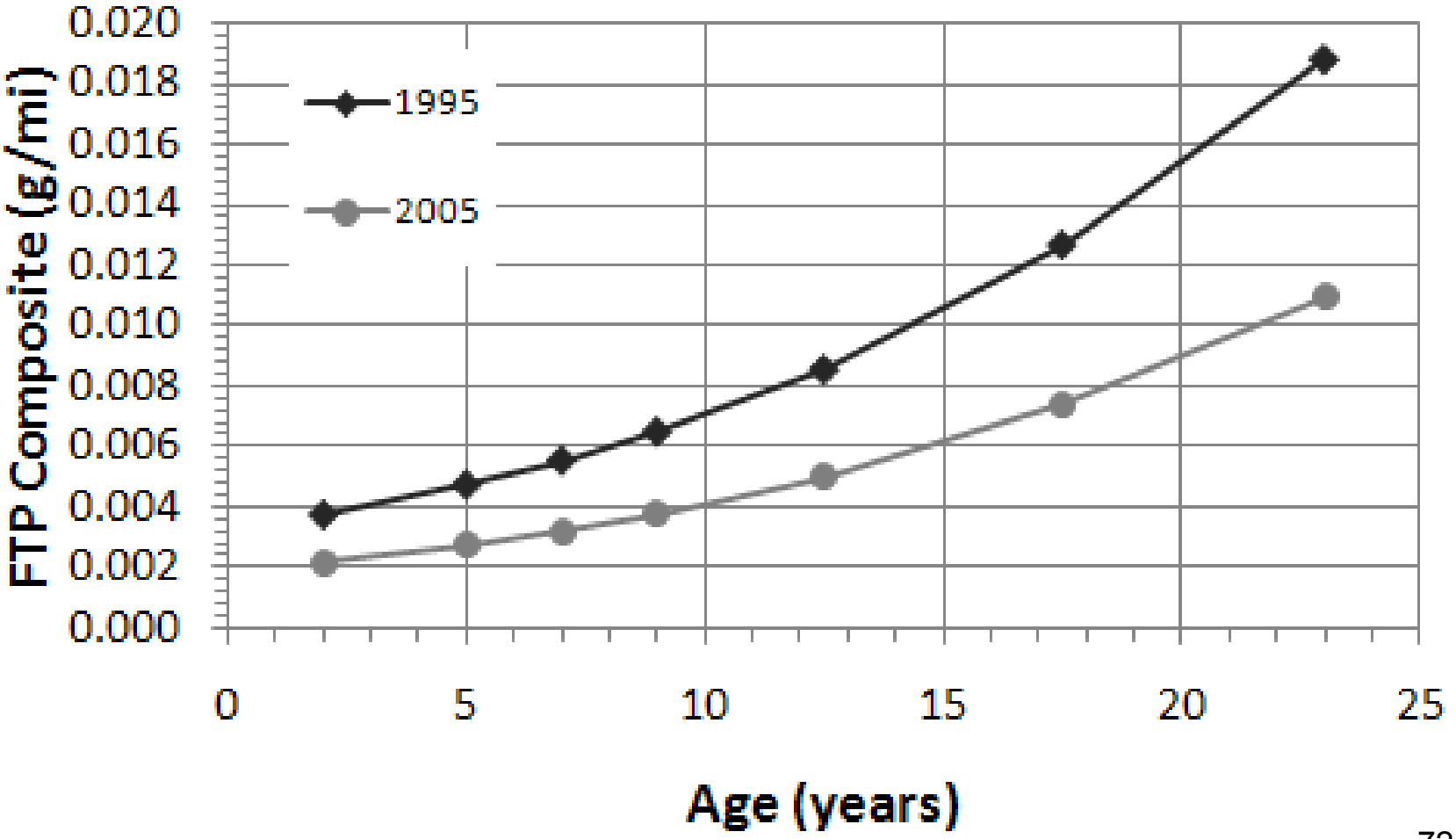
Elemental and Organic Carbon

- **Used data from photoacoustic instrument**
  - Representing elemental carbon (EC)
- **In relation to filter measurements**
  - Representing total PM2.5
- **As ratio …**
  - And OC calculated by difference
- **Ratios constant across**
  - Model year group
  - Age group
  - Vehicle class

$$\frac{EC}{PM} + \frac{OC}{PM} = 1$$

$$\frac{OC}{PM} = 1 - \frac{EC}{PM}$$

Simulated FTP Composites, PM2.5(OC)
Cars in two MY



Light-duty Diesel Vehicles
Gaseous and Particulate Emissions

(THC, CO, NOx, PM)

Light-duty Diesels

- **Sub-group 1: MY 2009 and earlier**
  - Estimate composites (on FTP)
    - By model-year group
  - Distinguish processes
    - Start, running (by regression)
  - Estimate rates by operating Mode
    - Start (through soak fractions)
    - Running (scaling down rates for light-heavy-duty)
- **Sub-group 2: MY 2010 and later**
  - Representing Tier-2 diesels
  - Represented by equivalent gasoline rates

Crankcase Emissions
Light-duty vehicles
Gasoline and Diesel

Gaseous and Particulate Emissions
(THC, CO, NOx, PM)

Crankcase Emissions

- **Source: "blowby" from cylinders into crankcase**
- **Control: Positive crankcase ventilation valve (PCV)**
  - Routes crankcase gases into cylinders
- **Assumptions:**
  - Gasoline: MY 1969 & later have PCV
  - Diesel: MY2007 & later have PCV
  - Working PCV = Zero emissions
  - PCV failure rate = 4.0%
- **Calculation:**
  - Non-PCV: crankcase = fraction of exhaust emissions
    - THC, CO, NOx, PM for start and running
  - PCV: crankcase = 4.0% of non-PCV crankcase