Framework for Context-Sensitive Spatially- and Temporally-Resolved Onroad Mobile Source Emissions Inventories

H. Christopher Frey[a], Nagui Rouphail[b], Xuesong Zhou[c], Bin Liu[a], Hao Lei[d], Jeffrey Taylor[d], Shams Tanvir[b]

NC STATE UNIVERSITY

[a] Dept. of Civil, Construction, and Environmental Engineering
[b] Institute for Transportation Research and Education
North Carolina State University
[c] **Arizona State University**
[d] **University of Utah**

For Presentation at:
U.S. Environmental Protection Agency
Science To Achieve Results (STAR) Webinar Series

June 12, 2017

Major Accomplishments

- Evaluation of MOVES model in comparison to independent empirical data
- Development of “MOVES Lite”
- Incorporation of “MOVES Lite” into DTALite dynamic traffic simulator
- Simulation experiments to test traffic management strategies and their effect on emissions

Key Publications

- Liu, B., and H.C. Frey, “Variability in Light Duty Gasoline Vehicle Emission Factors from Trip-Based Real-World Measurements,” *Environmental Science & Technology*, 49(20):12525-12534 (2015)
- Frey, H.C., and B. Liu, “Development and Evaluation of a Simplified Version of MOVES for Coupling with a Traffic Simulation Model,” Paper 13-1201, Proceedings of 92nd Annual Meeting of the Transportation Research Board, Washington, DC, January 13-17, 2013.
- Liu, B., and H.C. Frey, “Quantification and Application of Real-World Light Duty Vehicle Performance Envelope for Speed and Acceleration,” *Transportation Research Record*, 2503:128-136 (2015)
- Zhou, X., S. Tanvir, H. Lei, J. Taylor, B. Liu, N.M. Rouphail, and H.C. Frey, “Integrating a Simplified Emission Estimation Model and Mesoscopic Dynamic Traffic Simulator to Efficiently Evaluate Emission Impacts of Traffic Management Strategies,” *Transportation Research – Part D*, 37(2015):123-136

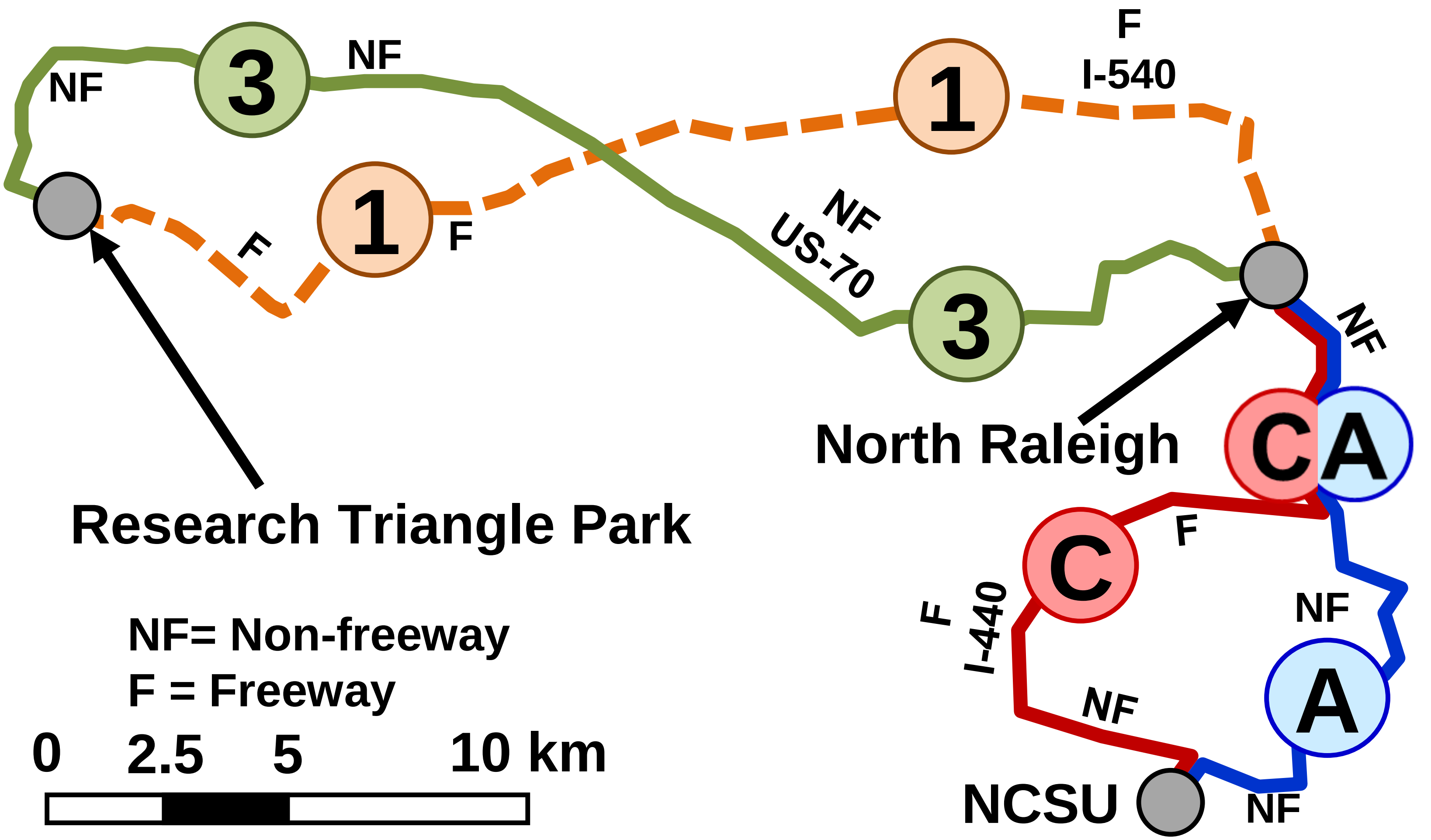
Model Evaluation

- MOVES has undergone some evaluation
  - Chassis dynamometer data: short duration, limited range of driving cycles
  - Remote sensing data: location-specific 'snapshots'
  - Tunnel studies: location-specific, difficult to resolve for individual types of vehicles
- Approach here: use independent path-based data from in-use driving for 100 vehicles each measured over 110 miles

NC STATE UNIVERSITY

Portable Emission Measurement System

Routes


NF
3
NF
1
F
I-540
1
F
F
NF
US-70
3
NF
North Raleigh
C
A
Research Triangle Park
C
F
F
I-440
NF
NF
A
NCSU
NF
NF= Non-freeway
F = Freeway
0
2.5
5
10 km

Vehicle Specific Power (VSP)

$$VSP = v\left\{(1+\varepsilon)a + g\left(\frac{r}{100}\right) + gC_r\right\} + \frac{1}{m}\frac{\rho_{air}}{2}AC_dv^3$$

a = vehicle acceleration (m/s^2)
A = vehicle frontal area (m^2)
C_d = aerodynamic drag coefficient
C_r = rolling resistance coefficient (0.0135)
g = acceleration of gravity (9.81 m/s^2)
m = vehicle mass (metric tons)

r = road grade (%)
v = vehicle speed (m/s)
VSP = Vehicle Specific Power (kW/ton)
ε = rotational masses factor (~ 0.1)
ρ_{air} = air density (1.207 kg/m^3 at 20 ºC)

For a typical light duty vehicle:

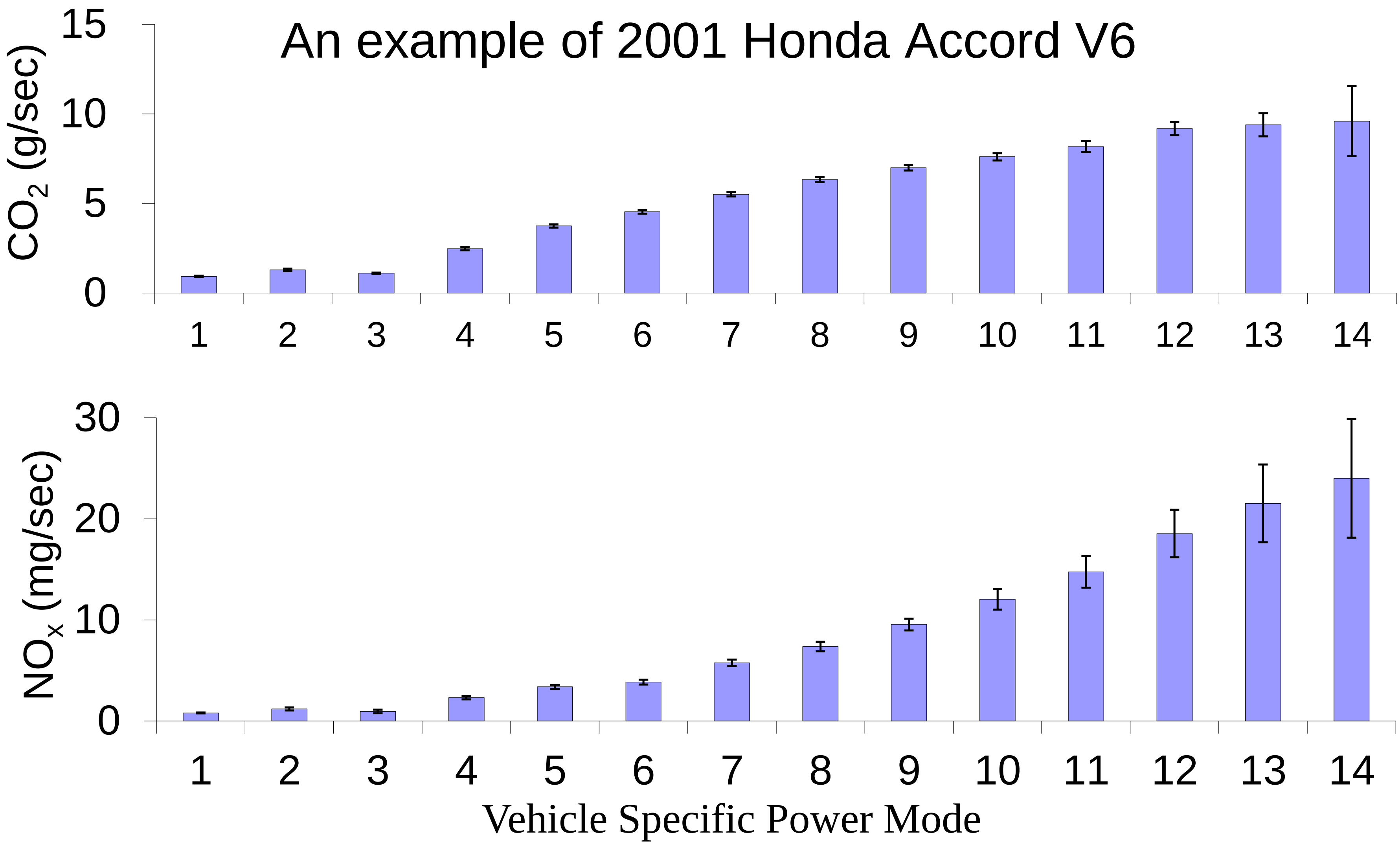
$$VSP = v\left\{1.1a + 9.81\left(\frac{r}{100}\right) + 0.132\right\} + 0.000302v^3$$

Definition of VSP Modes

	VSP mode	Definition (kW/ton)
Deceleration or Downhill	1	VSP < -2
	2	-2 ≤ VSP < 0
Idle	3	0 ≤ VSP < 1
Cruising, Acceleration, or Uphill	4	1 ≤ VSP < 4
	5	4 ≤ VSP < 7
	6	7 ≤ VSP < 10
	7	10 ≤ VSP < 13
	8	13 ≤ VSP < 16
	9	16 ≤ VSP < 19
	10	19 ≤ VSP < 23
	11	23 ≤ VSP < 28
	12	28 ≤ VSP < 33
	13	33 ≤ VSP < 39
	14	39 ≤ VSP

Frey et al. (2002), "Methodology for Developing Modal Emission Rates for EPA's Multi-Scale Motor Vehicle and Equipment Emission System", EPA420-R-02-027, Prepared by NC State for U.S. EPA

Example of VSP Modal CO_2 and NO_x Emission Rates



Characteristics of Measured Vehicles

- 100 Light Duty Gasoline Vehicles
- 63 Passenger Cars (PC)
- 37 Passenger Trucks (PT)
- 1996 to 2013 model years
- 0 to 14 years of age
- 600 to 230,000 accumulated miles
- 1.3 to 5.4 L
- 1,700 to 7,400 lb gross vehicle weight

Empirically-Based Emission Factors for Each Vehicle and Driving Cycle

$$EF_{v,c} = \frac{\left(\sum ER_{m,v} \bullet f_{m,c}\right) \bullet T_c}{L_c}$$

$EF_{v,c}$ = cycle average emission factor for vehicle *v* and cycle *c* (g/mi);

$ER_{m,v}$ = average emission rate for VSP mode *m* and vehicle *v* (g/s);

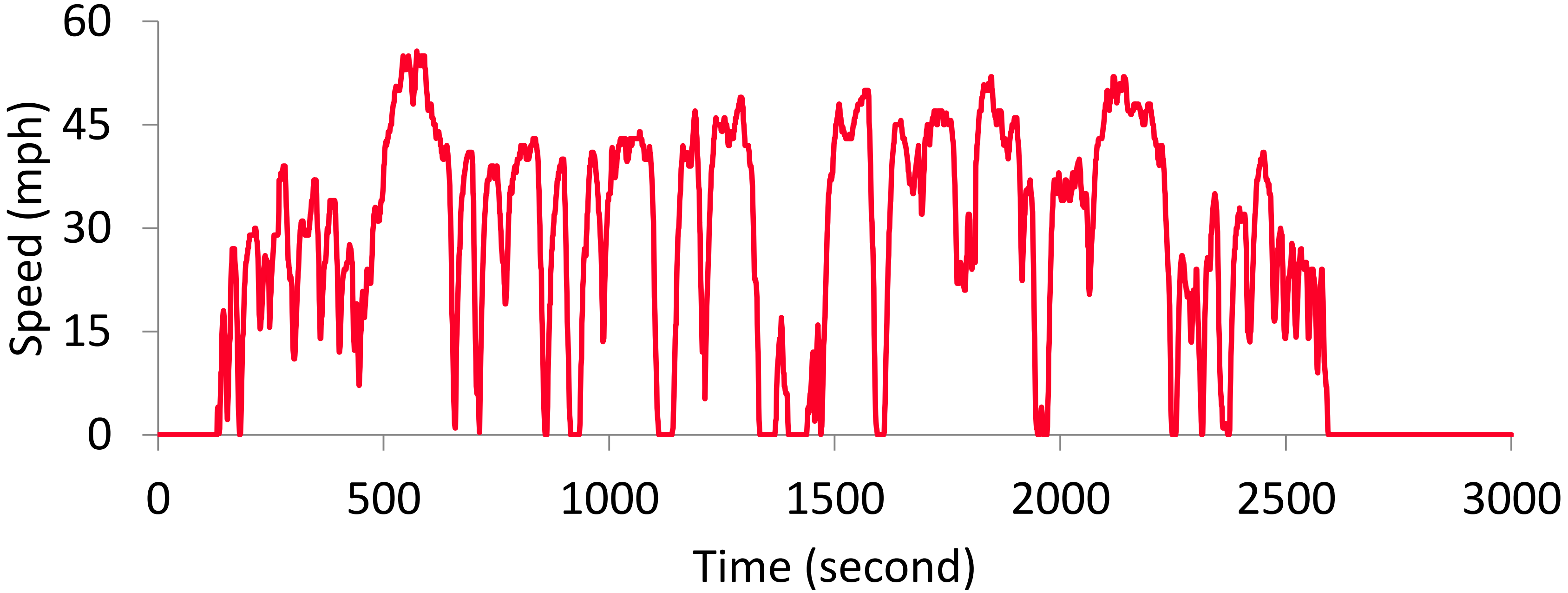
$F_{m,c}$ = fraction of time in VSP mode *m* for cycle *c;*

T_c = Total travel time for cycle *c* (sec);

L_c = Total travel distance for cycle *c* (mi);

Project Level MOVES Emission Factors

- User enters a driving schedule.
- Based on second-by-second speed and road grade.



An example of 2000 Mitsubishi Galant on Route A

Example of MOVES Input Data

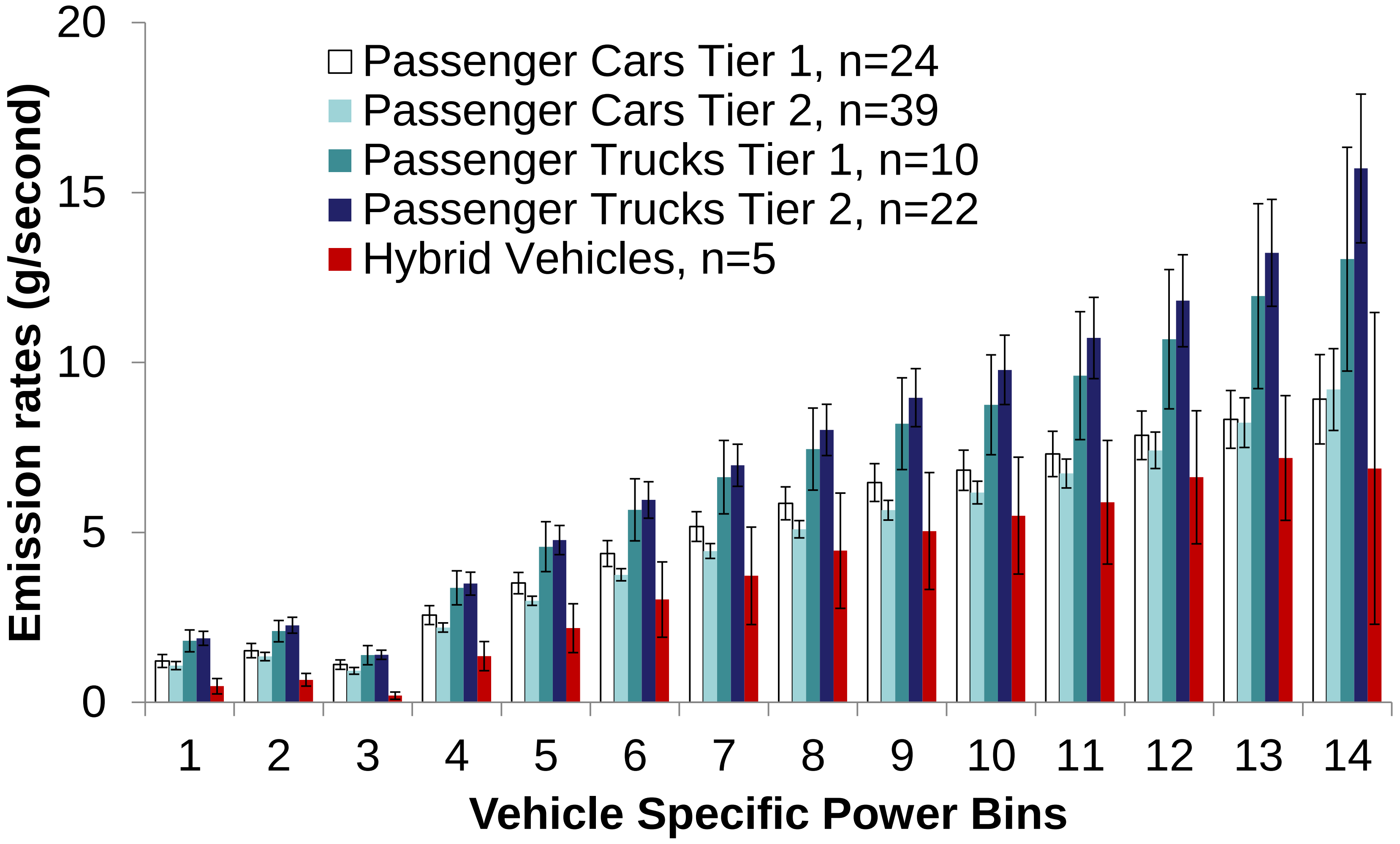
Example based on 2000 Mitsubishi Galant and Route A

Meteorological Data	97.3 ^{o}F; 32% Relative Humidity
Vehicle Type	Passenger Car
Age Distribution	10 years, Calendar Year 2010
Driving Schedule	Empirical data: Route A
Link Length	20.3 miles
Fuel	Gasoline
I/M Program	Wake County, NC

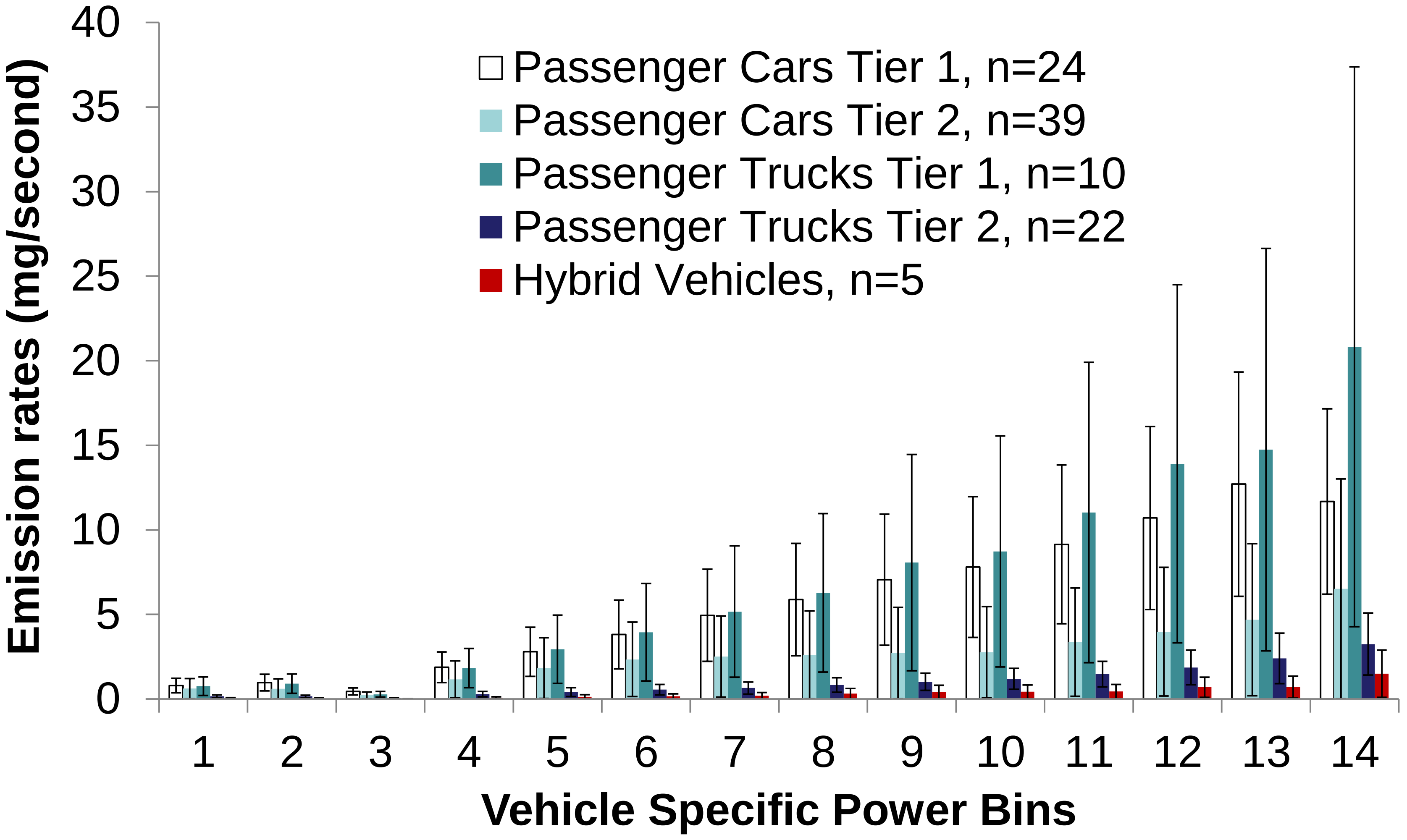
Objectives for Model Evaluation

- Evaluate MOVES sensitivity to:
  - vehicle type
  - driving cycles
  - road types
  - model year
  - age
- Focus is on similarity in relative trends

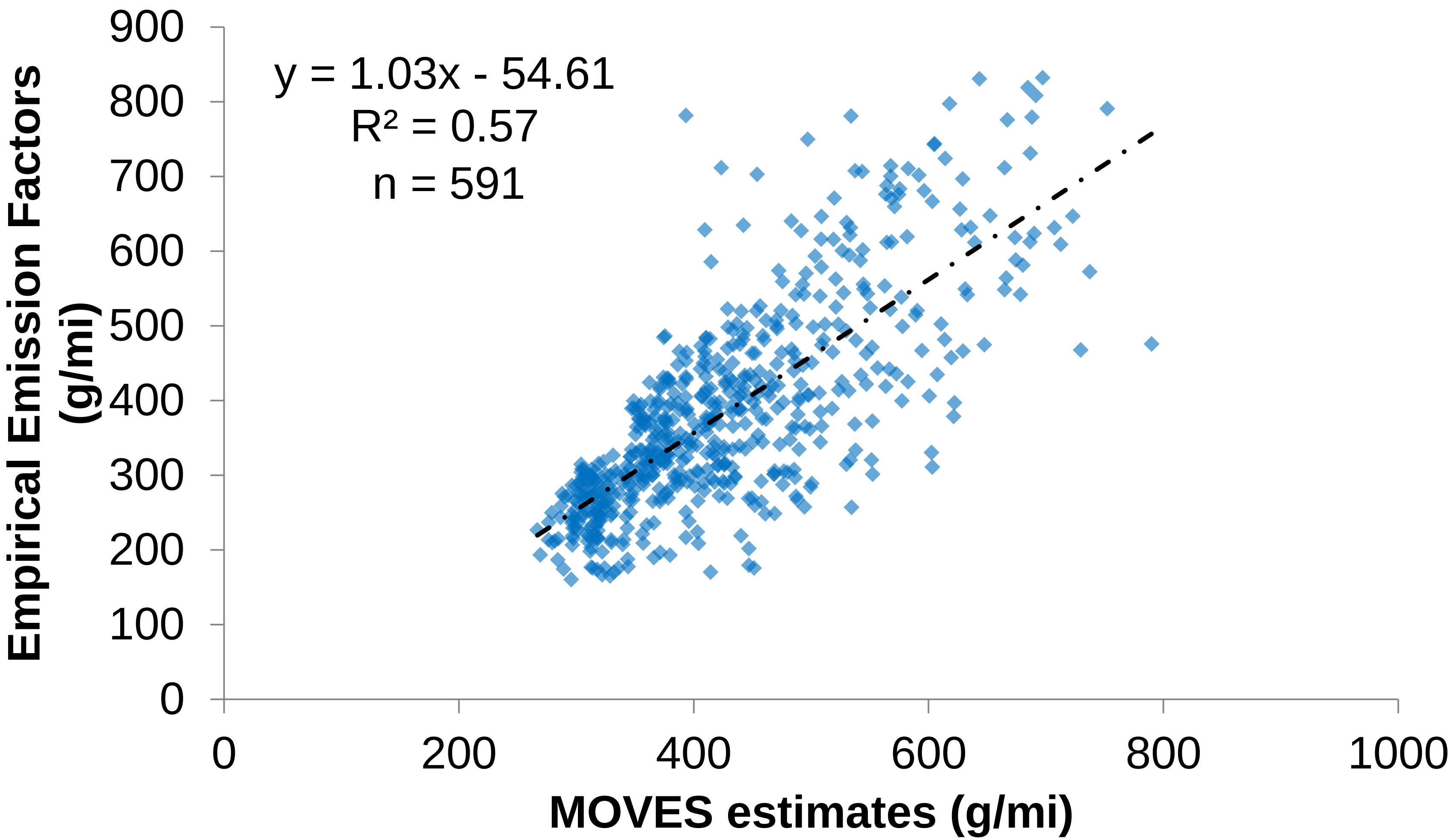
Measured CO_2 Modal Average Emission Rates



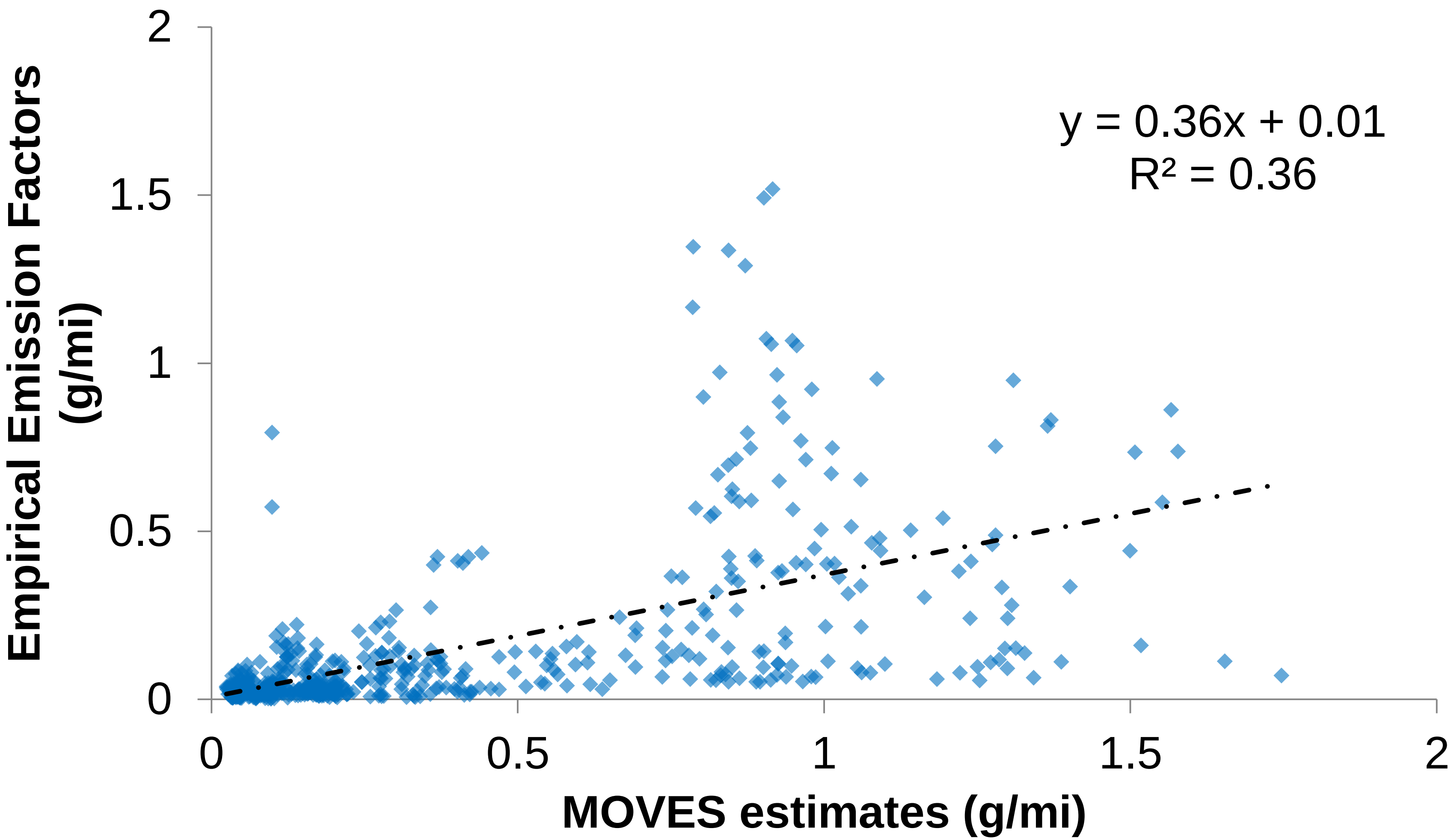
Measured NO_x Modal Average Emission Rates



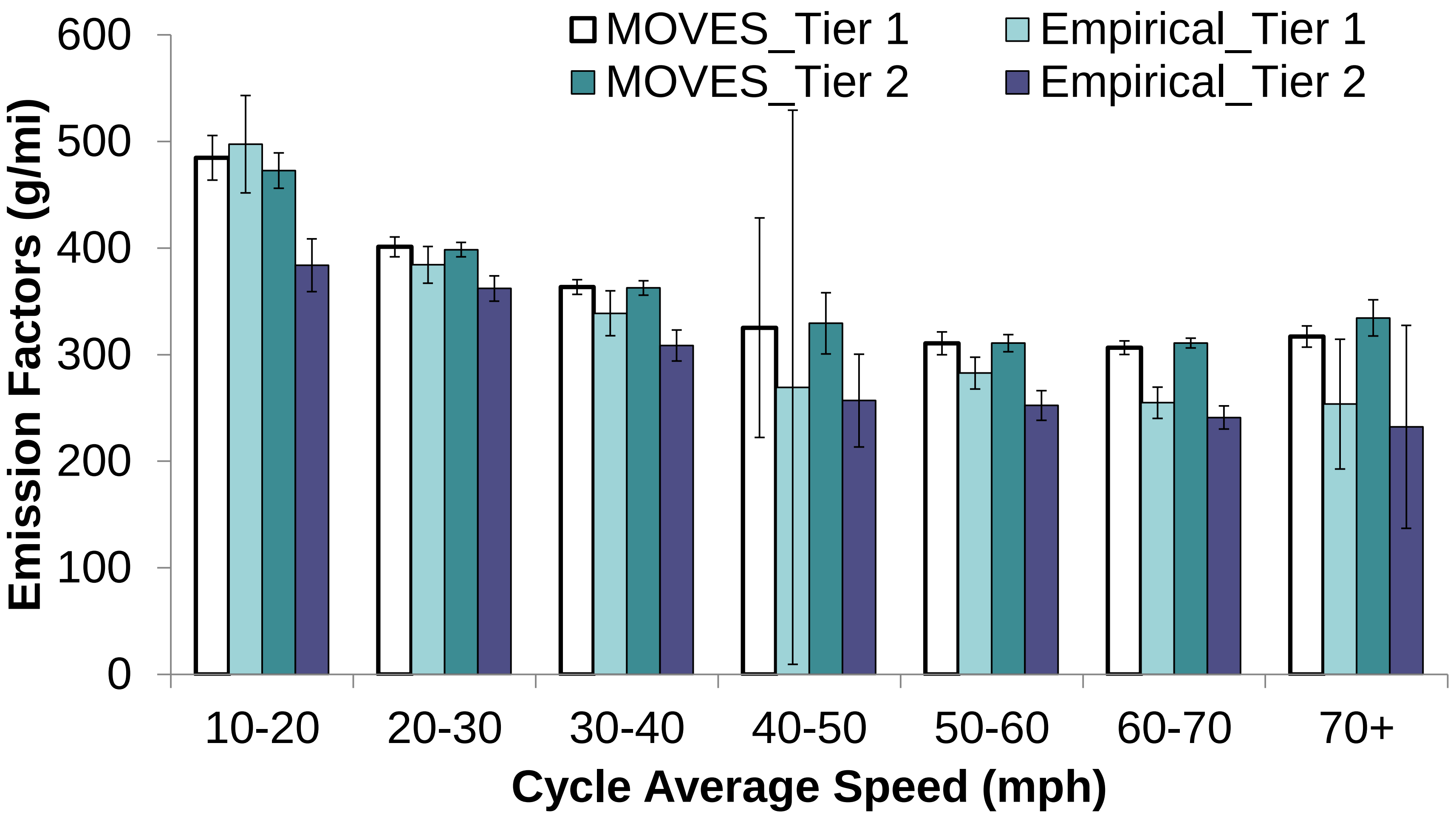
CO_2 Cycle Average Emission Factors



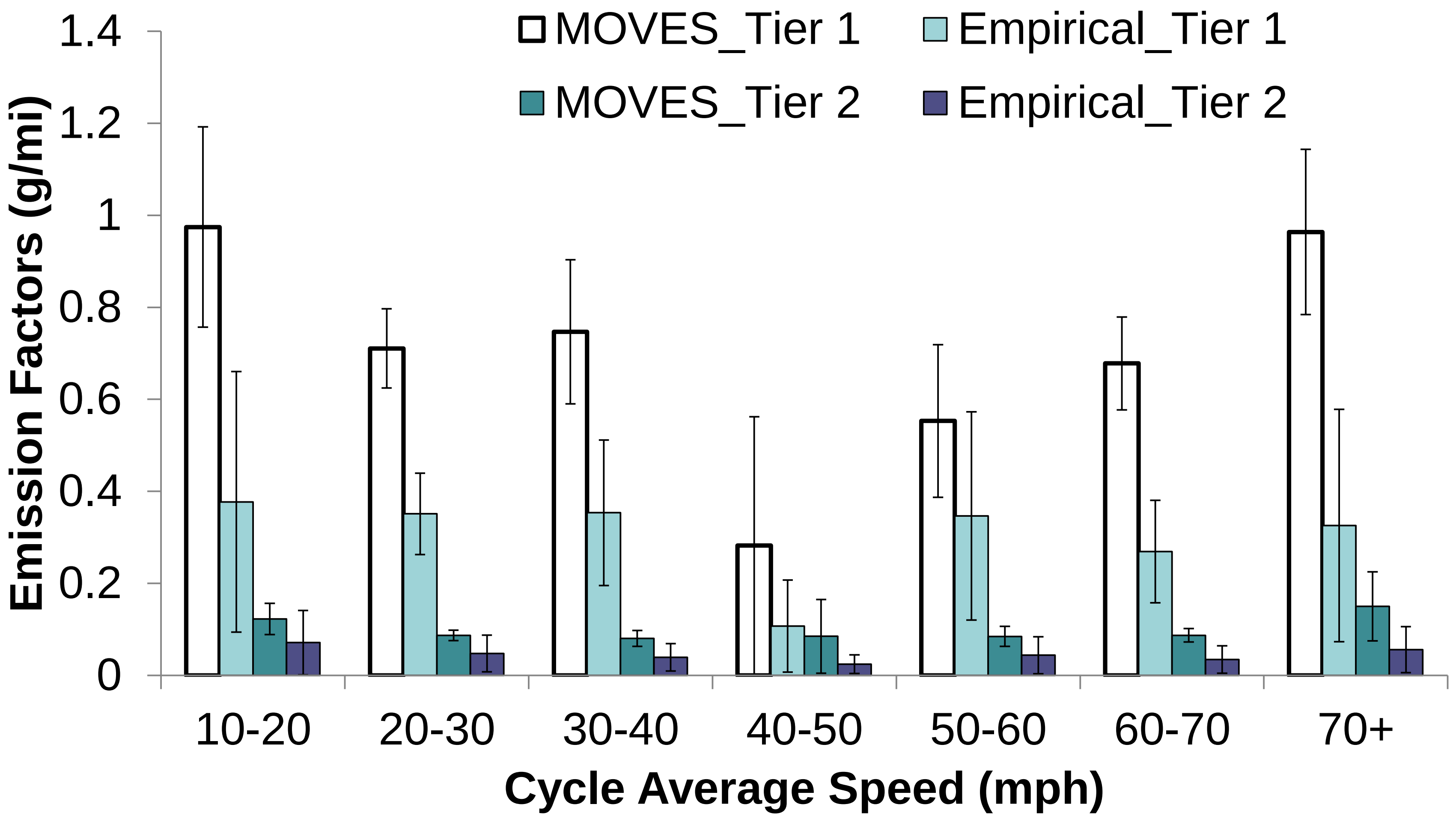
NO_x Cycle Average Emission Factors



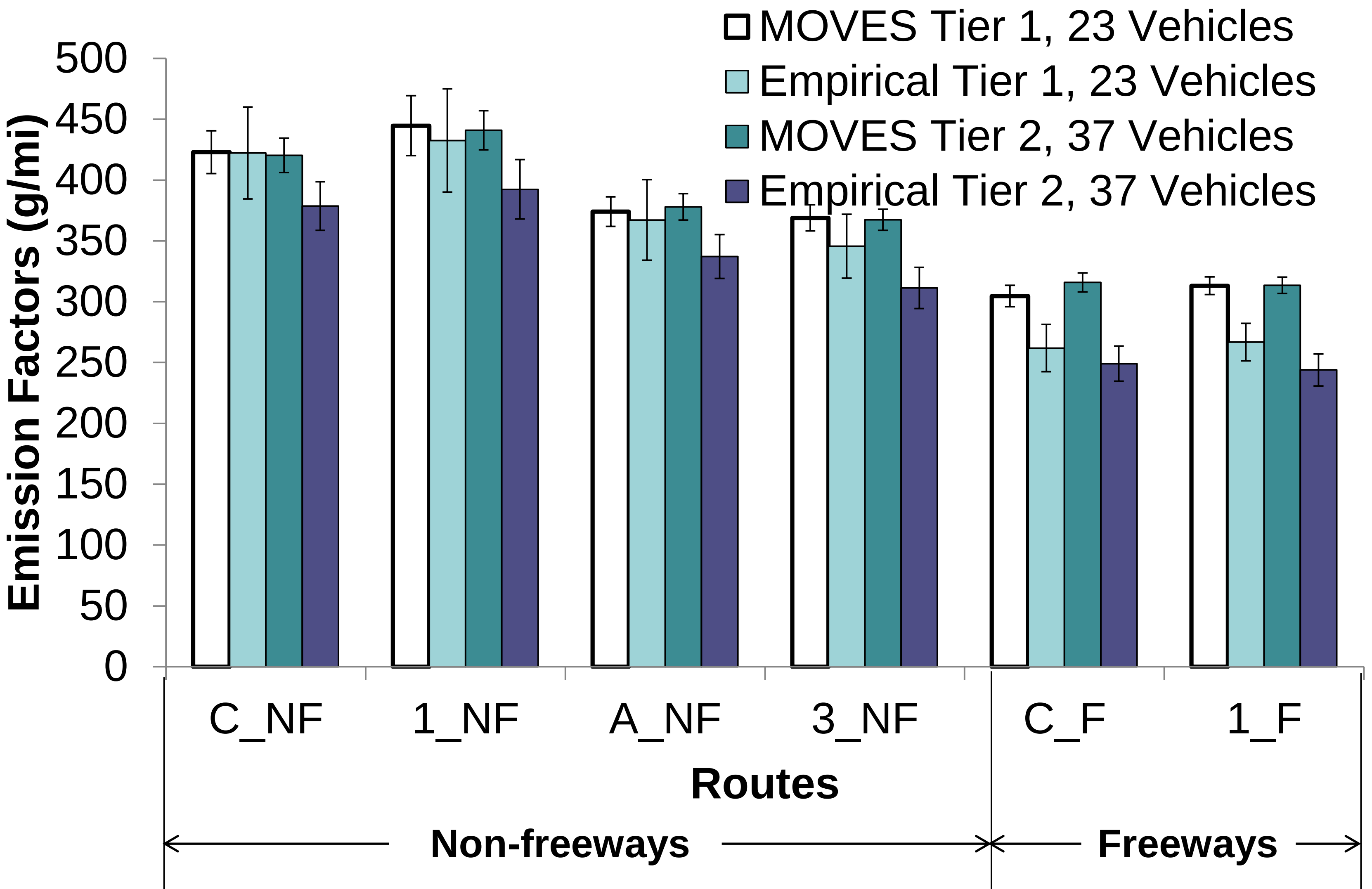
CO_2 Emission Factors by Speed Ranges



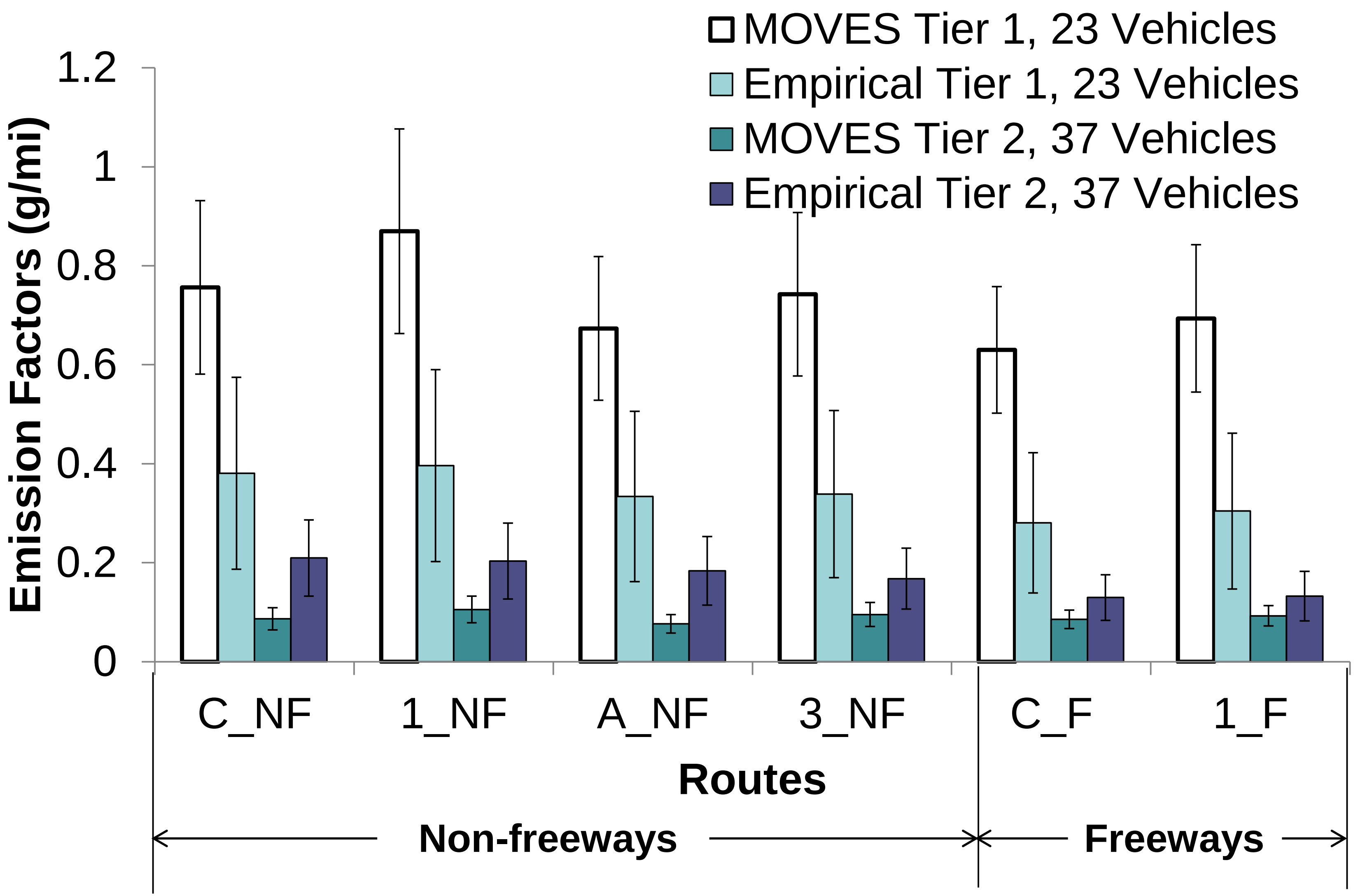
NO_x Emission Factors by Speed Ranges



CO_2 Emission Factors for Road Type



NO_x Emission Factors for Road Type



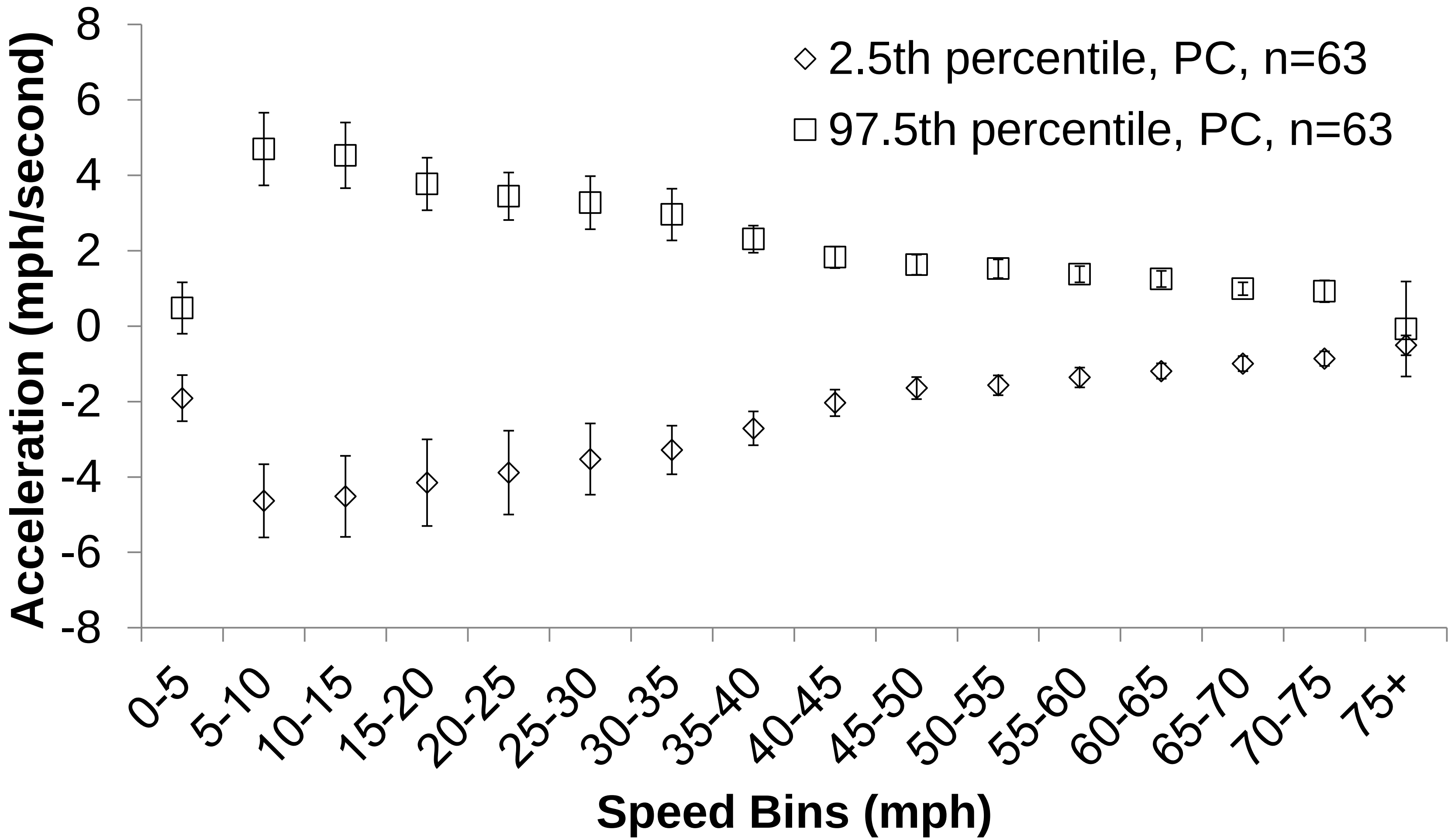
Results of MOVES Evaluation

- MOVES overall trend is consistent with empirical data
- MOVES may be over-estimating NO_x emission rates
- MOVES does not account for HEVs

Quantification of Vehicle Activity for Evaluation of Traffic Simulation Models

- Do all measured vehicles have the capability to operate on any observed cycle?
- Speed and acceleration generated from traffic simulation models needs to be evaluated and calibrated

Performance Envelope: Passenger Cars

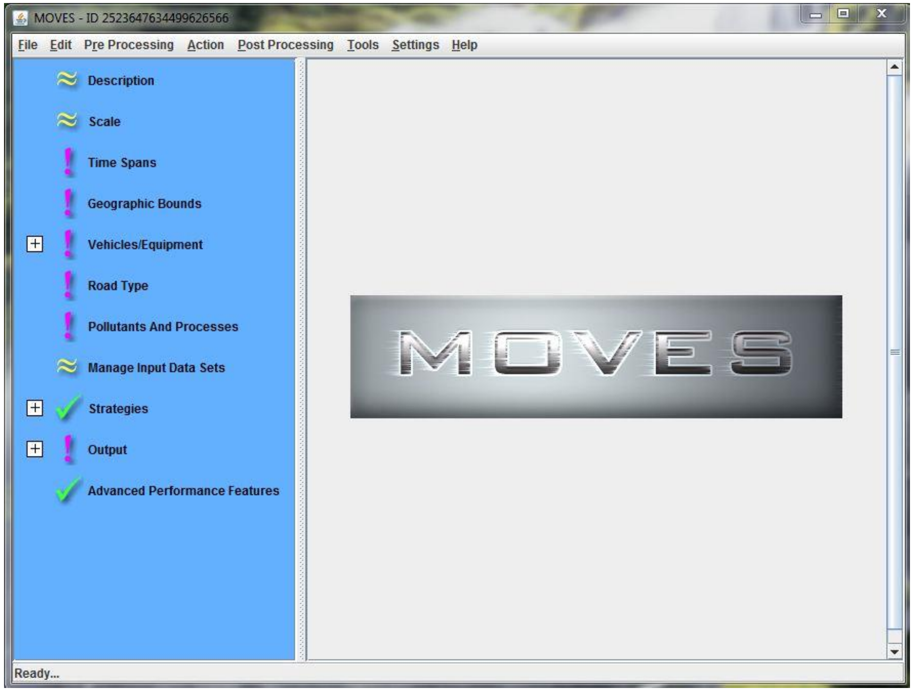


Performance Envelope Findings

- Performance envelopes are approximately similar for PCs, PTs, and HEVs.
- The marginal distribution of acceleration is dependent on speed
- Traffic simulation models should realistically estimate 1 Hz speed trajectories to enable accurate emissions estimation

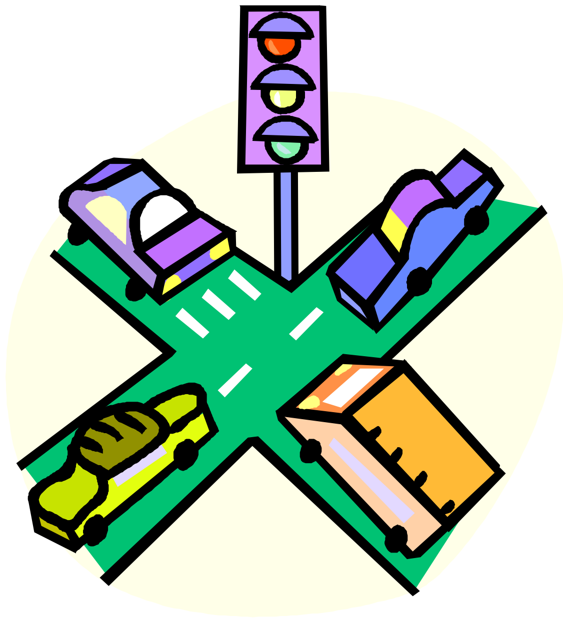
Development of “MOVES Lite”

- The U.S. EPA Motor Vehicle Emission Simulator (MOVES) is a computationally and data intensive model for estimating vehicle emission factors.

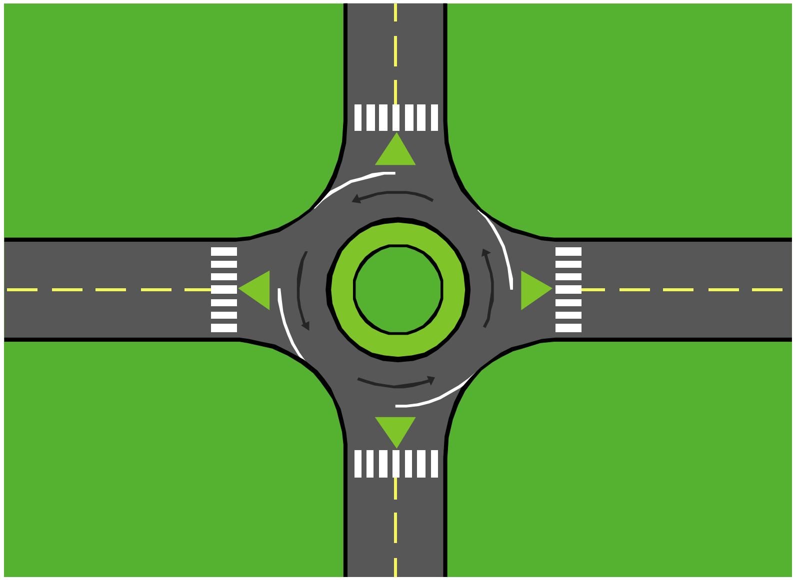


Motivation

- Traffic Simulation Models (TSMs) quantify the effect of infrastructure design and traffic control measures (TCMs) on vehicle dynamics (i.e. speed and acceleration of individual vehicles).

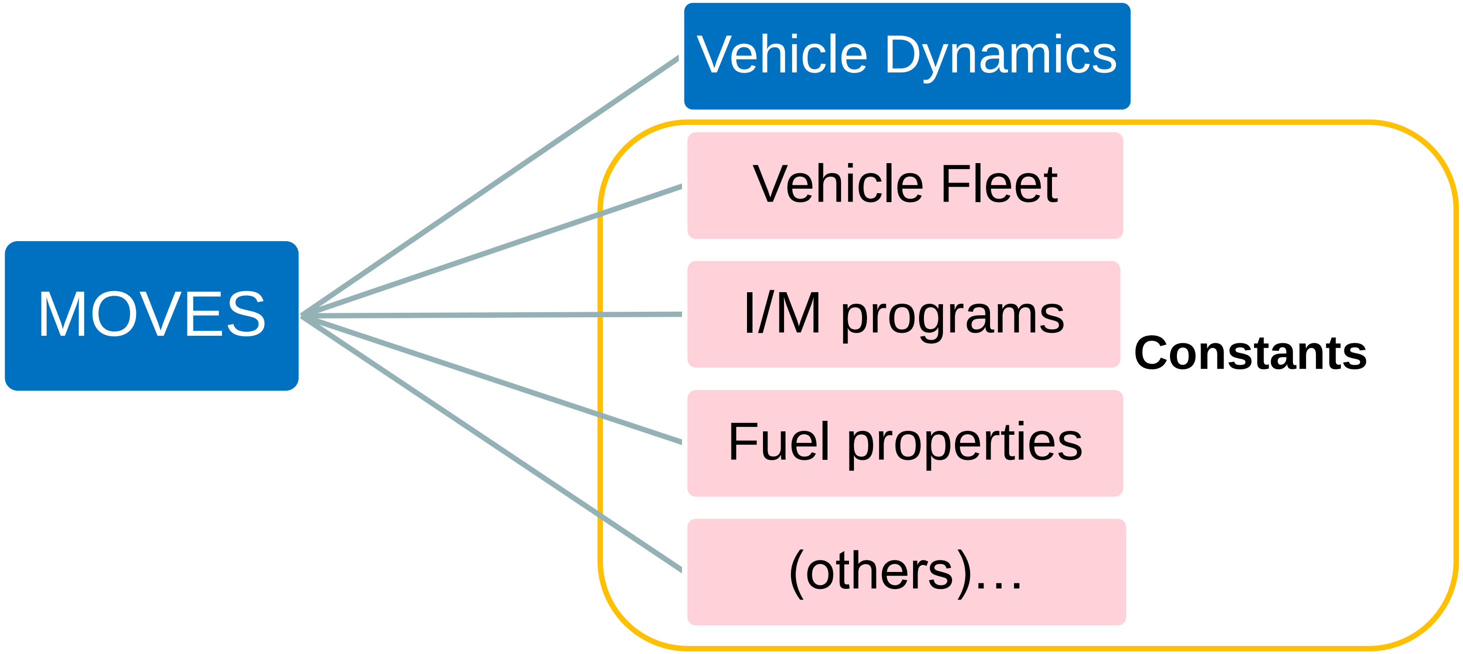


vs.



Motivation

- Because TSMs typically simulate only a few hours of vehicle activity, it is not necessary to dynamically simulate the effect of constant factors such as fuel properties and inspection/maintenance programs.



Objectives

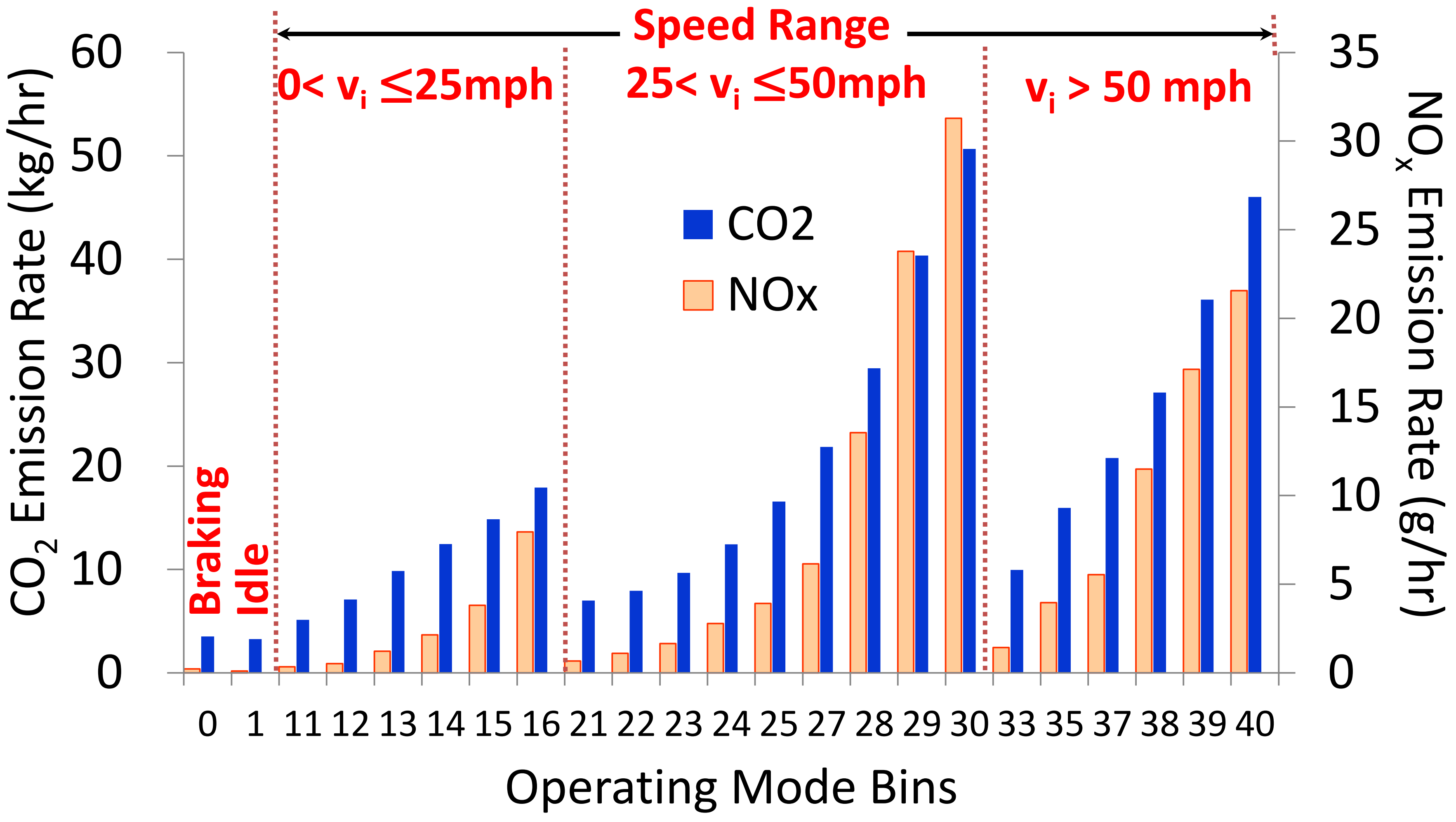
- Develop a simplified MOVES model that can be efficiently coupled with TSMs
- Evaluate the accuracy of the simplified model
- Evaluate the sensitivity of the simplified model to variations in driving cycles

Definition of MOVES Operating Mode Bins by Speed and VSP Ranges

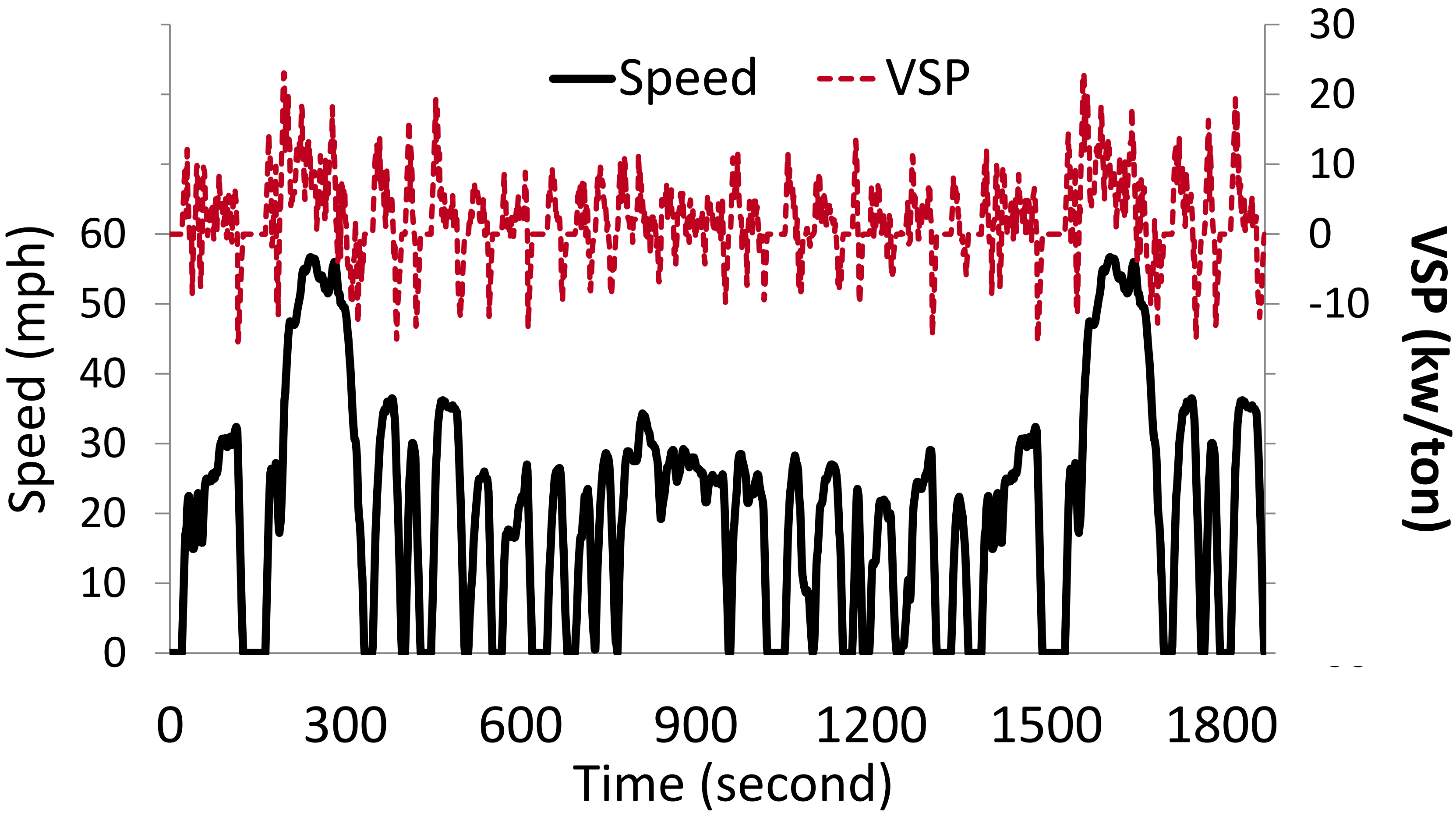
0 mph< v_i ≤25 mph		25 mph < v_i ≤50 mph		v_i >50 mph	
OpMode ID	Description	OpMode ID	Description	OpMode ID	Description
11	VSP< 0	21	VSP< 0		
12	0≤VSP< 3	22	0≤VSP< 3		
13	3≤VSP< 6	23	3≤VSP< 6	33	VSP< 6
14	6≤VSP< 9	24	6≤VSP< 9	35	6≤VSP<12
15	9≤VSP<12	25	9≤VSP<12		
16	12≤VSP	27	12≤VSP<18	37	12≤VSP<18
Other:		28	18≤VSP<24	38	18≤VSP<24
0	Braking	29	24≤VSP<30	39	24≤VSP<30
1	Idling	30	30≤VSP	40	30≤VSP

v_i: instantaneous speed of the i[th] second

Emission Rates for Operating Mode Bins in MOVES Default Database: 5 yr old Passenger Cars



Speed and Vehicle Specific Power (VSP) for Federal Test Procedure (FTP)



NC STATE UNIVERSITY

Simplified Model
Cycle Average Emission Rate

- Simplified Model:

$$CE_{p,c} = \sum_{v} \left\{ \left[\sum_{a} \left(EF_{p,b,a,v} \times CCF_{p,c,a,v} \times f_{a,v} \right) \right] \times f_{v} \right\} \quad (1)$$

$CE_{p,c,}$	=	cycle average emission factor for pollutant p, for any arbitrary driving cycle c, for a fleet of vehicles with mixed types and ages, gram/mi
$EF_{p,b,a,v}$	=	base emission rate for pollutant p, for base cycle b, age a, vehicle type v, gram/mi
$CCF_{p,c,a,v}$	=	cycle correction factor for pollutant p, driving cycle c, age a, vehicle type v
$f_{a,v}$	=	age fraction for age a and vehicle type v
f_{v}	=	vehicle type fraction for vehicle type v

Estimating the Cycle Correction Factor

$$CCF_{p,c,a,v} = \left(\frac{\left(\sum_m f_m^c \times ER_{p,a,v,m}\right)}{\left(\sum_m f_m^b \times ER_{p,a,v,m}\right)} \right) \left(\frac{V^b}{V^c} \right) \quad (2)$$

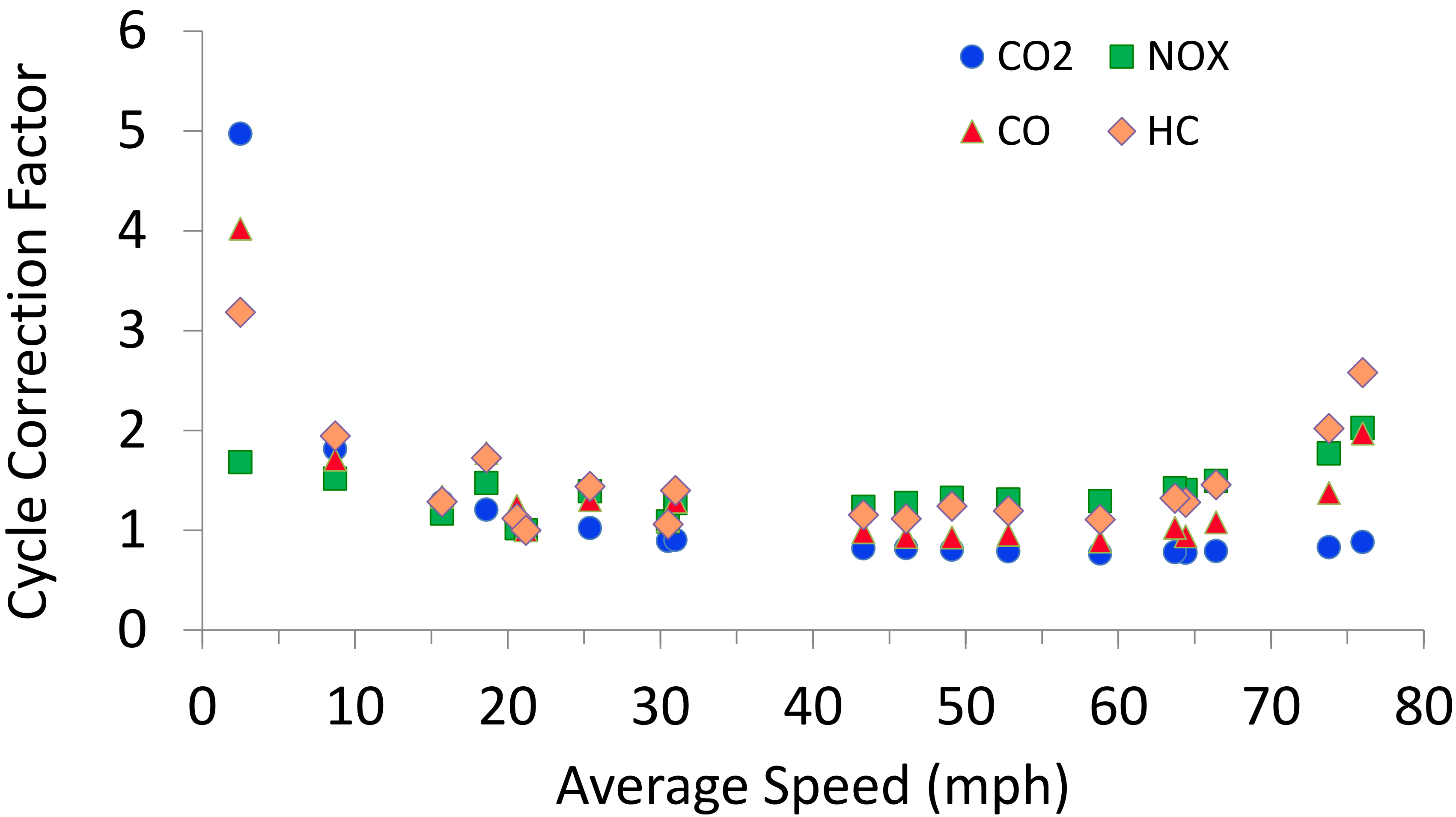
$ER_{p,a,v,m}$	=	default emission rate for pollutant p, age a, vehicle type v, in operating mode bin m, g/hr
$f_m{}^c$	=	fraction of time in OpMode bin m in cycle c
$f_m{}^b$	=	fraction of time in OpMode bin m for base cycle b
V^c	=	cycle average speed for cycle c, mph
V^b	=	cycle average speed for base cycle b, mph

Emission Factor Case Study

- Passenger Cars, 5 years old, Gasoline, Calendar year 2011
- 18 MOVES default driving cycles
- Base Cycle: Federal Test Procedure (FTP)
- Scenario Assumptions:
  - Ambient Temperature: 65 ^{o}F
  - Gasoline
- Estimate cycle average emission factors using simplified model
- Evaluate the accuracy of the simplified model compared to MOVES results

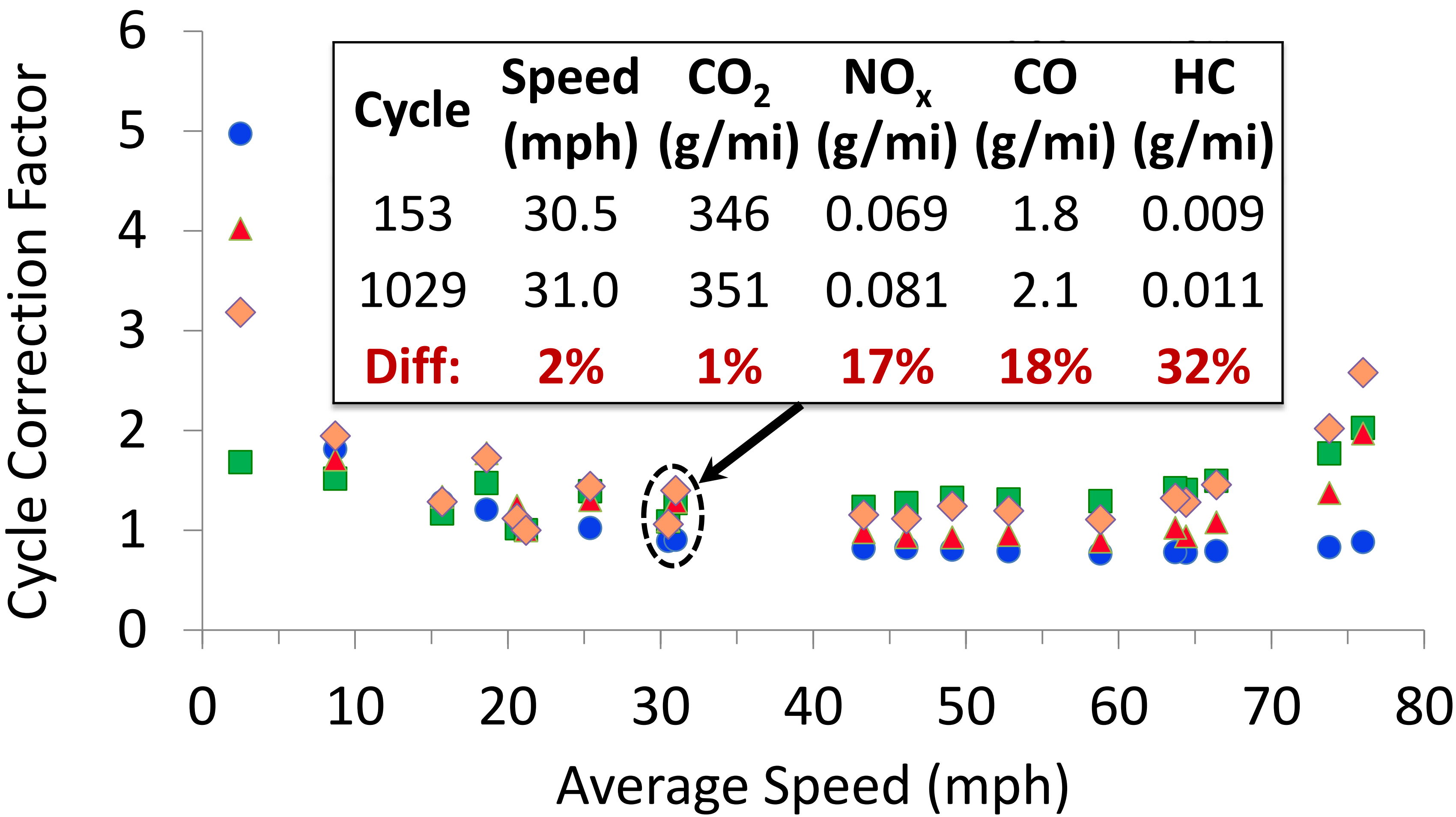
NC STATE UNIVERSITY

Cycle Correction Factors for 18 Driving Cycles



Calendar year 2011, 5 year old gasoline passenger car

Different Emission Rates for Cycles with Similar Average Speeds



Cycle	Speed (mph)	CO_2 (g/mi)	NO_x (g/mi)	CO (g/mi)	HC (g/mi)
153	30.5	346	0.069	1.8	0.009
1029	31.0	351	0.081	2.1	0.011
Diff:	**2%**	**1%**	**17%**	**18%**	**32%**

Calendar year 2011, 5 year old gasoline passenger car

Comparing Simplified Model and MOVES

Cycle Ave. Speed (mph)	CO_2			NO_x		
	MOVES (g/mi)	Simplified Model (g/mi)	% Diff.	MOVES (mg/mi)	Simplified Model (mg/mi)	% Diff.
2.5	1930	1930	0.35	39	39	0.39
30.5	347	347	-0.01	28	28	0.02
46.1	319	319	0.03	36	36	0.04
66.4	308	308	-0.05	47	47	0.00
73.8	323	323	-0.06	60	60	-0.14

Calendar year 2011, 5 year old gasoline passenger car

Average of Errors of the Simplified Model

Vehicle Types	Average Percent Error: Simplified vs. MOVES Models, All Selected Cycles			
	CO_2	NO_x	CO	HC
Passenger Car (PC)	0.02	0.03	0.02	0.04
Passenger Truck (PT)	0.01	-0.22	-0.07	0.17
Light Commercial Truck (LCT)	0.46	-0.35	0.28	-0.09
Single Unit Short Haul Truck (SHT)	-0.35	-0.43	-0.11	-0.09
Combination Long Haul Truck (LHT)	0.06	-0.41	0.06	0.20

18 driving cycles each for PC, PT, and LCT

11 driving cycles each for SHT and LHT.

These five vehicle types comprise more than 95% of the fleet.

Ages: 0, 5, 10, 15 years (2011 calendar year).

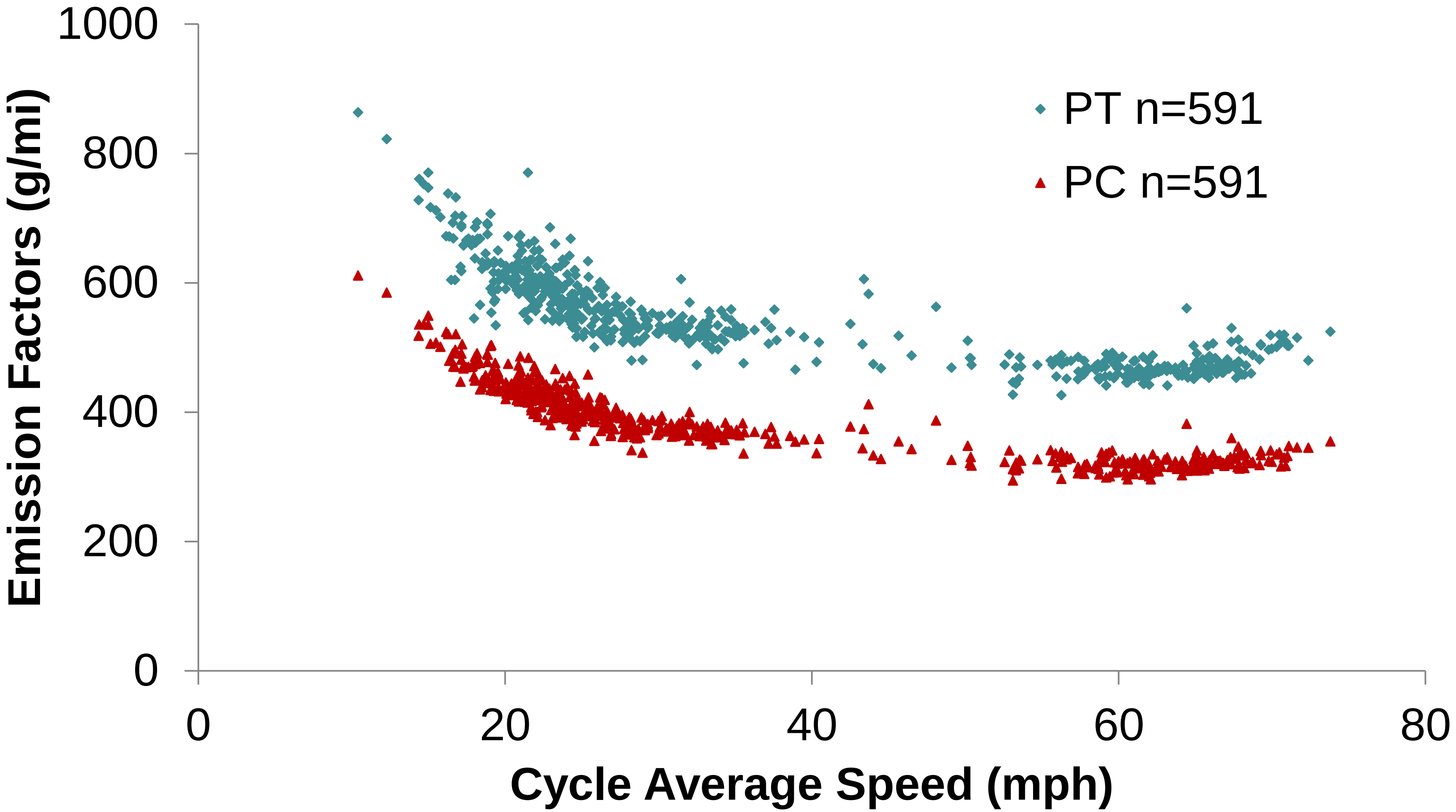
Run Time of the Simplified Model

- Simplified Model is implemented using MATLAB
- Estimating emission factors for 18 driving cycles

MOVES	Simplified Model
10 minutes	0.2 seconds

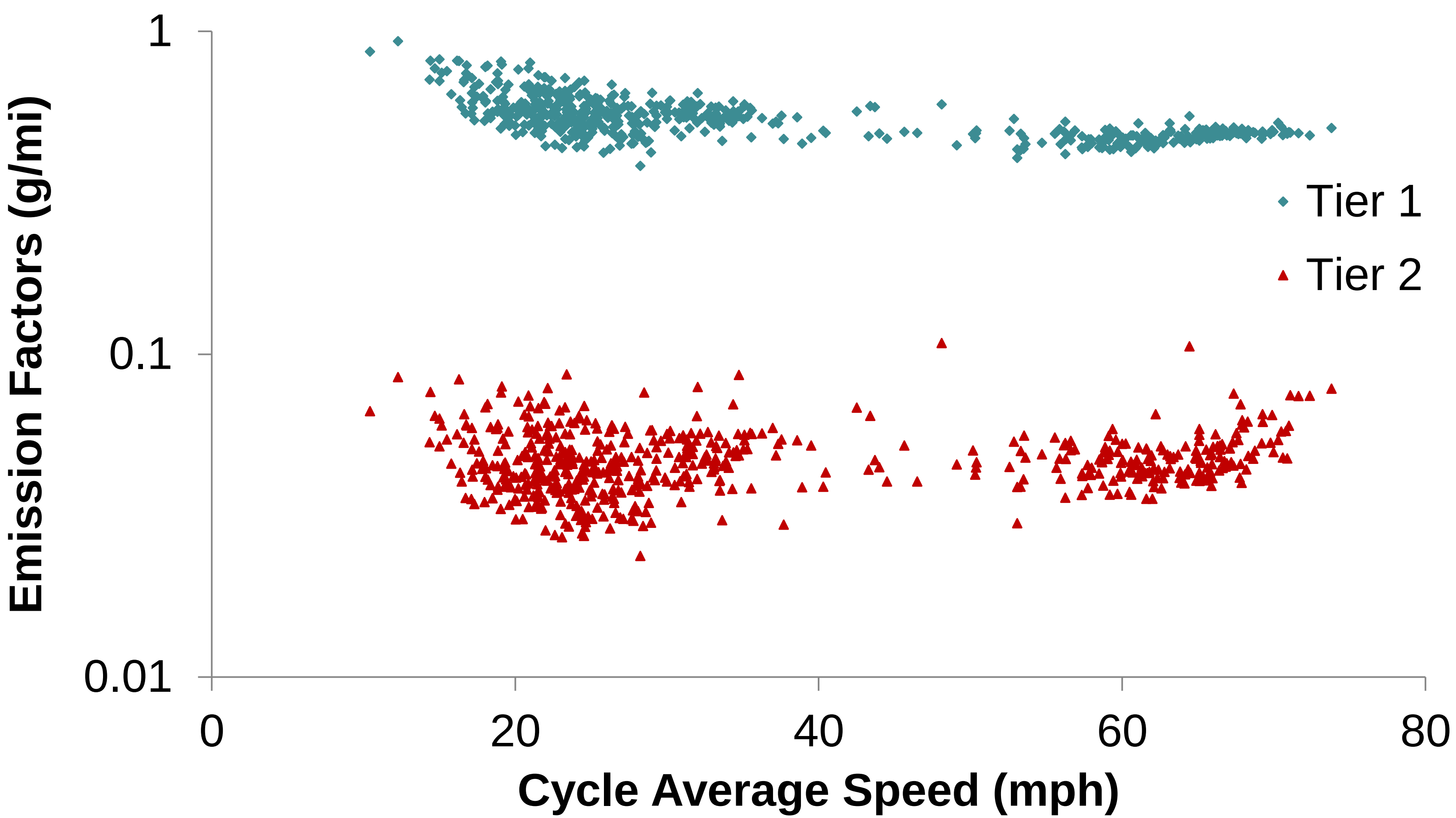
3,000 times faster

Example Application of MOVES Lite: High Throughput Estimation of CO_2 Emission Factors for Tier 1 Vehicles



NC STATE UNIVERSITY

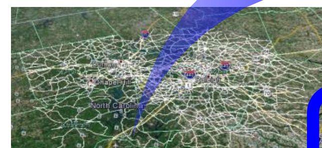
NO_x Emission Factors for Passenger Cars



Integrated MOVES Lite and DTALite Packages for Emission Analysis

Microscopic Vehicle Trajectory Reconstruction

Emission Aggregation

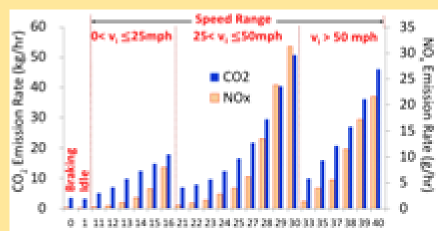


DTALite

Large-scale Dynamic Traffic Assignment & Simulator

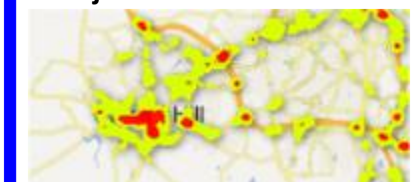
MOVES Lite

Simplified Emission Estimation Method

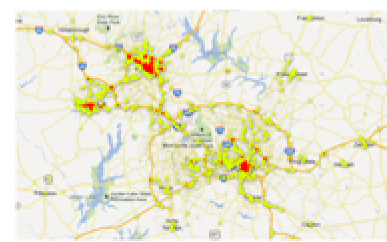


Emission Estimates

Project level



Network level

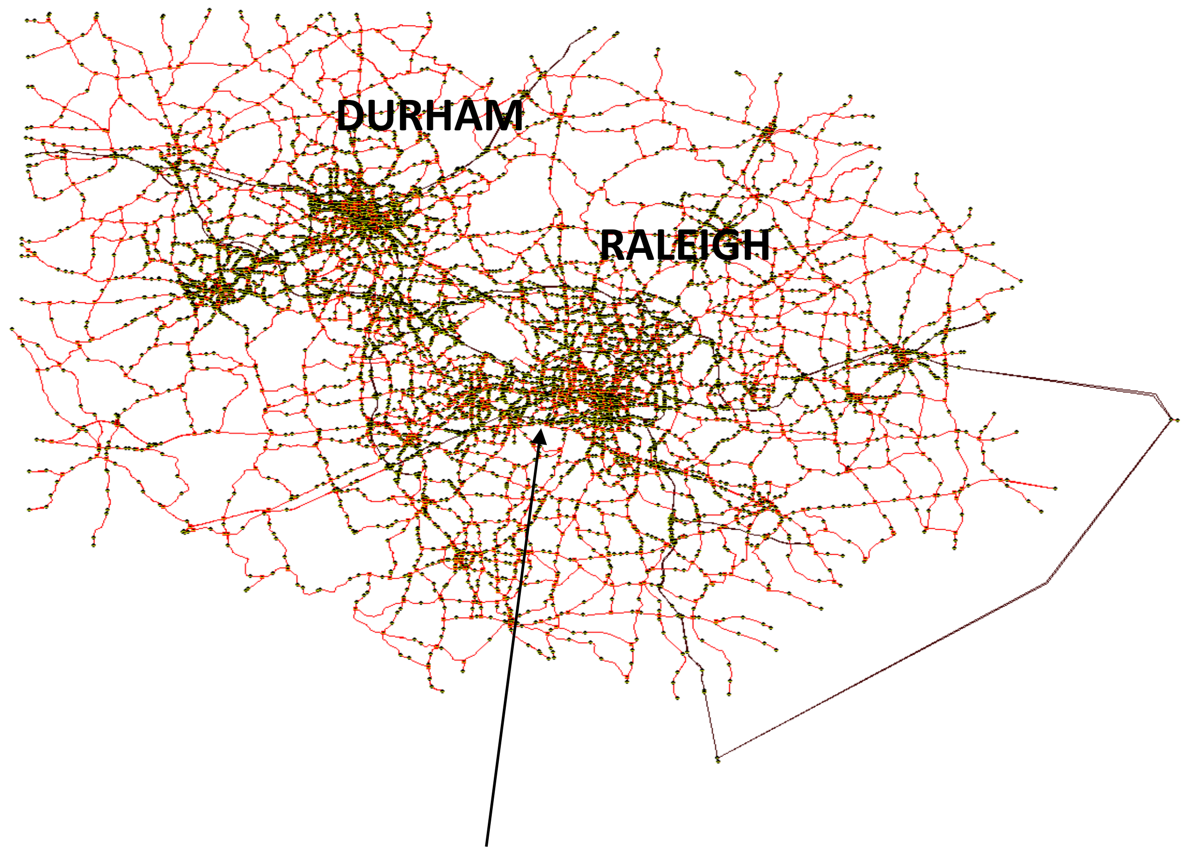


Linking Traffic and Emissions Simulation

- DTALite is a computationally efficient “mesoscopic” model
- DTALite simulates 1 Hz trajectories for individual vehicles with realistic combinations of speed and acceleration
- MOVES Lite is directly incorporated into DTALite
- DTALite with MOVES Lite enables assessment of a wide breadth of traffic management strategies, and their effect on emissions
- Access at: https://sites.google.com/site/dtalite/

Case Study Network

- **Triangle Regional Model** (TRM) network in Research Triangle Region, NC
- Contains **9,528 nodes, 20,258 links** and **7,193 origin-destination pair**s
- Baseline case study:
    - Weekday
    - 6 am to 11 am
    - **1,051,469 vehicles** enter the network
- 87% Single Occupant Vehicle (SOV) and 13% High Occupancy Vehicle (HOV)
- Vehicle age distribution as given by NC DENR for Wake County, NC



Major roadways indicated in green

Example Case Study: Sensitivity of Emissions to Change in Travel Demand

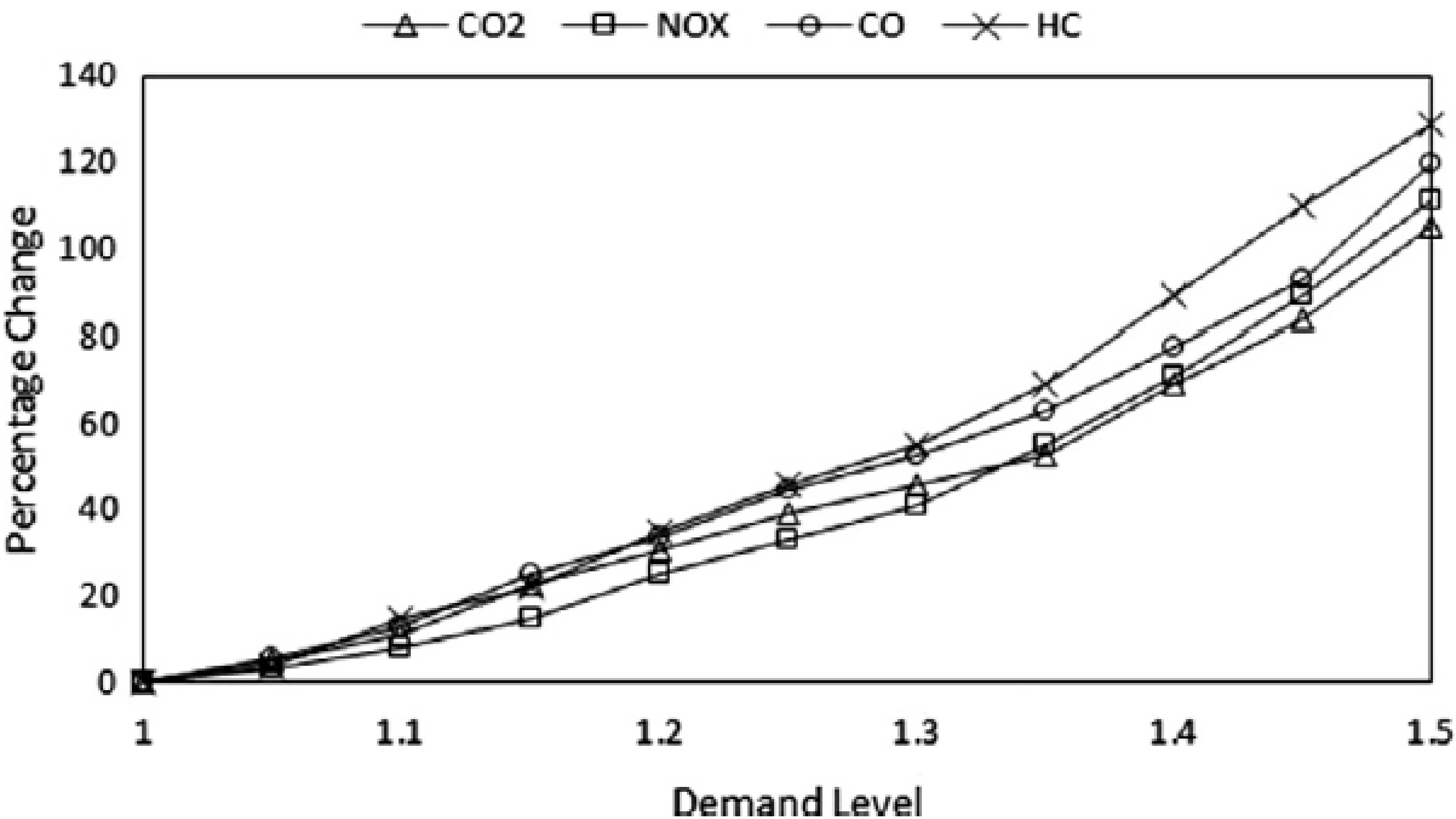


Fig. 6D. Percentage change of total energy and emissions for Triangle network.

Key Contributions

- Evaluation of MOVES based on PEMS data
- Simplified version of MOVES: sensitive to vehicle dynamics, vehicle type, and age distribution
- Incorporation of MOVES Lite into an open source dynamic traffic assignment model, DTALite
- Capability to test, via simulation, traffic management strategies at multiple scales (i.e. network, corridor)
- Traceability of the method: DTALite → MOVES Lite → MOVES → Empirical evaluation

Continuing Work

- Continued measurements of LDGV activity, energy use, and emissions using PEMS
- Current DOE ARPA-e funded project:
  - Updating MOVES Lite for energy estimation
  - Updating DTAlite with updated MOVES Lite

NC STATE UNIVERSITY

Acknowledgements

Although the research described here has been funded wholly or in part by the U.S. Environmental Protection Agency's STAR program through EPA Assistance ID No. RD-83455001, it has not been subjected to any EPA review and therefore does not necessarily reflect the views of the Agency, and no official endorsement should be inferred.

This research is funded by
U.S. EPA - Science To Achieve Results (STAR) Program
Grant # RD-83455001