Enhancing MOVES for Connected and Automated Vehicle Analysis

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TRANSPORTATION IS UNDERGOING FOUR MAJOR REVOLUTIONS

Shared Mobility:

- carsharing, ride hailing companies (e.g., Uber, Lyft), and advanced transit
- Drivers: Internet connectivity, convenience, and transportation costs

Electrification:

- electric drivetrains are becoming more common
- Drivers: advances in motors, controls, and batteries

Connectivity:

- Vehicles are increasingly "connected"
- Drivers: cellular communications, dedicated short range communications

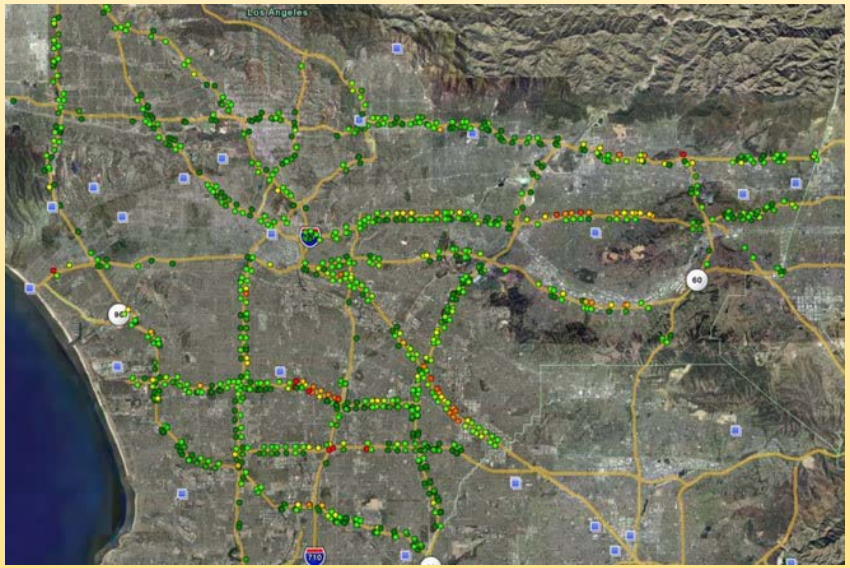
Automation:

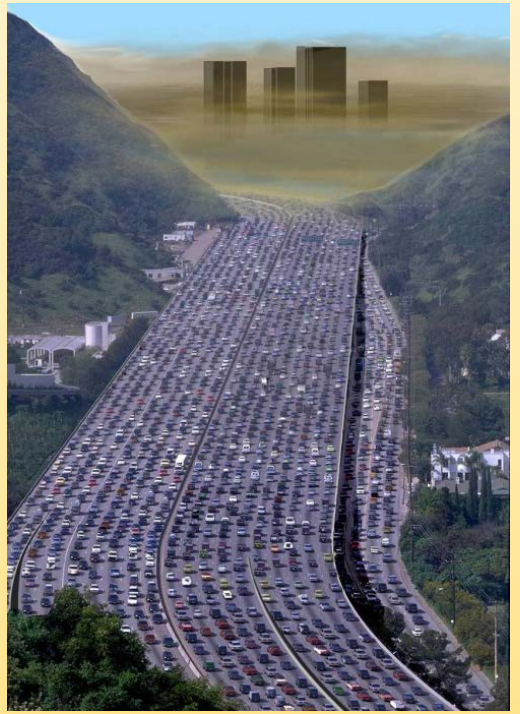
- Vehicle automation is emerging in many forms
- Automation comes with many social implications

General Components of a Transportation-based Emissions/Energy Inventory:

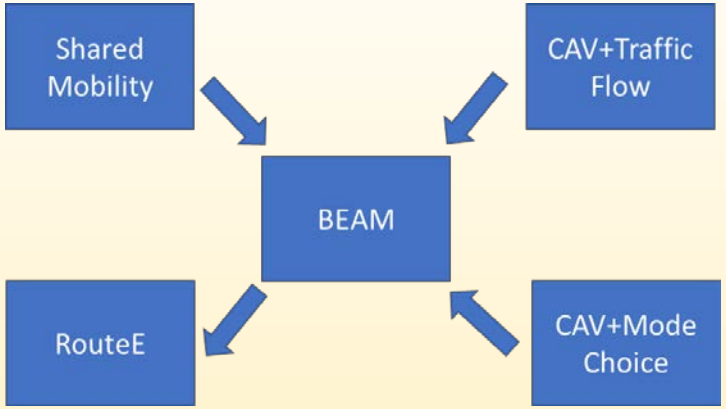
- *emissions/energy factors*
- *vehicle activity*
- *fleet composition*

environmental inventory





Future Transportation: Modeling Energy & Emissions



Shared Mobility:

- Vehicle Activity: Travel Demand Models need to change
- Vehicle Operation should remain the same

Electrification:

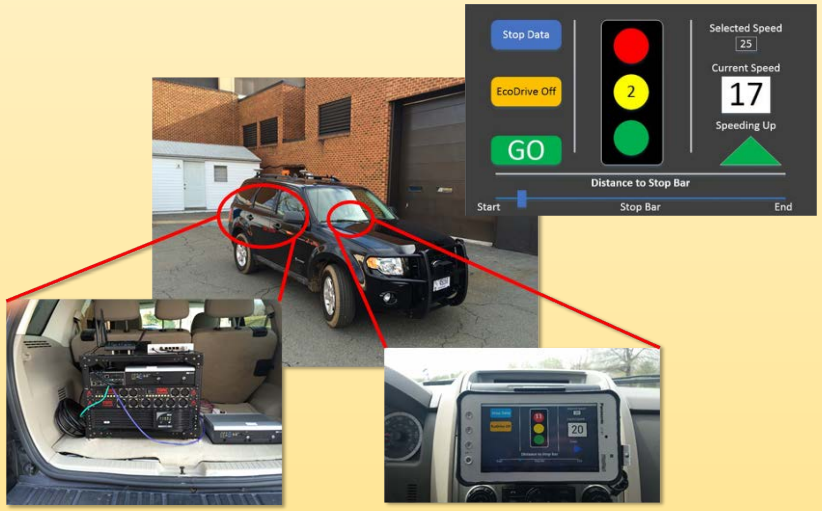
- Vehicle category is simply changed within MOVES
- Indirect Emissions: need to know energy sources that produce electricity

Connectivity:

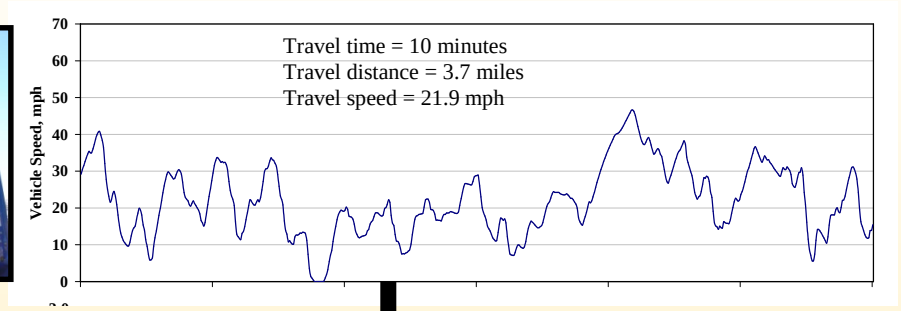
- Vehicle types will likely be newer, energy efficient, and low emissions
- Vehicle Operation/Activity will likely be smoother

Automation:

- Vehicle types will likely be newer, energy efficient, and low emissions
- Vehicle Operation/Activity will likely be smoother



Project-Level Emission Modeling



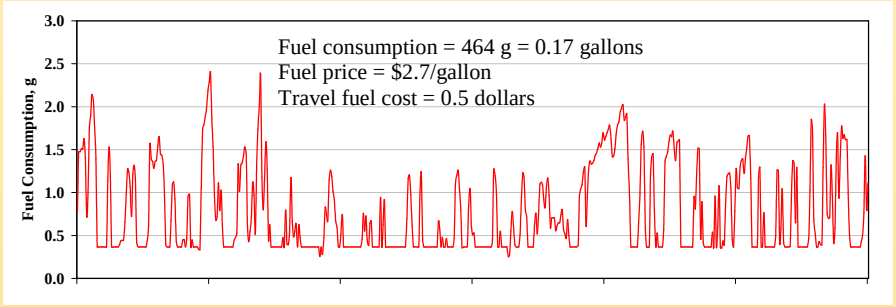
vehicle activity (velocity trajectory and grade if available)

or:

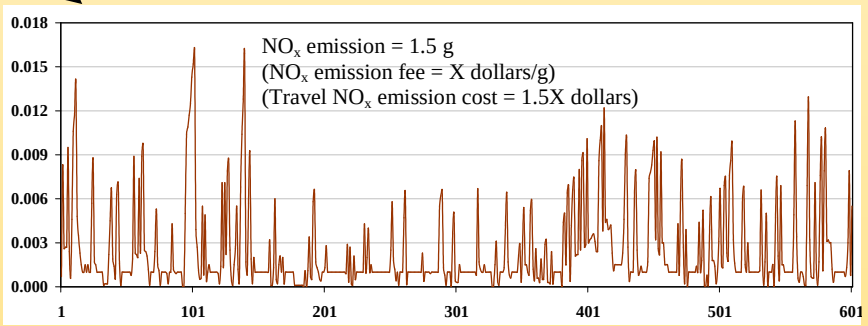
traffic simulation

Emissions Modeling

vehicle calibration parameters and emissions factors

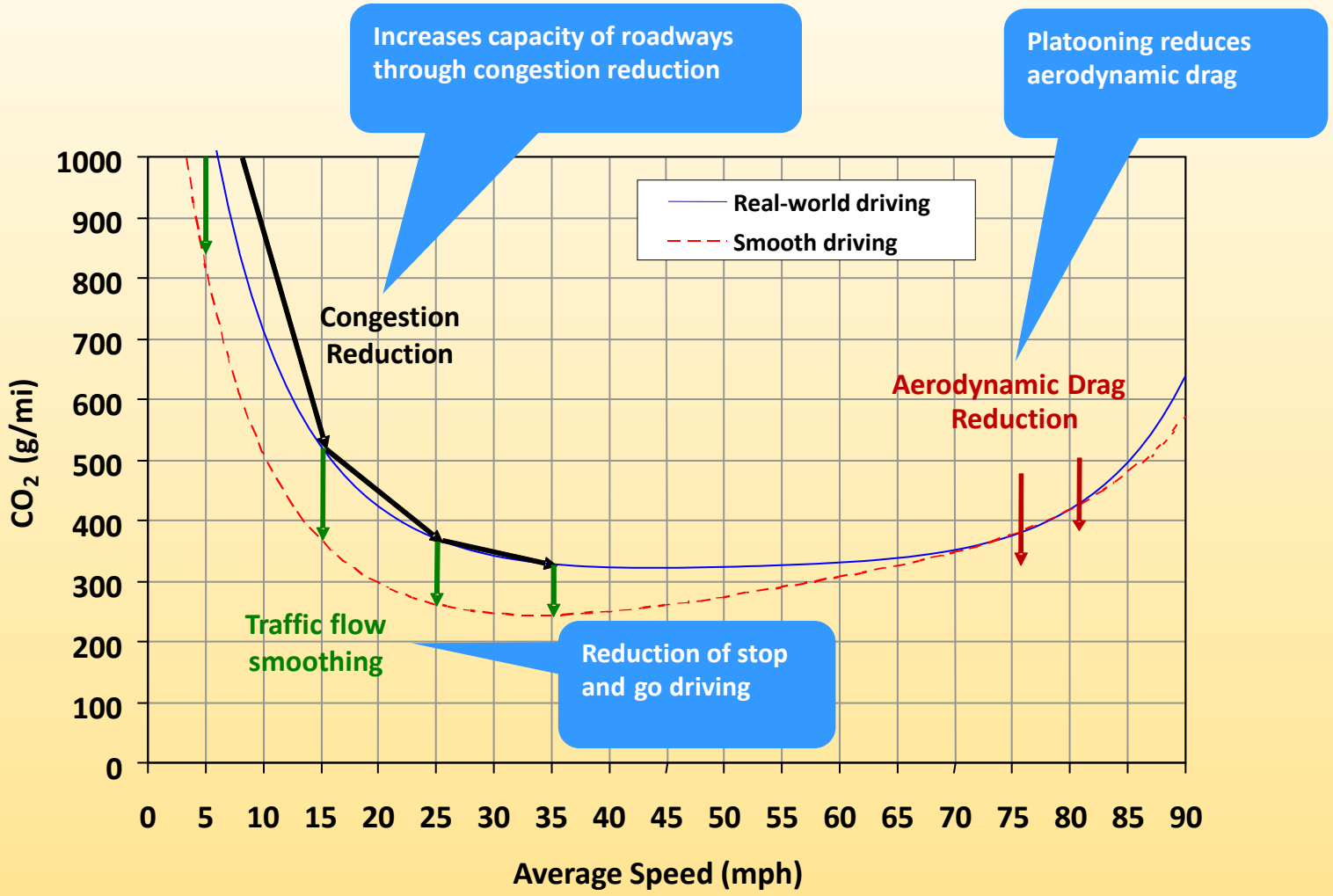


fuel consumption



emissions

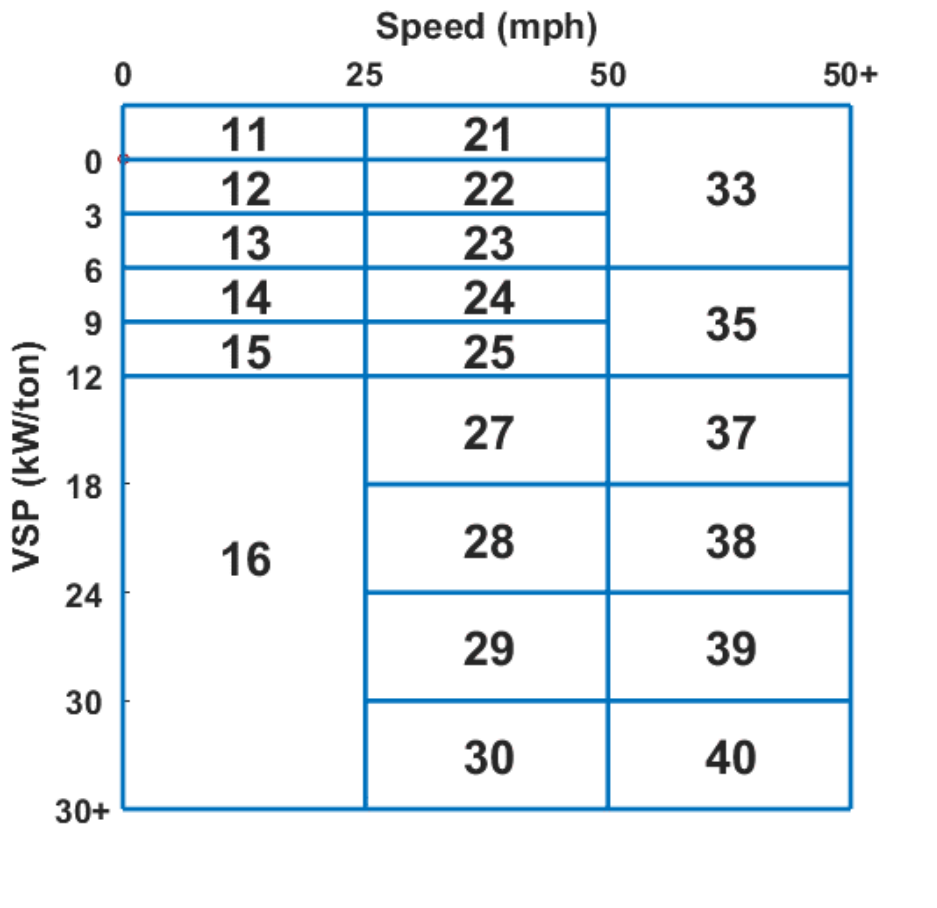
Three regimes on how Connected & Automated Vehicles can reduce on-road energy and emissions



Source: Barth, M. and Boriboonsomsin, K. (2008). Real-world carbon dioxide impacts of traffic congestion. *Transportation Research Record*, 2058, 163-171.

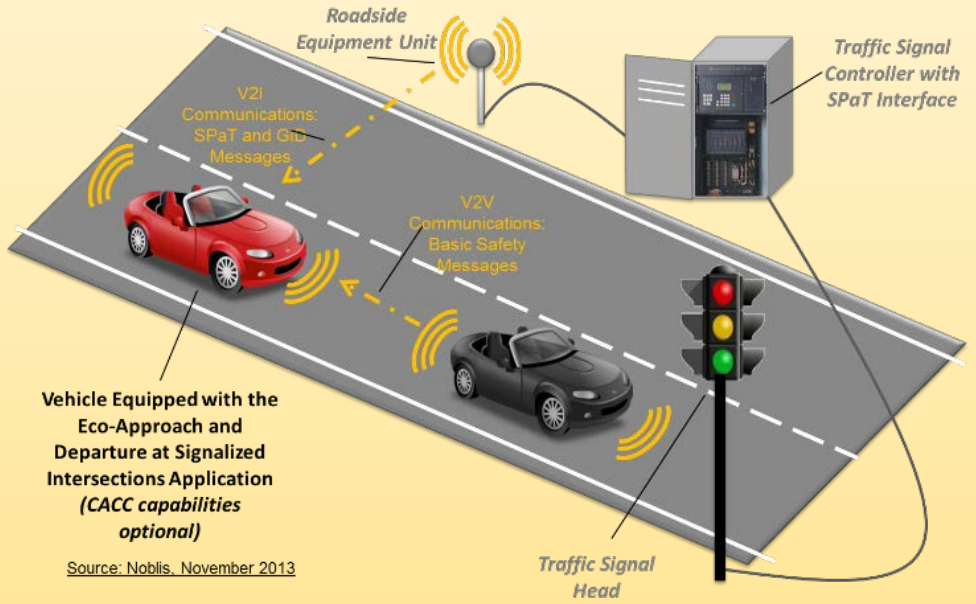
Motor Vehicle Emission Simulator (MOVES)

- **Data-Driven Emission Model**
- **Uses a Binning Approach for Vehicle Operation Mode (OpMode) and Emission Factors**



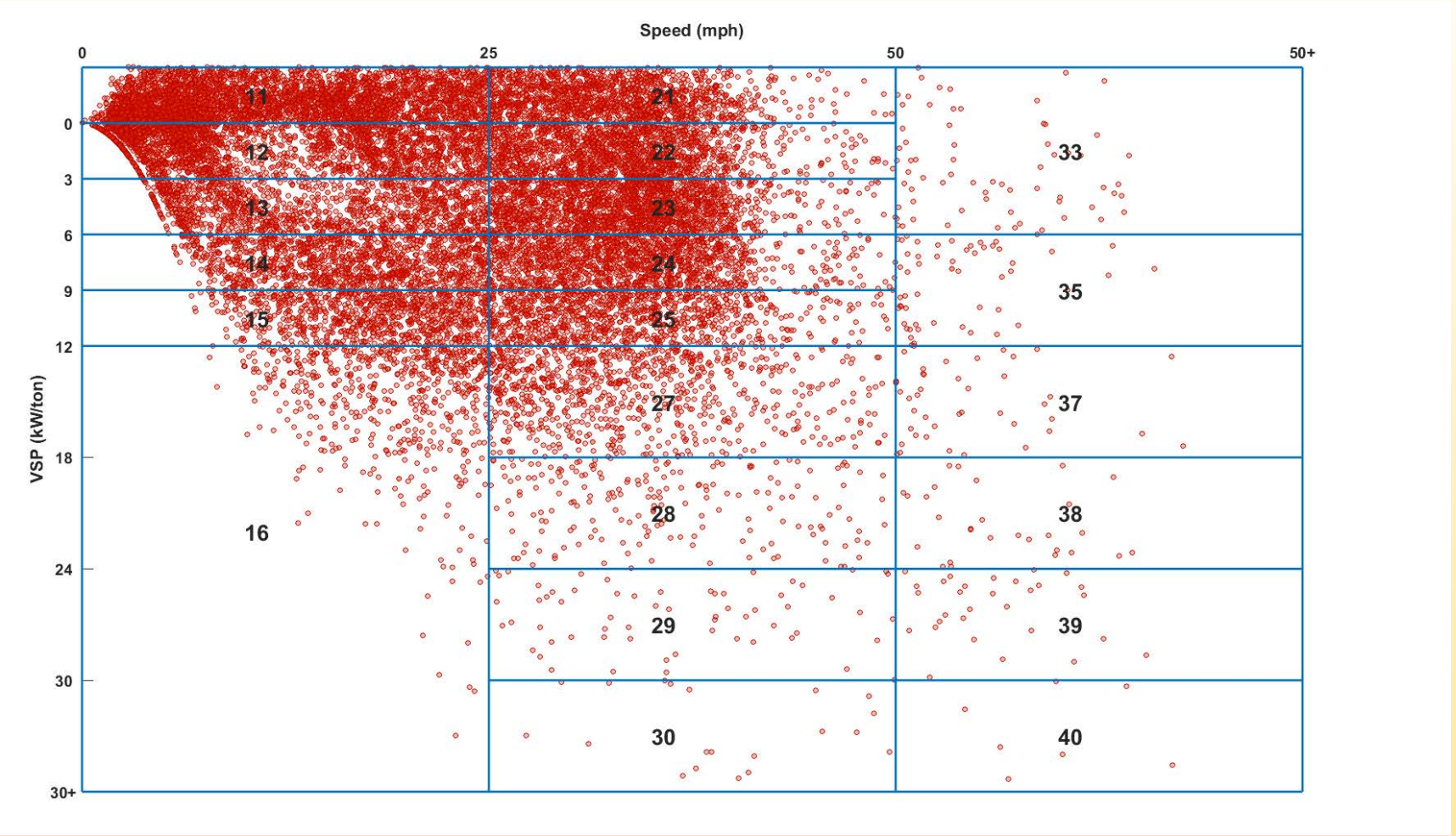
MOVES Sensitivity Analysis

- In our real-world connected and automated vehicle experiments, we noticed that MOVES was under predicting the energy and emissions benefits
- We initiated a study to compare real-world fuel consumption, MOVES, and CMEM



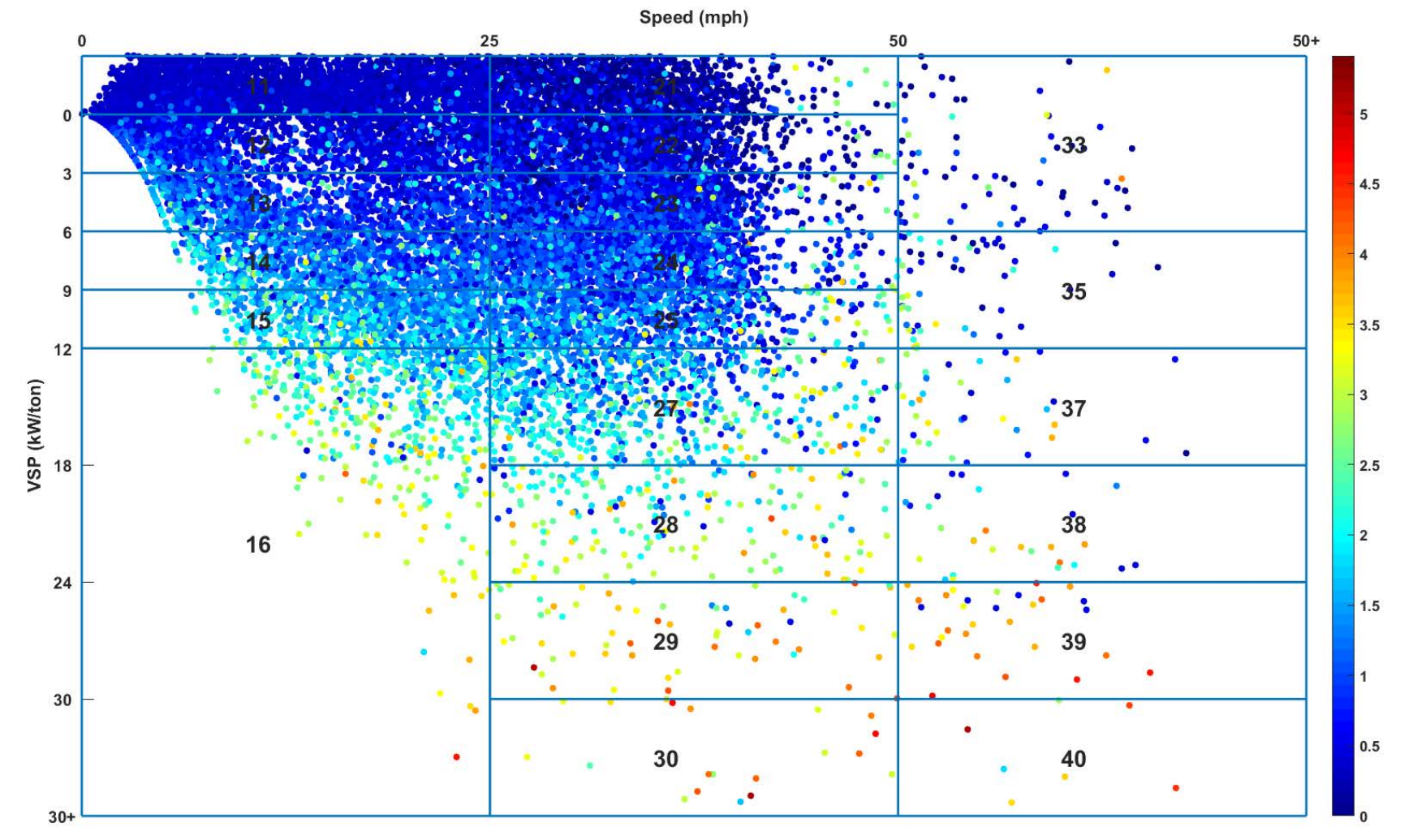
Source: Noblis, November 2013

Calibrating MOVES: Training Data Set



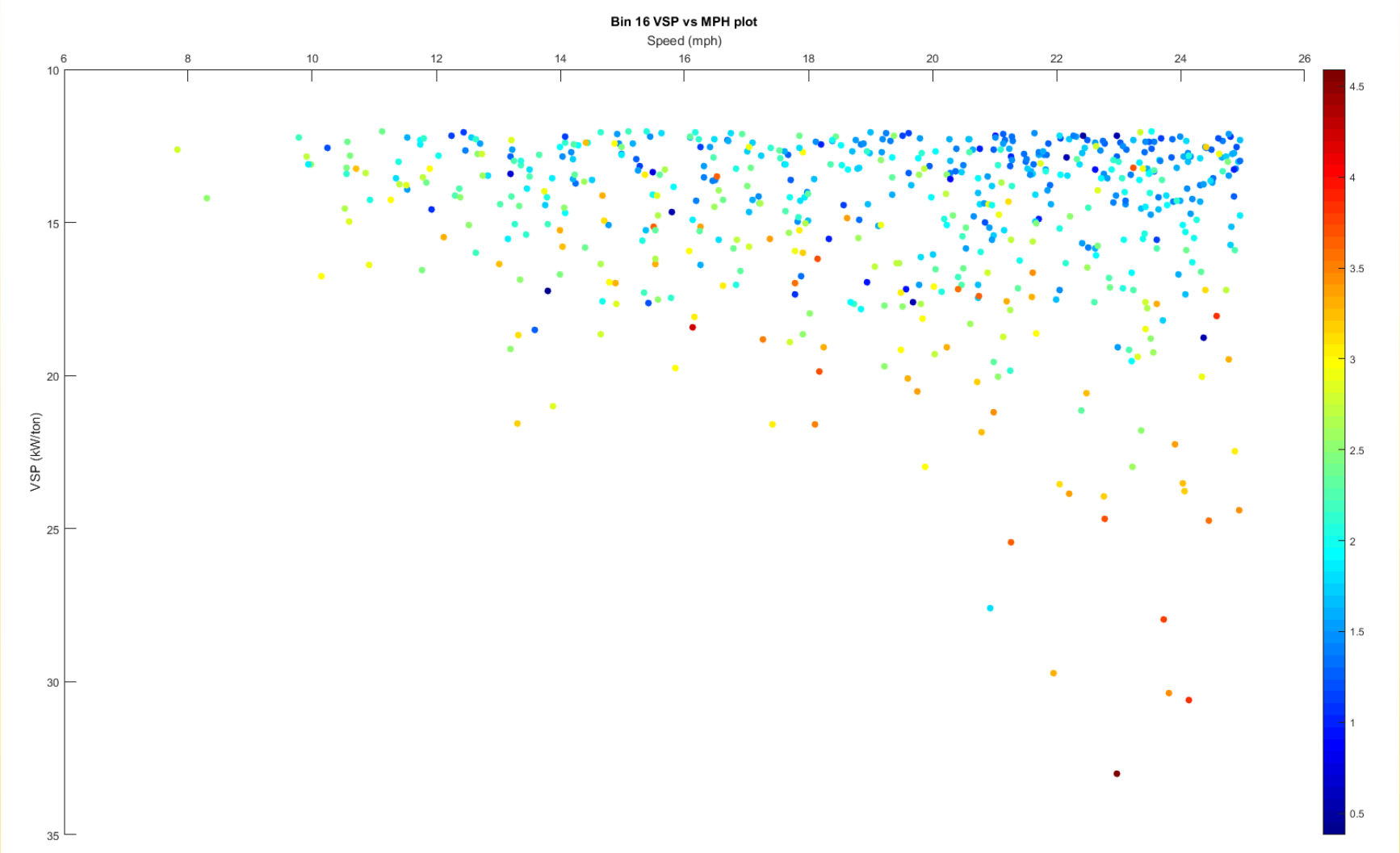
- Second-by-second data were collected from numerous driving trips and experiments
- Data are used to calibrate MOVES fuel consumption factors and activity in the various OpModes

Fuel Consumption mapped to MOVES bins



- **Second-by-second fuel consumption (grams/s)**
- **Max value: 5.41 grams/s**

Fuel Consumption map of MOVES Bin 16



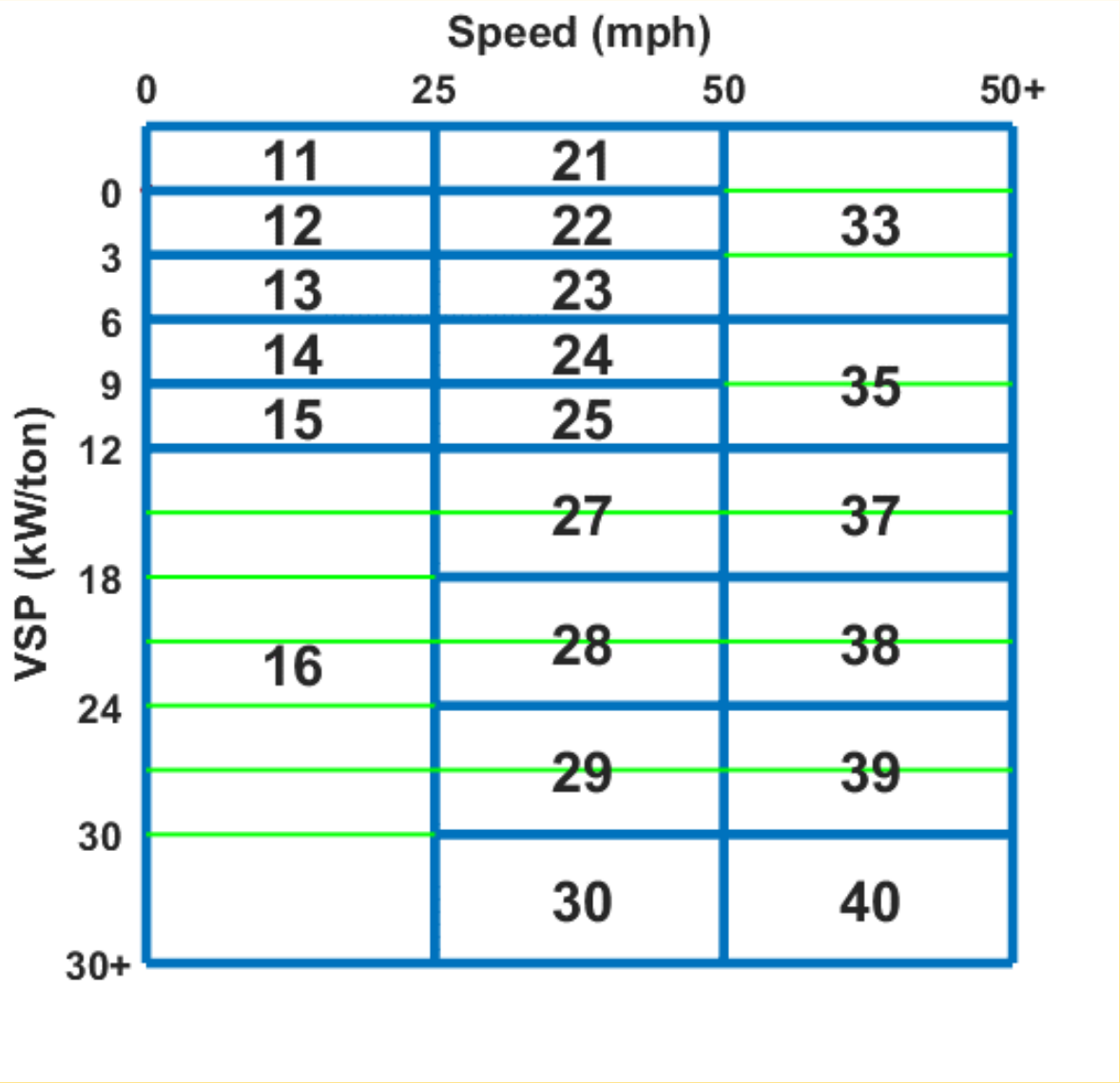
- **Wide range of values with lower VSP values dominated by lower fuel values**
- **Range: [0.38, 4.59]**

MOVES Bin Statistics

11	# of Values: 6057 Range: [0.199, 3.01]	Mean = 0.324 S.D. = 0.177	21	# of Values: 2923 Range: [0.23, 3.6266]	Mean = 0.195 S.D. = 0.323	33	# of Values: 108 Range: [0.327, 3.99]	Mean = 0.511 S.D. = 0.869
12	# of Values: 2335 Range: [0.21,2.967]	Mean = 0.624 S.D. = 0.357	22	# of Values: 1631 Range: [0.238,2.73]	Mean = 0.465 S.D. = 0.403			
13	# of Values: 1288 Range: [0.24, 2.856]	Mean = 0.953 S.D. = 0.429	23	# of Values: 1931 Range: [0.24, 3.566]	Mean = 0.714 S.D. = 0.412			
14	# of Values: 1229 Range: [0.27, 3.5]	Mean = 1.22 S.D. = 0.437	24	# of Values: 1470 Range: [0.26, 3.744]	Mean = 0.939 S.D. = 0.417	35	# of Values: 56 Range: [0.35, 3.51]	Mean = 1.2 S.D. = 1.139
15	# of Values: 914 Range: [0.34, 3.586]	Mean = 1.501 S.D. = 0.451	25	# of Values: 1002 Range: [0.247, 3.59]	Mean = 1.18 S.D. = 0.507			
16	# of Values: 600 Range: [0.38, 4.59]	Mean = 2.07 S.D. = 0.699	27	# of Values: 842 Range: [0.31, 4.11]	Mean = 1.64 S.D. = 0.651	37	# of Values: 42 Range: [0.368, 3.75]	Mean = 1.908 S.D. = 1.1454
			28	# of Values: 188 Range: [0.43, 4.37]	Mean = 2.39 S.D. = 0.831	38	# of Values: 28 Range: [0.4, 4.1159]	Mean = 2.14 S.D. = 1.282
			29	# of Values: 62 Range: [0.36, 5.1]	Mean = 3.17 S.D. = 0.892	39	# of Values: 30 Range: [0.4566, 4.745]	Mean = 3.23 S.D. = 1.435
			30	# of Values: 30 Range: [2.44, 5.22]	Mean = 3.745 S.D. = 0.856	40	# of Values: 30 Range: [0.67, 5.41]	Mean = 3.83 S.D. = 1.54

Improving Resolution Using Sub-Binning

- Green lines show new bin borders

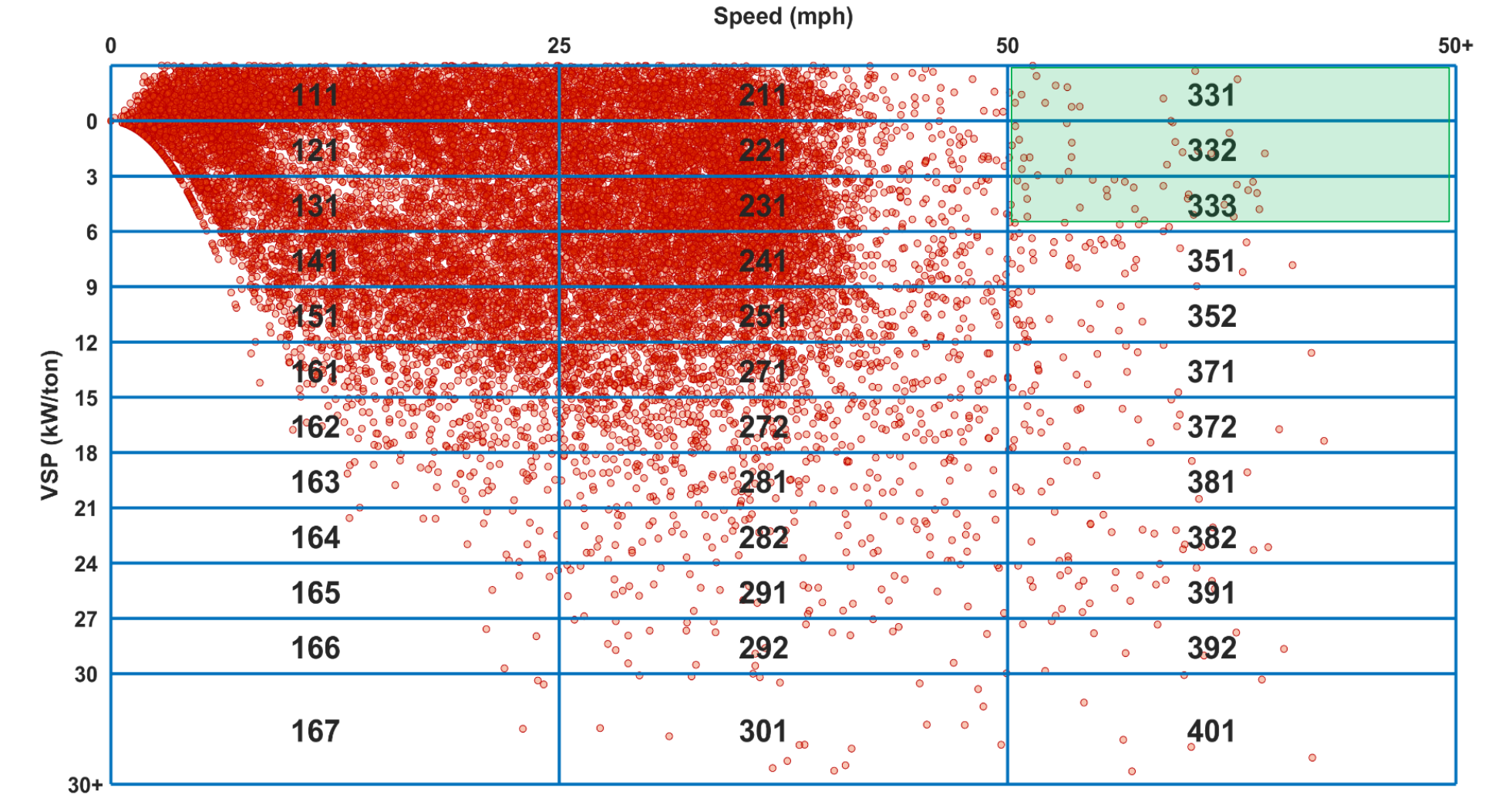


New Bin Definitions

VSP (kW/ton)	Speed (mph) 0	25	50	50+
0	111	211	331	
3	121	221	332	
6	131	231	333	
9	141	241	351	
12	151	251	352	
15	161	271	371	
18	162	272	372	
21	163	281	381	
24	164	282	382	
27	165	291	391	
30	166	292	392	
30+	167	301	401	

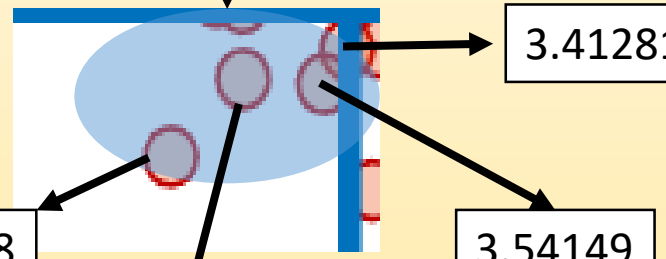
- **New Bin Numbering System**

New Bin Definitions



- Training data plotted in new bins
- Green boxes highlight what was changed

Emissions & Fuel Factors

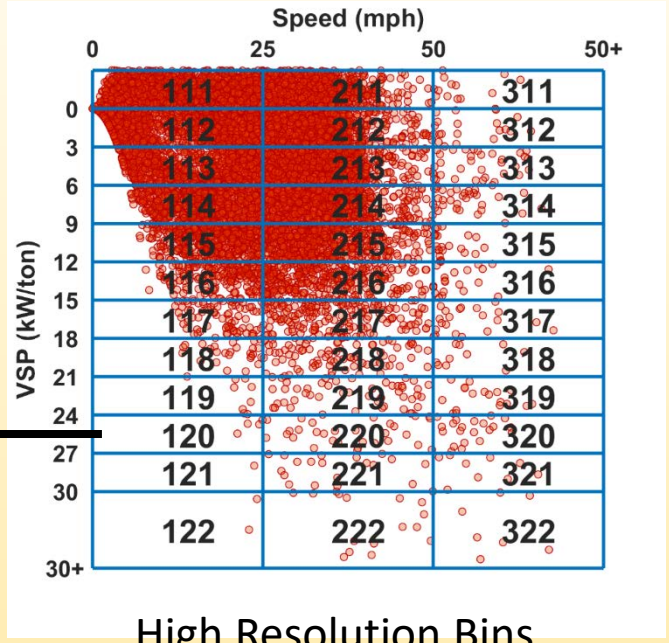


3.41281

3.64208

3.54149

3.67345

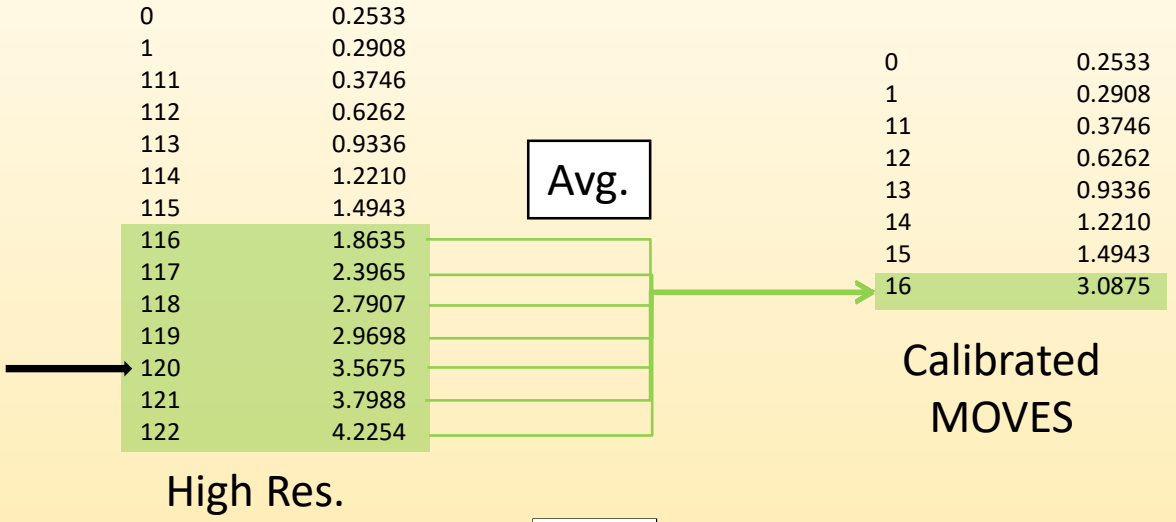


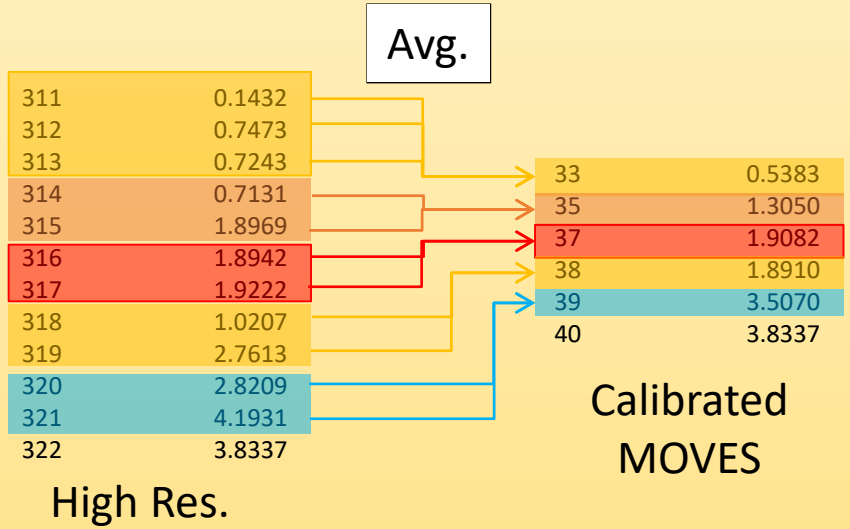
High Resolution Bins

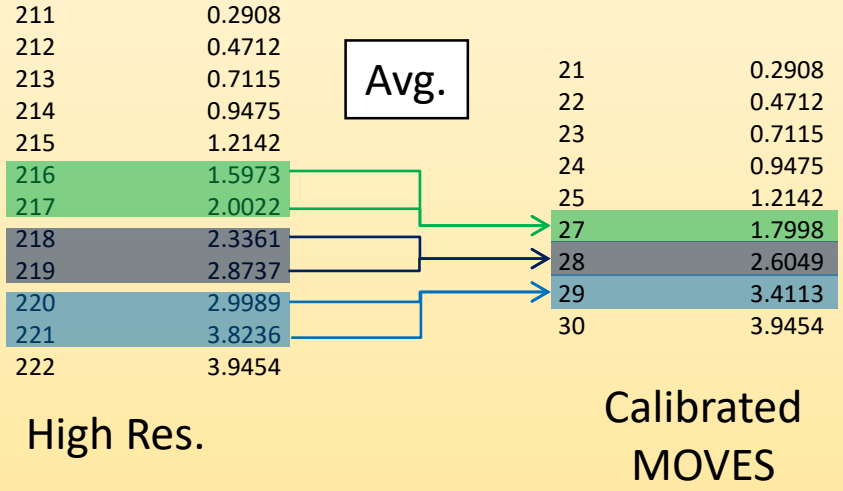
$$\frac{3.41281 + 3.54149 + 3.67345 + 3.64208}{4} = 3.5674575 \cong 3.5675$$

Emission factor for bin 120 is 3.5675 → Do the same process for each bin of High Res. MOVES

Calibration of Emissions & Fuel Factors





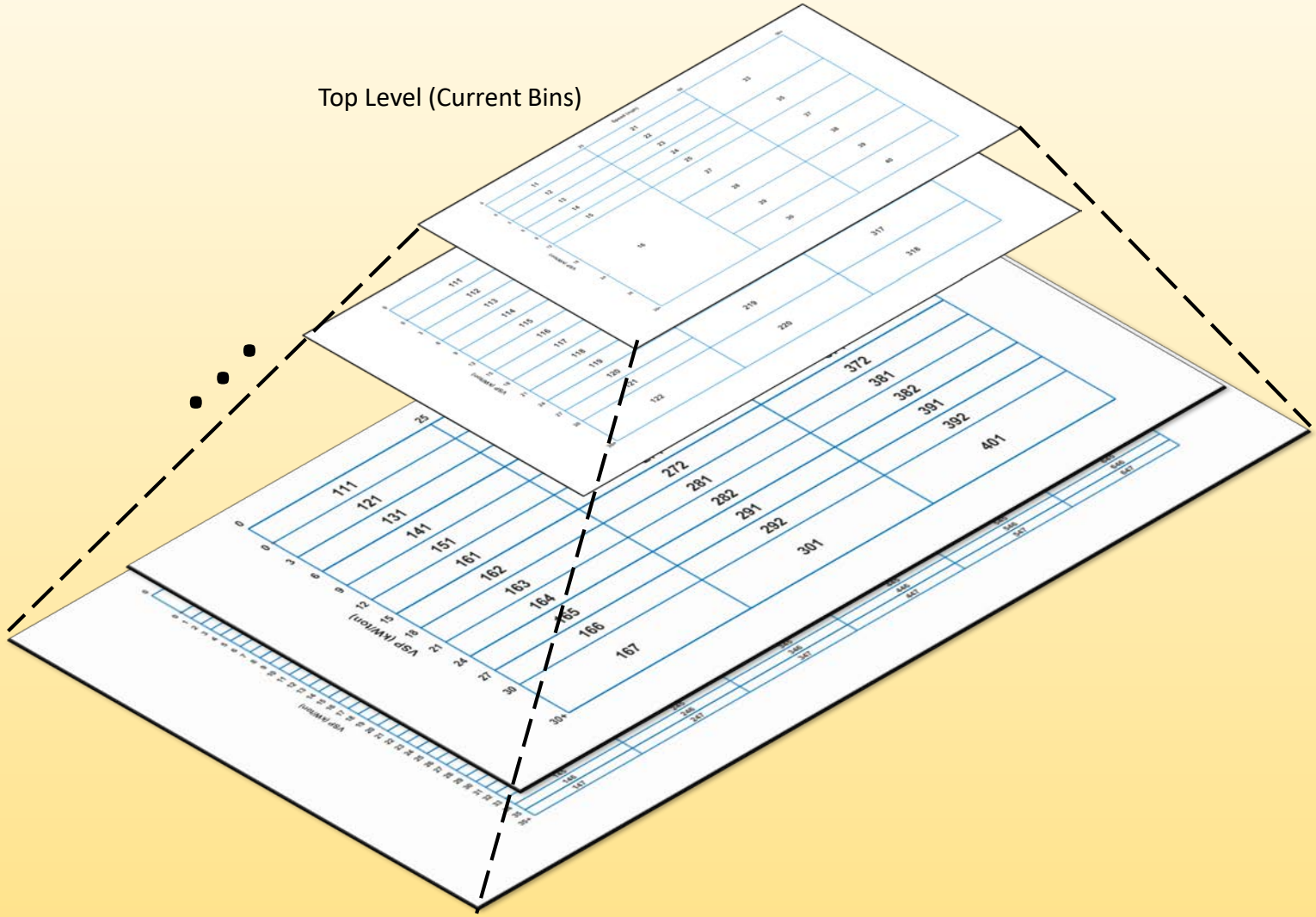


Comparison Results

Method	Fuel Consumption Avg. g/mile			
	Measured	MOVES	Calibrated MOVES	High Res. MOVES
gram/mile	147.9	170.5	154.69	150.41
% Diff		+15.3%	+4.59%	+1.69%

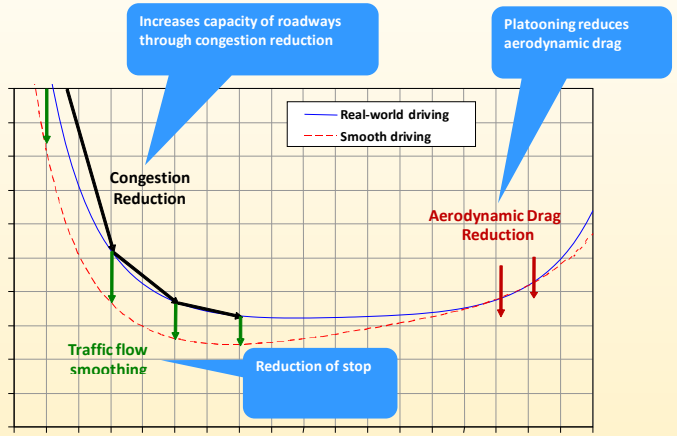
- Data from typical driving
- MOVES: uncalibrated results
- Calibrated MOVES: MOVES calibrated based on vehicle fuel consumption data
- High Resolution MOVES: uses sub-bins

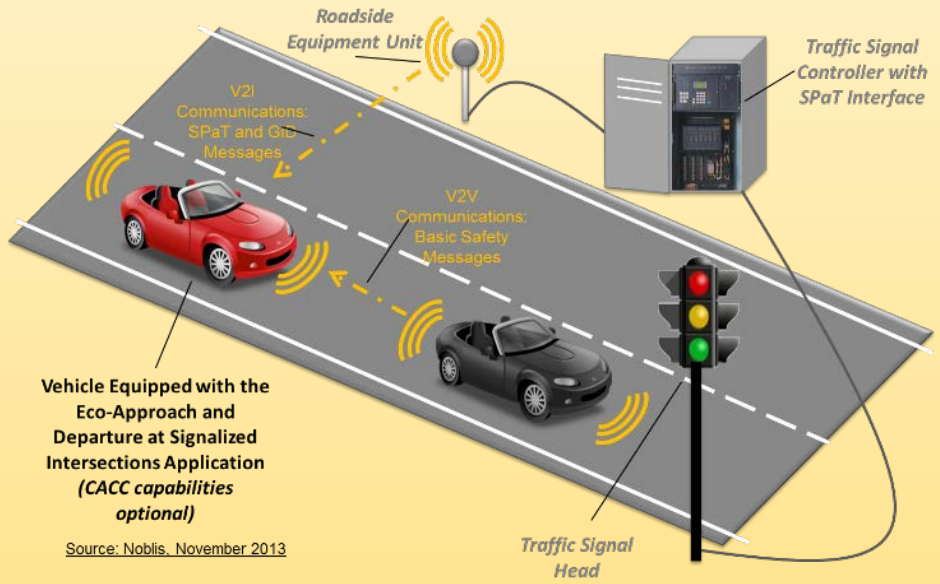
Extrapolation: Developing a Bin-Pyramid



Trajectory Smoothing

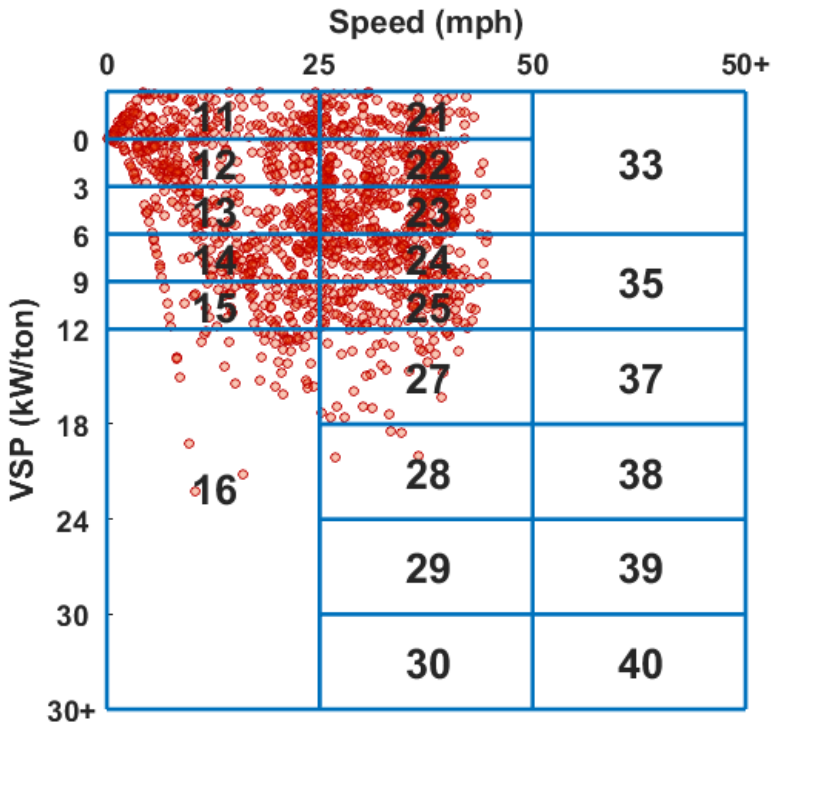
- There are many applications that attempt to “smooth” trajectories without loss of travel time: Eco-Pedal, traffic-light anticipation, etc.
- Example: the Eco-Approach and Departure (EAD) connected vehicle application
- Two cars drove at the same time on the same street, one using EAD techniques and the other driving normally



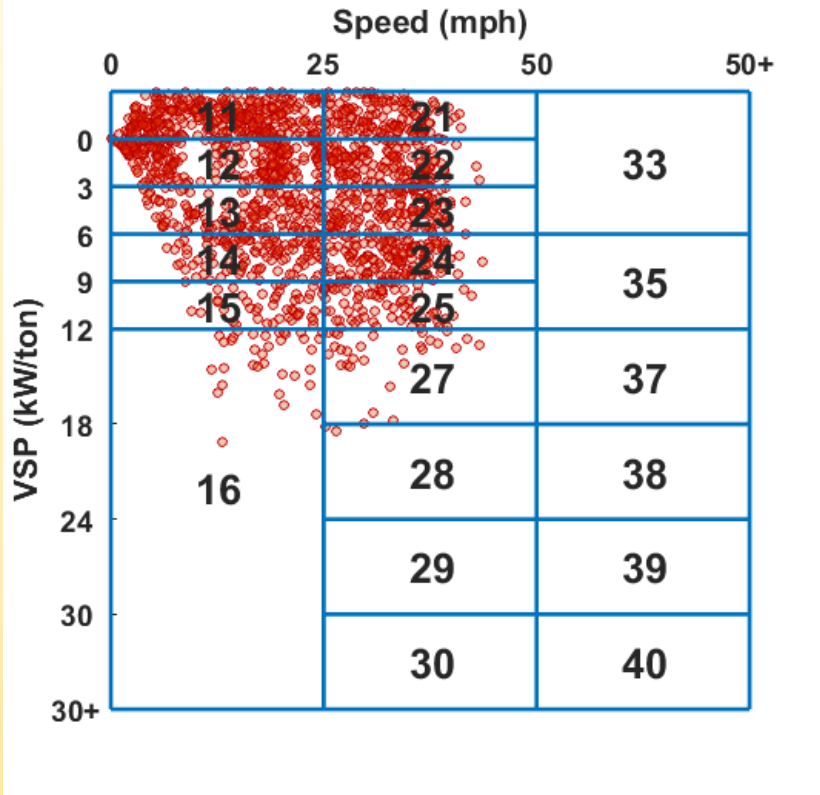


Source: Noblis, November 2013

EAD vs. Non-EAD Driving



Non-EAD

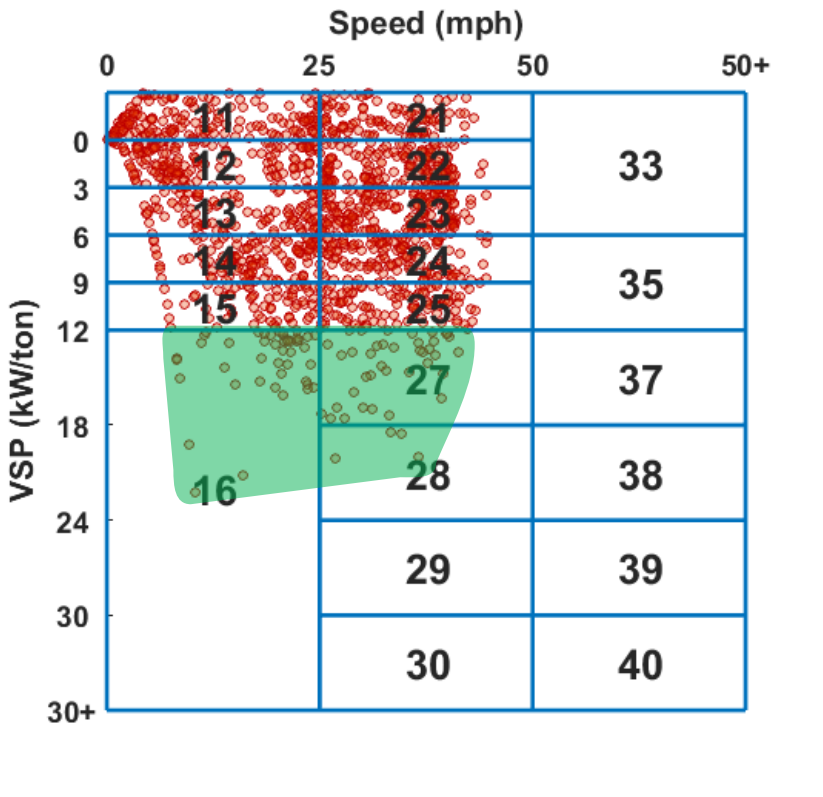


EAD

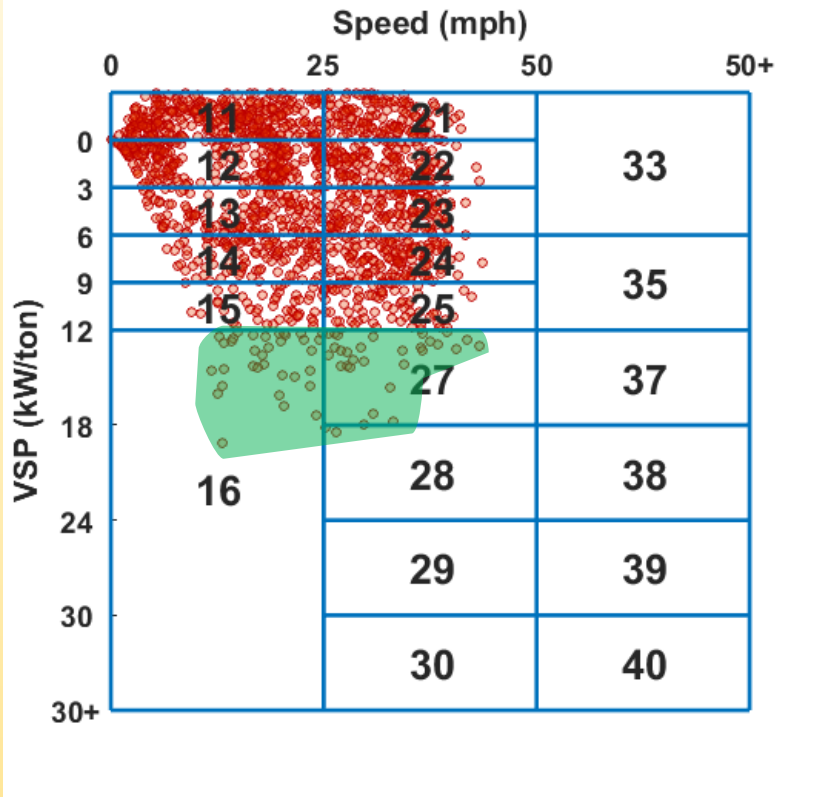
EAD vs. Non-EAD Driving

Method	Fuel Consumption Avg. g/mile			
	Measured	MOVES	Calibrated MOVES	High Res. MOVES
No EAD	137.63	158.3	144.9	140.63
EAD	128.51	154.6	141.2	136.3
Improvement	6.63%	2.33%	2.55%	3.08%

EAD vs. Non-EAD Driving

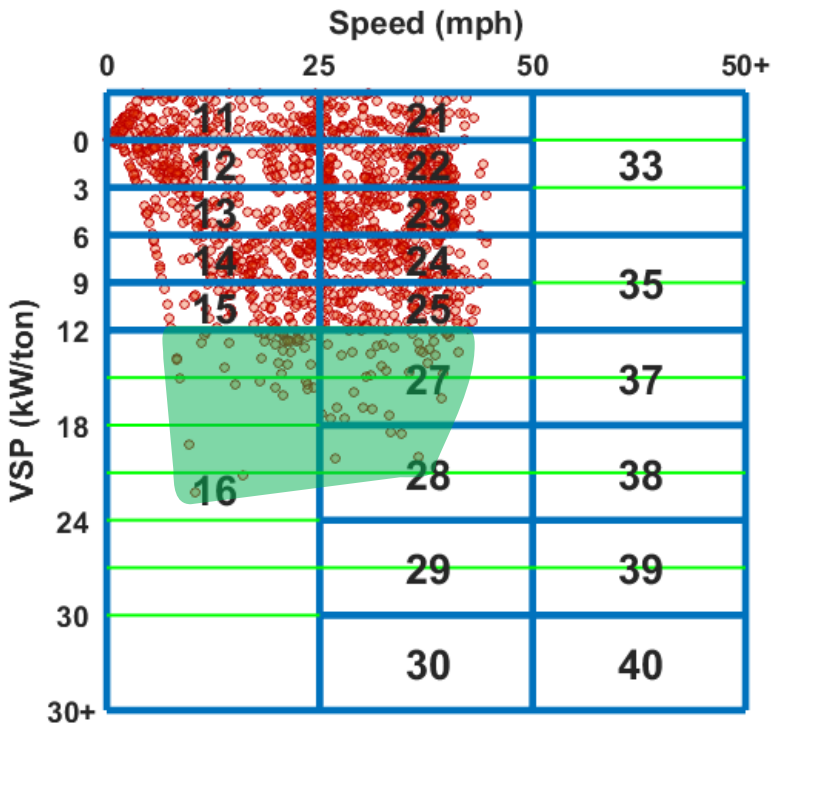


Non-EAD

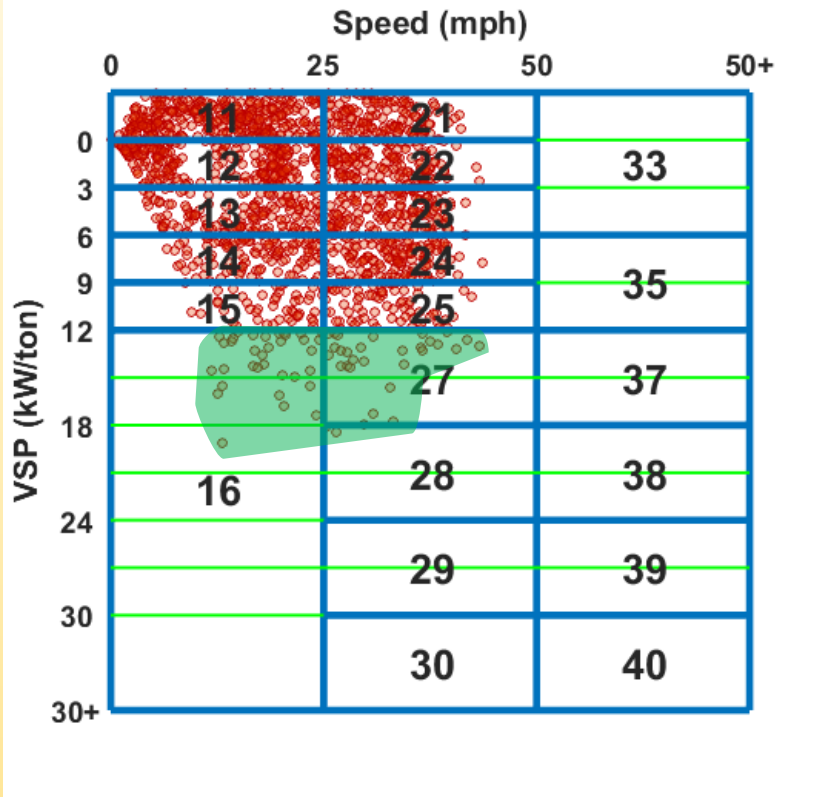


EAD

EAD vs. Non-EAD Driving

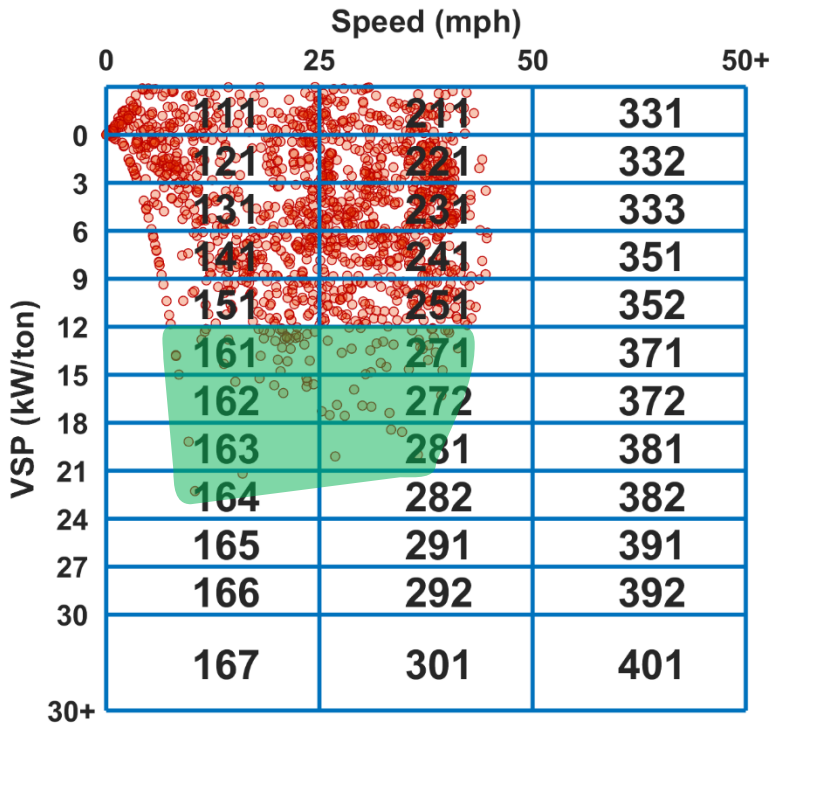


Non-EAD

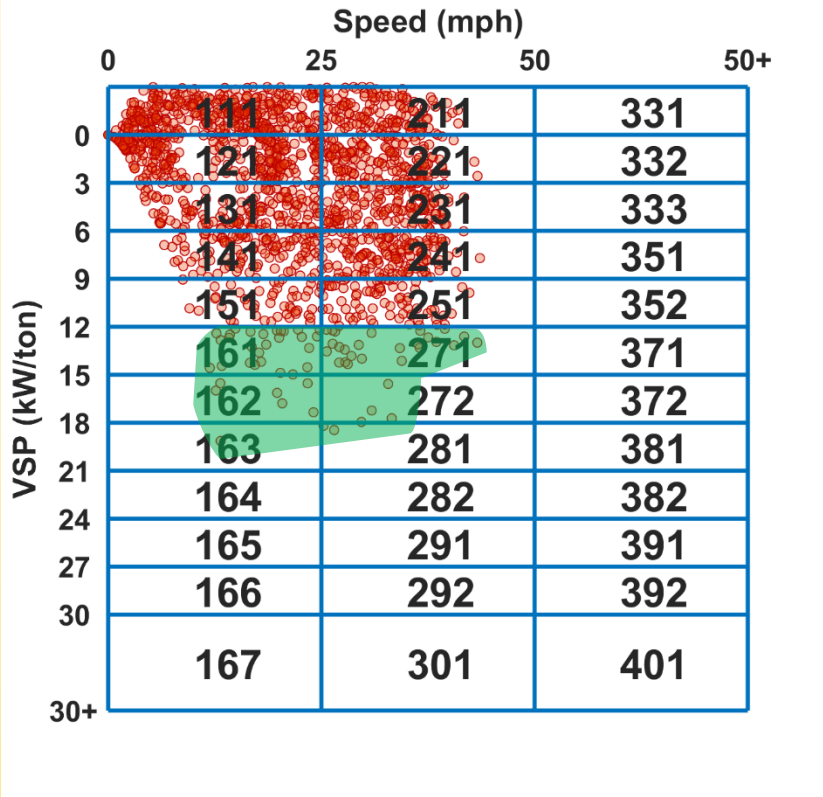


EAD

EAD vs. Non-EAD Driving



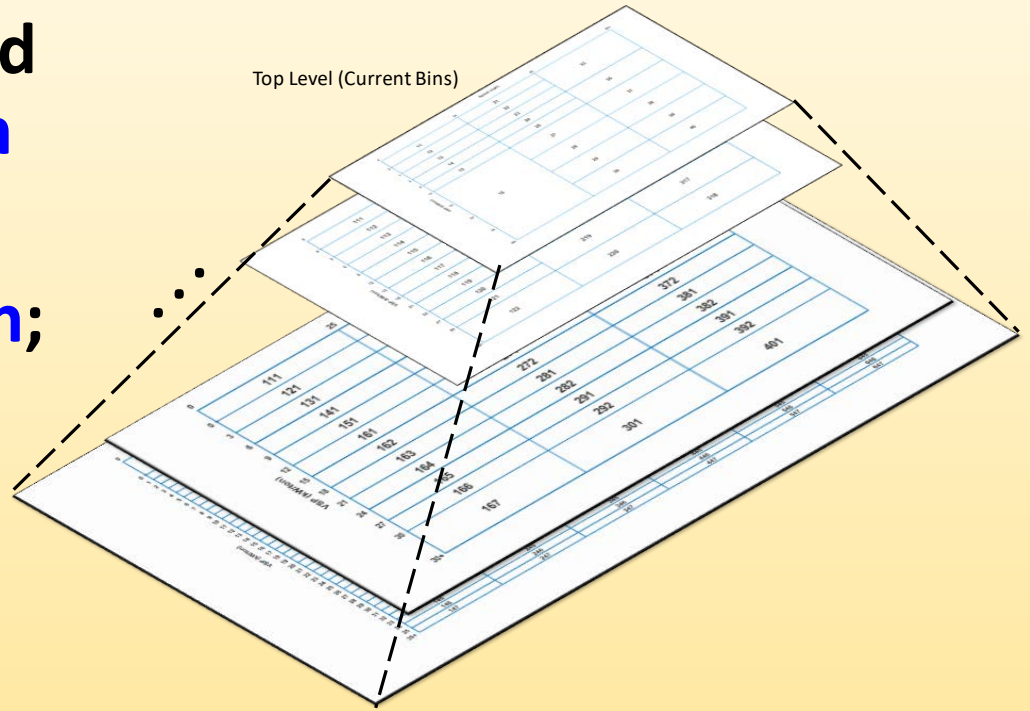
Non-EAD



EAD

Conclusions and Recommendations

- Traffic Smoothing effects tend to get washed out in MOVES due to bin size
- Recommendation: MOVES can be preserved and enhanced with a sub-binning approach
- MOVES could be used at different "resolutions" using a Bin-Pyramid approach; original MOVES model is preserved
- New Guidance Documents can be written that suggests what resolution should be used → automated resolution determination



Alternative Vehicle Emission Modeling Approaches

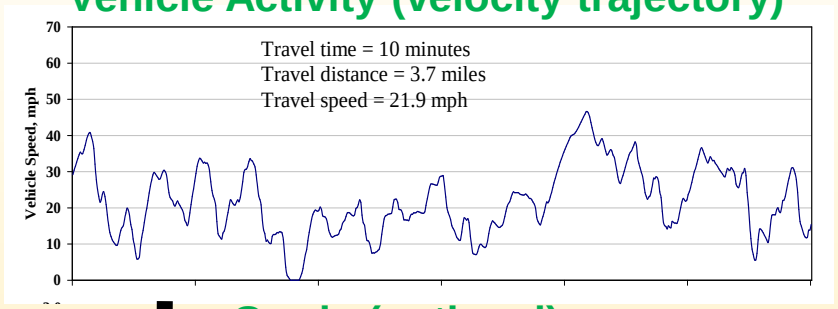
Array of new modeling techniques developed since the late 1990's:

- **Fuel-Based Emission Inventories**
  - **normalizes vehicle emissions to fuel consumption, not VMT**
  - **requires estimates of fuel use, e.g., from fuel tax**
  - **generates reasonable emission inventories for large databases**
- **Modal and instantaneous vehicle emission models:**
  - **concerned with estimating emissions as a function of vehicle operating mode, (e.g., idle, acceleration, cruise, deceleration)**
  - **predicts emissions second-by-second**
- **Statistical Models:**
  - **Many models exist…**

COMPREHENSIVE MODAL EMISSIONS MODEL (CMEM)

- Microscale emission model
  - Developed at UCR CE-CERT
  - Initially developed in the 1990's, lightly maintained
- Sponsorship
  - National Cooperative Highway Research Program (NCHRP)
  - U.S. Environmental Protection Agency (EPA)
- Objective
  - Model vehicle emissions at the project level (sec-by-sec)
  - Accurately reflect the impact on emissions from various operating conditions/parameters
    - vehicle speed, acceleration, and road grade
    - starting conditions, temperature (history effects)
    - secondary engine load, etc.

Vehicle Activity (velocity trajectory)



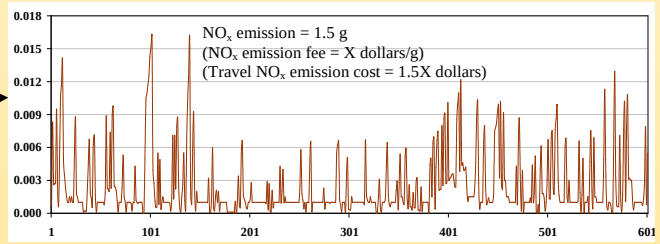
Grade (optional)

Calibration Vehicle Parameters

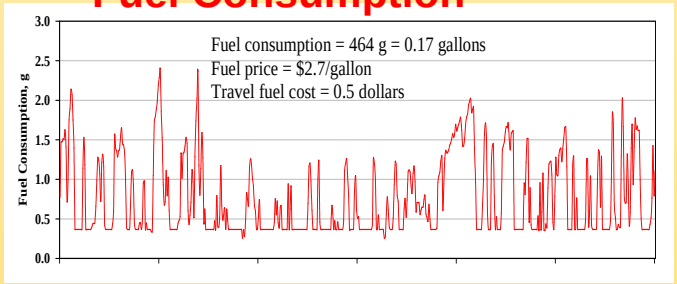
General Vehicle Parameters

CMEM

Emissions



Fuel Consumption

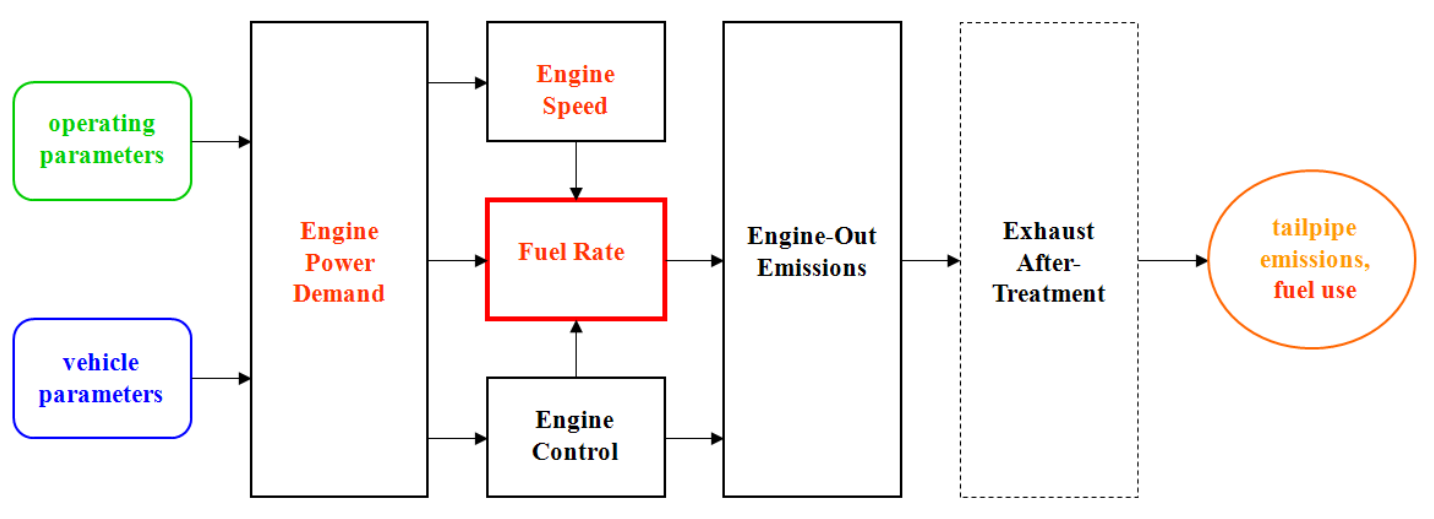


Category #	Vehicle Technology Category
	Normal Emitting Cars
1	No Catalyst
2	2-way Catalyst
3	3-way Catalyst, Carbureted
4	3-way Catalyst, FI, >50K miles, low power/weight
5	3-way Catalyst, FI, >50K miles, high power/weight
6	3-way Catalyst, FI, <50K miles, low power/weight
7	3-way Catalyst, FI, <50K miles, high power/weight
8	Tier 1, >50K miles, low power/weight
9	Tier 1, >50K miles, high power/weight
10	Tier 1, <50K miles, low power/weight
11	Tier 1, <50K miles, high power/weight
24	Tier 1, >100K miles
26	Ultra Low Emission Vehicle (ULEV)
27	Super Ultra Low Emission Vehicle (SULEV) / Partial Zero Emission Vehicle (PZEV)
	Normal Emitting Trucks
12	Pre-1979 (<=8500 GVW)
13	1979 to 1983 (<=8500 GVW)
14	1984 to 1987 (<=8500 GVW)
15	1988 to 1993, <=3750 LVW
16	1988 to 1993, >3750 LVW
17	Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)
18	Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)
25	Gasoline-powered, LDT (> 8500 GVW)
40	Diesel-powered, LDT (> 8500 GVW)
	High Emitting Vehicles
19	Runs lean
20	Runs rich
21	Misfire
22	Bad catalyst
23	Runs very rich
	Heavy Duty Diesel Trucks
45	1994 to 1997, 4-stroke, Elec. FI HDDT
46	1998, 4-stroke, Elec. FI HDDT
47	1999 to 2000, 4-stroke, Elec. FI HDDT

28 LDV

3 HDDV

CMEM Emission Model Structure



- Fuel is a function of Engine Power Demand and Engine Speed
- Fuel rate is related to emissions through analysis based on measured data
- Model Inputs
  - Operating parameters - vehicle speed, road grade, accessory power, etc.
  - Vehicle parameters – weight, gear ratios, calibrated emission parameters, etc.
- Model Outputs
  - Second–by–second emission data and fuel use

EAD vs. Non-EAD with CMEM

Method	Fuel Consumption Avg. g/mile				
	Measured	MOVES	Calibrated MOVES	High Res. MOVES	CMEM
No EAD	137.63	158.3	144.9	140.63	138.97
EAD	128.51	154.6	141.2	136.3	132.5
Improvement	6.63%	2.33%	2.55%	3.08%	4.65%

Conclusions and Recommendations

- **MOVES Modeling Approach** tends to under-estimate traffic smoothing effects due to connected and automated applications
- **Sub-Binning Approach** can improve resolution
- **All Modeling Approaches** tends to miss effects of aerodynamic drag reduction effects
- Consider adopting a complementary **physical modal or instantaneous emissions model** for connected and automated vehicle scenarios, as well as others that have a strong history effect in their emissions generation (SCR, after treatment, etc.)
- Dust off PERE emissions generator model that was previously used for MOVES?

THANK YOU!

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