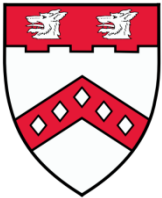


Framework for Context-Sensitive Spatially- and Temporally-Resolved Onroad Mobile Source Emissions Inventories

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For Presentation at:

U.S. Environmental Protection Agency

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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

Model Evaluation

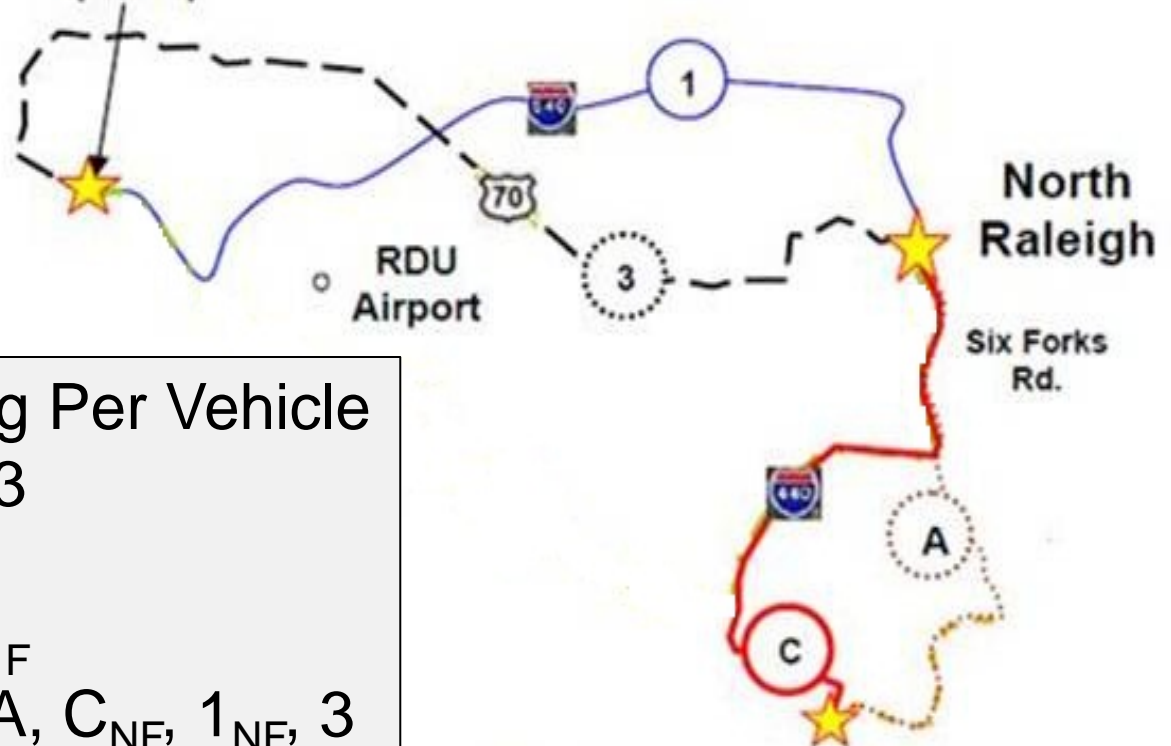
- MOVES has undergone some evaluation
 - Chassis dynamometer data: short duration, limited range of driving cycles
 - Remote sensing data: location-specific ‘snapshots’
 - Tunnel studies: location-specific, difficult to resolve for individual types of vehicles
- Approach here: use independent path-based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

Portable Emission Measurement System



Test Routes

Research Triangle Park
(RTP)



112 Miles of Driving Per Vehicle

4 Routes: A, C, 1, 3

6 Cycles

- Freeway: C_F , 1_F
- Non-Freeway: A, C_{NF} , 1_{NF} , 3

North Carolina State University
(NCSU)

Vehicle Specific Power

Modal average fuel use and emission factors are estimated based Vehicle Specific Power (VSP).

$$VSP = v[1.1a + 9.81(\sin(\arctan(r))) + 0.132] + 0.000302v^3$$

Where,

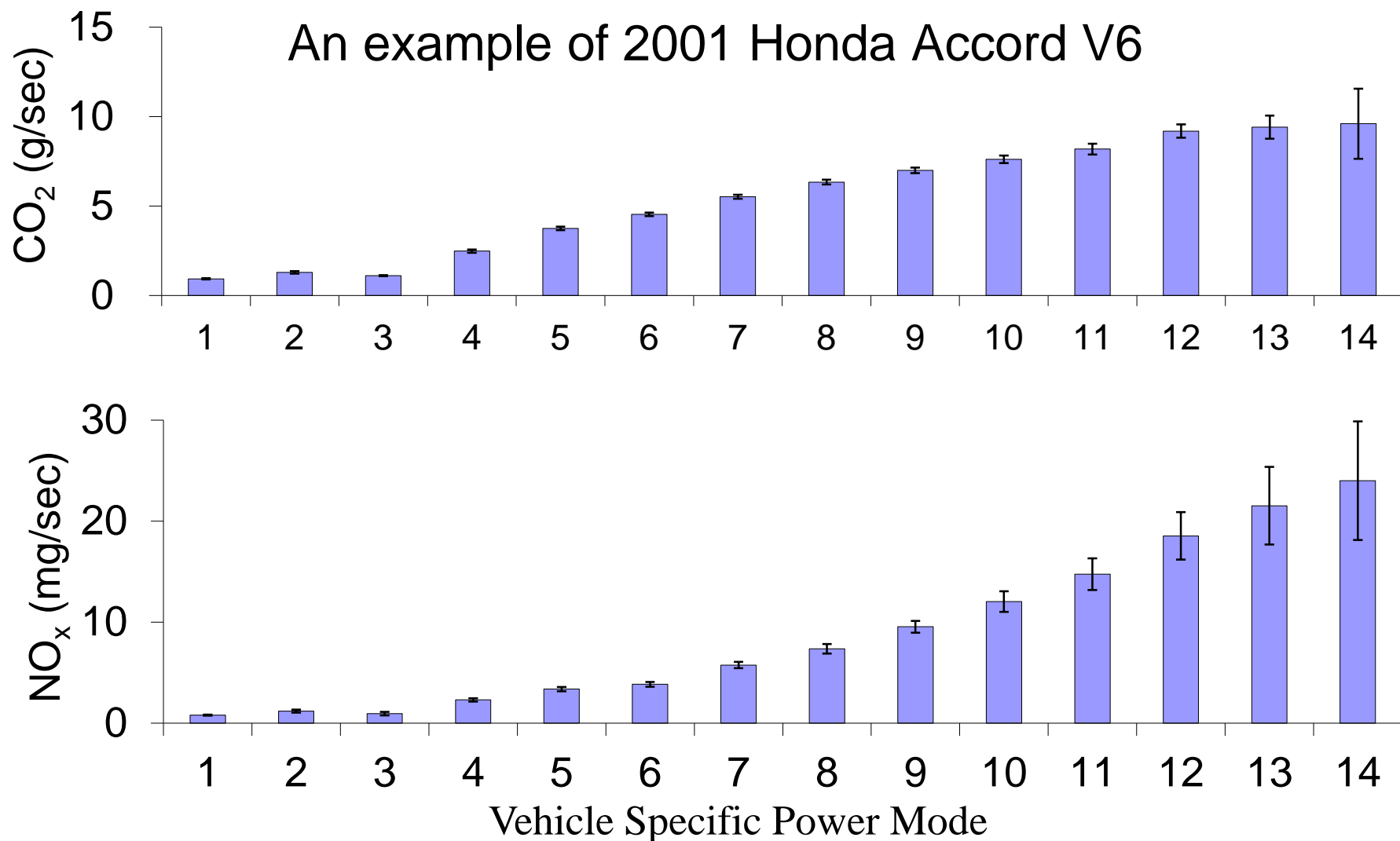
v = vehicle speed (km/h)

a = acceleration (km/h per sec)

r = road grade (%)

VSP = vehicle-specific power (kW/ton)

Example of VSP Modal CO₂ 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 GVW

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);

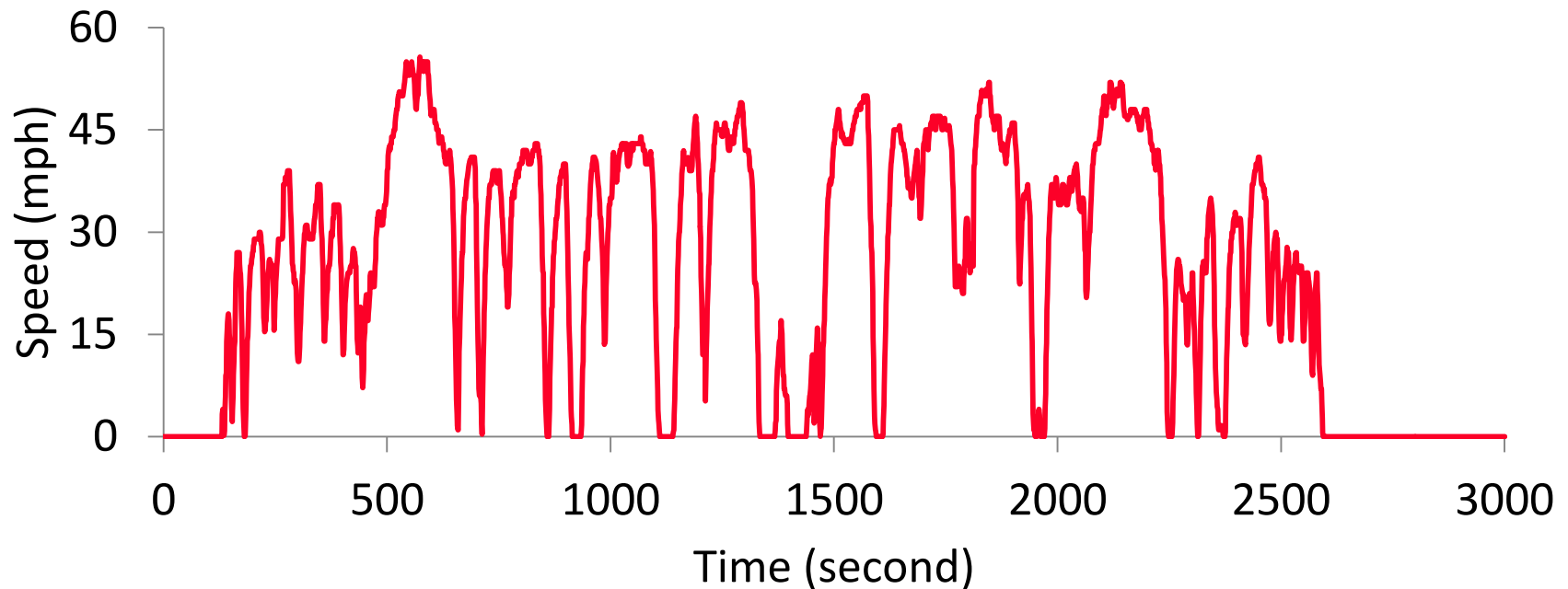
$F_{m,c}$ = fraction of time in VSP mode m for cycle c ;

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

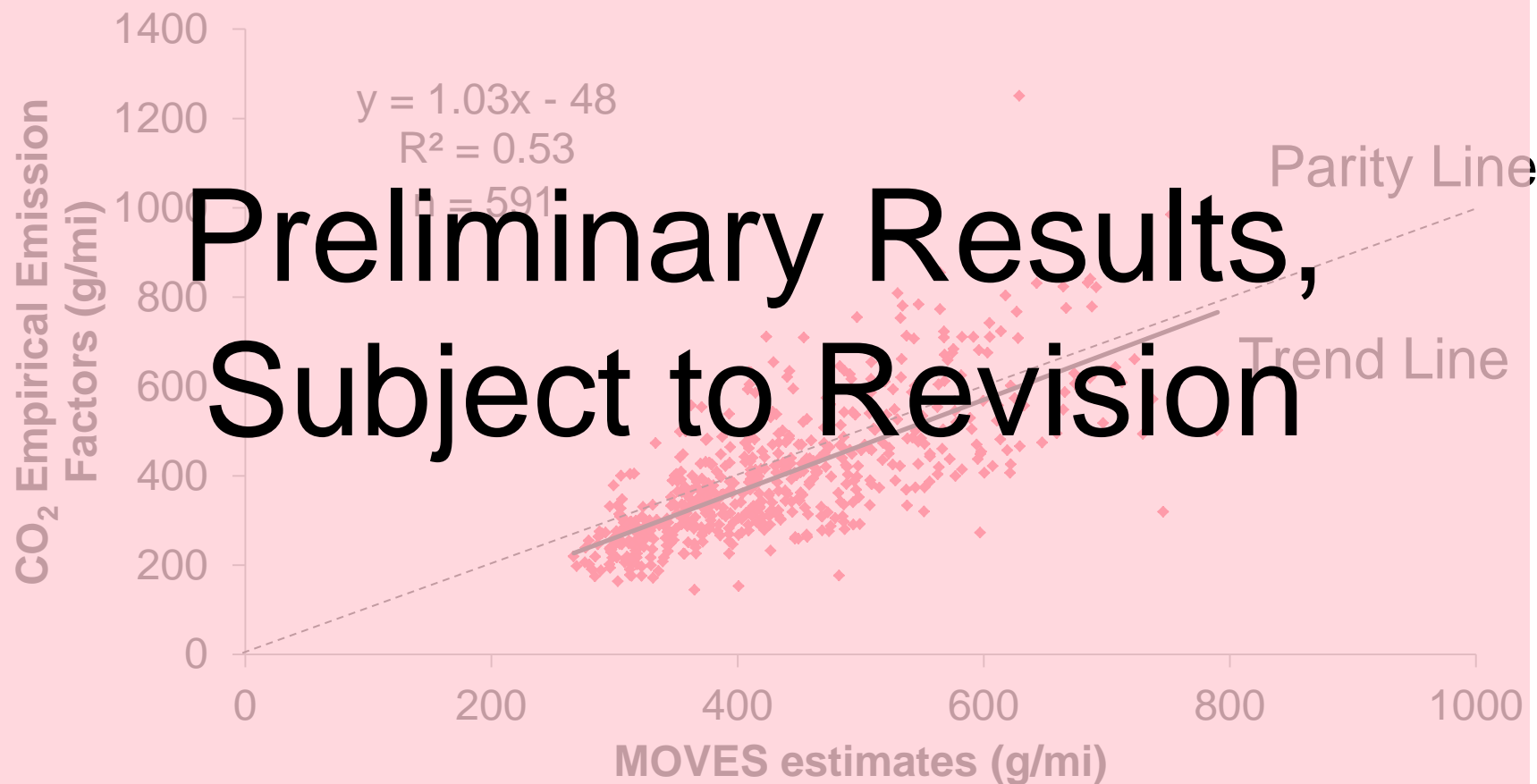
Example based on 2000 Mitsubishi Galant and Route A

Meteorological Data	97.3 °F; 32% Relative Humidity
Age Distribution	10 years, Calendar Year 2010
Driving Schedule	Empirical data: Route A
Link Source Type	100% passenger car
Link Length	20.3 miles
Fuel	Gasoline
I/M Program	Wake County, NC

Objectives for Model Evaluation

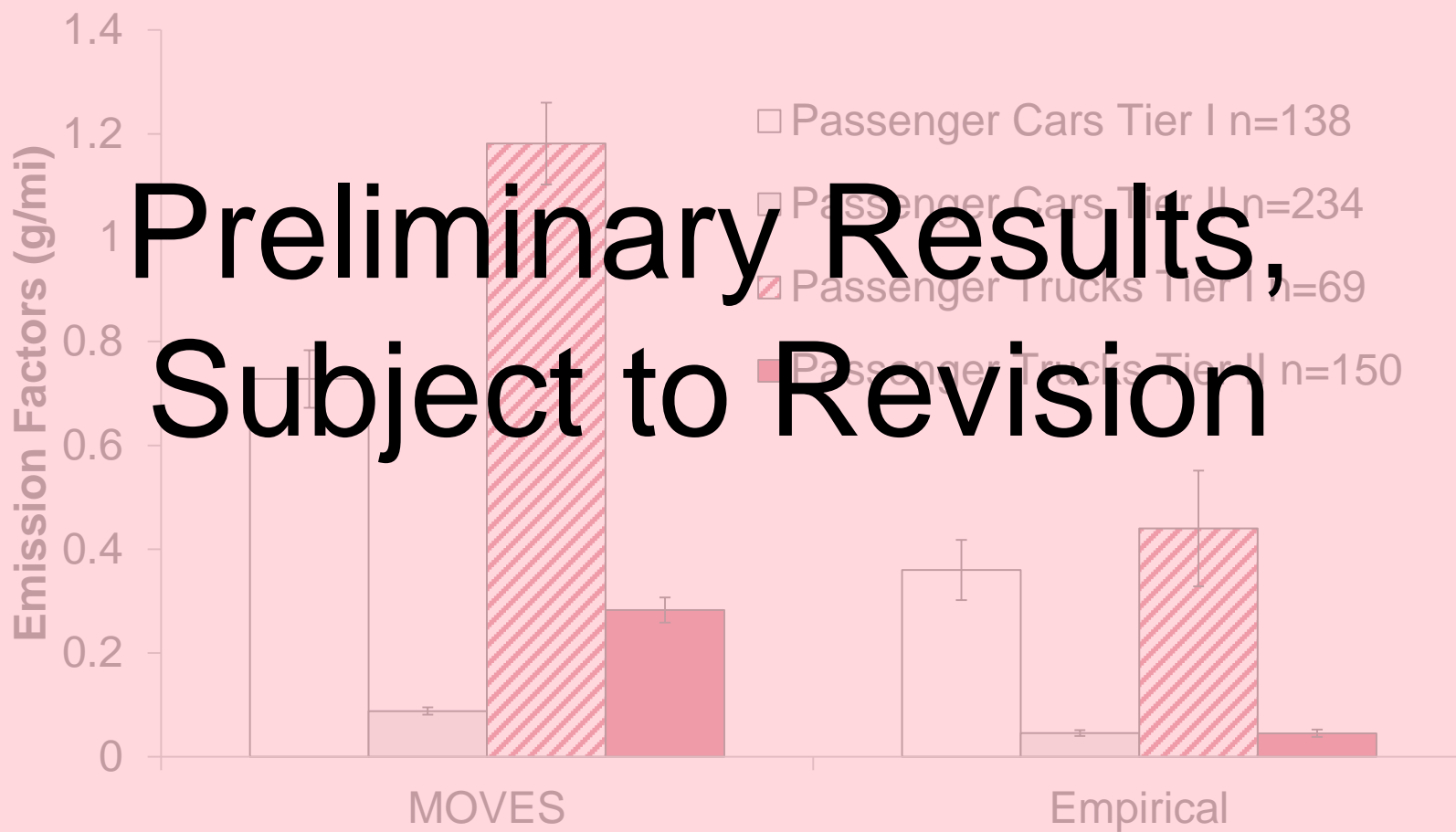
- Evaluate MOVES sensitivity to:
 - vehicle type
 - driving cycles
 - road types
 - model year
 - age and mileage
- Focus is on similarity in relative trends
- Results shown here are “preliminary” and undergoing some final data quality review

Empirical vs. MOVES: CO₂



MOVES is a *fleet* model. Empirical data are individual vehicles

Average NO_x Emission Factors: PC and PT, Tier I and Tier II, MOVES and Empirical



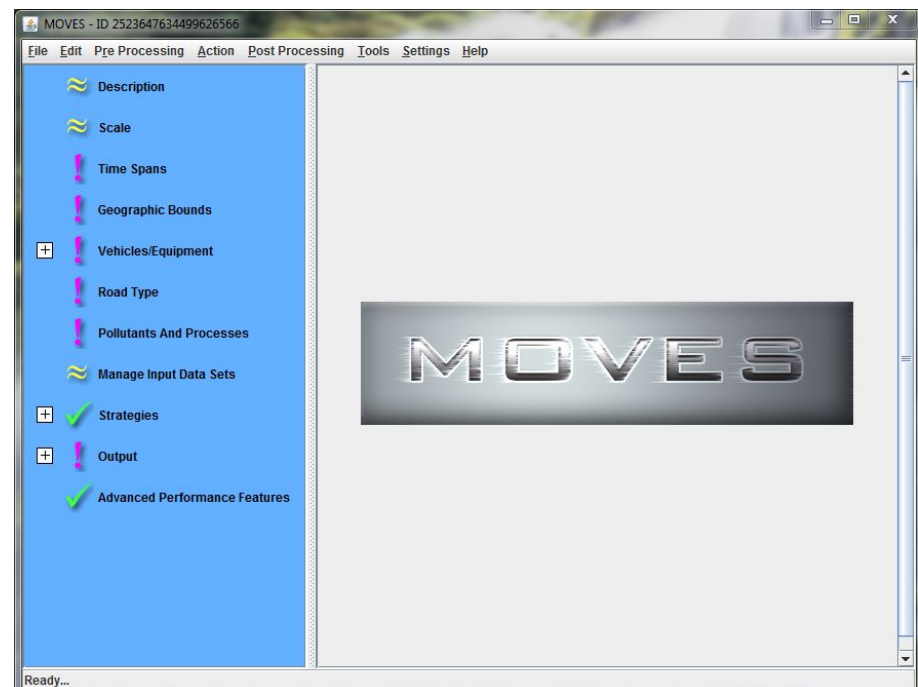
Trends are similar: Tier II < Tier I, PC < PT. MOVES > Empirical

Ongoing Work: MOVES vs. Empirical Data

- Road type: Freeway and Non-Freeway
- Mileage and Age: statistically significant trends for empirical data
- Distributions of inter-vehicle variation are often highly correlated when comparing one case to another (e.g., road type)

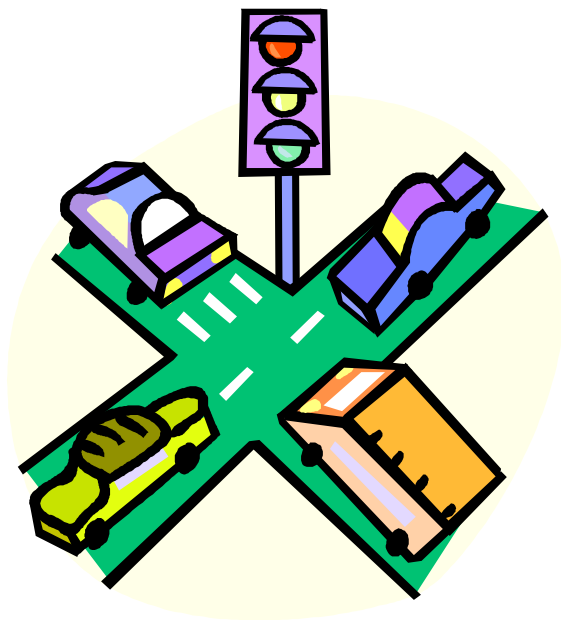
Development of “MOVES Lite”

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

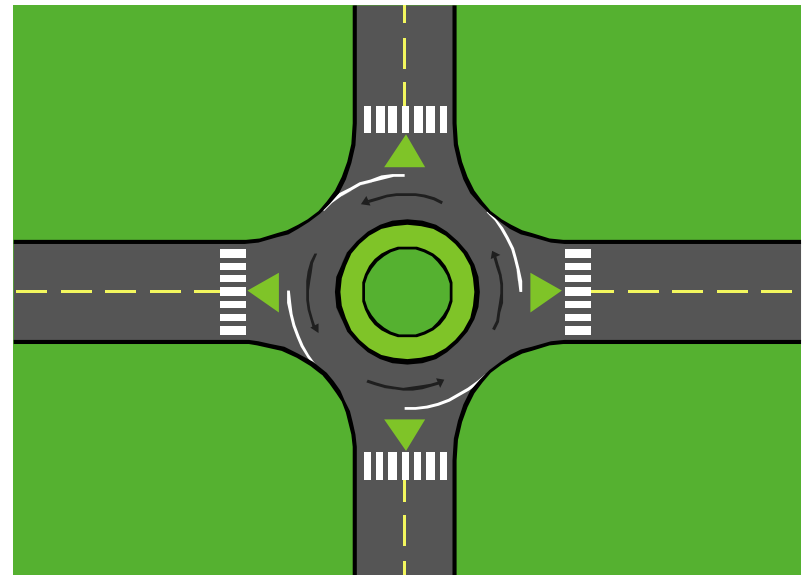


Motivation

- 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).

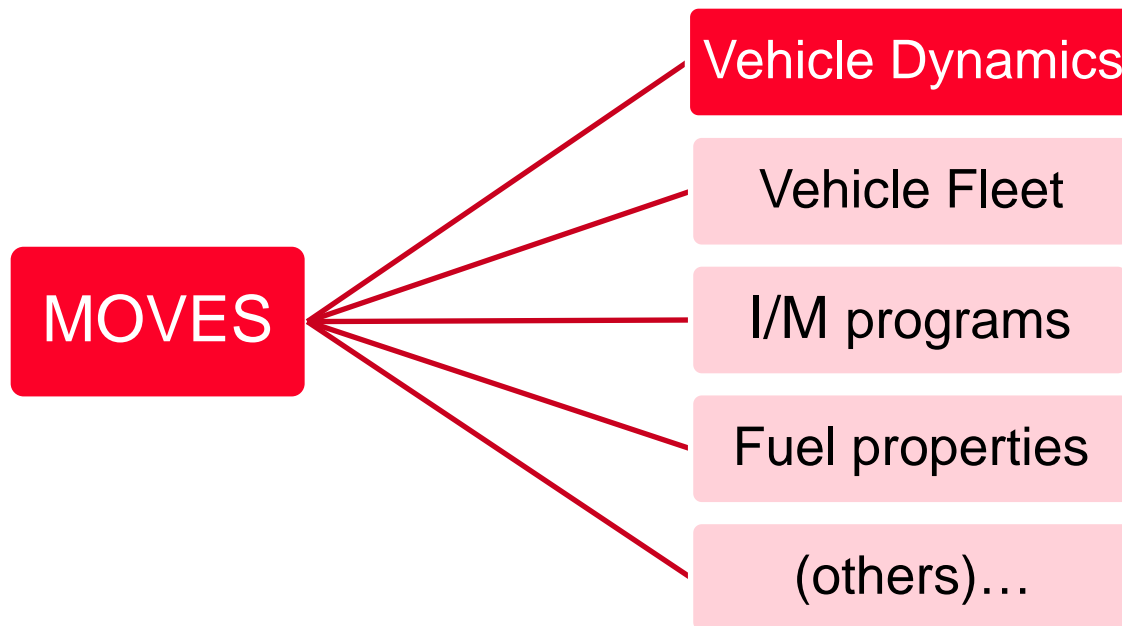


vs.



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

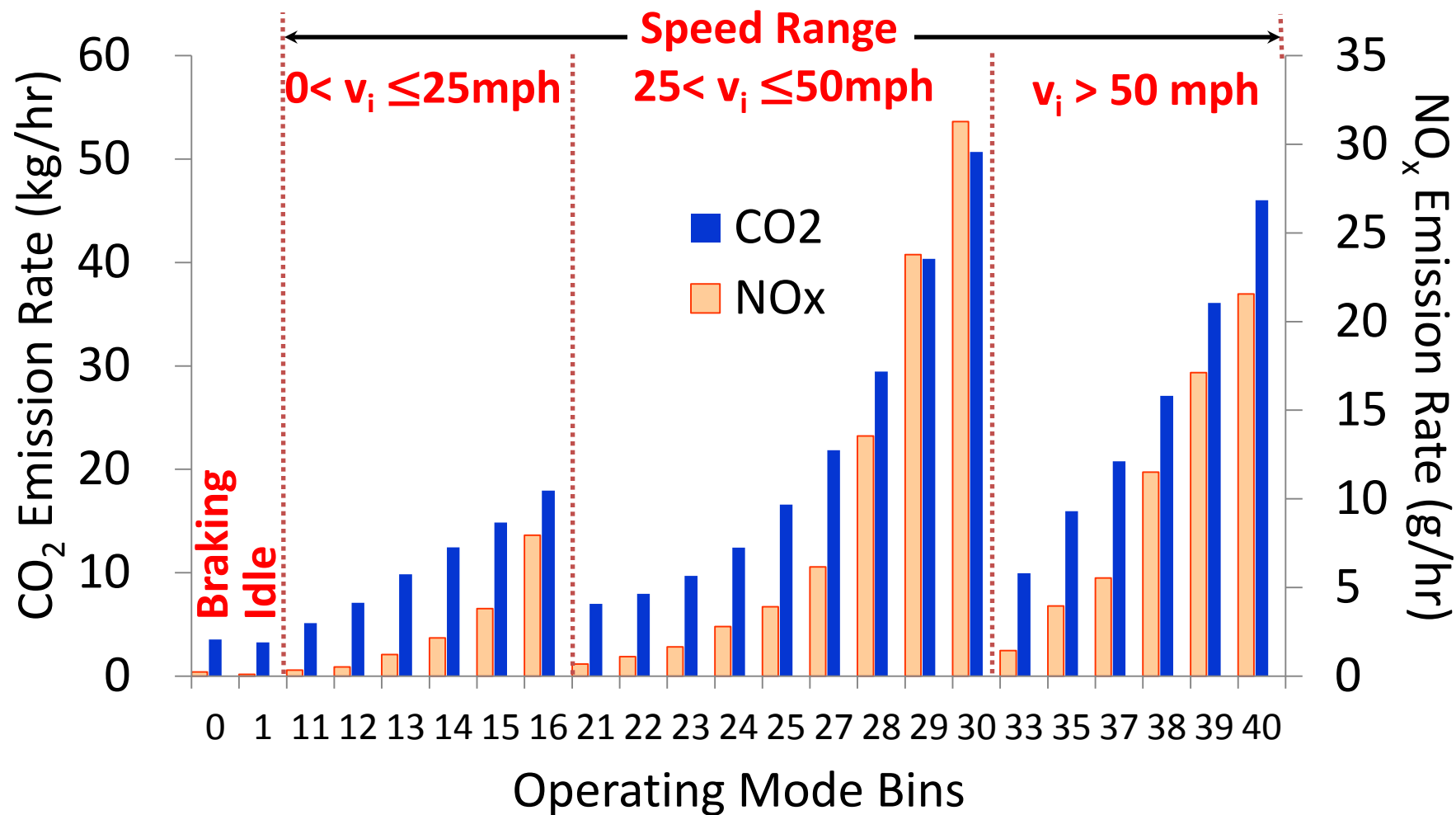
- Develop a simplified MOVES model that can be efficiently coupled with TSMs.
- Evaluate the accuracy of the simplified model.
- Evaluate the sensitivity of the simplified model to variations in driving cycles.

Definition of MOVES Operating Mode Bins by Speed and VSP Ranges

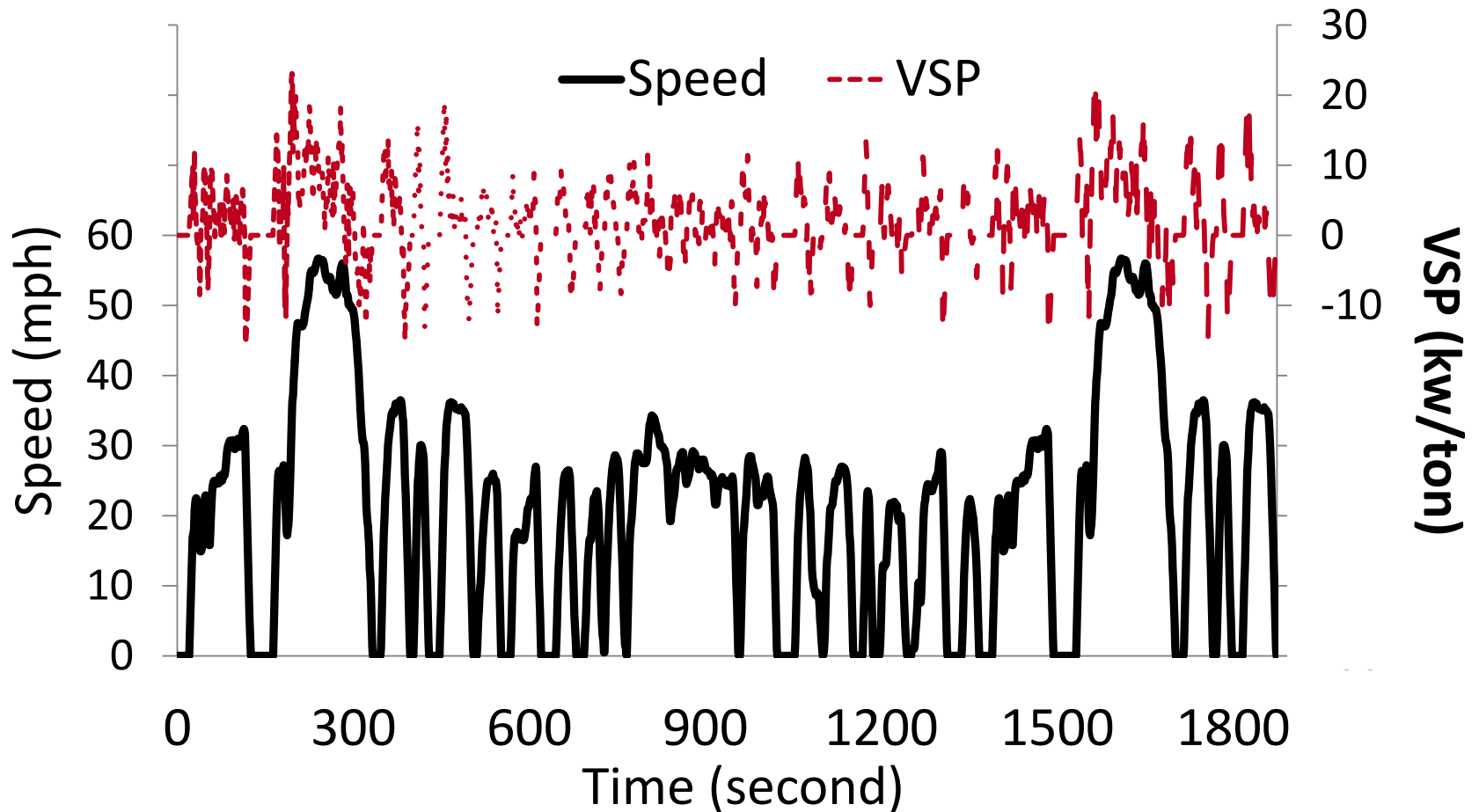
0 mph < v_i ≤ 25 mph		25 mph < v_i ≤ 50 mph		v_i > 50 mph	
OpMode ID	Description	OpMode ID	Description	OpMode ID	Description
11	VSP < 0	21	VSP < 0		
12	0 ≤ VSP < 3	22	0 ≤ VSP < 3		
13	3 ≤ VSP < 6	23	3 ≤ VSP < 6	33	VSP < 6
14	6 ≤ VSP < 9	24	6 ≤ VSP < 9	35	6 ≤ VSP < 12
15	9 ≤ VSP < 12	25	9 ≤ VSP < 12	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

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)



Simplified Model

Cycle Average Emission Rate

- Simplified Model:

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

$CE_{p,c}$	=	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

Simplified Model

Base Emission Rate From MOVES

Emission rate for a base cycle estimated using MOVES

$$CE_{p,c} = \sum_v \left\{ \left[\sum_a (EF_{p,b,a,v} \times CCF_{p,c,a,v} \times f_{a,v}) \right] \times f_v \right\}^{(1)}$$

$CE_{p,c}$	=	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
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$f_{a,v}$	=	age fraction for age a and vehicle type v
f_v	=	vehicle type fraction for vehicle type v

Simplified Model

Cycle Correction Factor

CCF for any arbitrary cycle c
calculated by Eq. 2

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

$CE_{p,c}$	=	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

Simplified Model: Distribution of Fleet Age

- Conceptual Model:

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

Distribution of vehicle type v fleet by age a

$CE_{p,c}$	=	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

Simplified Model: Distribution of Vehicle Types

- Conceptual Model:

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

Distribution of vehicle type v

$CE_{p,c}$	=	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

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

$ER_{p,a,v,m}$	=	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

Estimating the Cycle Correction Factor

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

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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

Distribution of time in OpMode bin ***m***
for base cycle ***b***

Estimating the Cycle Correction Factor

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

$ER_{p,a,v,m}$	=	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

Distribution of time in OpMode bin **m**
for any user-specified cycle **c**

Estimating the Cycle Correction Factor

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

$ER_{p,a,v,m}$	=	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

Default “OpMode Bin” mode ***m*** Emission Rates for Pollutant ***p***, vehicle Age ***a***, and Vehicle type ***v***.

Estimating the Cycle Correction Factor

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

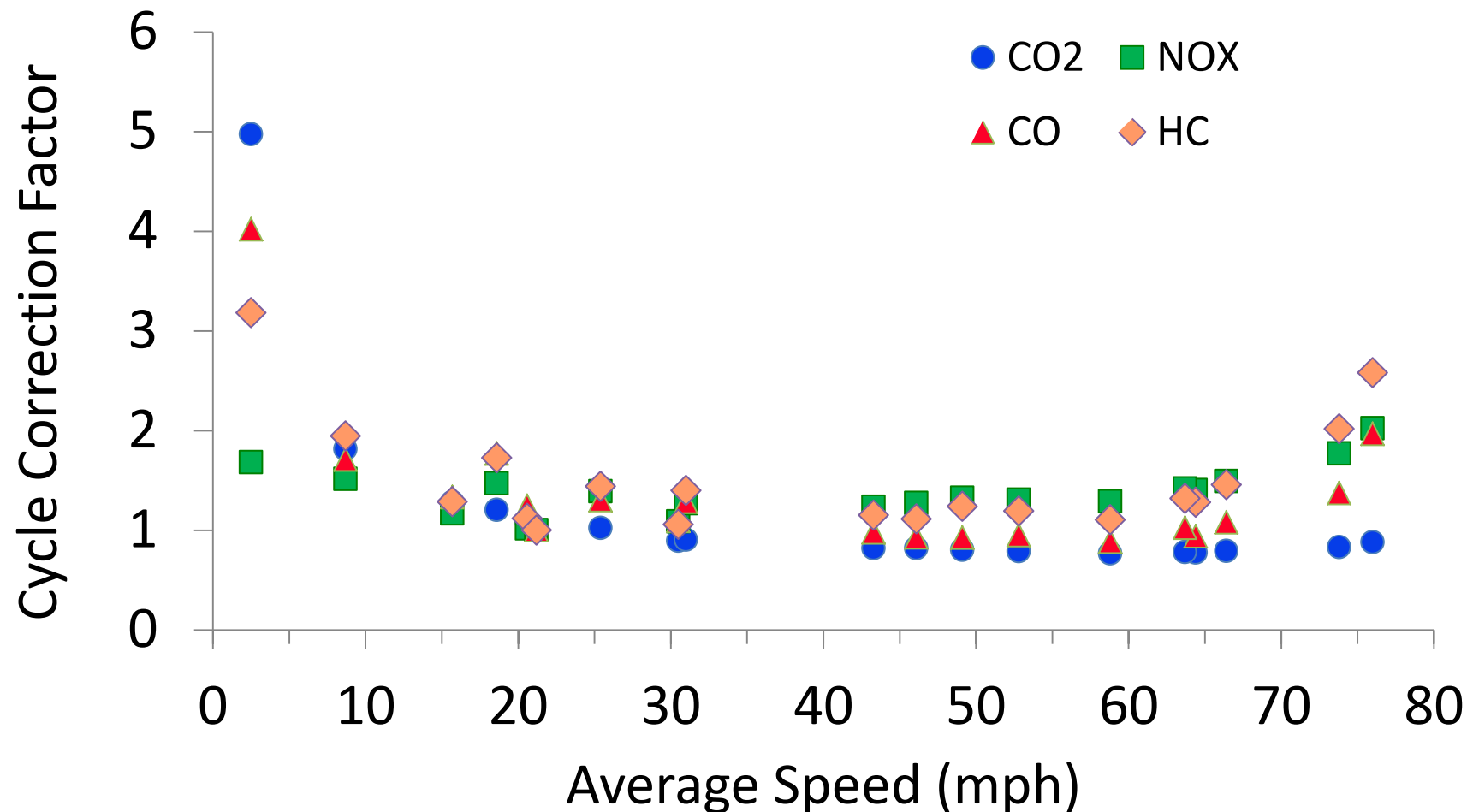
$ER_{p,a,v,m}$	=	default emission rate for pollutant p, age a, vehicle type v, in operating mode bin m, g/hr
f_m^c	=	fraction of time in OpMode bin m in cycle c
f_m^b	=	fraction of time in OpMode bin m for base cycle b
V^c	=	cycle average speed for cycle c, mph
V^b	=	cycle average speed for base cycle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

Ratio of average speeds for base and user-specific cycles to convert from 'per time' to 'per distance'

Emission Factor Case Study

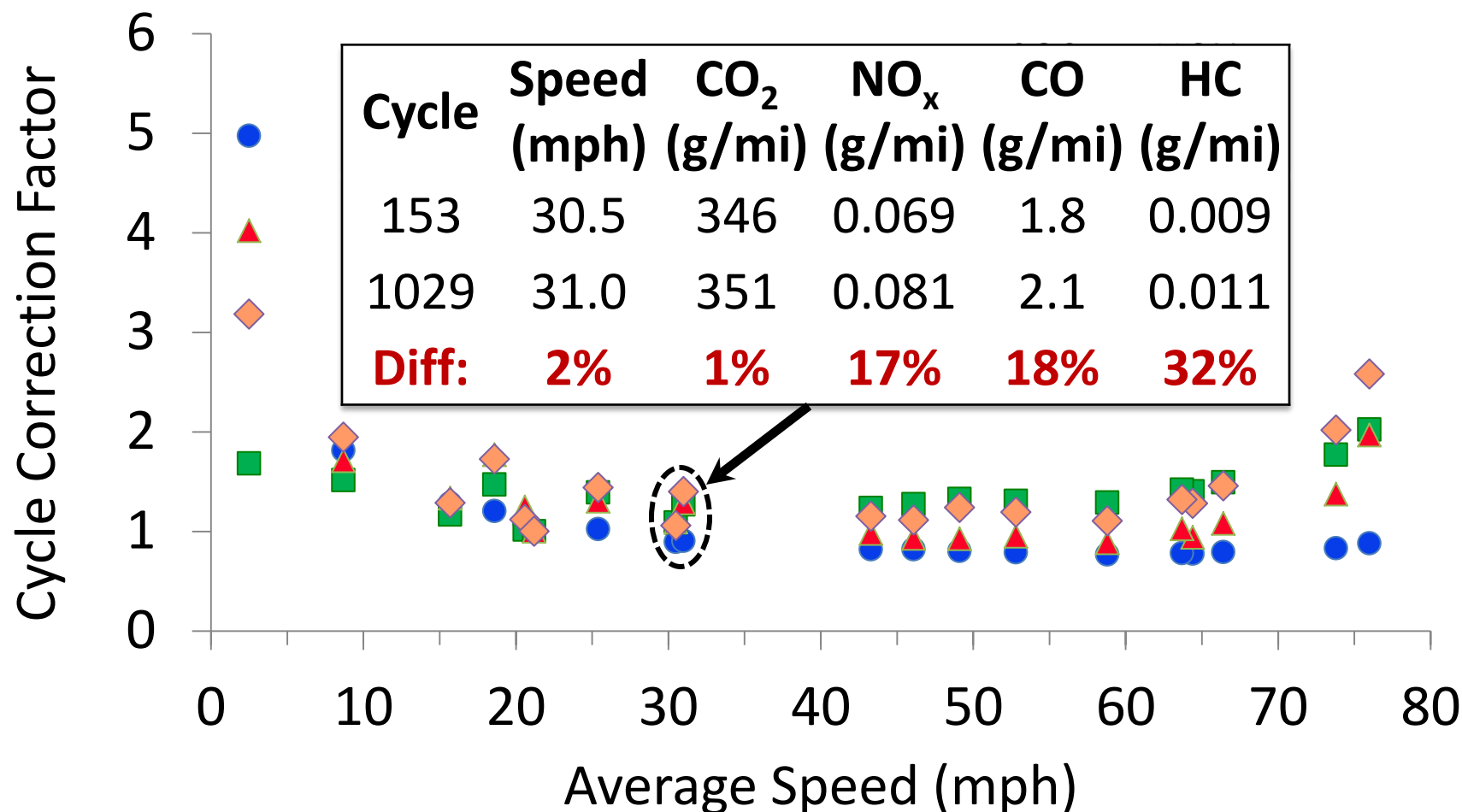
- Passenger Cars, 5 years old, Gasoline, Calendar year 2011
- 18 MOVES default driving cycles
- Base Cycle: Federal Test Procedure (FTP)
- Scenario Assumptions:
 - Ambient Temperature: 65 °F
 - Gasoline
- Estimate cycle average emission factors using simplified model
- Evaluate the accuracy of the simplified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

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



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).

Processing Time of the Simplified Model

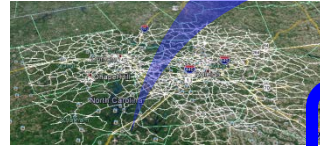
- About 3,000 times faster for the same driving cycles on the same computer

Ongoing Work: Integrated MOVES Lite and DTA Lite Packages for Emission Analysis

Microscopic Vehicle
Trajectory Reconstruction



Emission
Aggregation



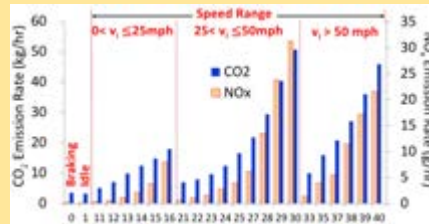
DTALite

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
 - no need for time consuming data file writing and use of MOVES
- DTALite with MOVES Lite enables assessment of a wide breadth of traffic management strategies, and their effect on emissions

DTALite at a glance

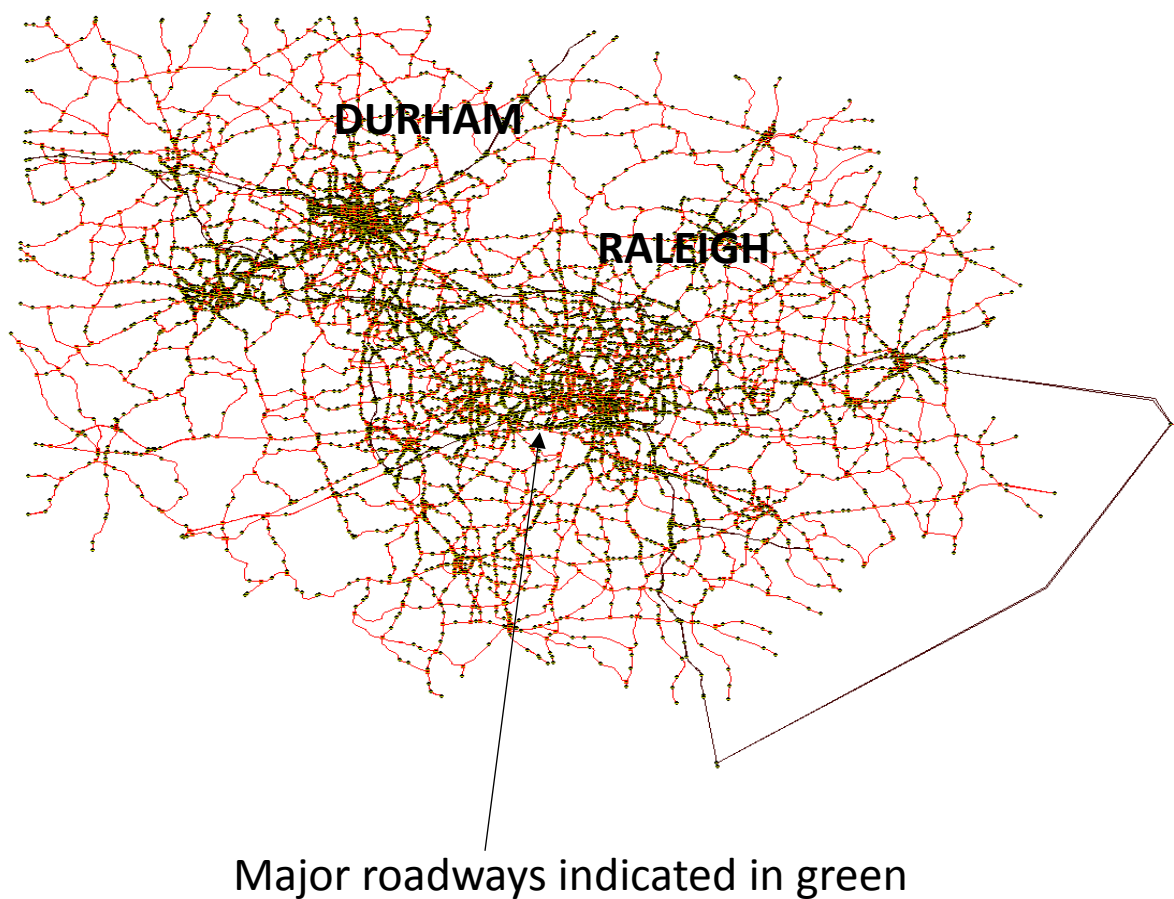
- **Open-source** DTA (Dynamic Traffic Assignment) Model
- Vehicle movements on links are governed by macroscopic (flow based) relationship of speed versus density
- However, vehicles are modeled individually (agents) from their origin to destination
- Can model large networks very efficiently (e.g., the case study network ~ 10 minutes per iteration).
- Using a specialized car following algorithm, micro-scale vehicle activity data are generated as input to emission calculations
- MOVES Lite is implemented within DTALite
- Model can assess the impact of many control measures:
 - Changing the vehicle fleet or age composition
 - Changing level of traveler information available (pre-trip, en route, etc.)
 - Incorporating tolled links or toll or HOV lanes
 - Improved incident response
 - And more...
- Access at: <https://sites.google.com/site/dtalite/>

Basic DTA Lite Inputs

- Detailed **network geometry** (link type, # of lanes, free flow speed or speed limit, capacity, toll rate, etc.)
- Time-dependent **Origin-Destination trip matrix** (15 min res.)
- *Much of the above can be directly imported from a travel demand model (e.g. TransCad)*
- **Link traffic model** (relationship between speed, flow and density)
- **Distribution of vehicle types** (cars, SUV's, short and long haul trucks, etc.) and **demand types** (SOV/ HOV / Trucks)
- **Distribution of drivers with information types** (% with access to no info., pre-trip, en-route, or dynamic congestion information)
- **Detailed incident data** (when applicable)
- Location of **variable message signs** and other **control devices** (when applicable)
- **Tolling protocols** (Time of Day, other) and value of time distribution

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 pairs**
- 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

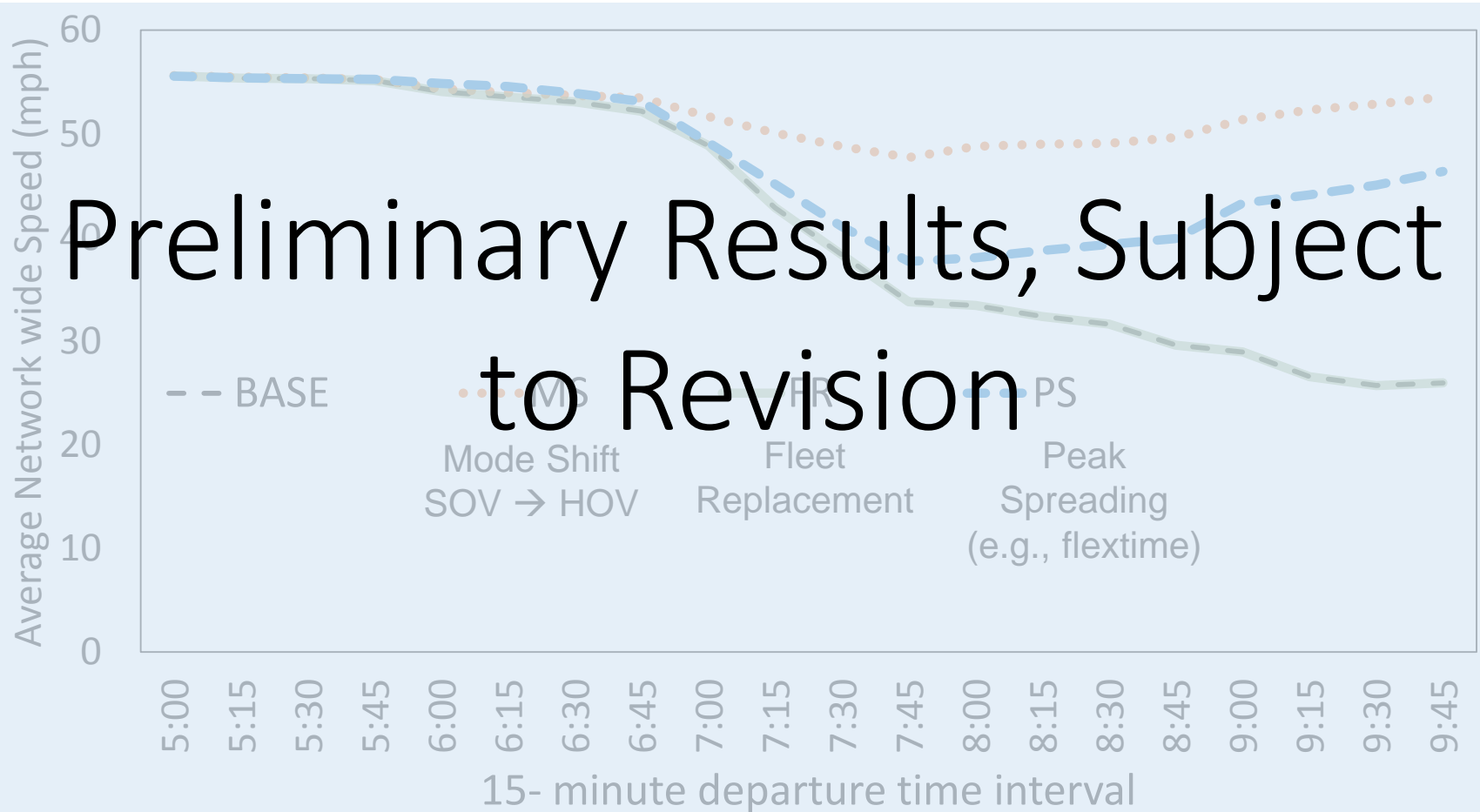


Case Study: Scenarios

Scenario	Label	Explanation	Motivation
Baseline*	BASE	Running the model with default demand and network data as calibrated for the region	Benchmark
Mode Shift*	MS	Switching 10% of travelers from SOV→ HOV, keeping total person travel the same— effect is to reduce total vehicle demand	Emissions Saved due vehicle reduction
Fleet Replacement*	FR	Substituting older vehicles with newer ones, by altering the default vehicle age distribution	Emissions Saved due to fleet replacement
Peak Spreading*	PS	Smoothing the arrivals in the peak hour to reduce the level of concentrated peaking	Emissions Saved due demand flattening
Special Study**: Incident No-Info	INC	Creating an incident on a major highway, where drivers have no access to information	Emissions impacts of major incident
Special Study**: Incident with VMS	VMS	Assessing how information disseminated to drivers via Variable Message Signage (VMS) can reduce congestion and emissions	Emission mitigation effects of VMS / Incident

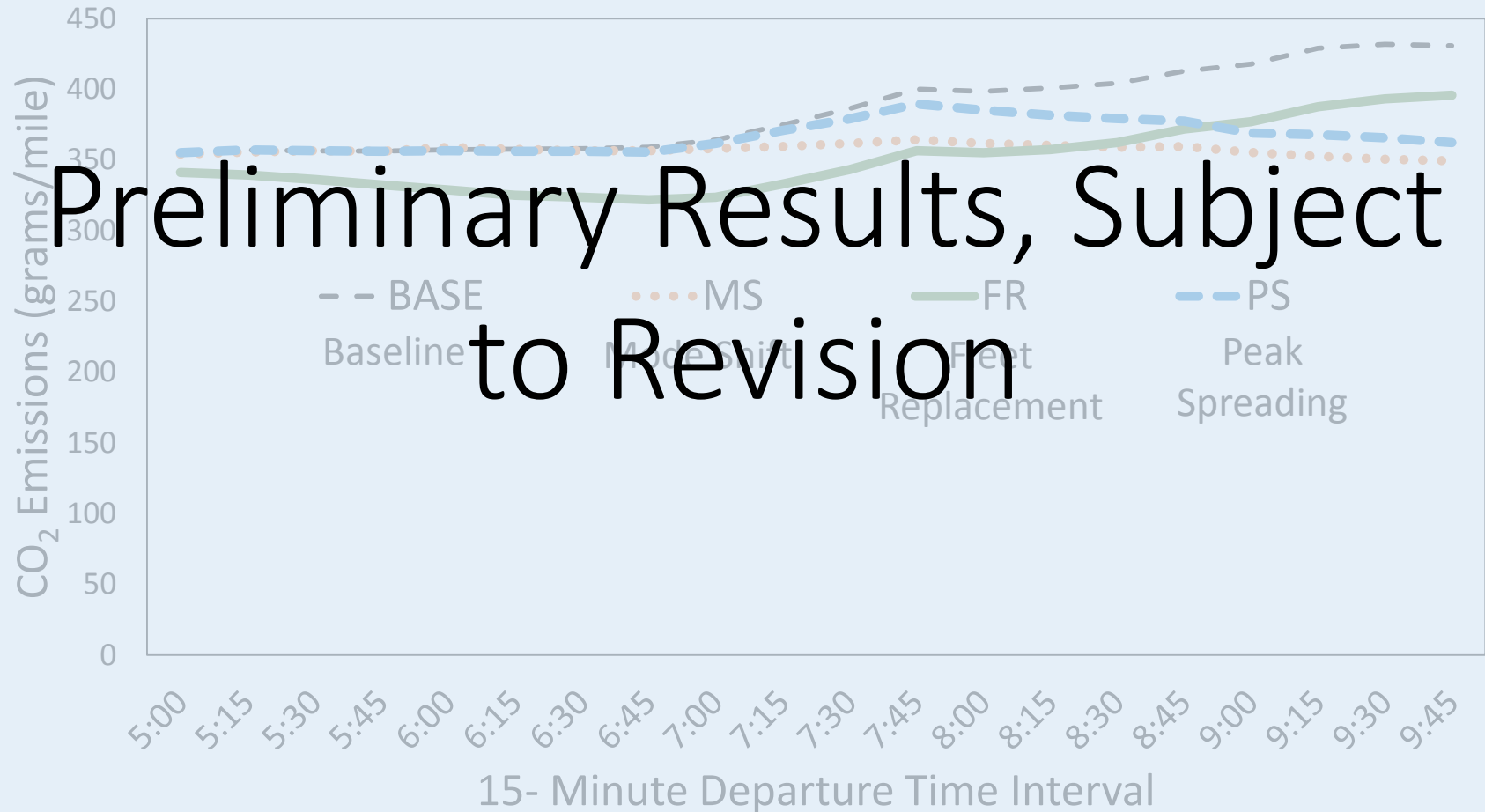
**Analysis at the network and I-40 path level **Analysis at the incident path level only*

Evaluating Strategies: Network Average Speed



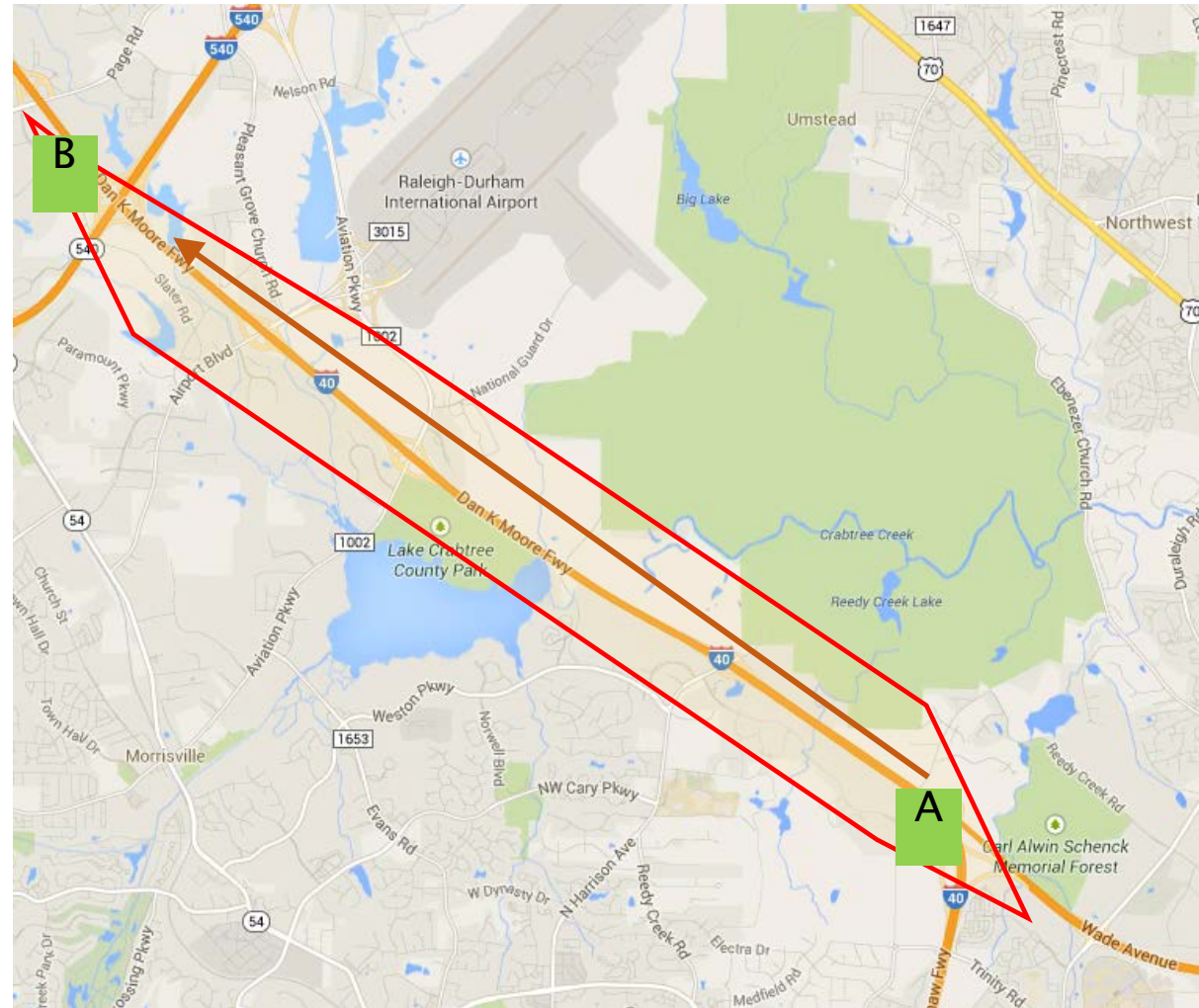
The fleet replacement scenario (FR) changes only the vehicle age distribution.

CO₂ Emissions per Mile over Network



I-40 Path for MS, FR and PS Strategies

- 5.89 mile section on I-40 in Wake County
- Free-flow travel time ~ 5 minutes (A→B)
- WB- from Merge point of Wade Avenue to I-40 at Exit 283B (I-540)
- Comprises Node #8938 to Node #9449, total of 17 model links



Summary Comparison:

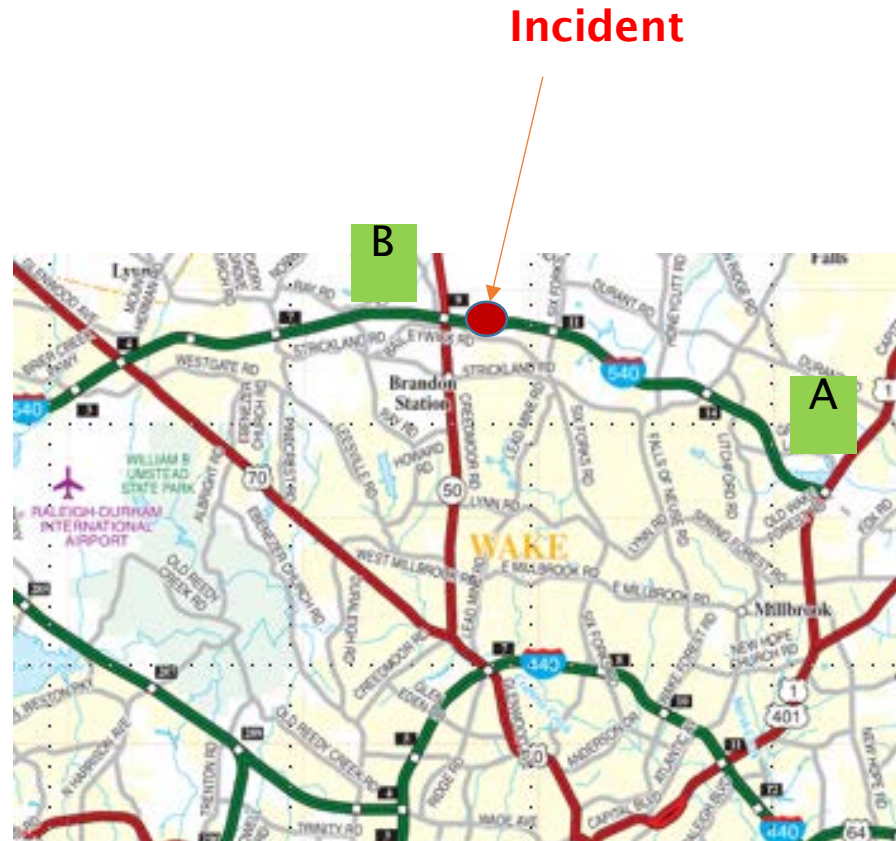
Pollutant: CO ₂						
Strategy	Network-wide			I-40 Path-based		
	Average Speed (mph)	Vehicle Miles Traveled (VMT) miles	Emissions g/mi	Average Speed (mph)	Vehicle Miles Traveled (VMT) miles	Emissions g/mi
BASE	38	12,474,022	386	55	348,868	351
Mode Shift	51	11,587,945	358	58	323,346	348
Peak Spread.	45	12,543,660	369	56	356,538	341

Example:

MS vs. BASE reduces network emissions by 14%
 PS vs. BASE reduces network emissions by 4%

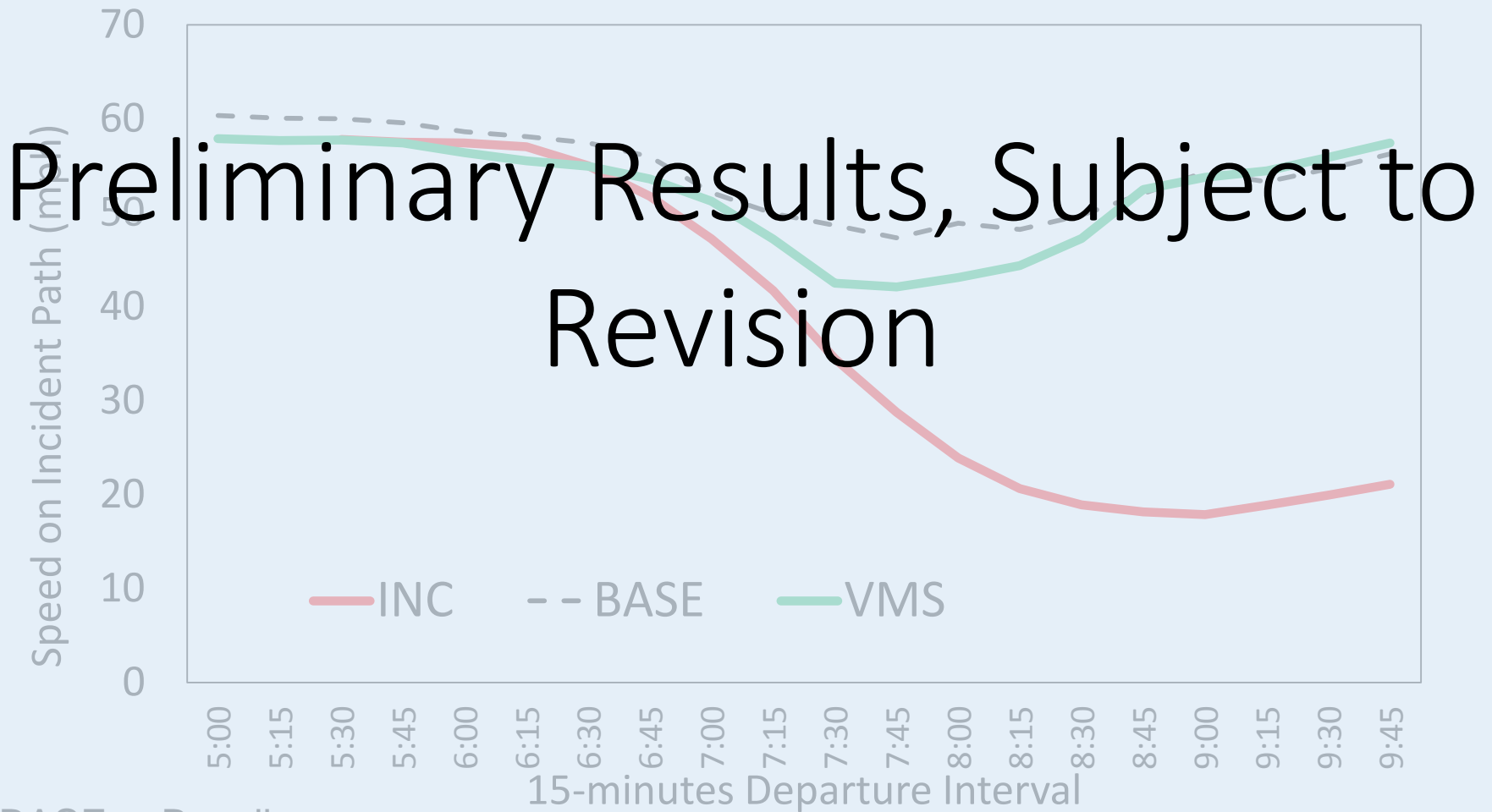
Special Study: Incident Impacts

- BASE: Selected Path A → B, comprising 22 Links, 9.54 miles, free-flow travel time 8.37 min
- INC: An incident is simulated from 5 AM to 10:40 AM with
 - 50% capacity reduction
 - and 30 mph speed limit
- VMS: Activate several upstream Variable Message Signs (VMS) to motivate diversion away from the incident site



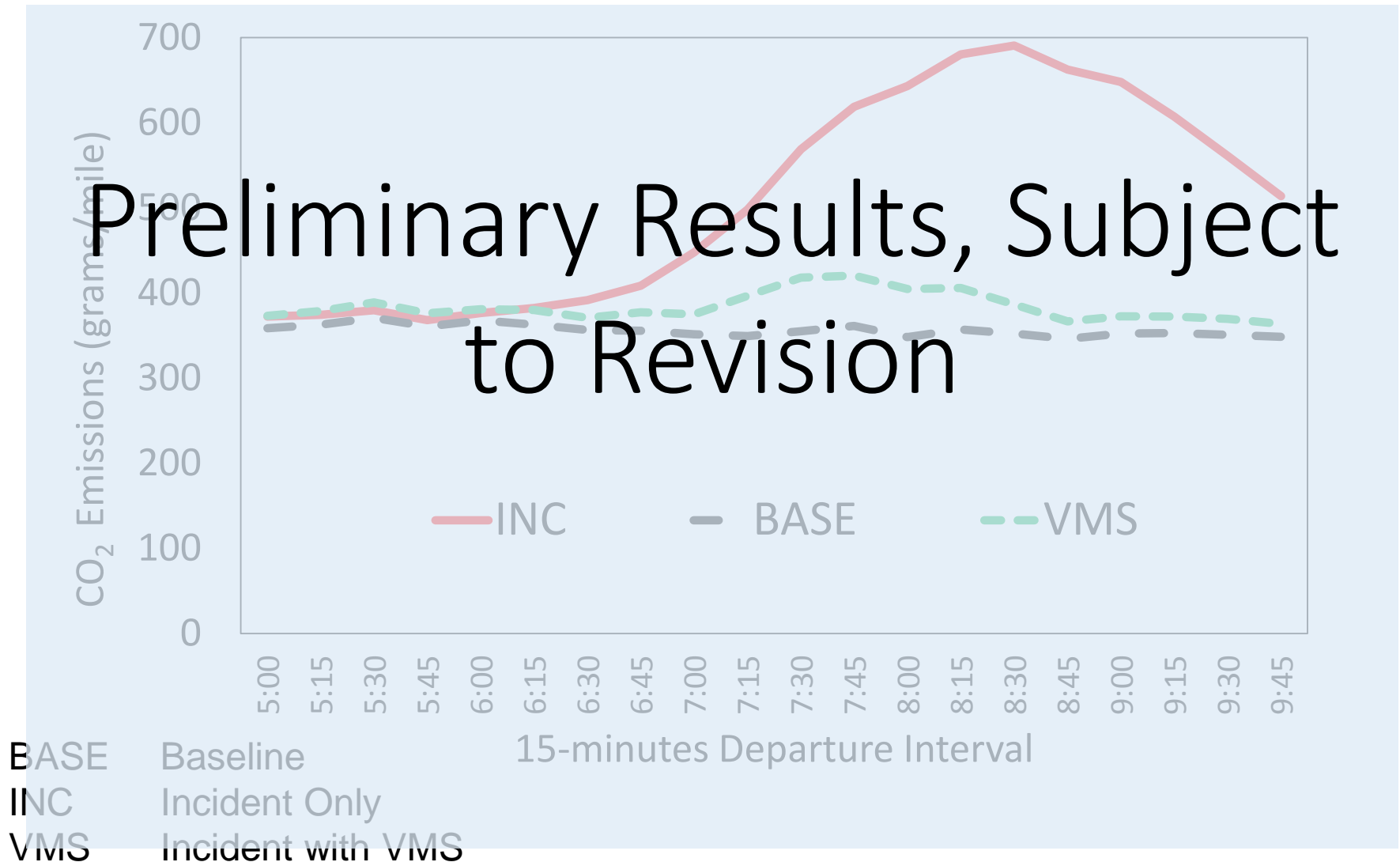
For VMS, assume 20% of drivers will consider diversion if they can find a faster path

Strategy VMS: Average Speed on Incident Path I-540



BASE Baseline
 INC Incident Only
 VMS Incident with VMS

Strategy VMS: Avg. CO₂ emission on Incident Path I-540



DTALite Work in Progress

- Refinement of the case studies and details of the methods for specification of model input
- Testing additional strategies including capacity improvements, tolling, ramp metering and work zone strategies
- Developing additional applications, such network evacuation modeling (due to weather or special events)
- Calibrating the simulated trajectories with second by second observations
- Applications to different network configurations
- Developing training material and user guides
 - e.g. www.learning-transportation.org

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

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