Potential Energy and Emissions Benefits of Vehicle Automation and Connectivity

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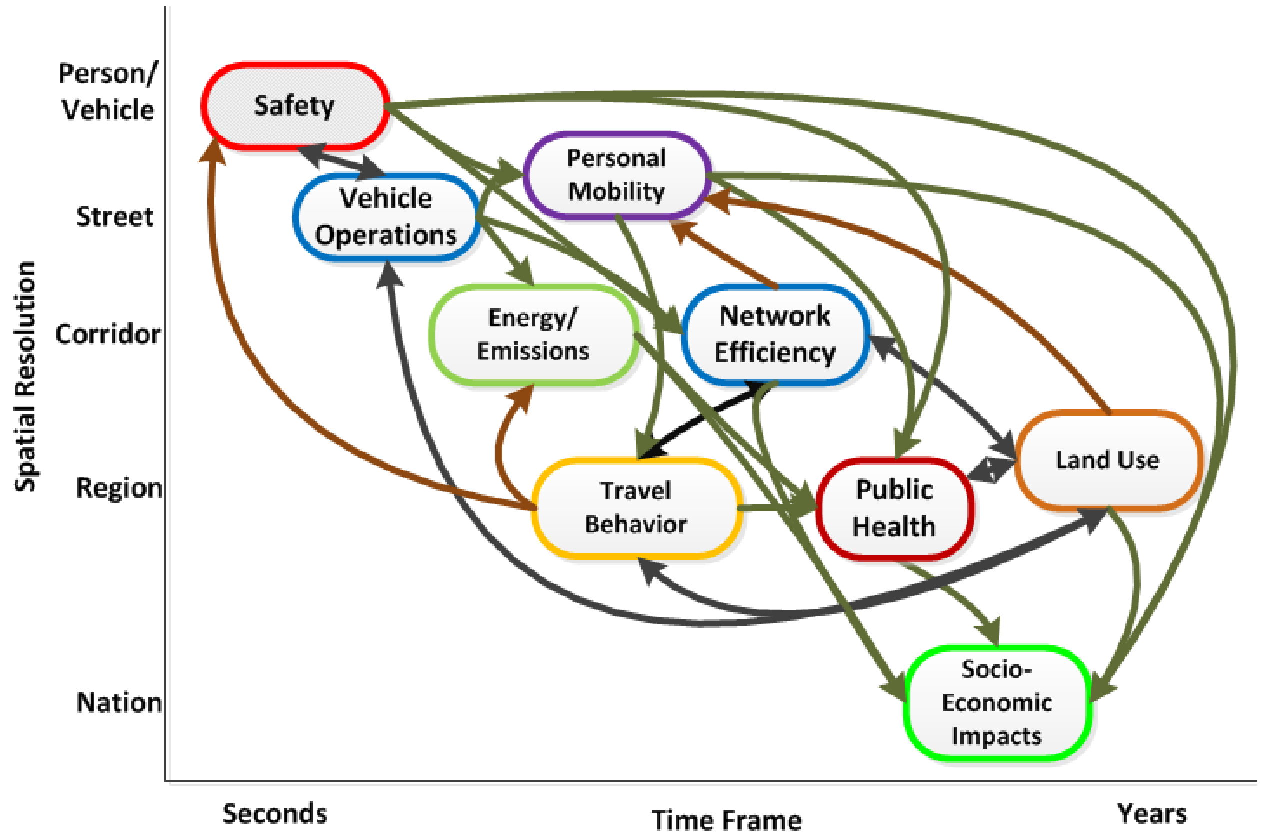
Framework for Automated Vehicle Benefits

- "Big picture" of automated vehicle impacts
- Short-term direct impacts
- Longer-term indirect impacts



- Focus on the relationship between the vehicle operations and energy/emissions
- Connected a traffic microsimulation software (PTV Vissim) with EPA's emission inventory model for highway vehicles (MOVES)

Three-Layered Modeling Framework

Automated Vehicle Technologies in Driving Behavior Models

- Adaptive Cruise Control (ACC)
- Cooperative Adaptive Cruise Control (CACC)
- Speed Harmonization
- Platooning

Microscopic Traffic Simulation Models

- i.e. PTV Vissim, Aimsun, INTEGRATION

Modal Vehicle Emissions Models

- MOVES
- CMEM
- VT-Micro

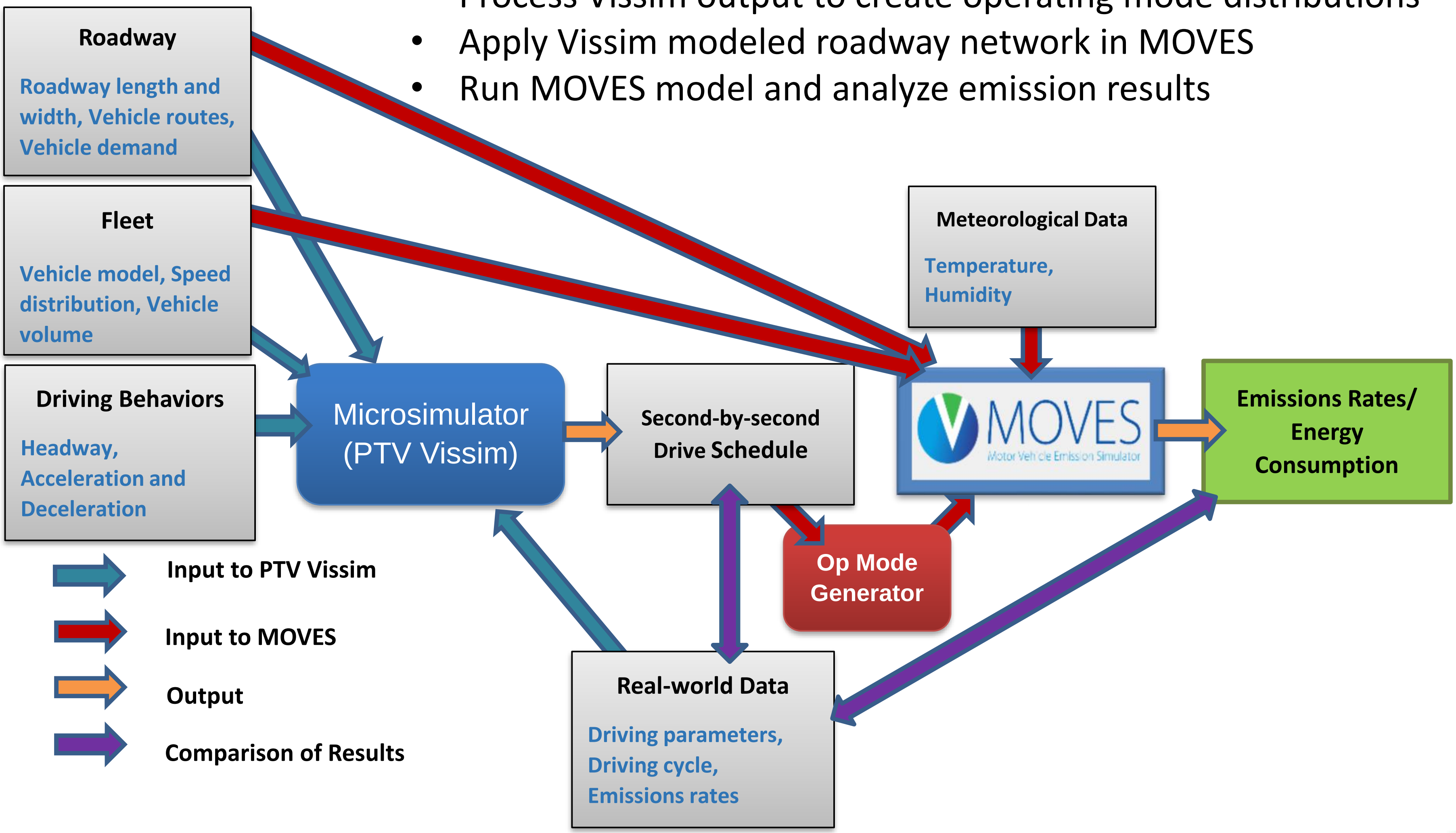
SAE J3016 Levels of Automation

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	**No Automation**	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	**Driver Assistance**	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	**Partial Automation**	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	**Conditional Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	**High Automation**	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	**Full Automation**	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

https://www.sae.org/misc/pdfs/automated_driving.pdf

Modeling Approach

- Produce 15 random Vissim seeds from speed distribution
- Process Vissim output to create operating mode distributions
- Apply Vissim modeled roadway network in MOVES
- Run MOVES model and analyze emission results

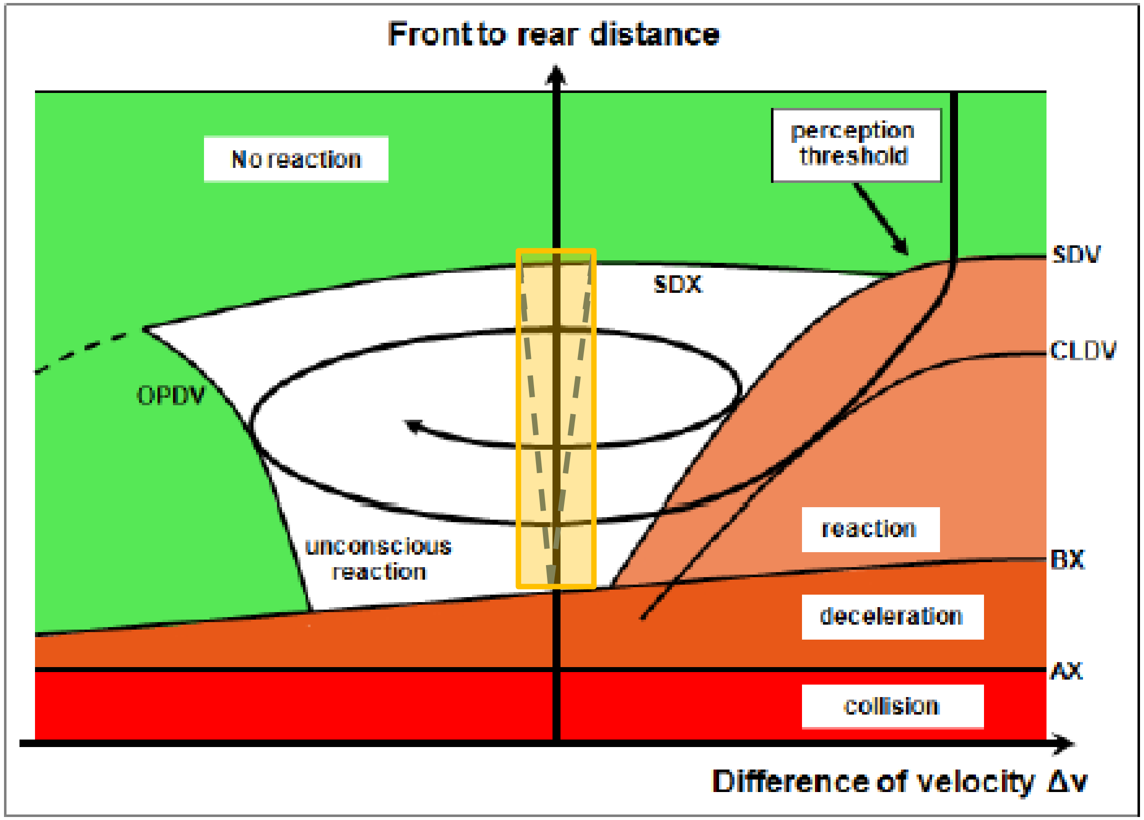


Scenario Development

- Modeled passenger cars on Interstate 91 northbound near Springfield, MA
  - Speeds and traffic volumes from MassDOT
- Modified CACC Driver Model DLL from Turner-Fairbank Highway Research Center (FHWA)
  - Does not include platooning, lane change, or designated lane
- Ran three different microsimulation scenarios in Vissim:
  1) Baseline with default Wiedemann 99 car-following algorithm
  2) All vehicles using CACC driver model
  3) Default Wiedemann 99 algorithm with traffic oscillations set to zero
- MOVES project-level energy and emissions calculated on a per vehicle basis for each scenario

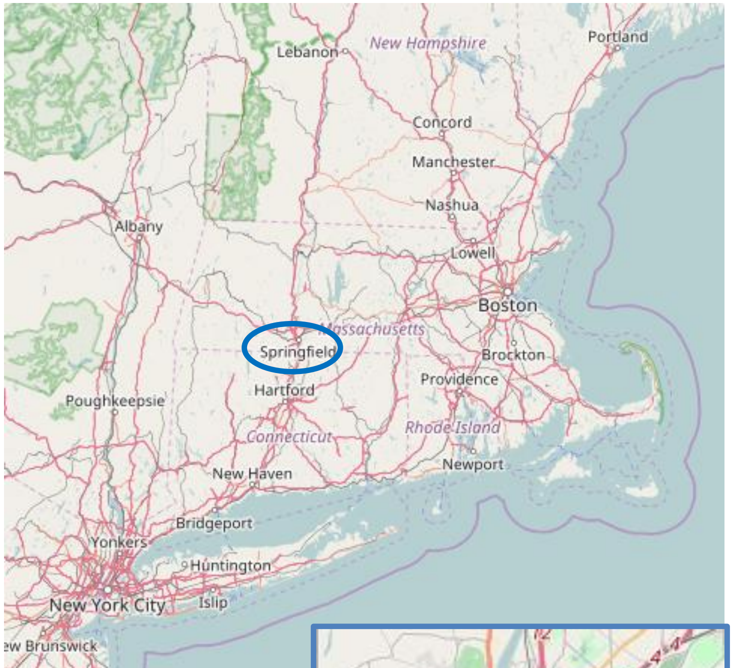
Weidemann Car Following

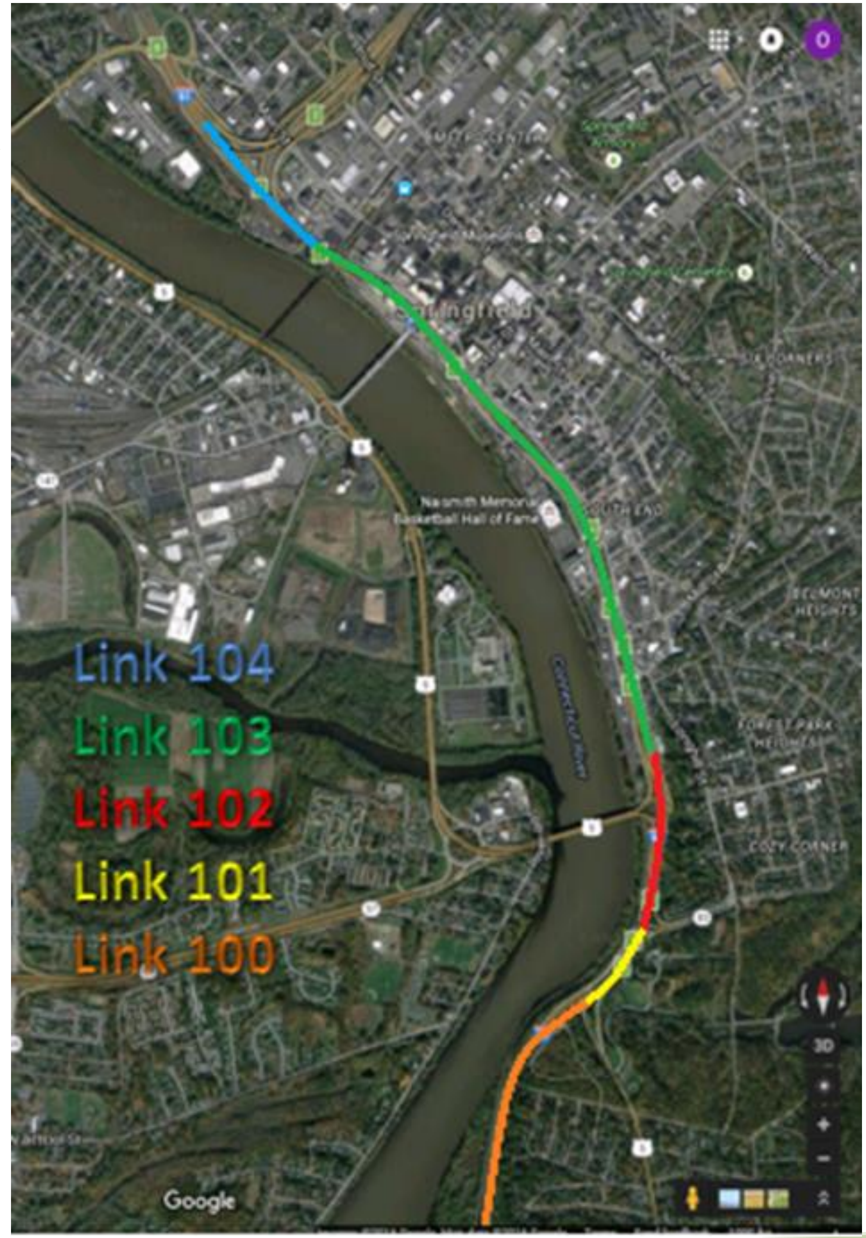
- A closer following headway
- The reduction of oscillations in driver car following behavior



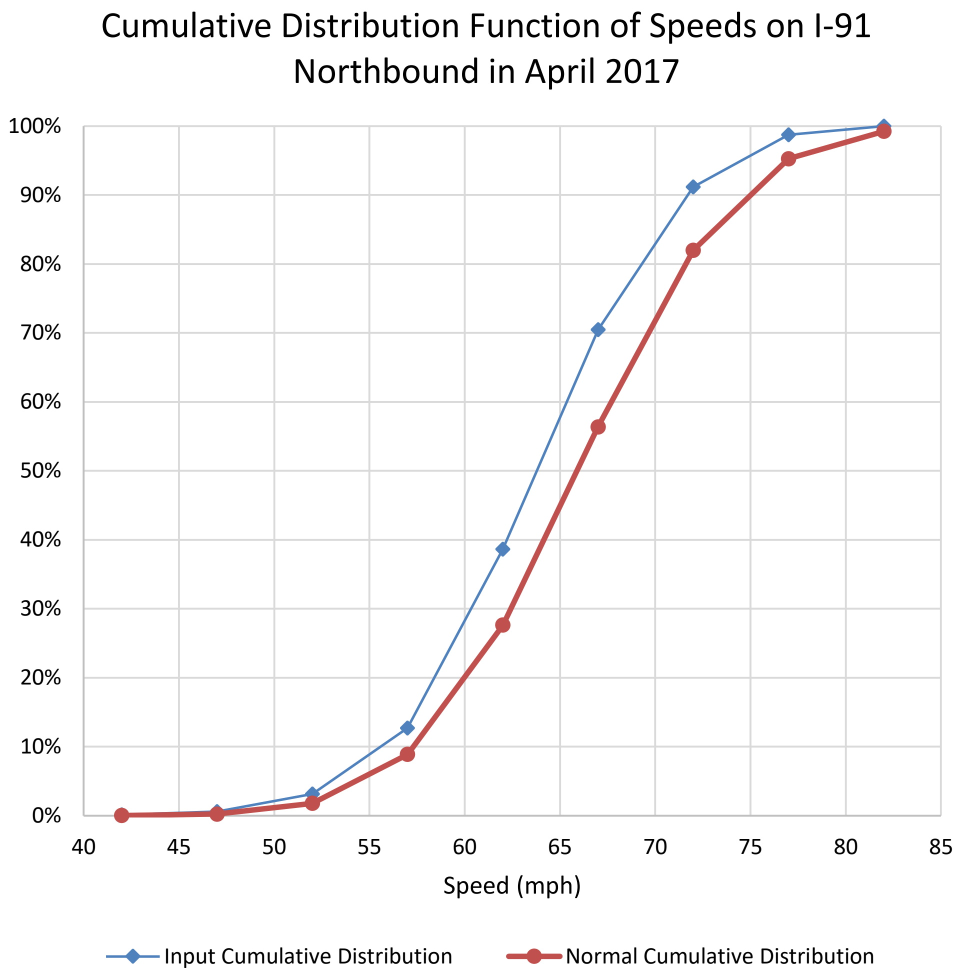
Capri (2012), International Journal of Traffic and Transportation Engineering

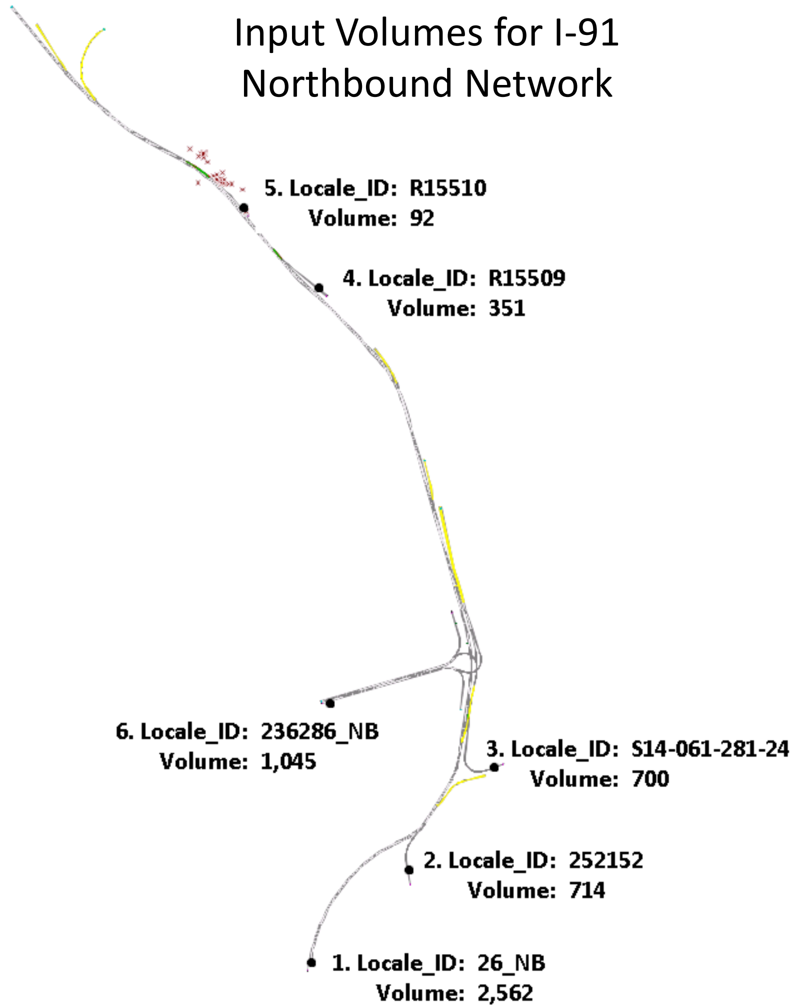
Map of I-91 Network





Input I-91 Traffic Speeds and Volumes





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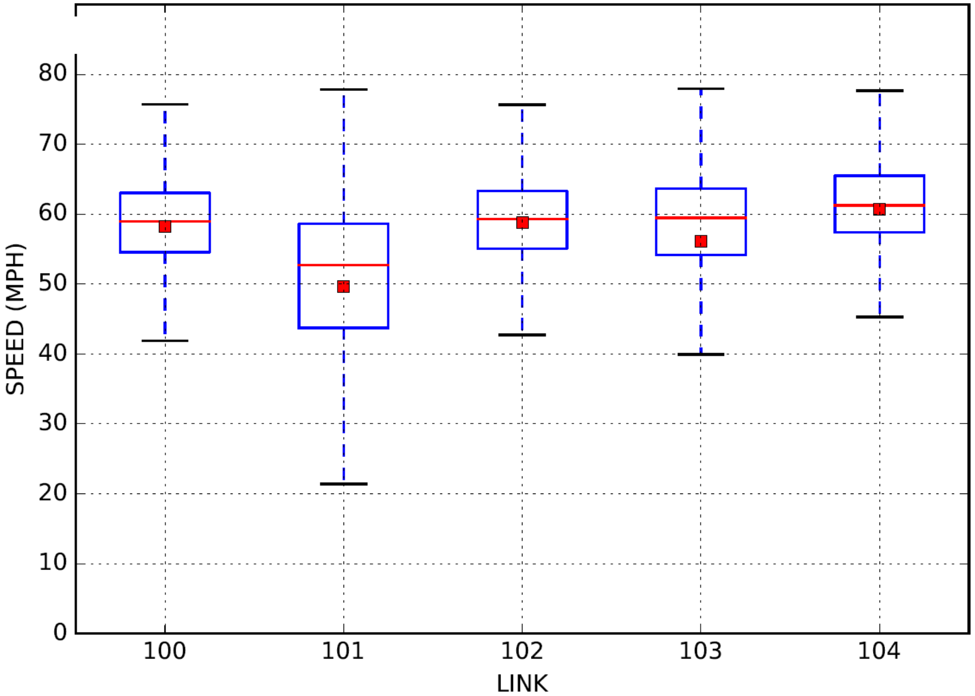
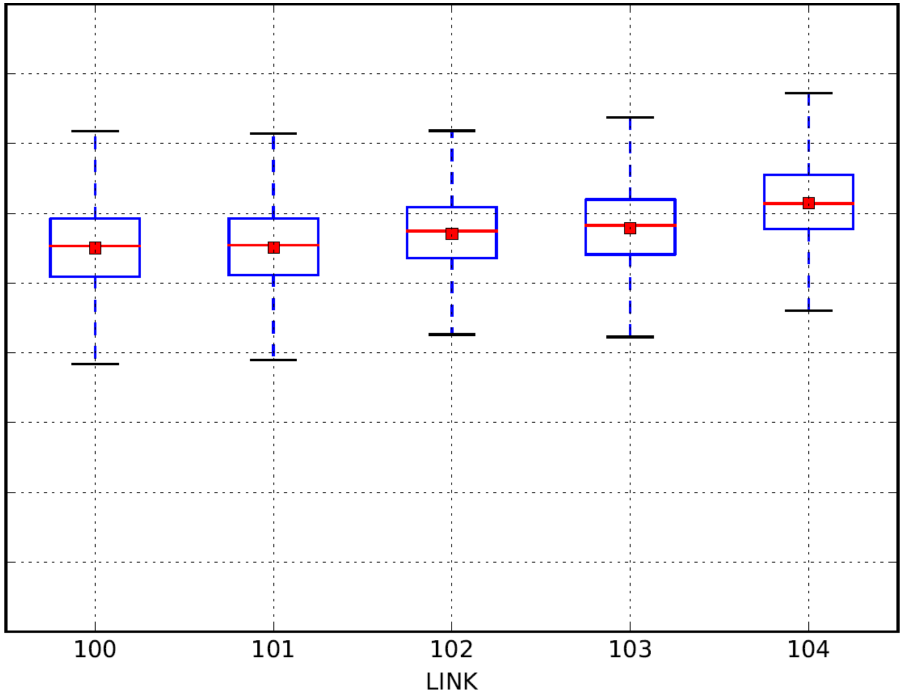
Network Performance

- **Box plots of speeds for each link**
  - **25th percentile, median, 75th percentile, mean (red dot)**

Baseline



CACC



MOVES Operating Modes

- Vehicle-specific power (VSP) and emissions are well correlated
- VSP is derived from instantaneous speed and acceleration along with other constants such as vehicle mass and aerodynamic drag
  - Microsimulations run at 10 Hz
- MOVES operating modes assigned according to VSP and speed bins
  - Separate op modes for braking (opModeID 0) and idling (opModeID 1)

Operating Modes for Running 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	

Beardsley (2011), MOVES Workshop

Vehicle-Specific Power (VSP)

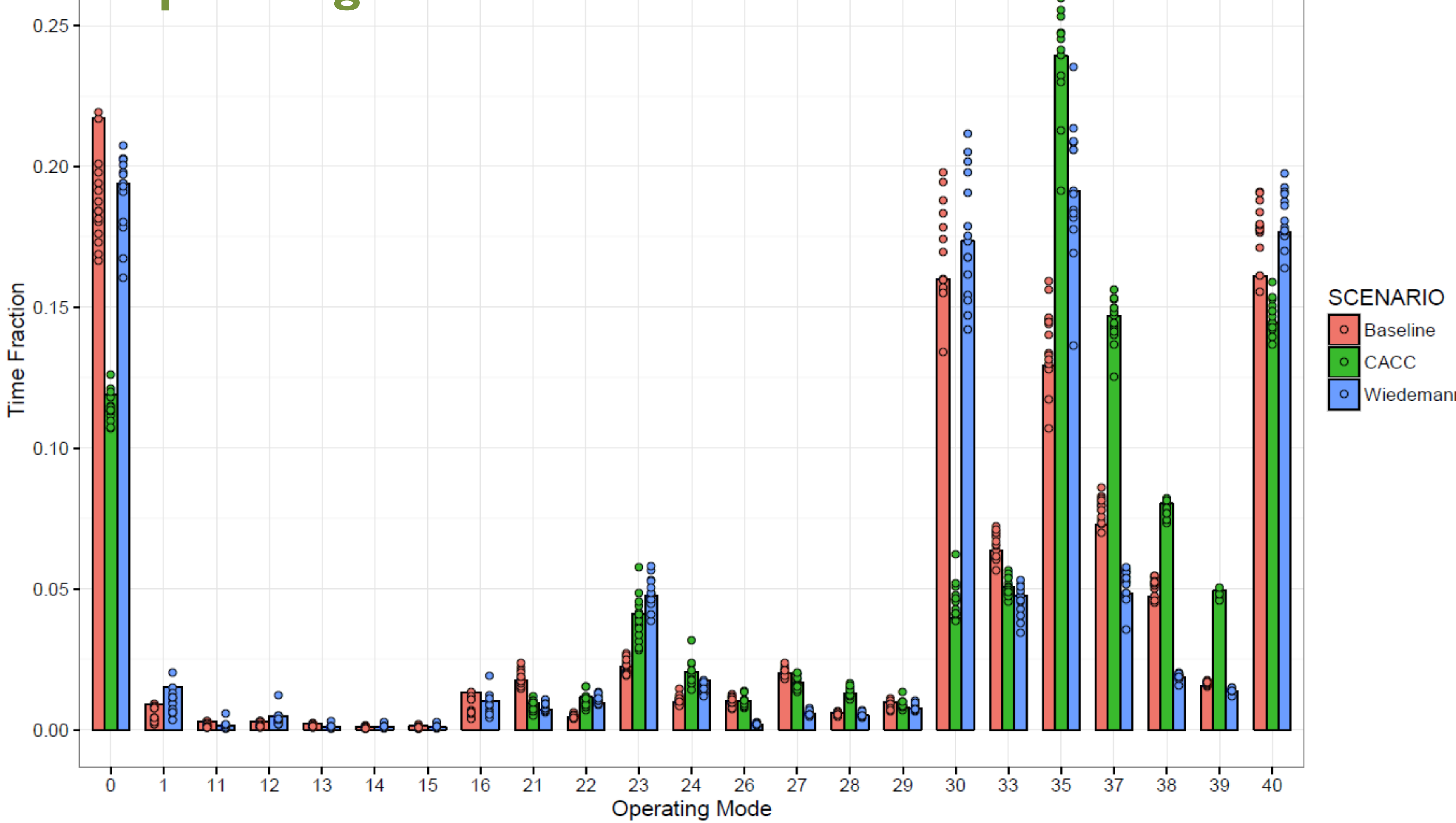
$$P_{V,t} = \frac{Av_t + Bv_t^2 + Cv_t^3 + mv_t a_t}{m}$$ **Equation 1-2**

In this form, VSP ($P_{V,t}$, kW/Mg) is estimated in terms of vehicles':

- speed at time t (v_t, m/sec),
- acceleration a_t, defined as $v_t - v_{t-1}$, (m/sec^2) ,
- - mass m (Mg) (usually referred to as "weight,"),
- - track-road load coefficients A, B and C, representing rolling resistance, rotational resistance and aerodynamic drag, in units of kW-sec/m, kW-sec^2/m^2 and kW-sec^3/m^3, respectively.[3]

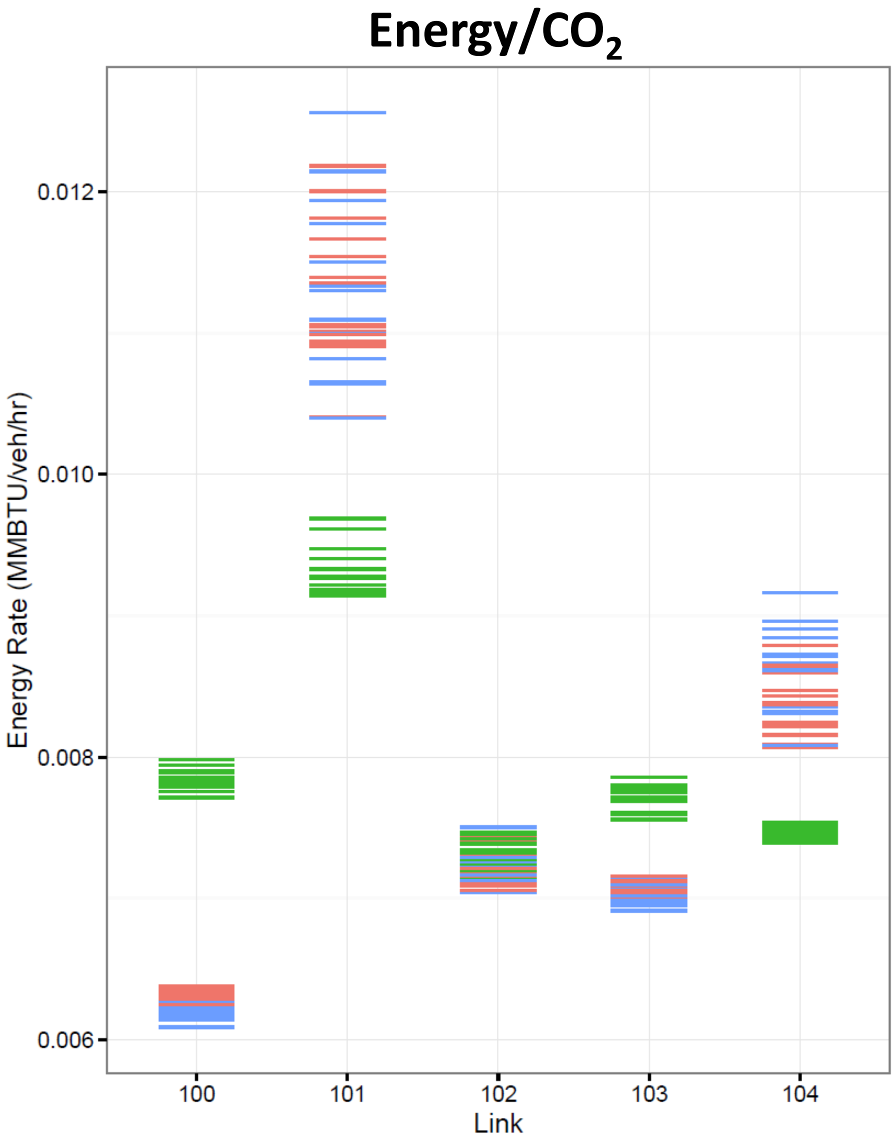
MOVES2014 LDV Emissions Technical Report

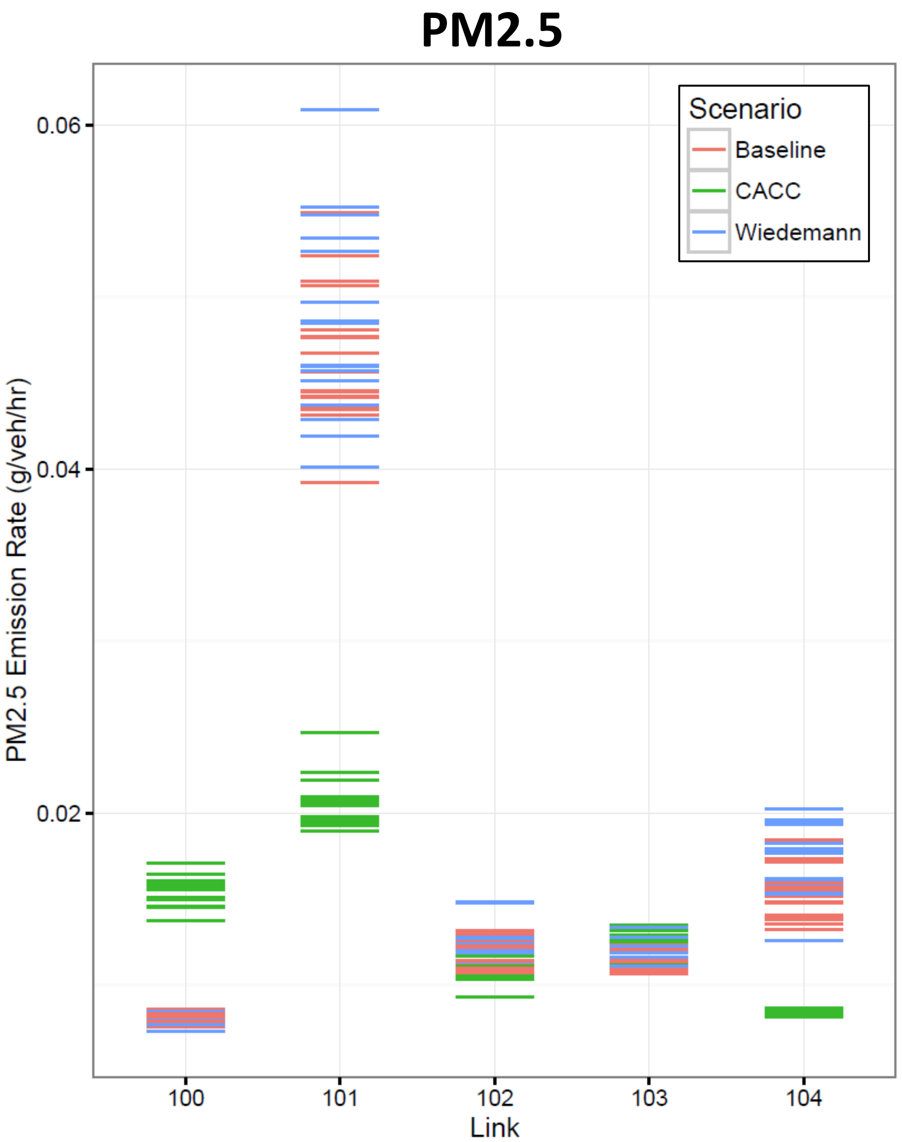
Operating Mode Distributions

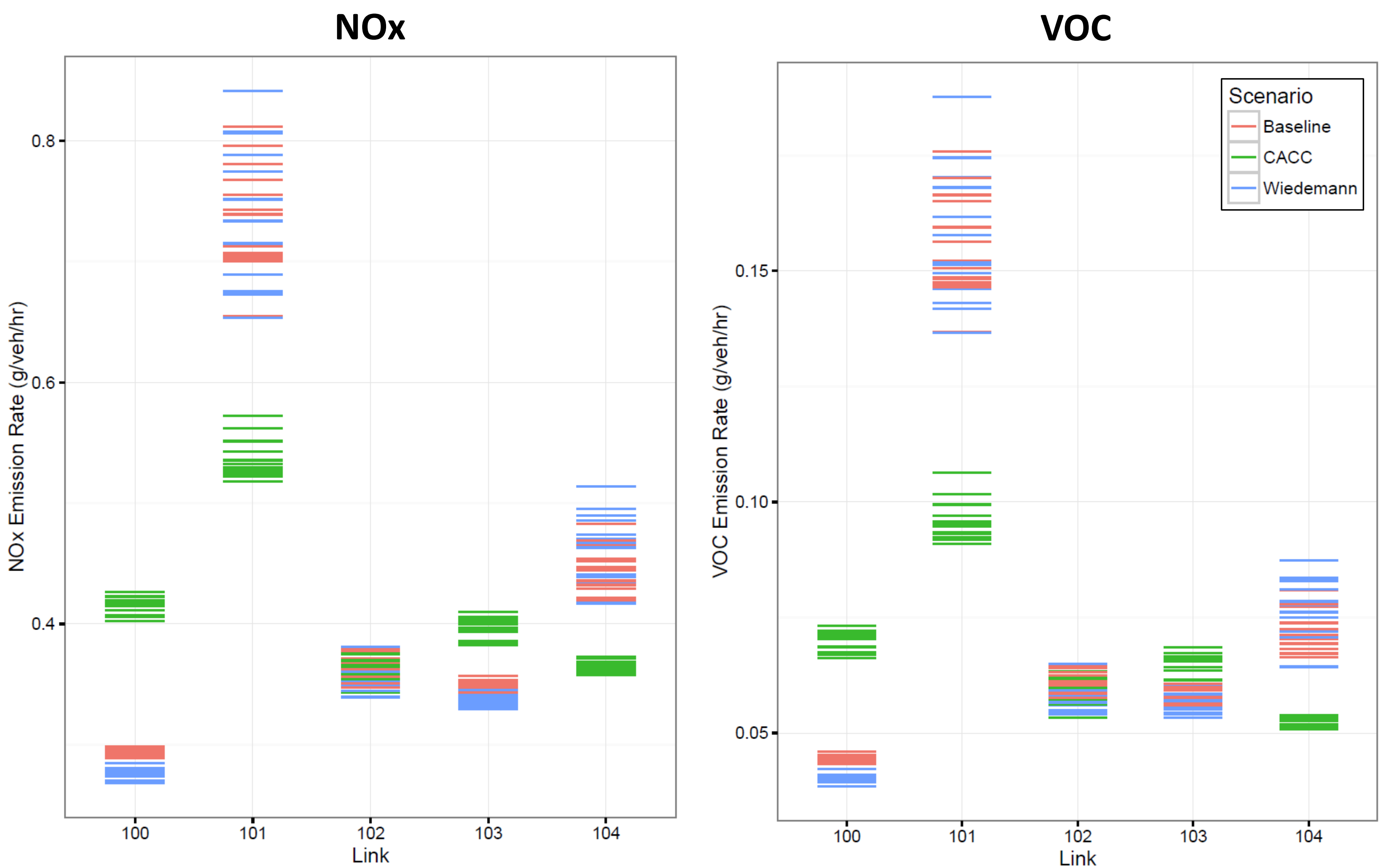


I-91 Springfield Link 101

Link-Level Emission and Energy Impacts

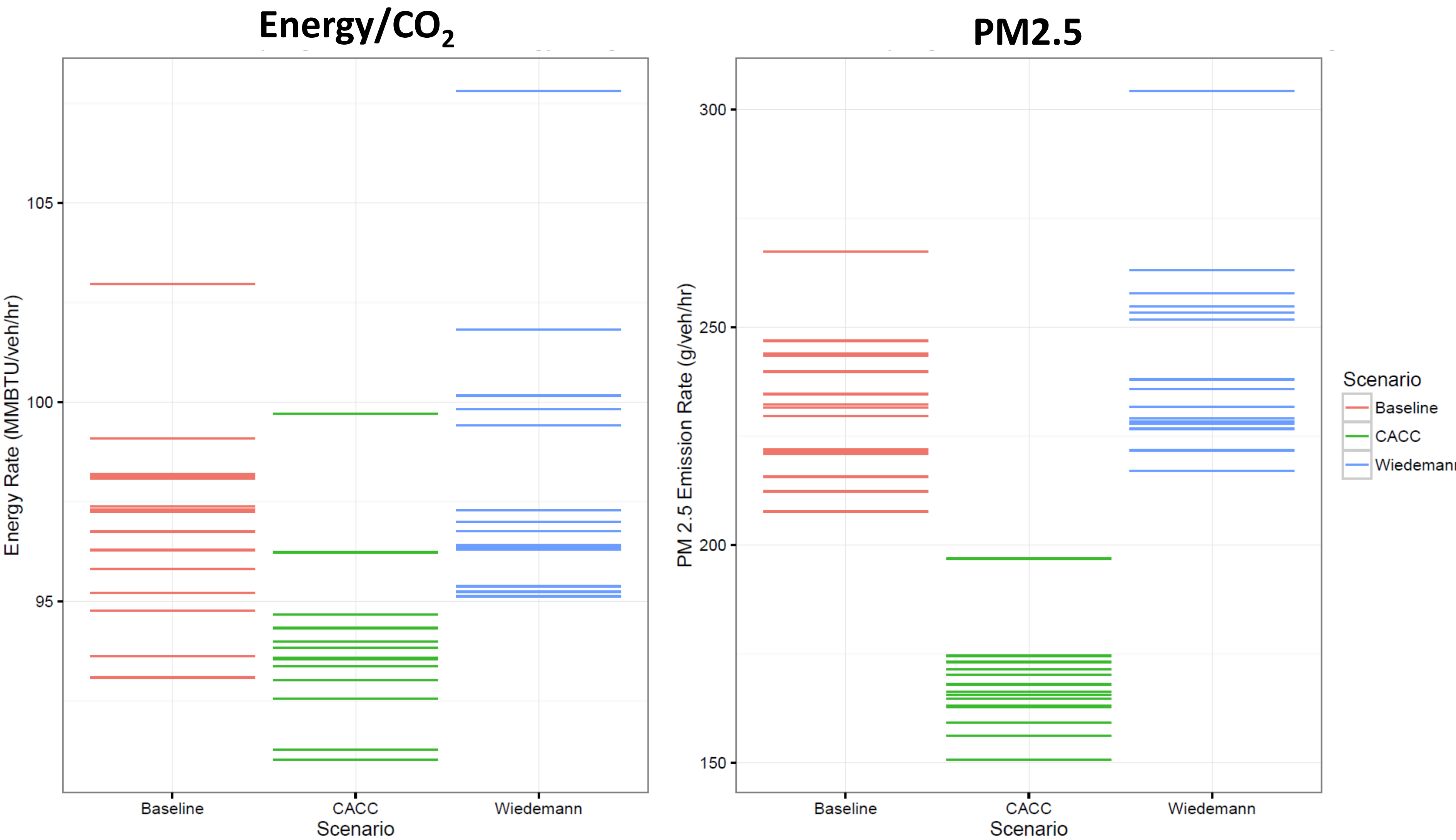


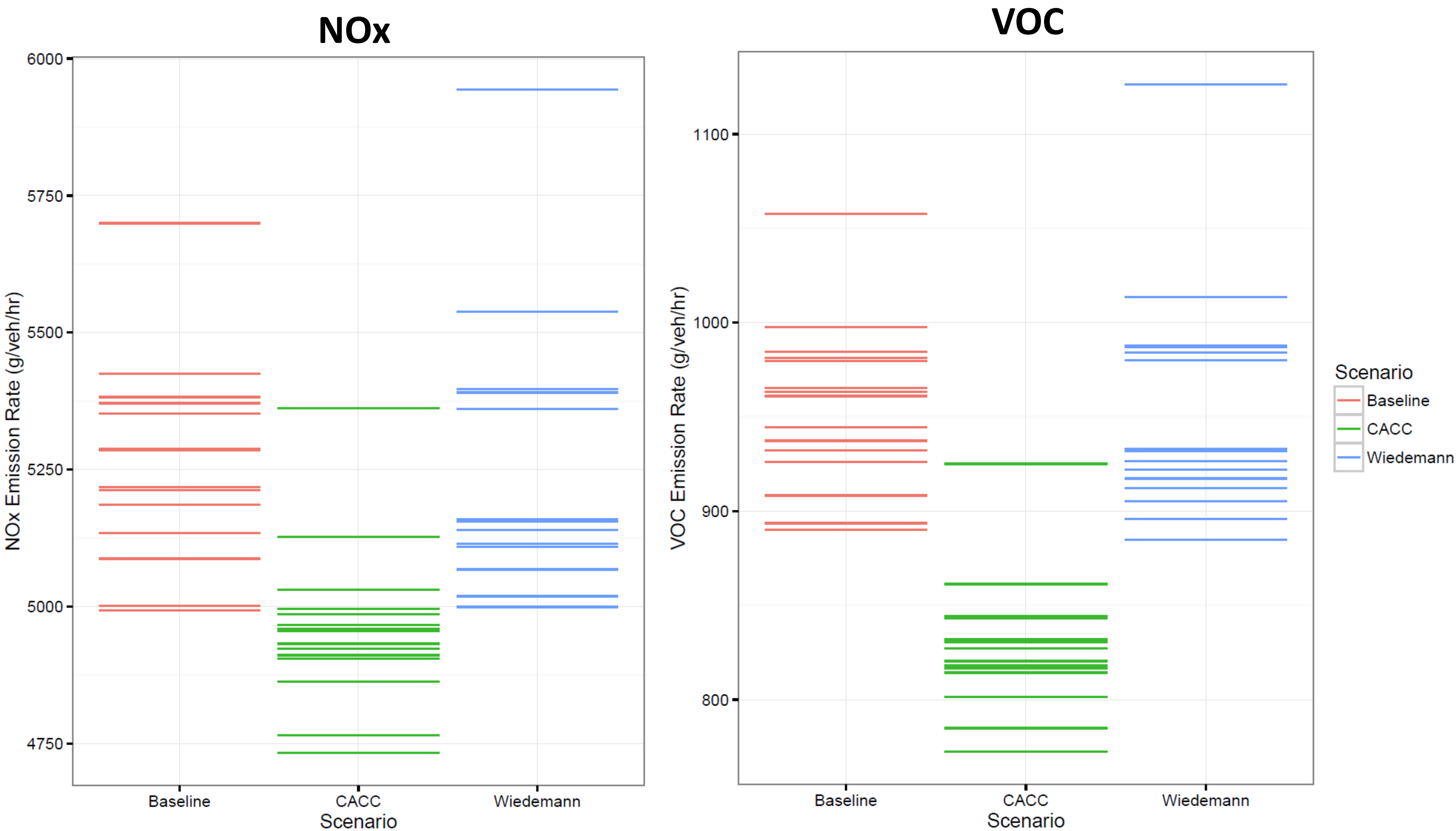




NOx
NOx Emission Rate (g/veh/hr)
0.8
0.6
0.4
100
101
102
103
104
Link
VOC
VOC Emission Rate (g/veh/hr)
0.15
0.10
0.05
100
101
102
103
104
Link
Scenario
Baseline
CACC
Wiedemann

Network Emissions and Energy Impacts




NOx
VOC
NOx Emission Rate (g/veh/hr)
6000
5750
5500
5250
5000
4750
VOC Emission Rate (g/veh/hr)
1100
1000
900
800
Baseline
CACC
Wiedemann
Scenario
Scenario
Baseline
CACC
Wiedemann

Minimum/Maximum Impacts

	CACC from Baseline		Wiedemann from Baseline	
Pollutant	**Min**	**Max**	**Min**	**Max**
THC	-2.2%	22.1%	-18.7%	15.4%
CO	2.5%	33.9%	-30.2%	17.6%
NOx	-5.6%	10.4%	-11.2%	10.6%
VOC	-2.2%	21.2%	-18.2%	14.8%
Energy/CO_2	-4.7%	4.7%	-7.5%	5.9%
PM2.5	6.8%	39.2%	-36.8%	17.3%

- CACC scenario shows mostly benefits from baseline
  - CO and PM2.5 only have reductions
- Wiedemann scenario without oscillations often has disbenefits
  - Possible benefits and disbenefits are approximately equal for NOx, VOC, and Energy/CO2

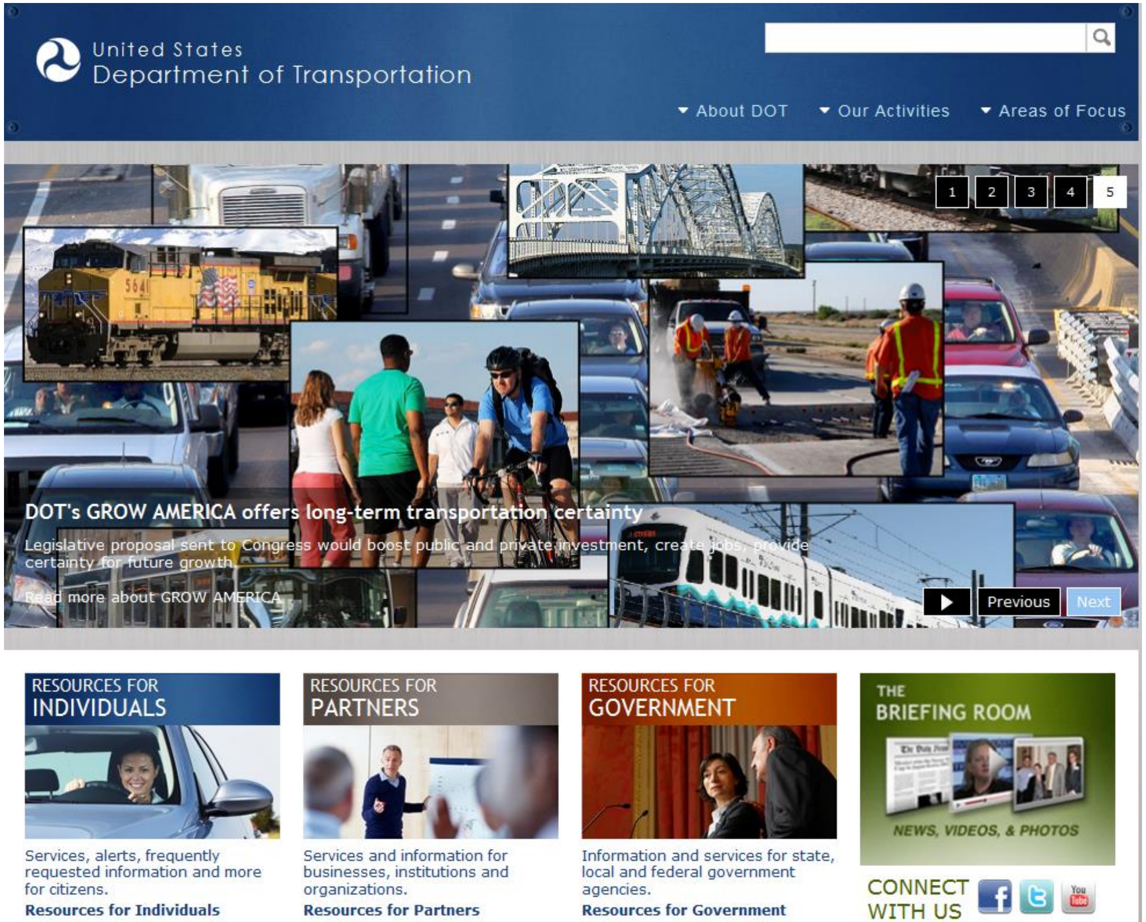
Conclusions and Future Work

- Results
  - Automated vehicles generally show **less braking**, leave **less headway**, and have **less fluctuations in speed and acceleration** than baseline
  - CACC has less of an effect on energy and emissions in freely flowing traffic
  - Wiedemann oscillation smoothing does not produce much benefit
  - DLL needs to be thoroughly tested and validated
- Next Steps
  - **Vary traffic volumes** to simulate more heavily congested scenarios
  - Experiment with **different penetrations of CACC**-enabled vehicles
  - Investigate lane changing capabilities to accommodate merging

Discussion

- Modeling Recommendations
  - Update tools to reflect connected and automated vehicle (CAV) technologies
    - Integrate CAV technologies into MOVES driving behavior
    - Add custom operating mode distributions for regulatory analysis
- Broader Issues
  - Travel behavior
    - Shared vehicles
    - Shared trips
    - Effect on VMT
    - Parking
  - Vehicle operations
    - Drivetrain technologies (fossil fuel vs. electric)
    - Emission sources (mobile vs. stationary)

For More Information



http://www.dot.gov/

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