Proposed Exhaust Emission Rates for Compressed Natural Gas Transit Buses in MOVES2013

MSTRS MOVES Review Work group

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Outline

- Overview
- Literature review
- MOVES2010b Analysis
- Creating Proposed MOVES2013 rates

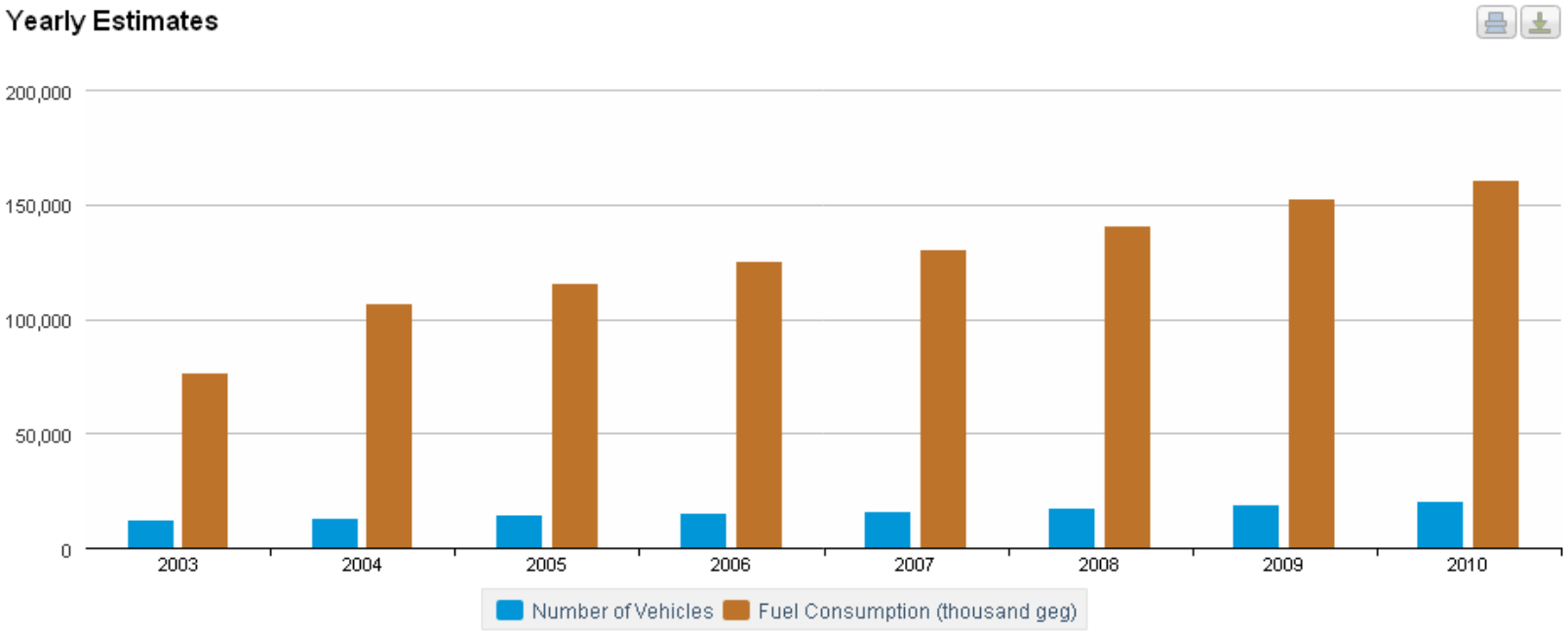
http://www.flickr.com/photos/channaher/2973554252/

Transit Bus Mileage Share by Fuel

Fuel	Mileage Share (2010)
Diesel fuel	63%
Compressed natural gas (CNG)	**14%**
Bio-diesel(BD)	8%
Gasoline	5%
Dual fuel	4%
Hybrid diesel	3%
Liquefied natural gas (LNG)	2%

Source - National Transit Database (Transit Way Mileage)
http://www.ntdprogram.gov/ntdprogram/datbase/2010_database/NTDdatabase.htm

Bus CNG Consumption



Yearly Totals	2003	2004	2005	2006	2007	2008	2009	2010
Total Vehicles	11,978	13,182	14,263	15,059	15,890	16,982	18,446	20,111
Total Fuel Consumed	76,683	106,512	115,141	125,308	130,305	140,591	152,496	160,549

- Chart from EIA Alternative Fuels Database (http://www.eia.gov/renewable/afv/users.cfm)

Background

- **Between 2003 and 2010, the number of CNG fueled buses and quantity of CNG consumed has approximately doubled**
- **Buses consume about 75% of the CNG used in transportation**
- **Considered by municipalities for a variety of reasons**
  - Price of fuel
  - Potential for central refueling infrastructures

CNG Buses in MOVES2010b

- **Motor gasoline, diesel, and CNG are the only fuels in the default vehicle population in MOVES2010b**
  - Other fuels (ex. electricity) are available to the user through the alternate vehicle and fuels importer (AVFT)

- **MOVES2010b CNG bus HC/CO/NOx/PM rates are the MOVES2010b gasoline medium heavy duty (MHD) rates**
  - Result of timing, priorities, and data limitations in MOVES2010
  - Increasing prevalence of CNG buses increases relevance for MOVES2013
    - MHD gasoline rates documented in “Development of Emission Rates for Heavy-Duty Vehicles in the Motor Vehicle Emissions Simulator MOVES2010 (EPA-420-B-12-049)”
    - MHD is regulatory class 46, 19k - 33k pounds GVWR

Benchmarking MOVES2010b CNG Bus Emission Rates

- **Conducted literature review**
  - Modal data (1 hz) was not readily available
  - EPA maintains longer term interest in this data
- **Compared test cycle results from literature against simulated test cycles using MOVES**
  - "On-road" vehicles more representative than certification data
  - Test cycle simulation
    - Configure and run MOVES with relevant drive cycle
      - Determine op mode distribution
    - Using op mode distribution, emission rates, and total cycle time, calculate emissions on test cycle
      - $\text{Emission Rate}_{\text{cycle}} = \sum(\text{Rate}_{\text{op mode}} * \text{Time}_{\text{op mode}}) \ / \ \text{Distance}_{\text{cycle}}$

HD Transit Bus Drive Traces

Figure SI-3. New York Bus Cycle (from Ref. (*4*), figure 4).

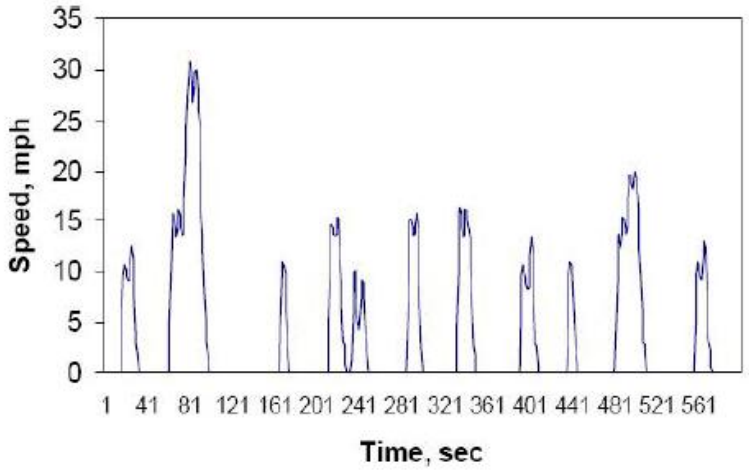
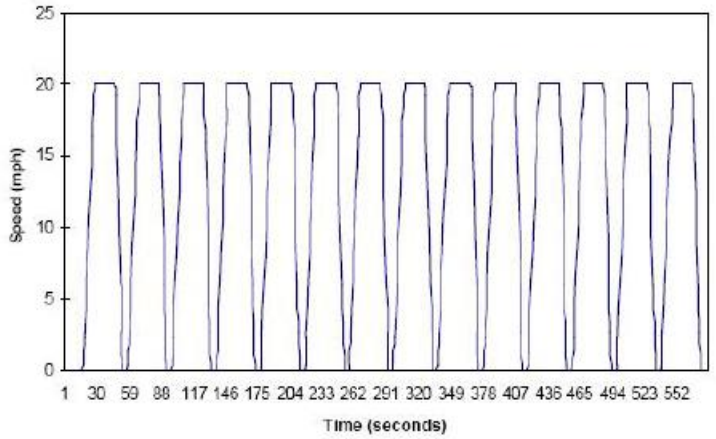


Figure SI-4. Central Business District Cycle (from Ref. (*4*), figure 5).



Drive trace images from DieselNet

HD Transit Bus Drive Traces

Figure SI-2. Urban Dynamometer Driving Schedule (from Ref. (4), figure 3).

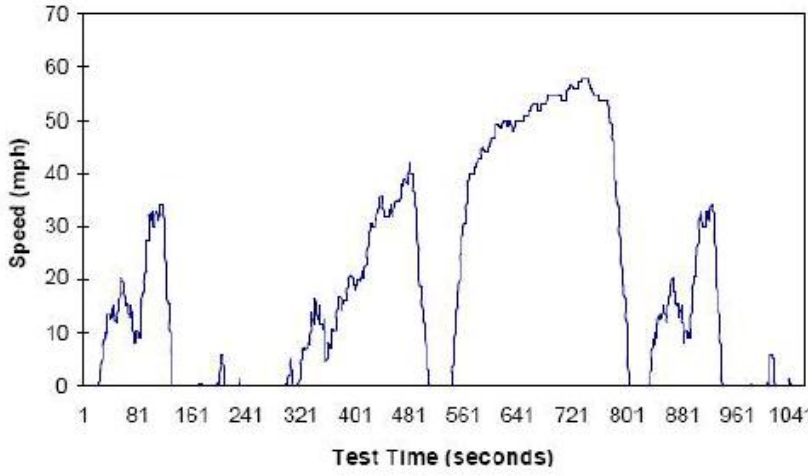
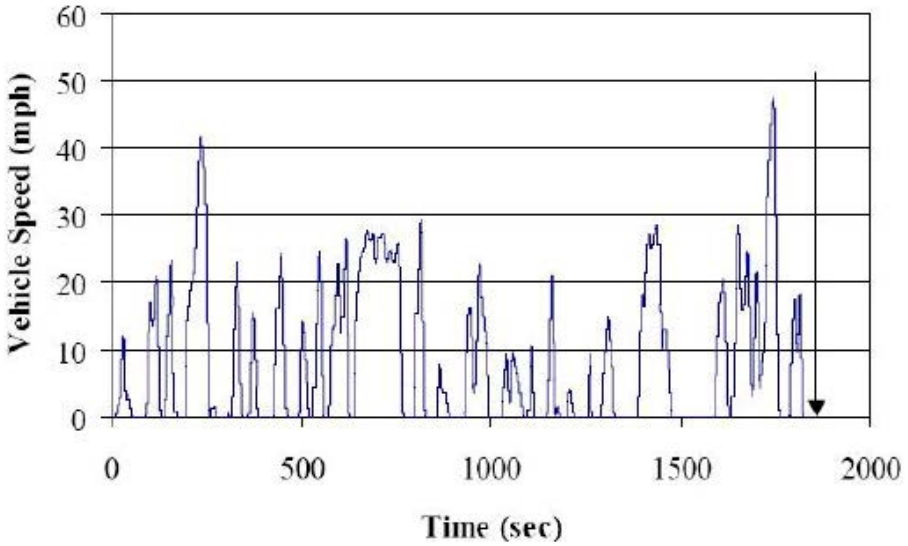


Figure SI-6. Washington Area Metropolitan Transit Authority Driving Cycle (from Ref. (23), figure 9).

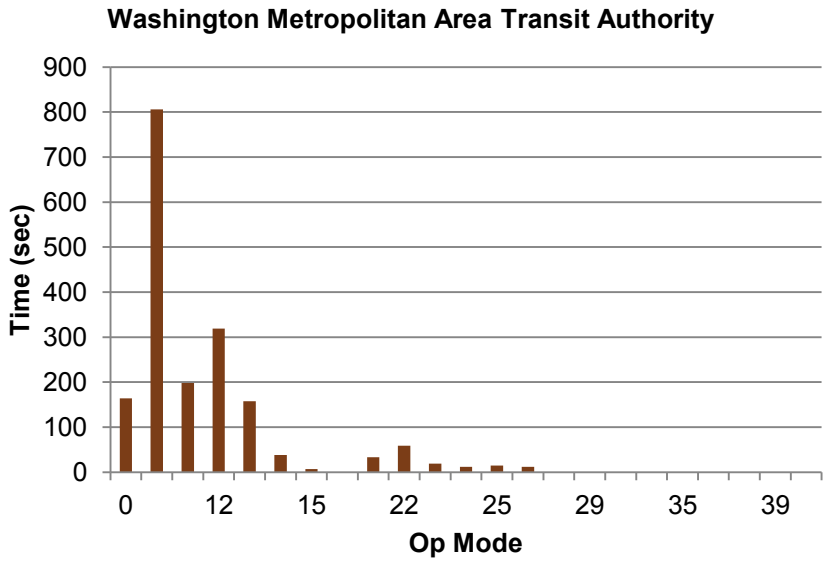


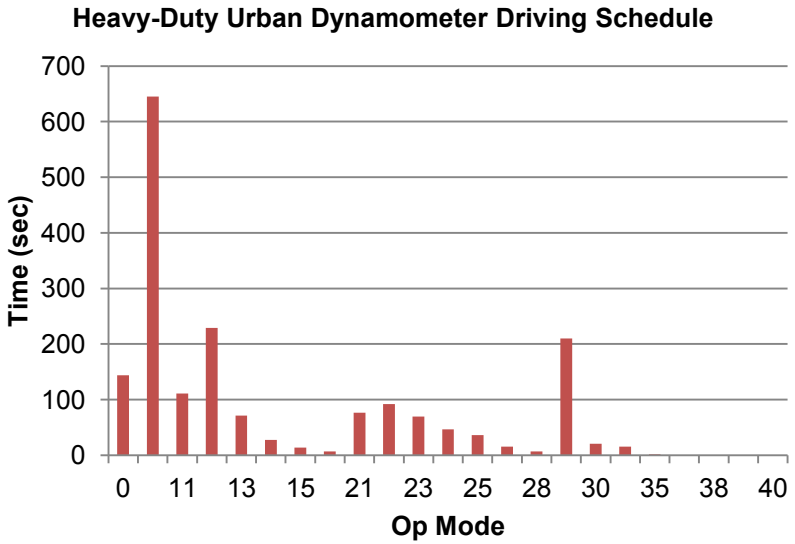
Drive trace images from DieselNet

Conversion to STP bins

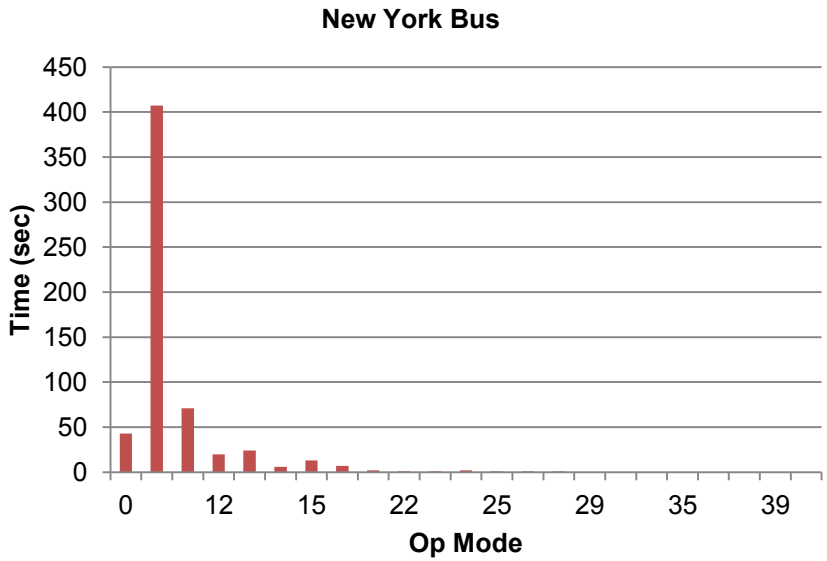
STP Class (kW/tonne)	Speed Class (MPH)		
	1-25	25-50	50+
30+	16	30	40
27-30		29	39
24-27			
21-24		28	38
18-21			
15-18		27	37
12-15			
9-12	15	25	35
6-9	14	24	
3-6	13	23	33
0-3	12	22	
<0	11	21	

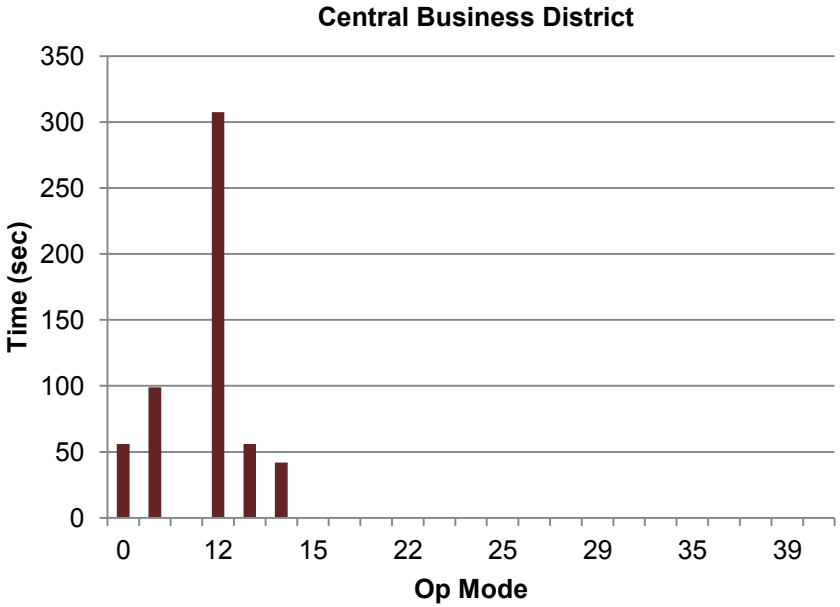
Corresponding Op Mode Distributions





Op Mode Distributions





EPA

Literature Reviewed

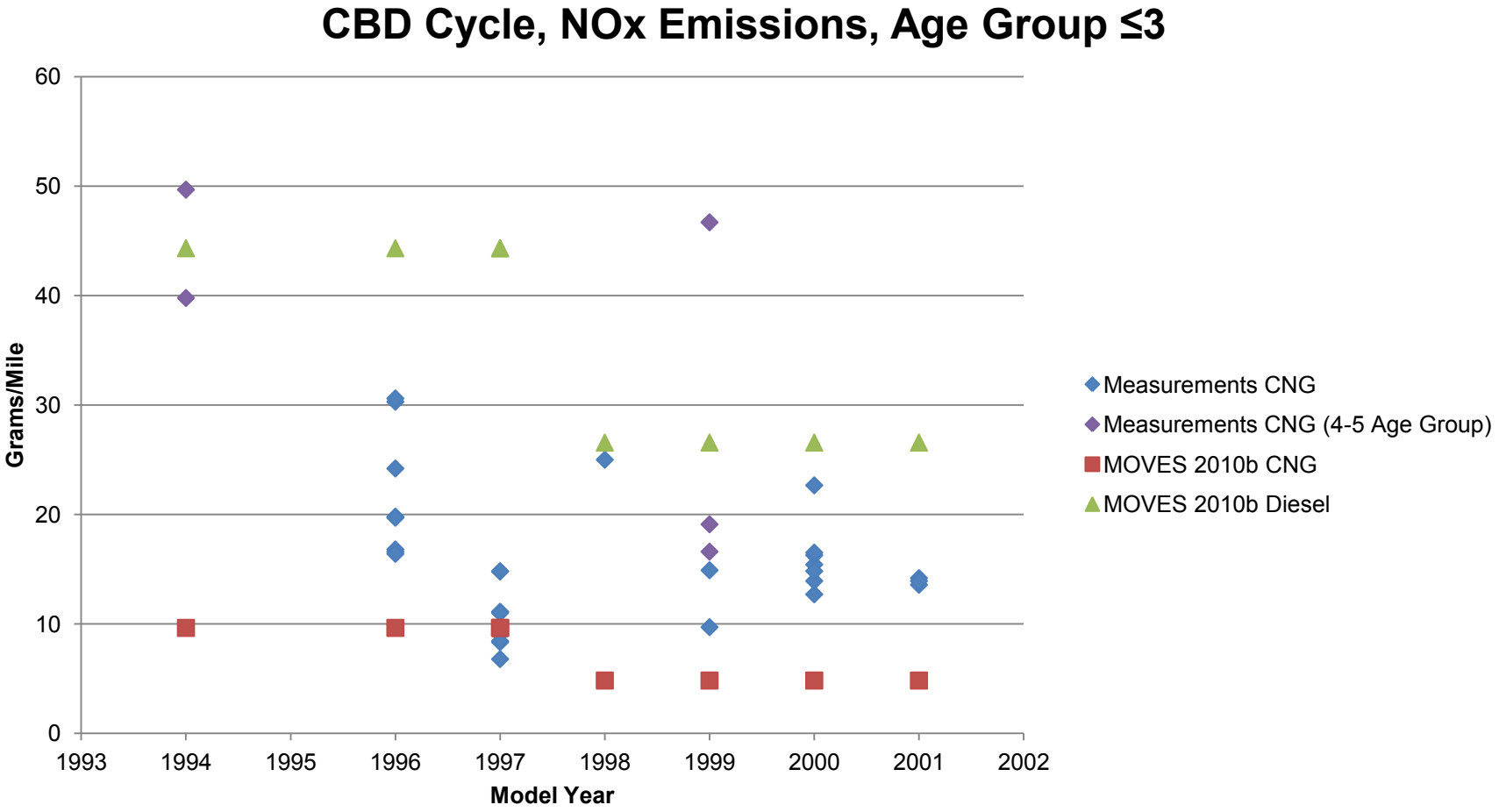
Paper/Article	Lead Research Unit	Driving Cycle(s)	Number of Unique Measurements
Melendez 2005	National Renewable Energy Laboratory (NREL)	WMATA	7
Clark 1999	West Virginia University (WVU)	CBD	7
Ayala 2002	California Air Resources Board (CARB)	CBD, NYB, S55, UDDS	8
Ayala 2003	CARB	CBD, SS55	12
Lanni 2003	New York Department of Environmental Conservation	CBD, NYB	6
McCormick 1999	Colorado School of Mines	CBD, UDDS	8
LaTavec 2002	ARCO (a BP Company)	CBD	2
McKain 2000	WVU	CBD, NYB	6
Clark 1997	WVU	CBD	10
TOTAL			**66**

Full references in appendix slide

Literature Analysis

- **9 papers, 66 unique dynamometer measurements**
  - A similar analysis on CNG and diesel buses was performed by Navistar in 2007
- **Majority of vehicles are pre-2004, low age**
  - 53 of 66 measurements are age 0-3, remainder were 4-5
    - Additional data is welcome
  - No published second by second data
- **38 measurements made on the CBD cycle**
  - Focused on this analysis, but the other trends were generally similar

Comparing MOVES Projections to Measurements



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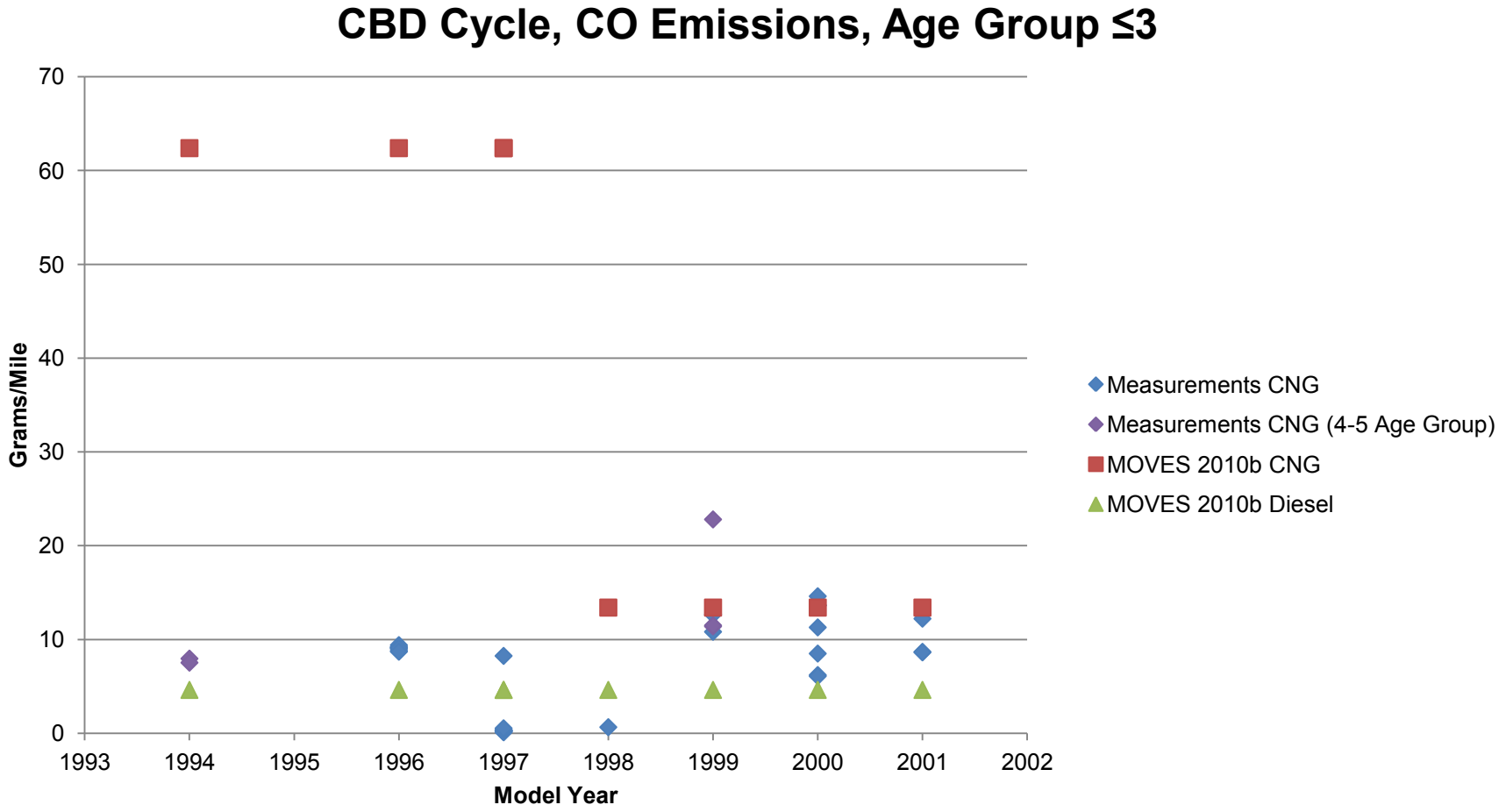

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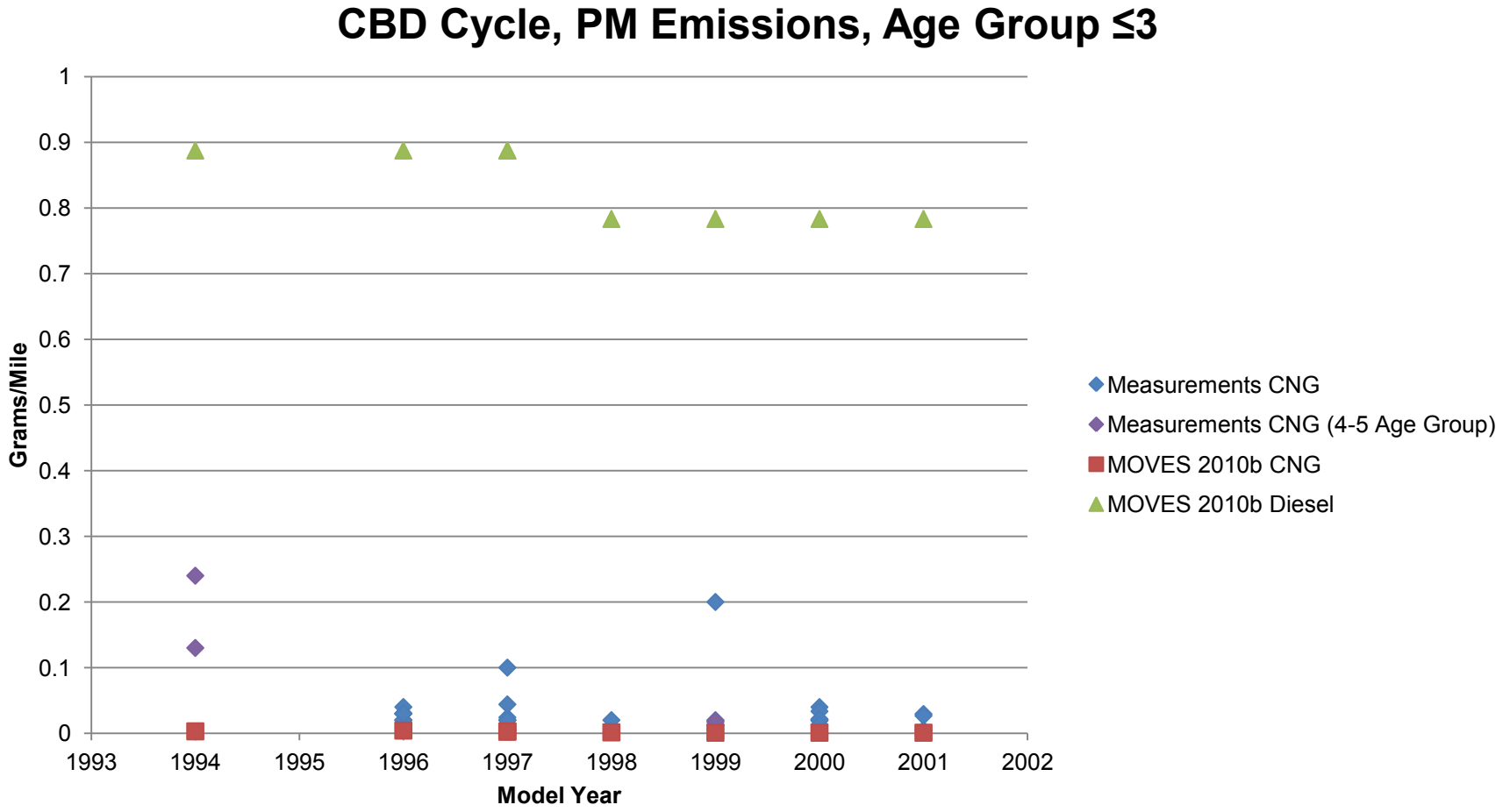

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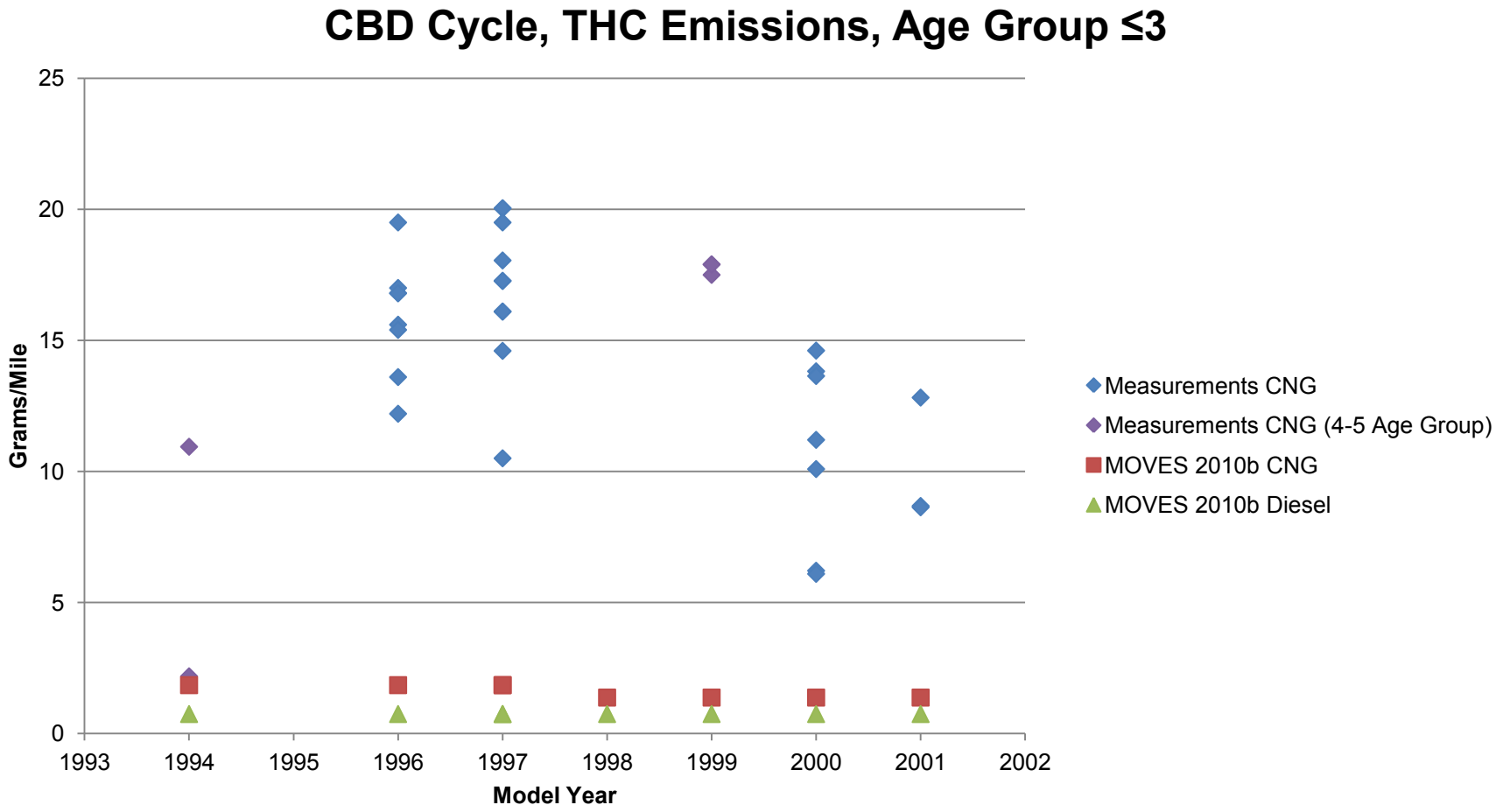

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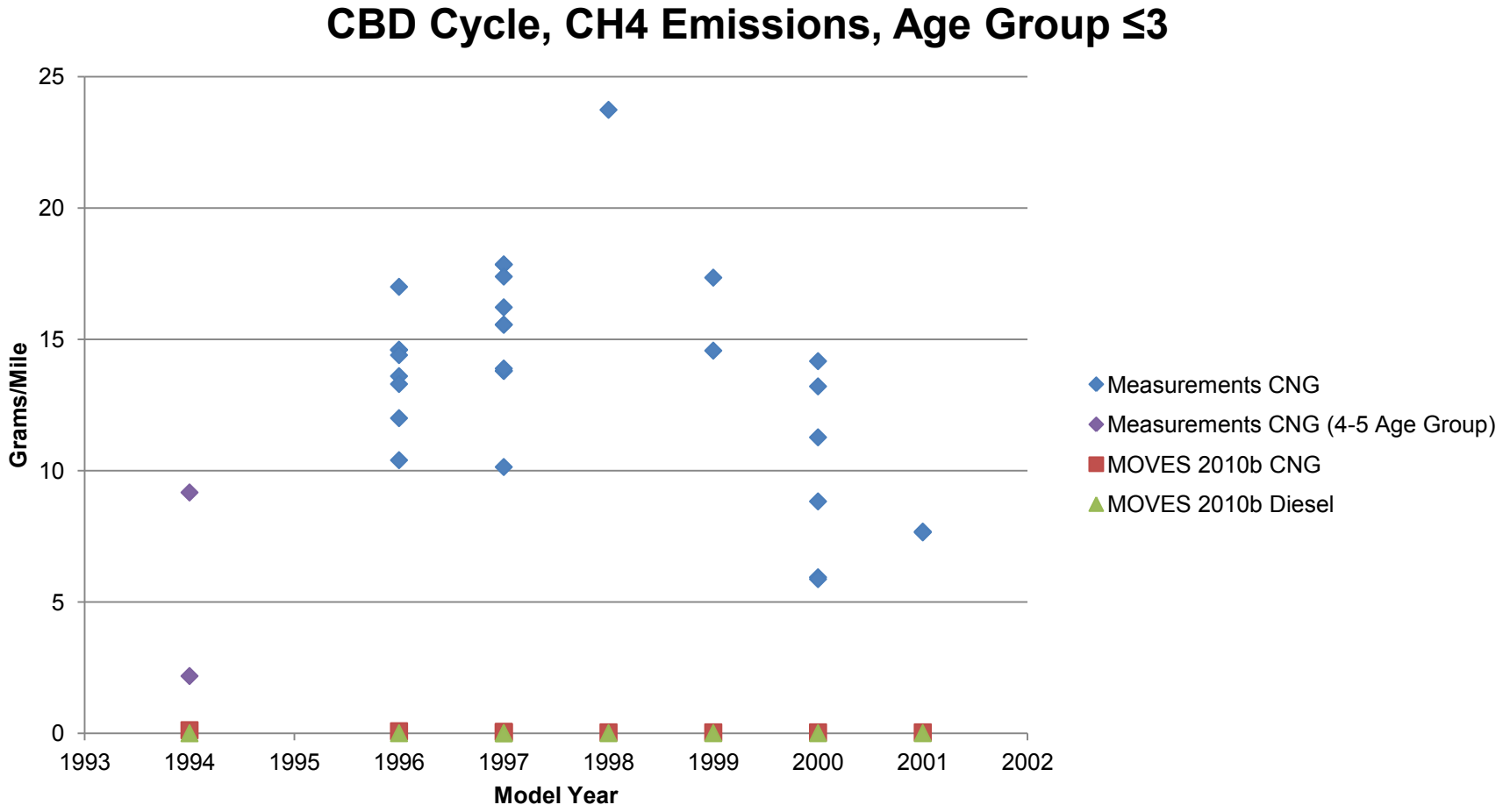
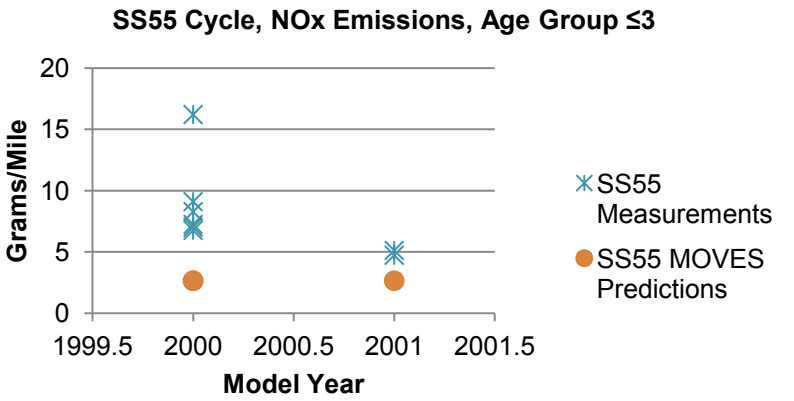
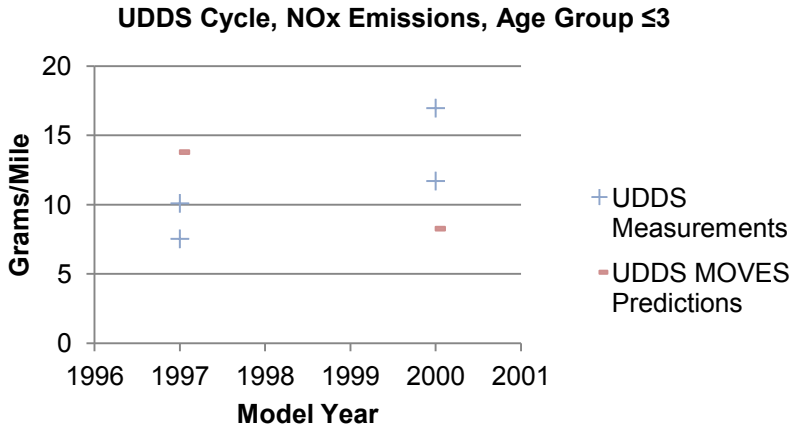
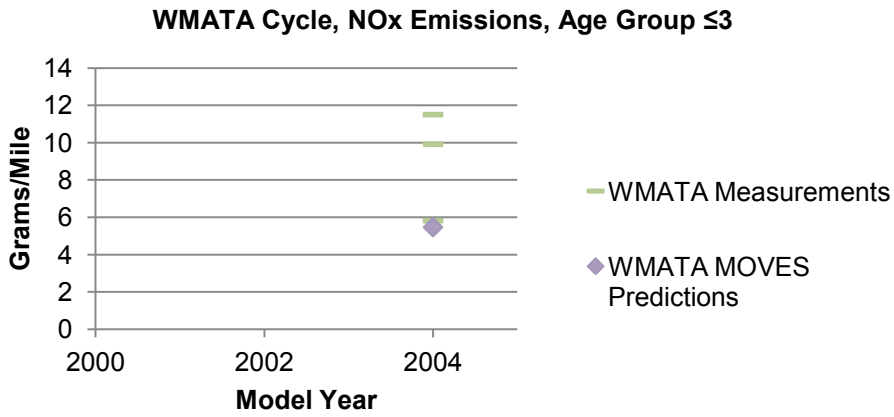
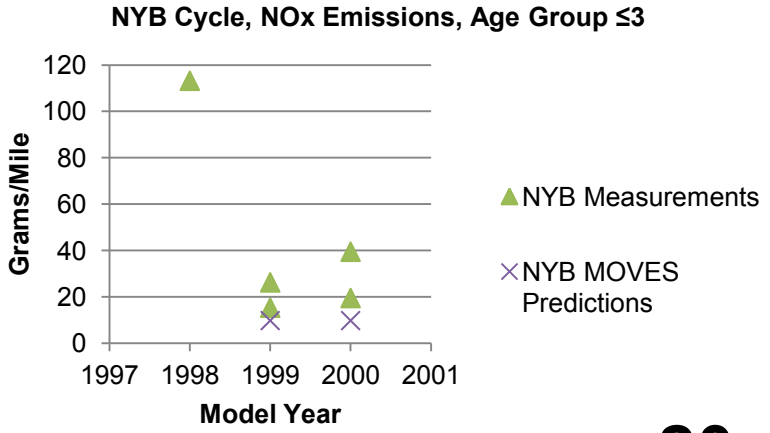


Other Cycles – Consistent Trends









MY 1994-2001 Literature Review

- **Literature shows much higher THC and CH4 emissions than MOVES2010b CNG rates**
  - MOVES2010b CNG is based on gasoline emission rates
  - CH4 is uncombusted fuel from CNG vehicle
  - Majority of THC increase is CH4
- **Literature PM rates are higher than MOVES2010b**
  - Much lower than diesel buses without trap
- **Literature NOx rates are higher than MOVES2010b**
- **Literature CO rates are similar**
- **Other cycles show similar, but not identical conclusions**

Developing Modal Rates

- **No modal data from papers**
  - Potentially available from some authors
  - Significant additional time and financial investment
    - Acquisition costs
    - Quality Assurance
    - Analysis
  - Potentially a future option
- **Scaled MOVES2010b CNG rates so that simulated drive cycle emissions are at appropriate level**
  - Simulate drive cycle in MOVES
  - Match to equivalent data from paper
  - Develop scaling factor
    - Assuming same ratio applies to running and start emissions
  - Assume same age trends, except for CH4
    - CH4 is assumed to remain same proportion of THC

Proposed MOVES2013 CNG bus rates

- **Categorized CNG buses into 3 model year groups**
  - A: 1994-2001 (Most MYs contained in literature review)
  - B: 2002-2006 (Additional MYs – WMATA cycle)
  - C: 2007 and later
- **For group A & B, emission rates from literature**
- **For 2007 and later MYs, scaled group B emission rates by ratio to sales-weighted certification data**
  - Portions of certification data (ie, projected sales) are CBI.

Current and Draft Proposed Rates

	Current MOVES2010b CNG Rates (g/mile)							
MY	Age Group	Cycle	NOx	CO	PM_OC	PM_EC	THC	CH4
1997	0-3	CBD	9.6	62.4	2.4E-03	1.8E-04	1.8	0.05
2004 and later	0-3	CBD	4.8	13.4	2.4E-03	1.7E-04	1.4	0.03
1997	0-3	WMATA	9.5	90.0	4.0E-03	2.9E-04	2.5	0.07
2004 and later	0-3	WMATA	5.5	19.0	3.5E-03	2.6E-04	1.4	0.03
	Proposed MOVES2013 CNG Rates (g/mile - measured/estimated from analysis)							
MY	Age Group	Cycle	NOx	CO	PM_OC	PM_EC	THC	CH4
1994-2001	0-3	CBD	18.1	7.6	3.3E-02	3.7E-03	14.3	13.1
2002-2006	0-3	WMATA	9.1	2.3	3.9E-03	4.3E-04	11.2	10.6
2007 and later	0-3	WMATA	2.2	20.0	1.6E-03	1.8E-04	4.3	4.1

Summary

- **Improvement in CNG bus rates from MOVES2010b**
  - Emissions reflect CNG bus emission rates
  - Significant increase in CH4 and THC
  - Smaller changes in NOx, CO
- **Incorporated analysis of 66 vehicle measurements**
  - Additional area for improvement exists
    - Modal data
    - More recent data
    - Aged vehicle data
- **Also fixed a MOVES2010b bug (no VOC emissions)**

Appendix: References

- Clark, N., Gautam, M., Rapp, B., Lyons, D. et al., "Diesel and CNG Transit Bus Emissions Characterization by Two Chassis Dynamometer Laboratories: Results and Issues," Society of Automotive Engineers, SAE Technical Paper 1999-01-1469, 1999, (http://papers.sae.org/1999-01-1469).
- Ayala, A., Kado, N., Okamoto, R., Holmén, B. et al., "Diesel and CNG Heavy-duty Transit Bus Emissions over Multiple Driving Schedules: Regulated Pollutants and Project Overview," Society of Automotive Engineers, SAE Technical Paper 2002-01-1722, 2002. (http://papers.sae.org/2002-01-1722).
- Ayala, A., Gebel, M., Okamoto, R., Rieger, P. et al., "Oxidation Catalyst Effect on CNG Transit Bus Emissions," Society of Automotive Engineers, SAE Technical Paper 2003-01-1900, 2003. (http://papers.sae.org/2003-01-1900).
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- McCormick, R., Graboski, M., Alleman, T., Herring, A. et al., "In-Use Emissions from Natural Gas Fueled Heavy-Duty Vehicles," Society of Automotive Engineers, SAE Technical Paper 1999-01-1507, 1999. (http://papers.sae.org/1999-01-1507).
- LeTavec, C., Uihlein, J., Vertin, K., Chatterjee, S. et al., "Year-Long Evaluation of Trucks and Buses Equipped with Passive Diesel Particulate Filters," Society of Automotive Engineers. SAE Technical Paper 2002-01-0433, 2002. (http://papers.sae.org/2002-01-0433).
- McKain, D., Clark, N., Balon, T., Moynihan, P. et al., "Characterization of Emissions from Hybrid-Electric and Conventional Transit Buses," Society of Automotive Engineers, SAE Technical Paper 2000-01-2011, 2000. (http://papers.sae.org/2000-01-2011).
- Clark, N., Gautam, M., Lyons, D., Bata, R. et al., "Natural Gas and Diesel Transit Bus Emissions: Review and Recent Data," Society of Automotive Engineers, SAE Technical Paper 973203, 1997. (http://papers.sae.org/973203).