



Update on MOVES Model Evaluation: NOx

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MOVES Review Work Group

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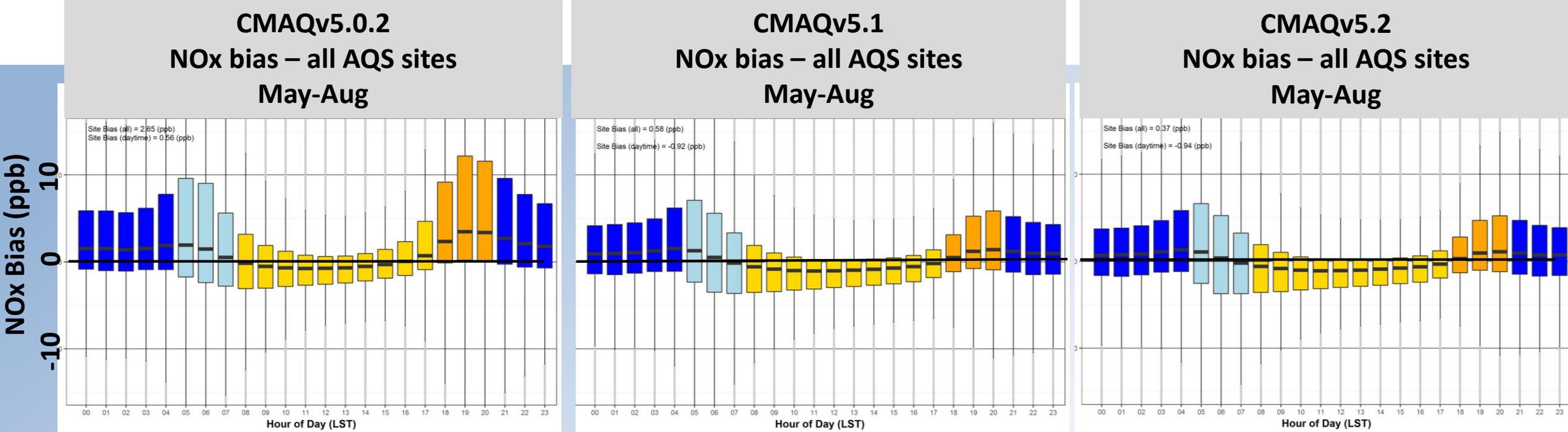
Review: March 2017

- “Model Evaluation” talk, March 2017 MOVES Review Workgroup meeting
 - Background on MOVES model evaluation
 - Context of current MOVES evaluation
 - MOVES2014a comparisons to light-duty NO_x from:
 - Inspection/Maintenance (I/M)
 - Remote sensing data (RSD)
 - Tunnel studies
- We have since conducted additional work on the light-duty NO_x evaluation, which we are presenting here

Agenda

- Review the context for the focus on evaluation of light-duty NO_x emission rates in MOVES
- Review the evaluation from:
 - Inspection/Maintenance (I/M)
 - Tunnel studies
- Present new analysis from:
 - Remote sensing data (RSD) comparison to MOVES
 - Sensitivity of predicted NO_x concentrations in the air quality platform due to mobile NO_x emission estimates and space-time allocation
- Discuss next steps in the MOVES NO_x evaluation analysis

What's the issue? Air quality models over-predict NOx compared to monitored concentrations

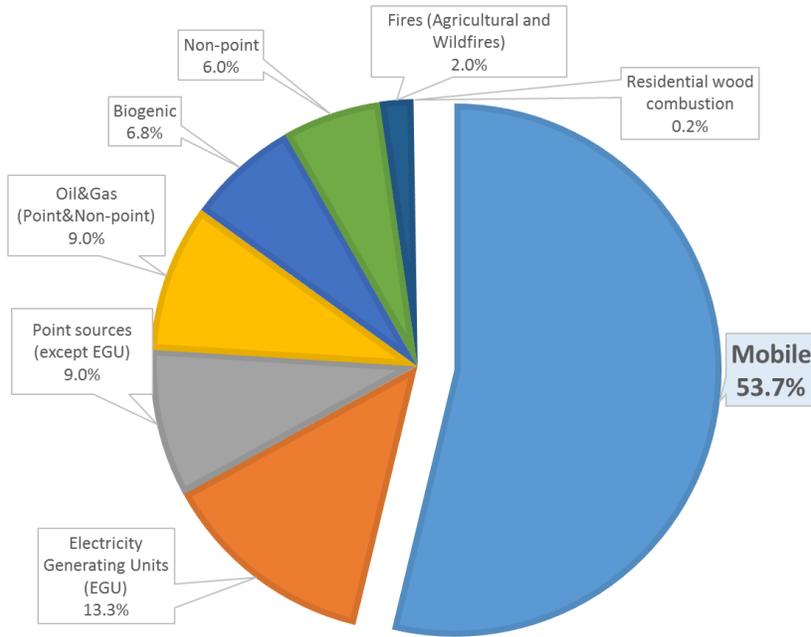


- Air quality model (CMAQ) over-predicts NOx compared to monitored concentrations from 2011 from the Air Quality System (AQS)
- NOx is generally **unbiased** or **under-predicted** during daytime (■) but is **over-predicted** in morning (□) and evening (■) transition hours and at night (■)
- CMAQv5.1 has improved characterization of mixing in morning/evening transitions and at night compared to CMAQv5.0.2
 - NOx biases decrease in CMAQv5.1 versus CMAQv5.0.2
- CAMx v6.2 biases in NOx generally fall between biases from CMAQv5.0.2 and v5.1

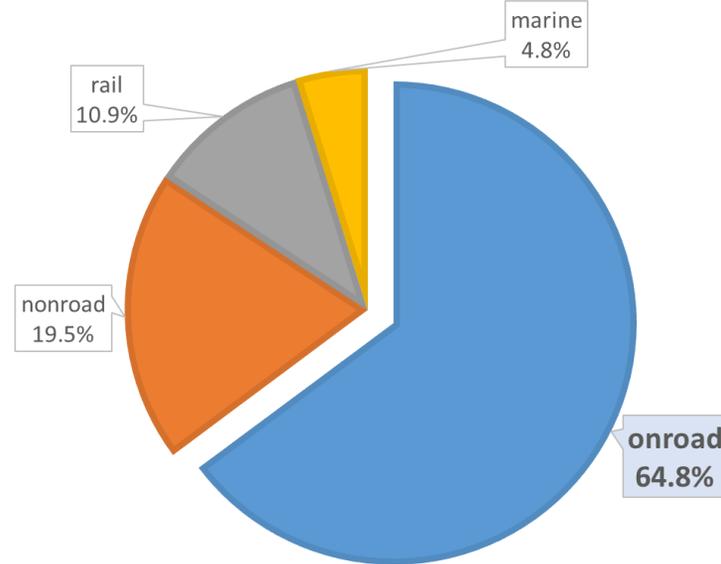
Why focus on light-duty NOx?

- Several researchers have suggested mobile emissions, specifically light-duty NOx emissions, may be overestimated
- Mobile sources contribute ~54% of NOx emissions in the 2014 NEI
- ~65% of which are on-road emissions
- ~37% of which are light-duty gasoline running emissions
- In counties observed with large NOx discrepancy between monitored and modeled values during 2011 summer months, starts and diesel extended idle emissions are minor contributors to total NOx

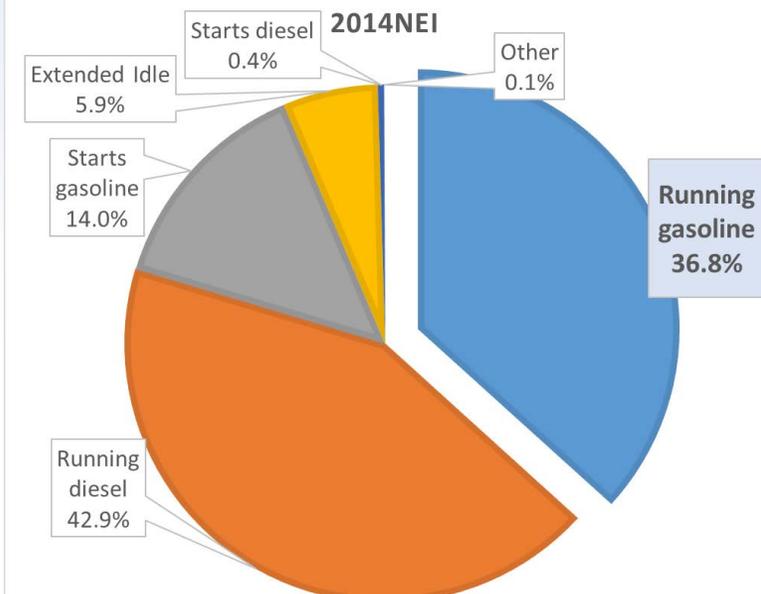
TOTAL NOX EMISSIONS 2014NEI



TOTAL MOBILE NOX EMISSIONS 2014NEI



TOTAL ONROAD NOX EMISSIONS 2014NEI



Review: Data for Evaluating Light-Duty Rates

	Tunnels	Inspection/Maintenance	Remote Sensing
Individual vehicle measurements?	No: Fleet average	Yes	Yes
Calendar Years	1997,2001,2003,2006,2010	2008-2015	1999-2015
Number of cities	Two	Denver	Fourteen
Ability to capture rare high emitters?	Yes	Yes	Yes
Known operating conditions ? (for replicating in MOVES)	Estimated based on sample vehicle speed traces in 1996	Yes: preconditioned IM240	Yes: vehicle speed & acceleration recorded
Real-world driving conditions?	1 km of driving through Caldecott Tunnel on urban freeway. ¼ km of driving of major arterial (3-lanes in both directions) in Van Nuys Tunnel	IM240 driving cycle on chassis dynamometer	Snapshot (typically during vehicle acceleration on freeway ramps)
Known vehicle characteristics? (car/truck, gas/diesel, model year/age)	Some: age distribution and fleet mix measured in 2006 for Caldecott Tunnel, and 2010 in Van Nuys.	Yes	Yes: from VIN decoding

Review: Denver I/M Dynamometer Testing Data

- Denver Inspection & Maintenance (I/M) test data on light-duty vehicles
 - NOx emissions on IM240 cycle
 - Random evaluation sample
 - Calendar years 2008-2015
 - Corrected for bias due to testing exemption for clean cars
 - Tier 1 cars (1996-2000 model years)
 - Tier 2 cars and trucks (2010-2016 model years)
- MOVES comparisons
 - Compare emissions by vehicle age and vehicle class, and federal emission standards (Tier 1 and Tier 2)
 - Simulate IM240 using MOVES base rates
 - No MOVES adjustments for temperature/humidity and fuel properties

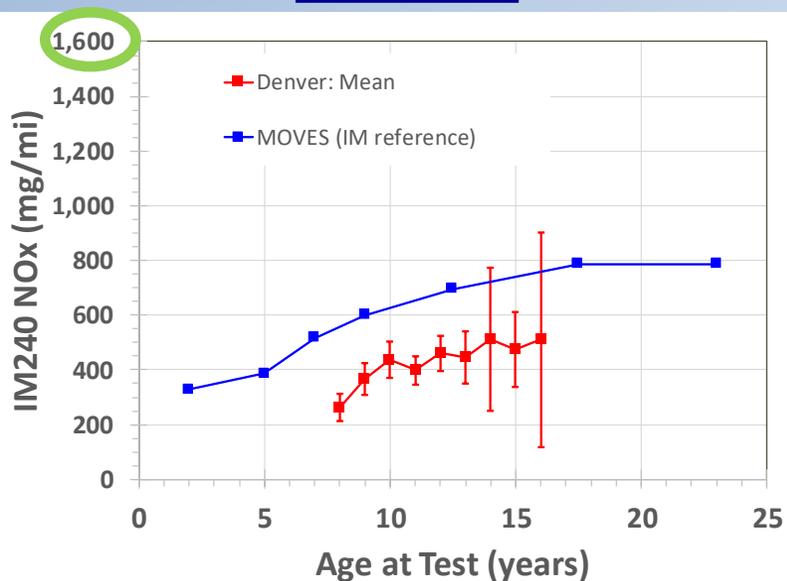


Denver Post, 2007

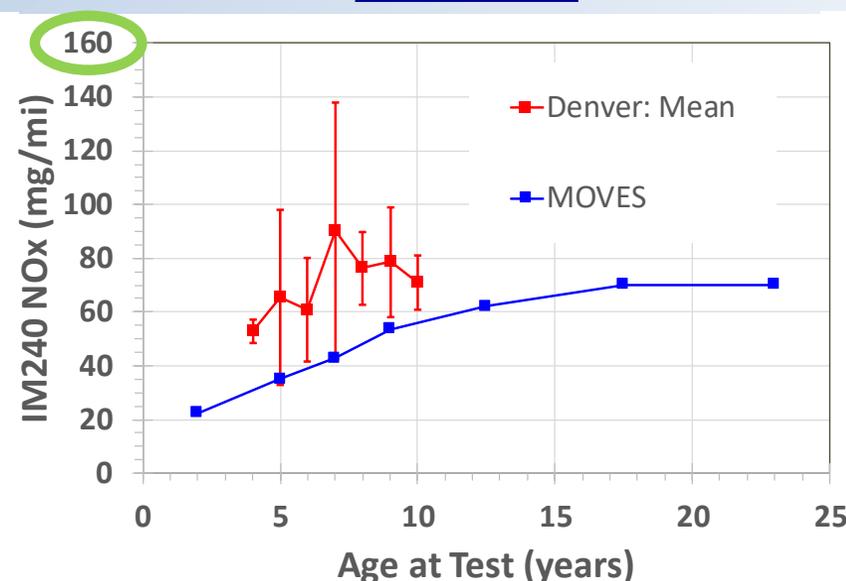
Review: Denver I/M Comparison to MOVES

- MOVES is higher than I/M data for pre-2000 (Tier 1) cars
- MOVES is lower than I/M data for 2010+ (Tier 2) cars
- Tier 2 light trucks estimated well
- MOVES deterioration trends compare well
- Projected impact on NOx inventory: MOVES higher than an inventory developed using I/M data for calendar year 2010 and earlier, and lower for 2015 and later

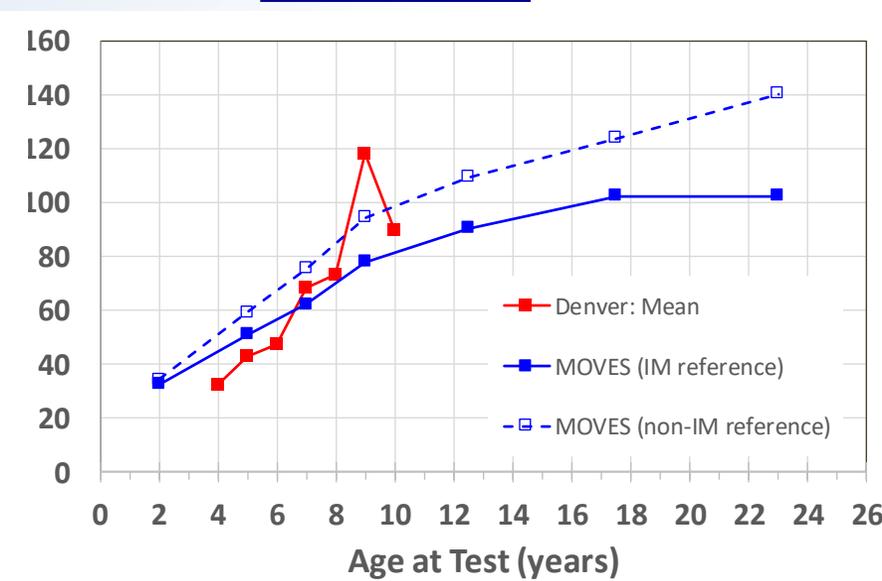
Tier 1 cars



Tier 2 cars



Tier 2 trucks



Review: Comparison to Tunnel Studies

- Caldecott Tunnel, Oakland, CA
 - Summer, 1997², 2001³, 2006⁴, 2010^{5,6} (UC-Berkeley)
 - 37 mph, 4% uphill grade
 - 2 tunnel bores, with light-duty-only bore
- Van Nuys Tunnel, Los Angeles, CA
 - Summer, 2010⁷
 - 41 mph, 1.7% downhill grade (entrance), 1% uphill grade (exit)
 - Single bore with mixed traffic (1.3% heavy-duty traffic)
- MOVES run in project-mode with local inputs
 - Roadway conditions (grade, speed)
 - Vehicle operating modes from 1 Hz speed trace data
 - Vehicle fleet mix (LD vs. HD)
 - Vehicle age distribution
 - Local fuel properties (fuel survey data)
 - July average for temperature/humidity for 5 pm



Caldecott Tunnel

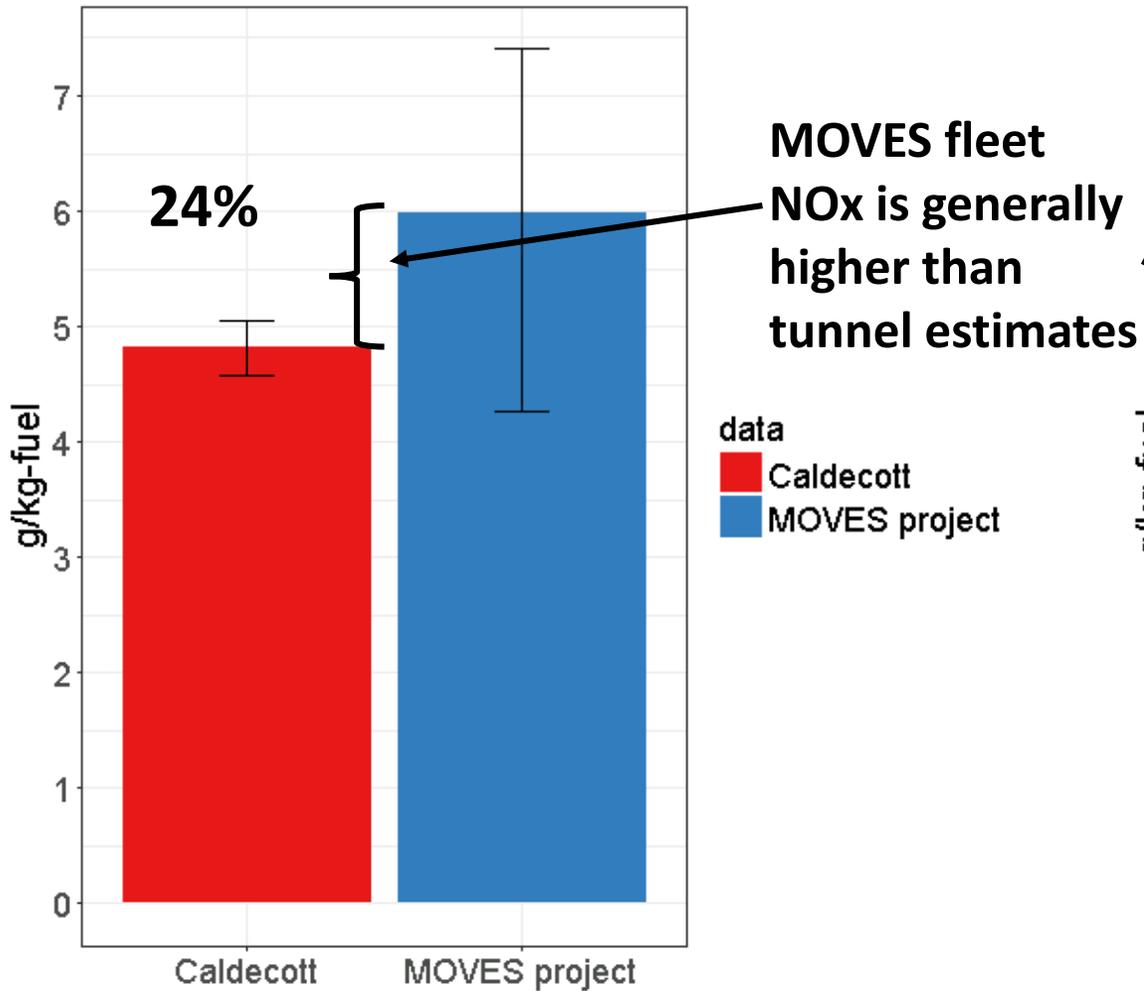
Image from Dallman et al. (2012)⁶



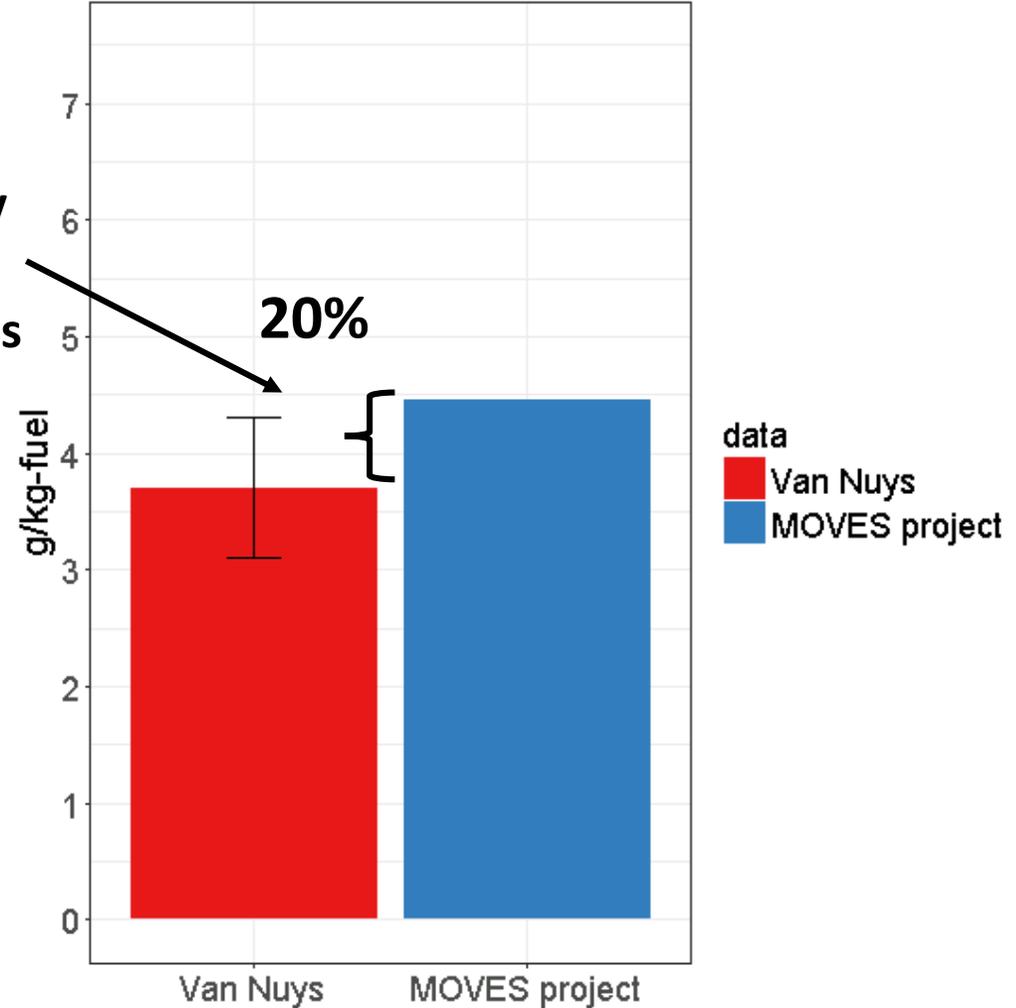
Van Nuys Tunnel Sherman Way,

Image from Google StreetView

Oxides of Nitrogen (NOx) Caldecott Tunnel, July 2010



Oxides of Nitrogen (NOx) , Van Nuys Tunnel, August 2010

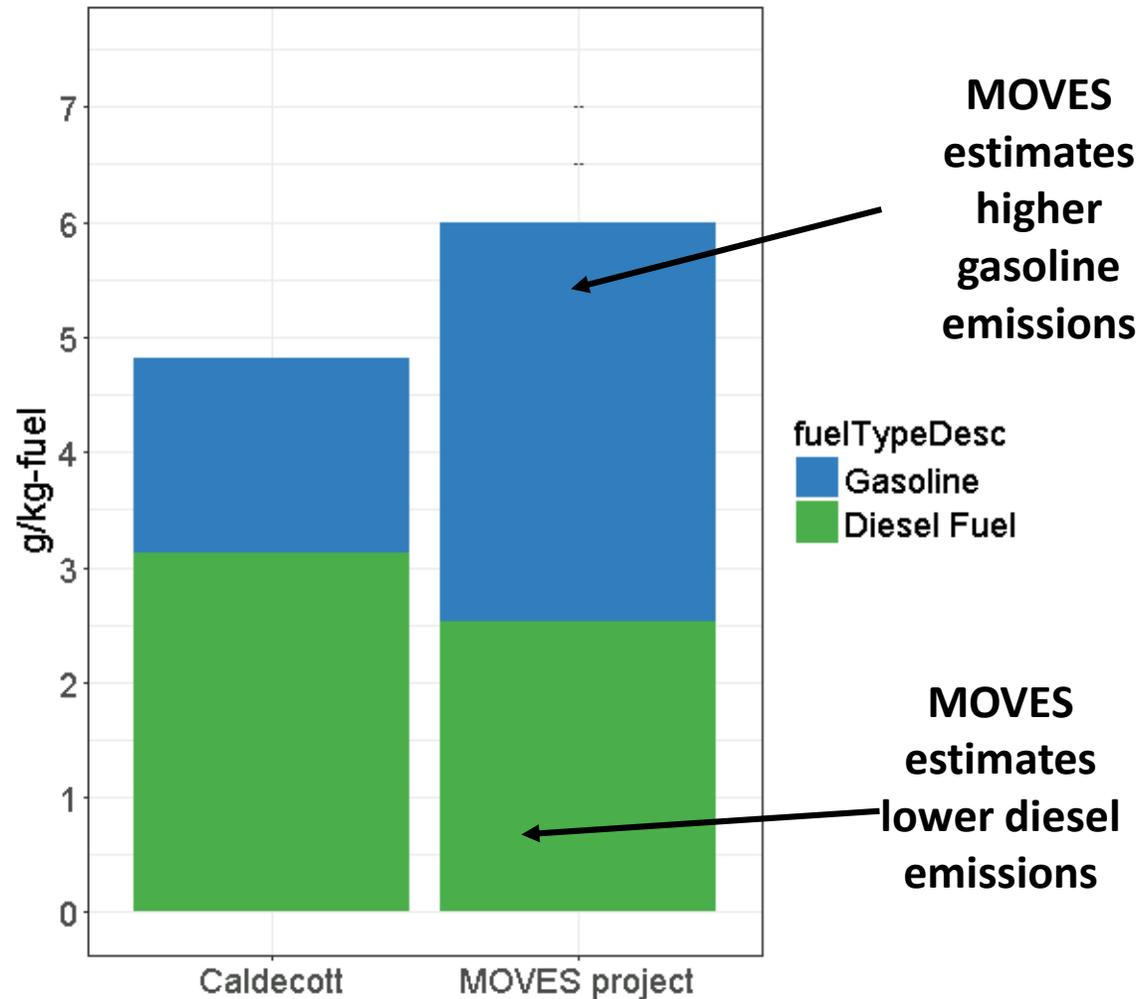


Light-duty gas/Heavy-duty diesel vehicle miles traveled split estimated from EMFAC2014 for Contra Costa County

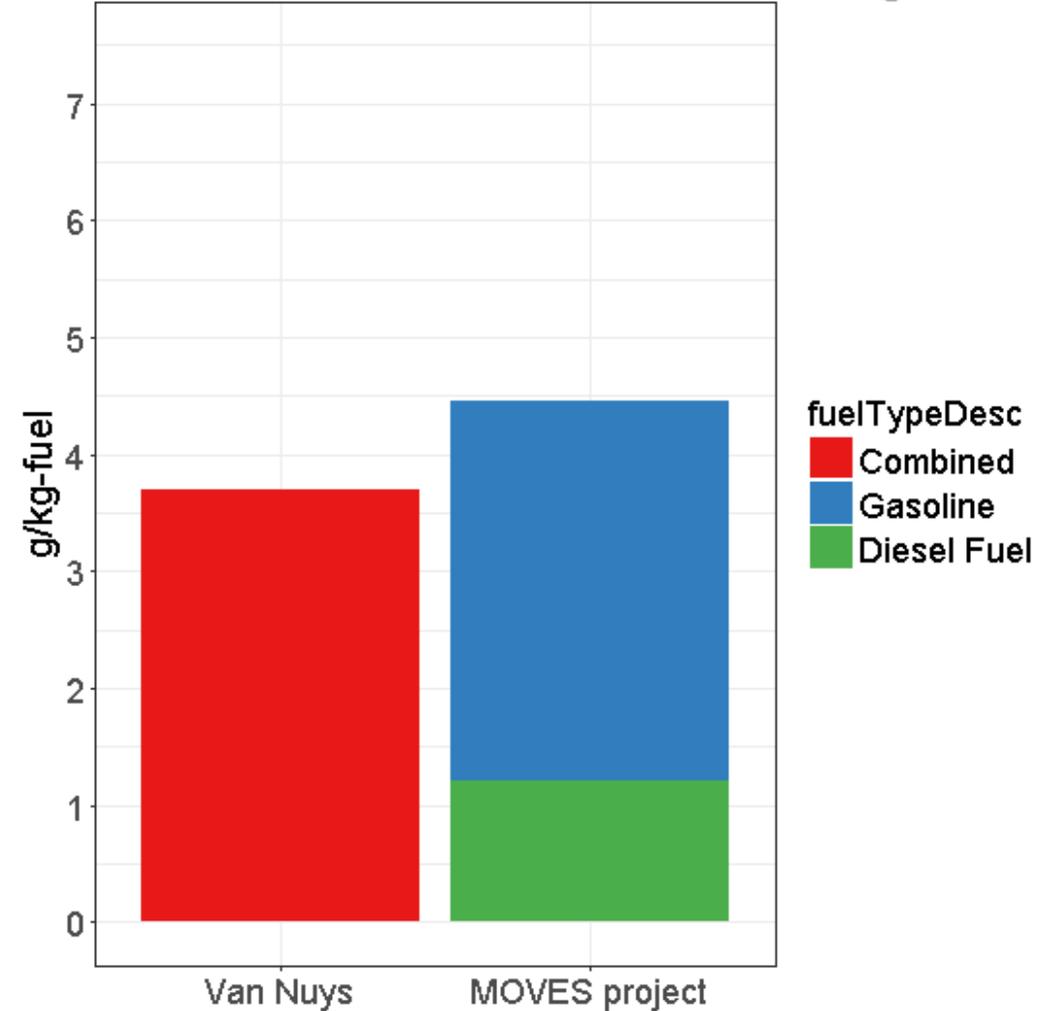
Light-duty gas/Heavy-duty diesel split estimated from counts made during the study

Note: MOVES is not designed to model California emissions. MOVES runs for the Caldecott tunnel were adjusted to account for the California LEV standards, but do not account for the California pre-1994 vehicle NOx standards, which would account for some of the observed differences. This adds significant uncertainty to the MOVES results presented here.

Oxides of Nitrogen (NOx) Caldecott Tunnel, July 2010



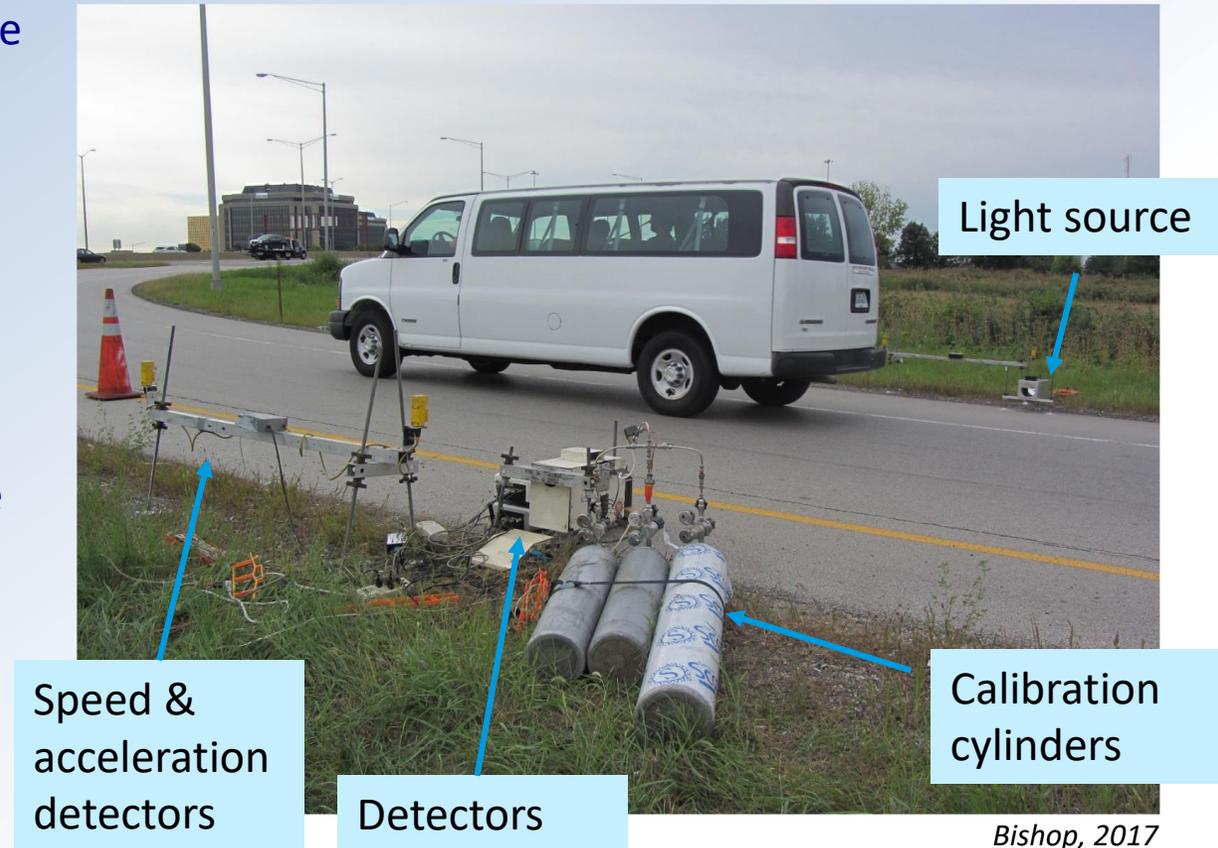
Oxides of Nitrogen (NOx) Van Nuys Tunnel, August 2010



Note: MOVES is not designed to model California emissions. MOVES runs for the Caldecott tunnel were adjusted to account for the California LEV standards, but do not account for the California pre-1994 vehicle NOx standards, which would account for some of the observed differences. This adds significant uncertainty to the MOVES results presented here.

Evaluation using Onroad Remote Sensing Device (RSD) Data

- Studies conducted by University of Denver⁸
 - Individual vehicles measured remotely from the road-side
 - Using the FEAT remote sensor
 - Reported percent concentration of NO[†]
- Vehicle information (i.e., make and model) obtained from license plate and vehicle registration data
- Data includes
 - Vehicle operating conditions (speed/acceleration/vehicle specific power (VSP))
 - Measurement conditions (temperature/humidity/road grade)
 - Flags for invalid measurements



[†] Converted to fuel-specific rates (g/kg fuel) in NO₂ mass-equivalence

RSD Data Summary

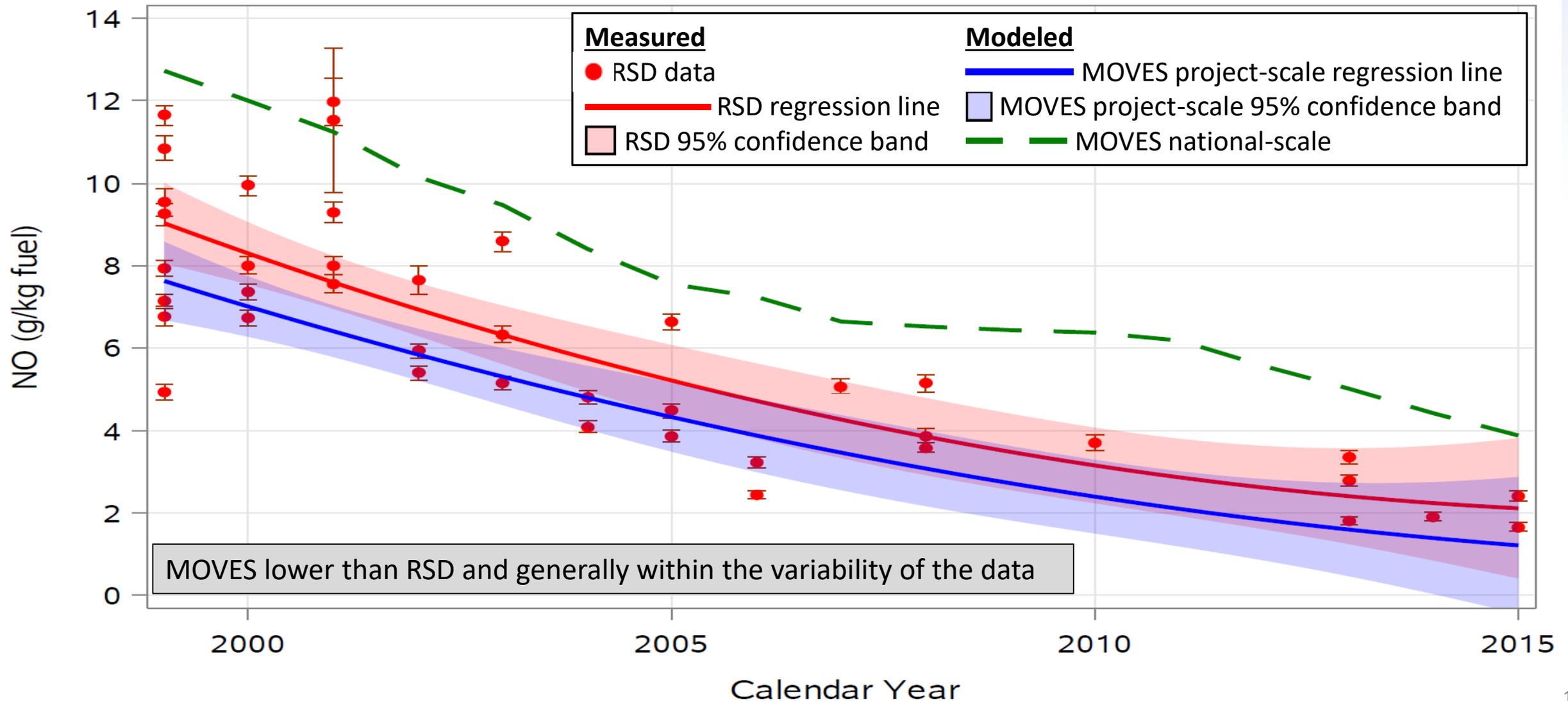
Studies and years in bold:
data NOT presented in March

RSD Sites	Calendar Years	Number of Valid Measurements
Phoenix, AZ	1999, 2000, 2002, 2004, 2006	95,226
Los Angeles, CA (LA710)	1999	9,336
Sacramento, CA	1999	12,965
Riverside, CA	1999-2001	49,878
San Jose, CA	1999, 2008	49,550
Fresno, CA	2008	11,595
Van Nuys, CA	2010	10,669
Los Angeles, CA (LaBrea Blvd)	1999, 2001, 2003, 2005, 2008, 2013, 2015	120,436
Denver, CO (6 th Ave)	1999-2001, 2003, 2005, 2007, 2013	127,518
Glenwood Springs, CO	2001	324
Grand Junction, CO	2001	3,346
Denver, CO (Speer Blvd)	2002	8,311
Chicago, IL	1999, 2000, 2002, 2004, 2006, 2014	107,007
Tulsa, OK	2003, 2005, 2013, 2015	64,658
TOTAL		670,819

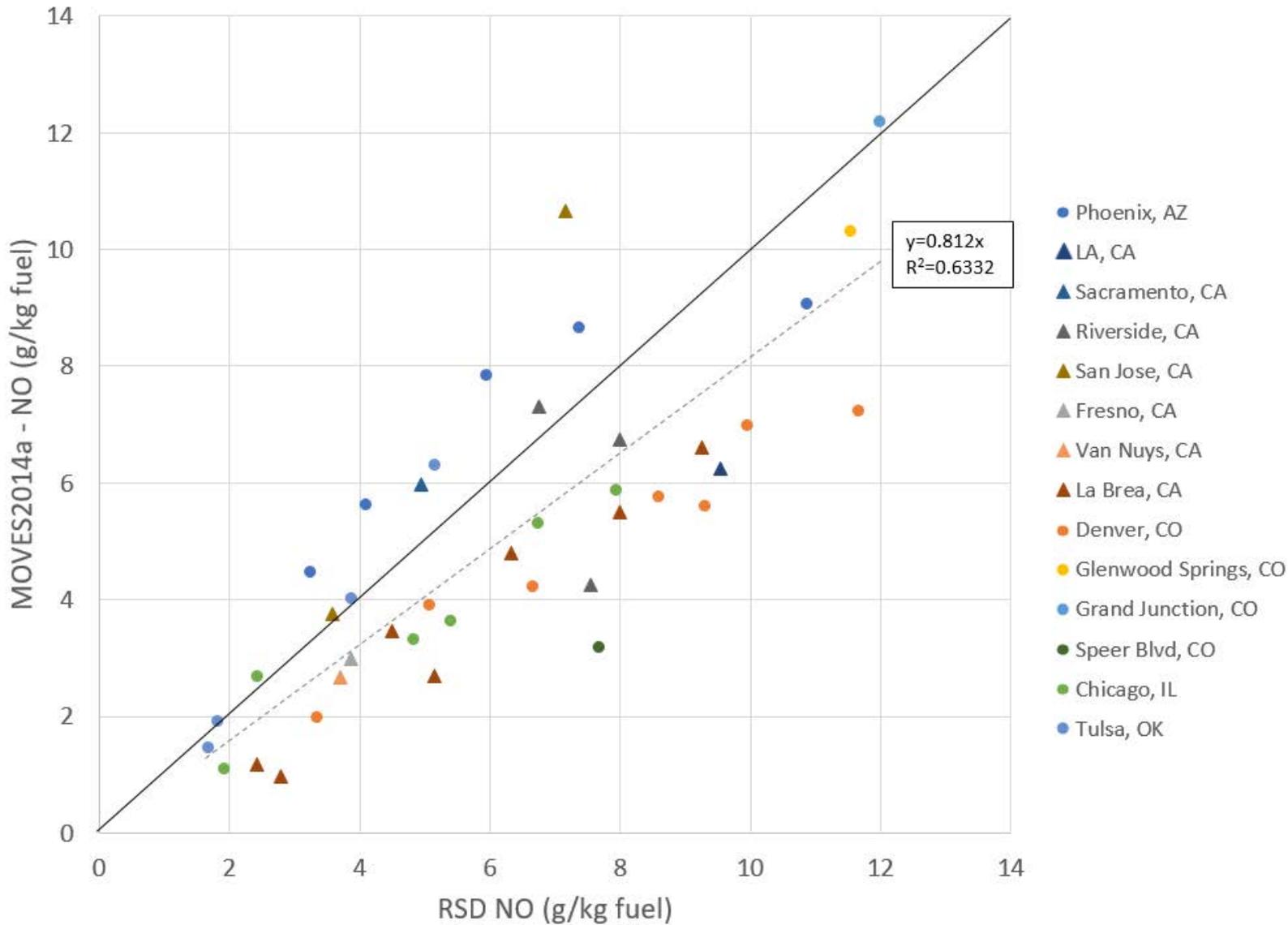
MOVES Model Runs

- Project-scale runs with inputs customized to remote sensing sites
 - Operating mode distribution (function of vehicle speed, acceleration, VSP)
 - Age distribution
 - Vehicle class distribution (passenger car vs. truck)
 - Adoption of 1994-and-later California vehicle emission standards, where applicable†
 - Calendar-specific fuel sulfur level based on EPA's fuel compliance data⁹
 - Inspection & Maintenance programs, where applicable
 - Local temperature/humidity
- National-scale runs
 - Use MOVES default inputs
 - Do not account for the measurement conditions

Comparisons of RSD and MOVES



Comparison of RSD and MOVES – 1:1 Plot



- MOVES predictions lower than the data for majority of the remote sensing sites
- Differences in NO rates between MOVES and RSD similar between CA and non-CA sites

Comparisons of RSD and MOVES

- MOVES project-scale
 - Under-predicts onroad remote sensing measurements
 - For most years, MOVES predictions within the data variability
 - Demonstrates the importance of accounting for the measurement conditions (e.g. fleet composition, vehicle activity) when evaluating MOVES
- MOVES national scale
 - Using the MOVES default inputs can show clear over-prediction
 - Consistent with what's reported in the literature¹
 - NOT a proper way to compare MOVES to independent data

MOVES Defaults and NEI

- At the county level, MOVES national scale \neq NEI MOVES emissions
 - State provided inputs will differ from MOVES national defaults
 - When data not provided by states, EPA provided NEI inputs may differ from MOVES national defaults (e.g. county-specific age distribution from CRC A-88)
 - *Excerpt. Full table in Technical Support Documentation for 2011NEIv2¹¹

Table 4-20: Source of defaults for data tables in MOVES CDBs*

CDB Table	Description of Content	Default CDB Table Content
sourcetypeagedistribution	Distribution of vehicle ages	For sourcetypes 21, 31 and 32: CRC A-88 estimates for each county. For all other source types: MOVES2010b national default for 2011
sourcetypeyear	Vehicle Populations	For sourcetypes 21, 31 and 32: CRC A-88 estimates for each county. For all other source types: calculated from county-level VMT based on ratios of population to VMT from state-level FHWA data.
hpmsvtypeyear	Total annual VMT by HPMS vehicle type	2011 county-level data from FHWA

Summary: MOVES Light-duty NOx Comparison

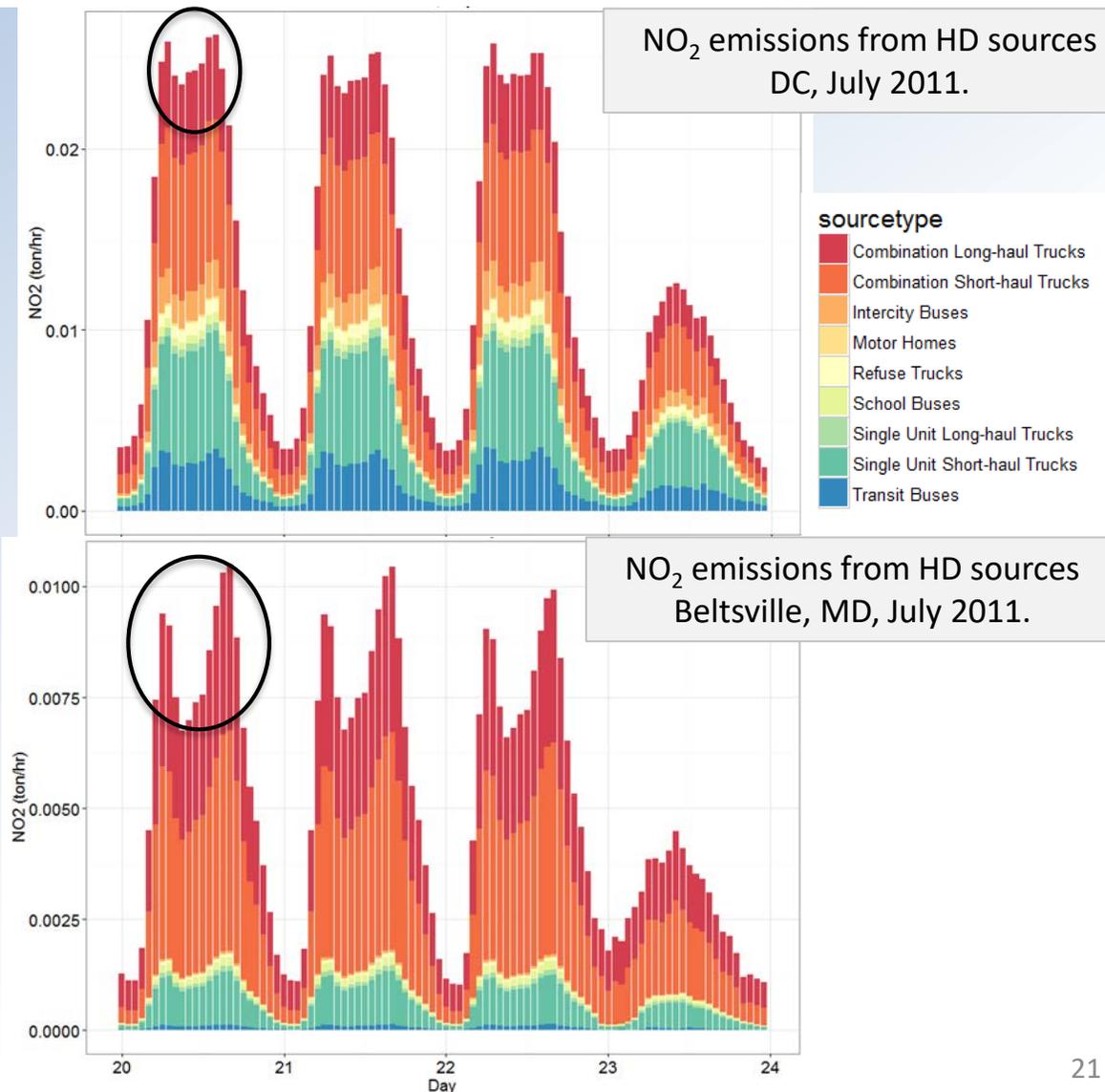
- EPA's evaluation of MOVES light-duty NOx emission rate shows mixed results:
 - California tunnel comparisons suggest MOVES fleet NOx rate is generally higher than tunnel estimates
 - Denver I/M dynamometer suggest MOVES NOx emission rates may be too high for Tier 1 passenger cars, and too low for Tier 2 passenger cars
 - Roadside RSD studies suggest MOVES light-duty NOx emission rates are low but generally within the data variability
 - MOVES gasoline consumption is within 5% of Federal Highway's fuel sales data
- Uncertainties remain. For example:
 - Pre-1994 California emission standards not modeled in tunnels or RSD
 - Uncertainty about appropriate inputs for tunnels.
- EPA has not concluded that MOVES Light Duty NOx rates are too high.
- We are continuing our investigation.

NOx Emissions and Air Quality Modeling Platform Sensitivity Analysis

- Cross-EPA effort:
 - Office of Air Quality Planning & Standards (OAQPS), Office of Transportation & Air Quality (OTAQ), Office of Research & Development (ORD)
- Evaluating sensitivity of predicted NOx emissions from the 2011 air quality modeling platform by modifying uncertain inputs, using CAMx.
- Conducted multiple sensitivity analyses, including two regarding mobile source NOx emissions in the current platform:
 - Temporal allocation of HD running emissions
 - Growth/temporal allocation of nonroad equipment

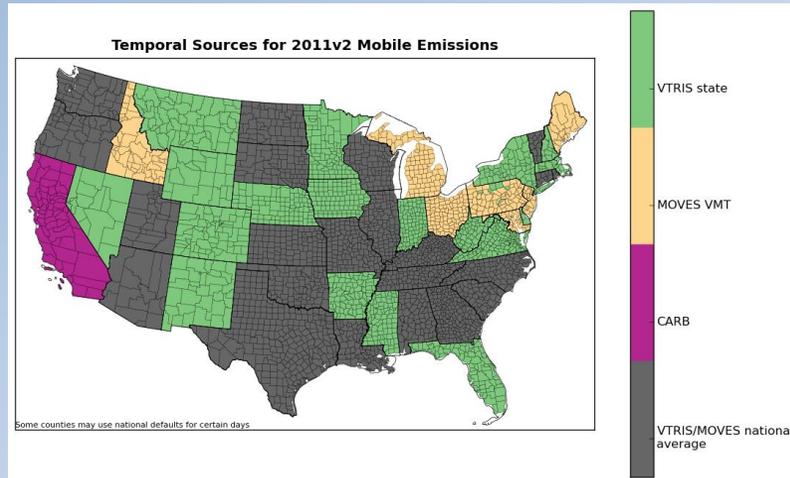
CAMx Sensitivity Simulations: Temporal Allocation of HD Running Emissions

- **Background:** EPA developed new national default hour of day profiles for LD cars/trucks and HD diesel trucks that were incorporated into the 2011 modeling platform
- National Emissions Inventory (NEI) inputs from Maryland follow the temporal pattern of light-duty traffic instead of heavy-duty traffic

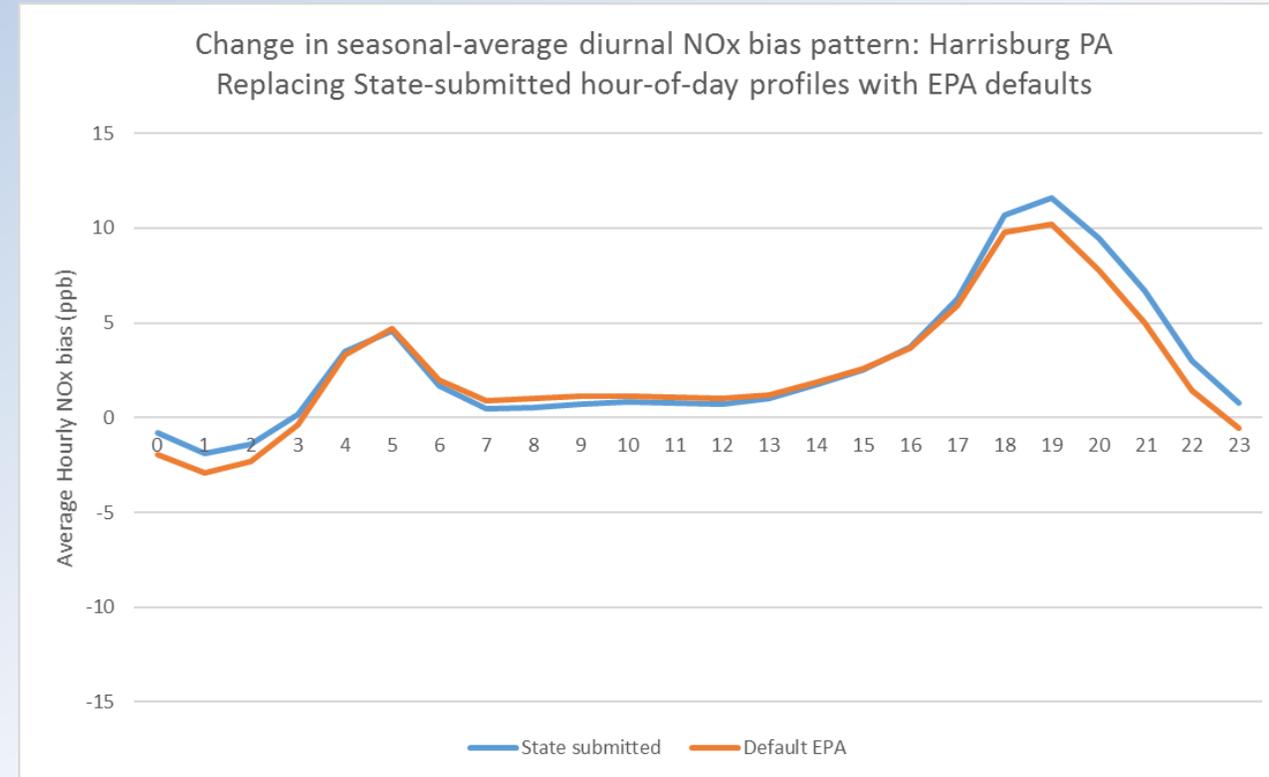


CAMx Sensitivity Simulations: Temporal Allocation of HD Running Emissions

- **Sensitivity:** Re-run CAMx for summer 2011 using national default hourly profiles for onroad LD and HD emissions
- Temporal profiles for states shaded yellow and green were updated to use the VTRIS/MOVES national average profiles



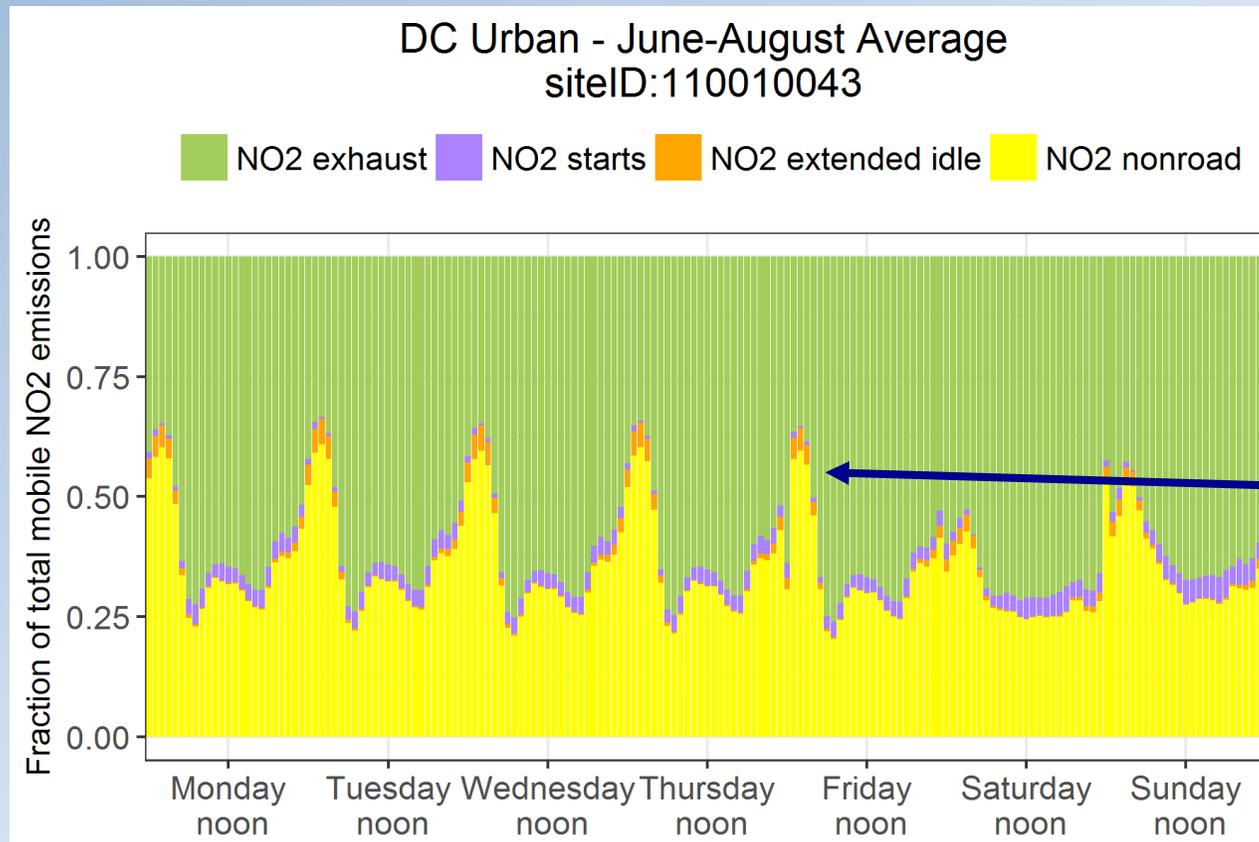
- **Results:** Change tends to slightly dampen “bridge pattern” in diurnal NO_x/NO_y biases (reducing overestimates at night), but changes small from a national perspective



Harrisburg PA shows the largest NO_x bias improvement of any site.

CAMx Sensitivity Simulations: Nonroad Emissions Evaluation

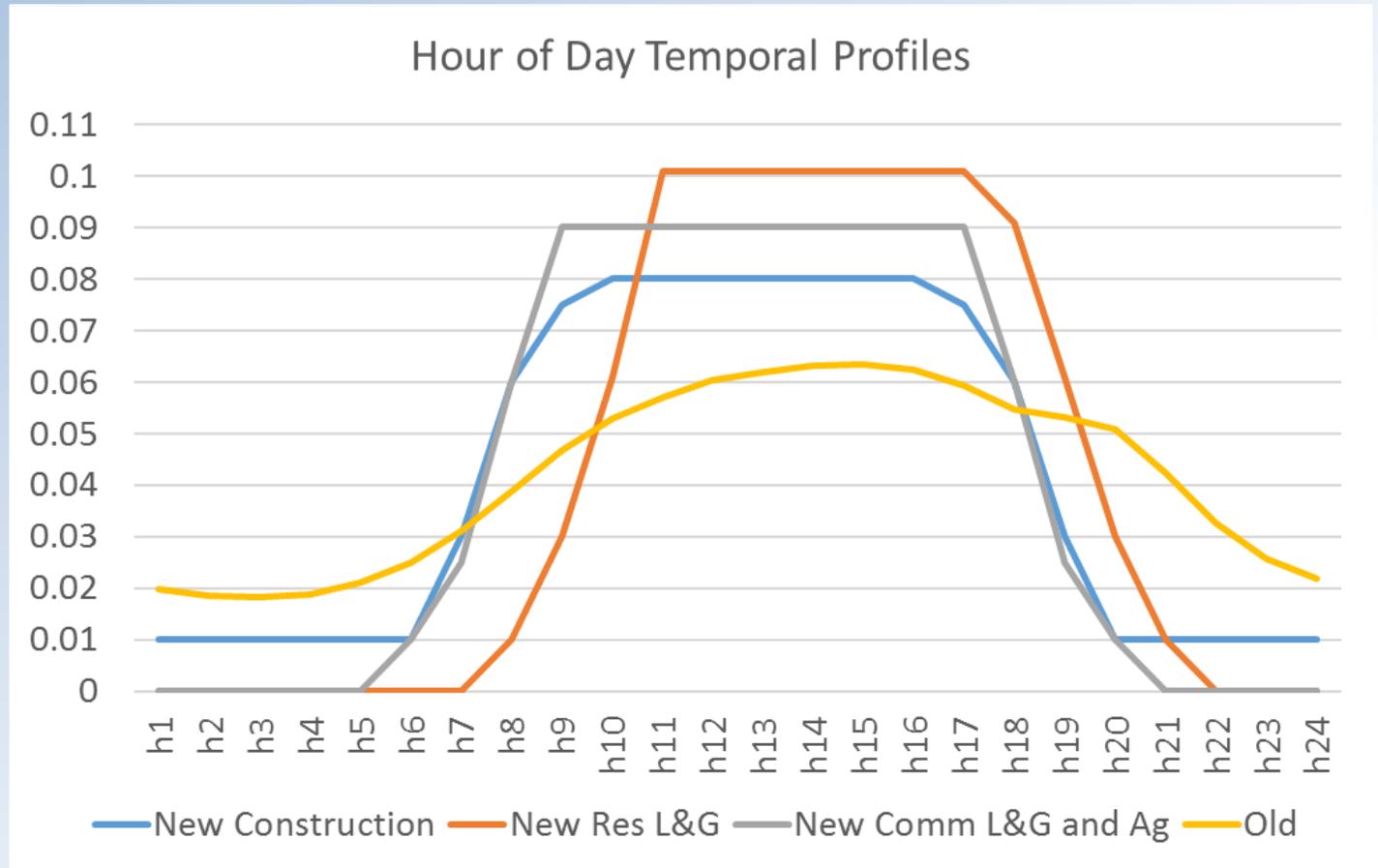
- Nonroad contribution as fraction of total mobile source emissions during the nighttime/early morning hours is significant
 - In DC/MD area, construction equipment and lawn and garden are the largest contributors
 - Source apportionment analysis suggests that this sector is a significant predictor of NO_x bias



During nighttime hours, nonroad contributed > 50% of NO₂ emissions

CAMx Sensitivity Simulations: Nonroad Emissions Evaluation

- We have identified several uncertainties in NONROAD emissions
 - Population based on growth factors from late 1990s
 - Day-of-week temporal allocation
 - Hour-of-day temporal allocation



“Old” profile has been used in prior NEIs for all L&G, Ag, and construction.

CAMx Sensitivity Simulations: Nonroad Emissions Evaluation

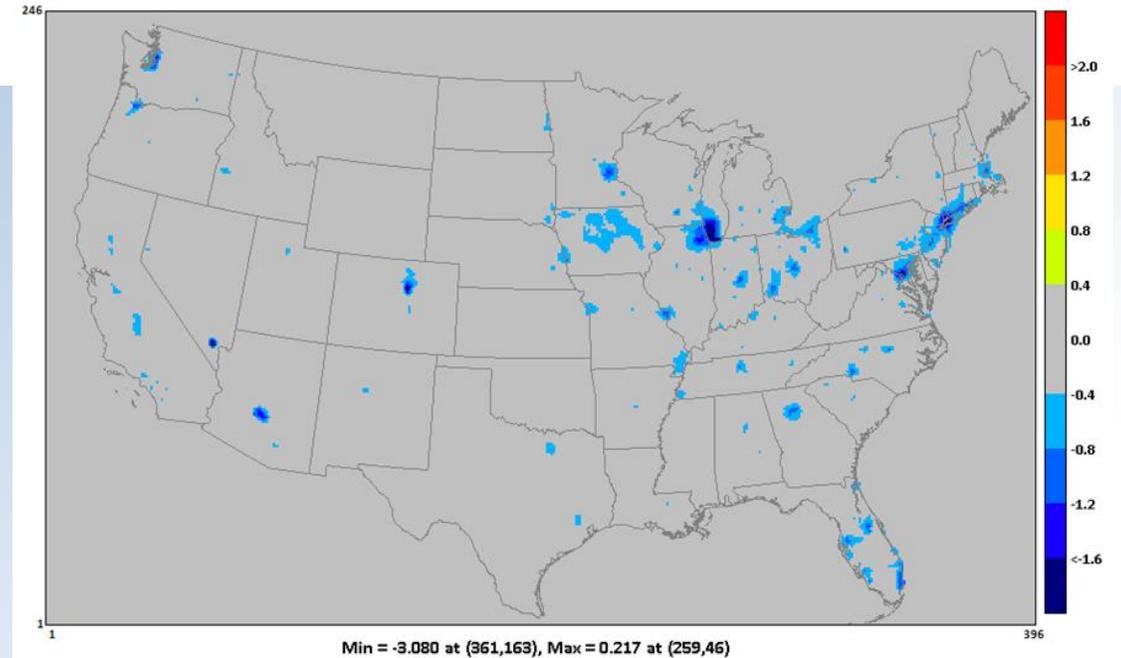
Multi-pronged sensitivity:

- Interim national average scaling factors for nonroad growth rates by sector: National reduction in 2011 nonroad NOx emissions of ~ 7%
- Revised day-of-week temporal profiles for L/G and construction
- Revised hour-of-day temporal profiles for construction, L/G and agriculture

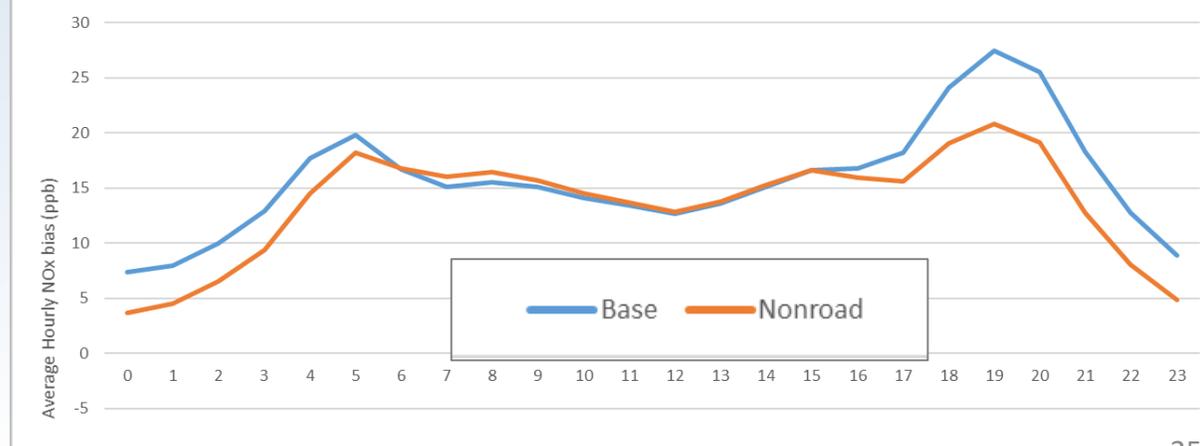
Results:

- Largest reductions in monthly average NOx in NYC, Chicago, and Baltimore/DC where reductions of 2.0 ppb are noted
- Although a small decrease in NOx national average, the change impacts NOx bias during non-daytime hours
- The single most impacted site was Bronx, NYC (see bottom, right) where lower, re-allocated nonroad emissions translate to lower NOx bias, especially in non-daytime hours

Change in July Average NOx: Impact of Nonroad Emissions Changes



Change in seasonal-average diurnal NOx bias pattern: Bronx NY
Scaled nonroad emissions w/ new temporal allocations for key sectors



Summary: EPA Cross-Office NOx Evaluation Work

- Current analysis suggests that the issue of NOx bias observed between air quality models and air quality measurements is complex and multi-faceted
 - We have not found a silver bullet to solve this issue
 - Air quality model over-predictions are likely due to multiple compounding errors— each contributing only a portion of the bias
 - Efforts have identified several plausible hypotheses, while ruling out others, for the NOx positive biases seen at certain times/locations in the modeling
 - Some of the hypotheses involve issues directly related to the mobile emissions estimates and/or their time-space allocations; others involve other model inputs such as vertical mixing depths within air quality models

Next Steps: MOVES-related Efforts

- We are continuing to evaluate MOVES NO_x light-duty gasoline emission rates, including comparing rates to additional vehicle emission studies
- We are continuing efforts to update nonroad population estimates and spatial and temporal allocation surrogates
- We are evaluating and improving the MOVES inputs used in the National Emissions Inventory
- We encourage further work in evaluating MOVES and improving MOVES inputs for all scales of modeling

Next Steps: EPA Cross-Office NOx Evaluation Work

- Evaluation of hypotheses that could lead to overestimation of NOx in the air quality model platform is ongoing.
- US EPA Conference presentations:
 - Emissions Inventory Conference special session on NOx emissions evaluations – August 18, 2017
 - Presentations will be available online
 - Community Modeling Analysis System (CMAS) conference special session on NOx emissions evaluation – Oct 23-25, 2017
 - "Leveraging Inventories, Observations and Models to Improve the Scientific Basis of Emissions"
Session at American Geophysical Union conference – Dec 11-15, 2017

References

1. McDonald, B. C., T. R. Dallmann, E. W. Martin and R. A. Harley (2012). Long-term trends in nitrogen oxide emissions from motor vehicles at national, state, and air basin scales. *Journal of Geophysical Research: Atmospheres* 117.
2. Kirchstetter, T. W., B. C. Singer, R. A. Harley, G. R. Kendall and M. Traverse (1999). Impact of California Reformulated Gasoline on Motor Vehicle Emissions. 1. Mass Emission Rates. *Environ Sci Technol* 33(2): 318-328.
3. Kean, A. J., R. F. Sawyer, R. A. Harley and G. R. Kendall (2002). Trends in Exhaust Emissions from In-Use California Light-Duty Vehicles, 1994-2001, SAE International.
4. Ban-Weiss, G. A., J. P. McLaughlin, R. A. Harley, M. M. Lunden, T. W. Kirchstetter, A. J. Kean, A. W. Strawa, E. D. Stevenson and G. R. Kendall (2008). Long-term changes in emissions of nitrogen oxides and particulate matter from on-road gasoline and diesel vehicles. *Atmospheric Environment* 42(2): 220-232. <http://dx.doi.org/10.1016/j.atmosenv.2007.09.049>.
5. Dallmann, T. R., T. W. Kirchstetter, S. J. DeMartini and R. A. Harley (2013). Quantifying On-Road Emissions from Gasoline-Powered Motor Vehicles: Accounting for the Presence of Medium- and Heavy-Duty Diesel Trucks. *Environ Sci Technol* 47(23): 13873-13881.
6. Dallmann, T. R., S. J. DeMartini, T. W. Kirchstetter, S. C. Herndon, T. B. Onasch, E. C. Wood and R. A. Harley (2012). On-Road Measurement of Gas and Particle Phase Pollutant Emission Factors for Individual Heavy-Duty Diesel Trucks. *Environ Sci Technol* 46(15): 8511-8518.
7. Fujita, E. M., D. E. Campbell, B. Zielinska, J. C. Chow, C. E. Lindhjem, A. DenBleyker, G. A. Bishop, B. G. Schuchmann, D. H. Stedman and D. R. Lawson (2012). Comparison of the MOVES2010a, MOBILE6.2, and EMFAC2007 mobile source emission models with on-road traffic tunnel and remote sensing measurements. *Journal of the Air & Waste Management Association* 62(10): 1134-1149.
8. http://www.feat.biochem.du.edu/light_duty_vehicles.html
9. <https://www.epa.gov/sites/production/files/2017-02/documents/conventional-gasoline.pdf>
10. Light-Duty Vehicles and Light-Duty Trucks: Tier 0, Tier 1, and National Low Emission Vehicle (NLEV) Implementation Schedule <https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockkey=P100O9ZN.pdf>
11. <https://www.epa.gov/air-emissions-inventories/2011-national-emissions-inventory-nei-technical-support-document>