Energy Efficient Maneuvering Of Connected And Automated Vehicles With Situational Awareness At Intersections

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Project ID: EEMS084

SOUTHWEST RESEARCH INSTITUTE®

Continental

HYUNDAI MOTOR GROUP
HYUNDAI AMERICA TECHNICAL CENTER, INC.

FROST & SULLIVAN

Alamo Area Clean Cities

June 22, 2021

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Overview

Timeline

- ❑ ***Start date:*** October 1, 2019
- ❑ ***End date:*** December 31, 2022
- ❑ ***Percentage complete:*** ~ 50%

Budget

- ❑ ***Total:*** $4,214,135
  - ❑ ***Govt. Share:*** $3,207,135
  - ❑ ***Cost-share:*** $1,007,000

Barriers & Technical Targets

Reference: Vehicle-Mobility Systems Analysis Tech Team (VMSATT) Roadmap

Target Outcome 1: Develop framework for estimating energy, emissions, and cost benefits of vehicle technologies under research and development (Vehicle System)

Target Outcome 2: Quantify and validate with real-world data the energy savings benefits of optimized advanced vehicle control (Vehicle System)

Target Outcome 3: Explore and quantify the benefits of intelligent intersection platforms with connected and automated vehicle technologies (Infrastructure)

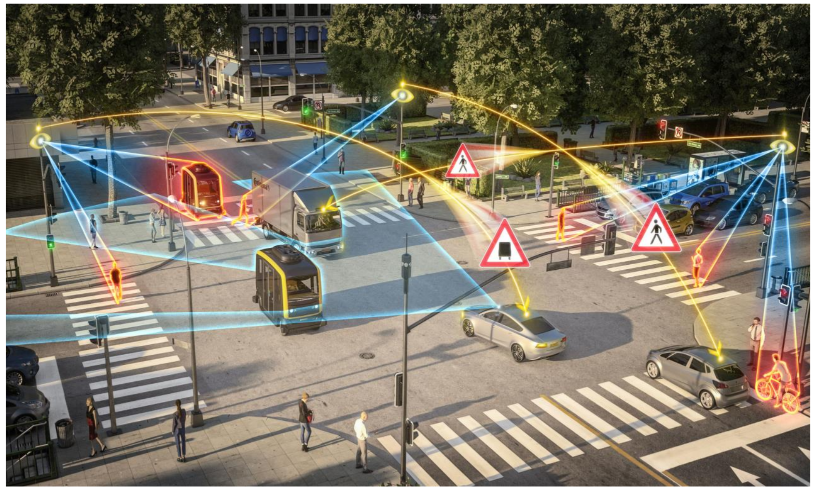
Partners

- ❑ ***Tier-1 partner:*** Continental Inc.
- ❑ ***OEM partner:*** Hyundai-Kia America Technical Center, Inc.
- ❑ ***Tech-To-Market partner:*** Frost & Sullivan
- ❑ ***Outreach partner:*** Alamo Area Clean Cities Coalition

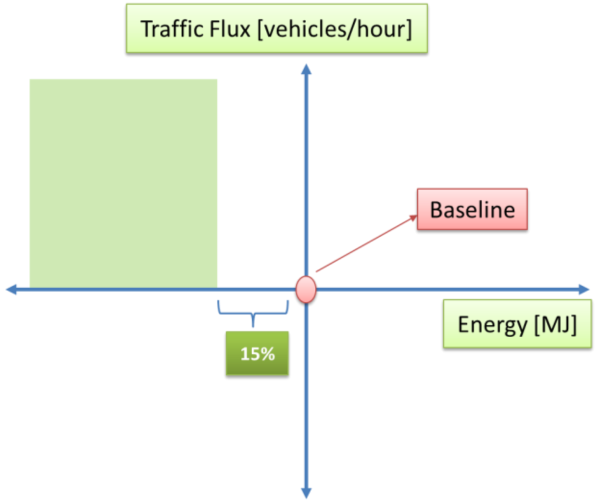
Relevance – Project Objectives

- **Project Objectives**
  - Quantify and understand the benefits of connected and automated vehicle technologies on a wide array of vehicles with different
    - *Powertrain types:* internal combustion engines, hybrid electric and pure electric
    - *Automation Levels:* SAE Level 0 through Level 4
  - In depth analysis on an *urban corridor*
  - Understand the impact of *intelligent infrastructure* platforms from an energy efficiency perspective

- **Performance Target**
  - Reduce energy consumption at corridor level by 15% without negatively impacting traffic flux



		Automation Levels				
		L0	L1	L2	L2+	L4
Powertrain	ICE	Hyundai Elantra				Chrysler 300
	HEV					
	PHEV			Toyota Prius Prime		
	EV			Kia Soul	Tesla Model 3	Easy Mile EZ 10



Milestones – Budget Period 1 (Oct'19 – Dec'20)

Milestone	Description	Type	Status
Road network for traffic simulation validated	Road network for traffic simulation complete.	Technical	Complete
Macroscopic traffic simulation validated	Demonstrate relevant metrics from simulation within 10% of measured value.	Technical	Complete
Traffic simulation with intersection functionality validated	Completion of the initial version of traffic simulation with intersection-based traffic mix. This would be validated with real data recorded at intersections.	Technical	Complete
Vehicle & powertrain models for energy consumption on transient drive cycles validated	Completion of initial vehicle and powertrain models for the vehicle mix selected for the program. Validation will be using dynamometer or Environmental Protection Agency (EPA) published (effective) fuel consumption on standard test cycles.	GO/NO-GO	Complete

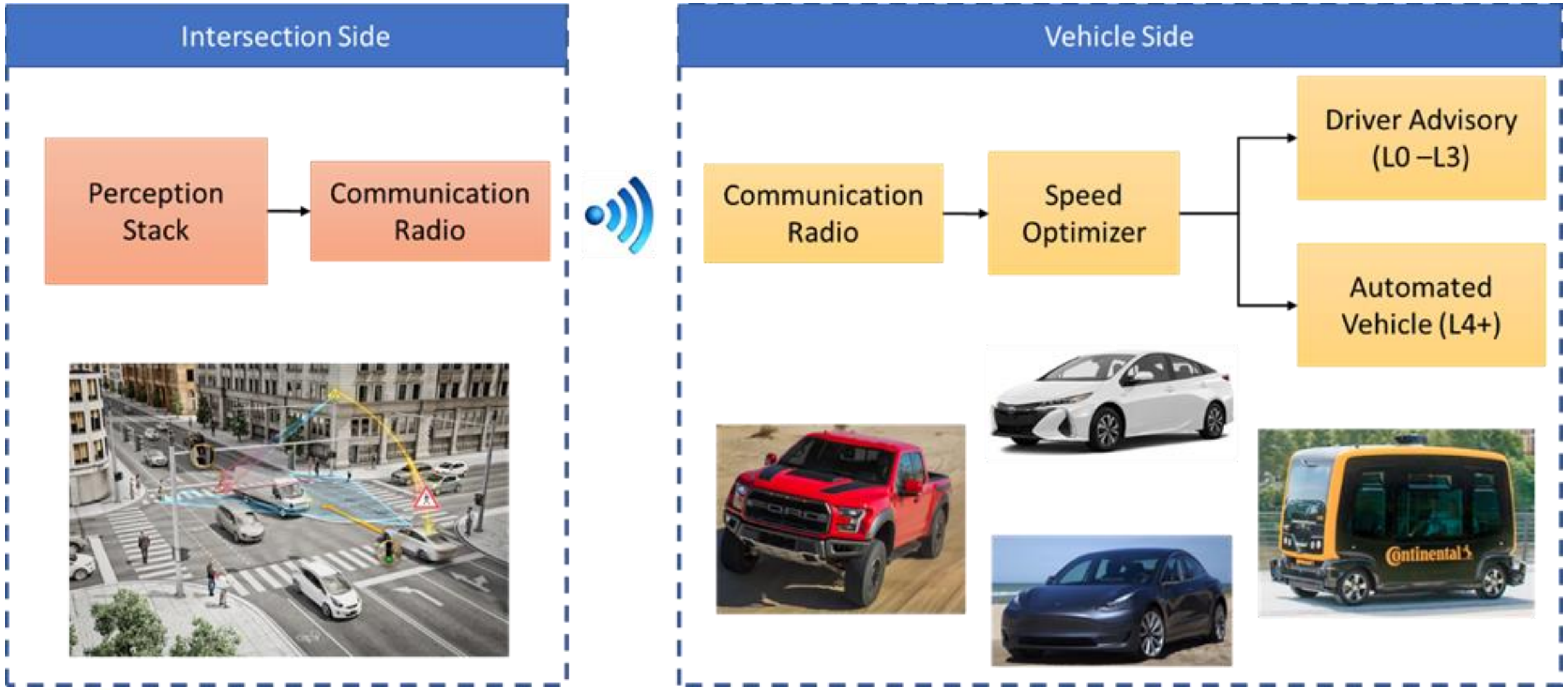
Milestones – Budget Period 2 (Jan'21 – Dec '21)

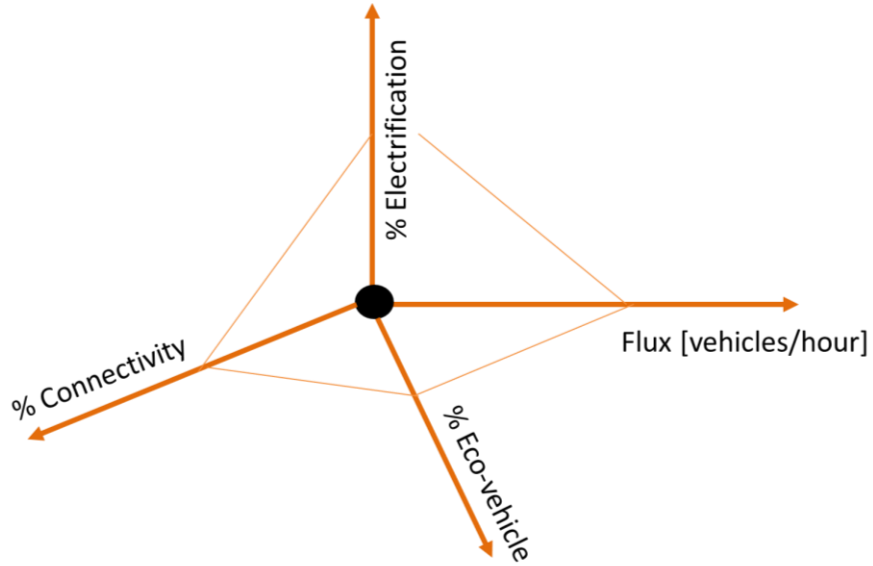
Milestone	Description	Type	Status
Intersection stack validated with real traffic data	Validate operation of the intersection stack with real traffic data.	Technical	**On Track**
Demonstrate 15% energy savings via proposed methodology in simulation	Final demonstration of energy consumption benefits in simulation for overall fleet.	Technical	**On Track**
First draft of Techno-Economic-Analysis complete	Generate a cost performance model that provides insight into the trade-offs and interactions between product design, cost and performance.	Technical	**Not Started**
Demonstrate 10% energy savings on a Connected Automated Vehicle (CAV) dynamometer	Demonstration of energy consumption benefits on a hub dynamometer integrated with a real-time traffic simulator.	**GO/NO-GO**	**On Track**

Technical Approach

- Connectivity common theme across ‘smart’ vehicle fleet (CAV and eco-driving)
- Leverage intelligent intersection stack to communicate scene understanding
- Speed optimization leveraging Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) info and intersection stack → Energy savings
- Savings propagate to non-connected vehicles enabling system level benefits

		Automation Levels				
		L0	L1	L2	L2+	L4
Powertrain	ICE	Hyundai Elantra				Chrysler 300
	HEV					
	PHEV			Toyota Prius Prime		
	EV			Kia Soul	Tesla Model 3	Easy Mile EZ 10





Key Modules – Budget Period 1

Simulate velocity trajectories for all vehicles

1

2

Intelligent Intersection

Sensing	*Perception*	*Processing*	*Comms*

V2V: distance, speed
V2I: distance to light, phase, time remaining in phase

Eco-Driving (multiple)

Optimal Speed

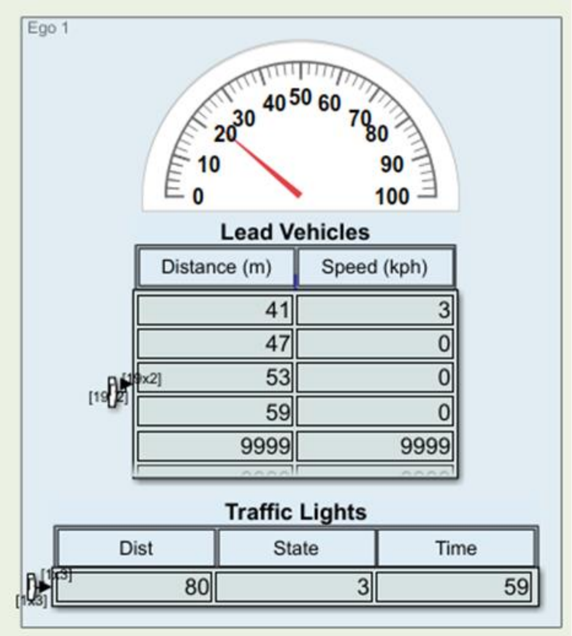
3

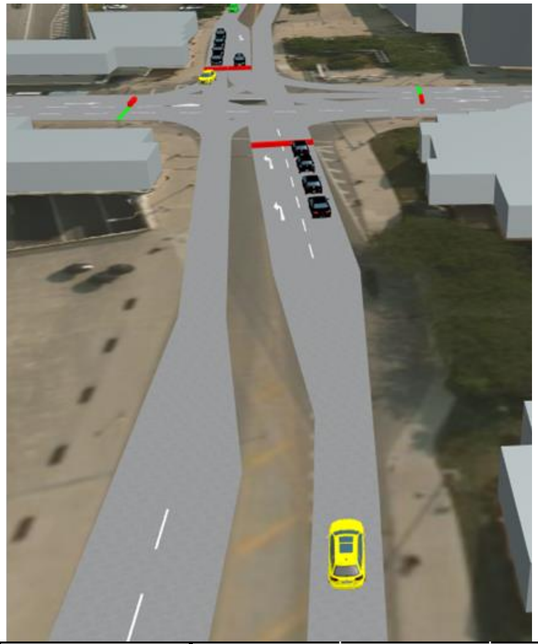
Time, Speed trace for all vehicles → Vehicle Simulator → *Energy Consumption*

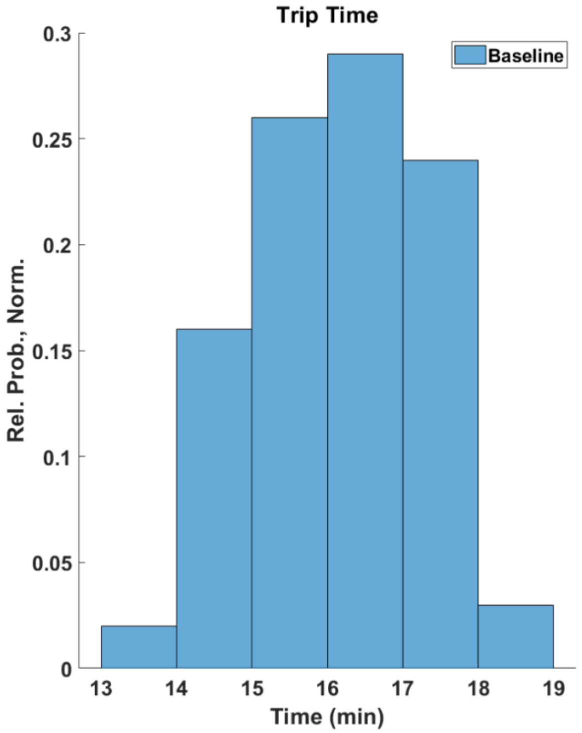
Technical Accomplishments and Progress:

Corridor Traffic Simulation

- High street corridor based in Columbus, OH selected
- Realistic traffic environment created in PTV Vissim
- Continental intelligent intersection stack deployed at High Street/Goodale intersection
- Traffic signal timing patterns and intersection camera footage provided by City of Columbus
- Fused additional info from public cameras for traffic counts and Google Maps® for corridor trip times
- Trip times and traffic volumes within 10% of real-world data







Location, Direction	Vehicles per Hour: CCTV 8am 2020-09-23	Conti 8am 2020-11-04	Sim 120 Base
1.1: Main NR	180		181
1.2: Main N	**170**		**166**
1.3: Main WRS	180		175
1.4: Main S	120		122
2.1: Good N	**140**	**56-152**	**146**
2.2: Good S	180	184-223	182
3.1: 12 N	**240**		**238**
3.2: 12 WLN	**30**		**28**
3.3: 12 S	220		224
3.4: 12 SL	20		31
3.5: 12 SR	40		30
4.1: Lane N	**160**		**161**
4.2: Lane S	240		246

*Bold locations are relevant to High St Northbound

Technical Accomplishments and Progress:

Vehicle Powertrain Modeling

- Vehicle powertrain models critical to quantify corridor level improvements – [dyno + simulation] data
- Powertrain models built in GT-Suite and MATLAB/Simulink
- Normalized Cross-Correlation Power (NCCP) analysis to validate transient performance against dynamometer/EPA data
- Challenges obtaining powertrain data on Easy Mile EZ10 shuttle
  - No road load coefficients/EPA test numbers for dyno testing
  - Top speed of 15 miles/hour (university shuttle)
  - Assigned EZ10 for track testing in year 3 and added Tesla Model 3 to year 2 dynamometer testing

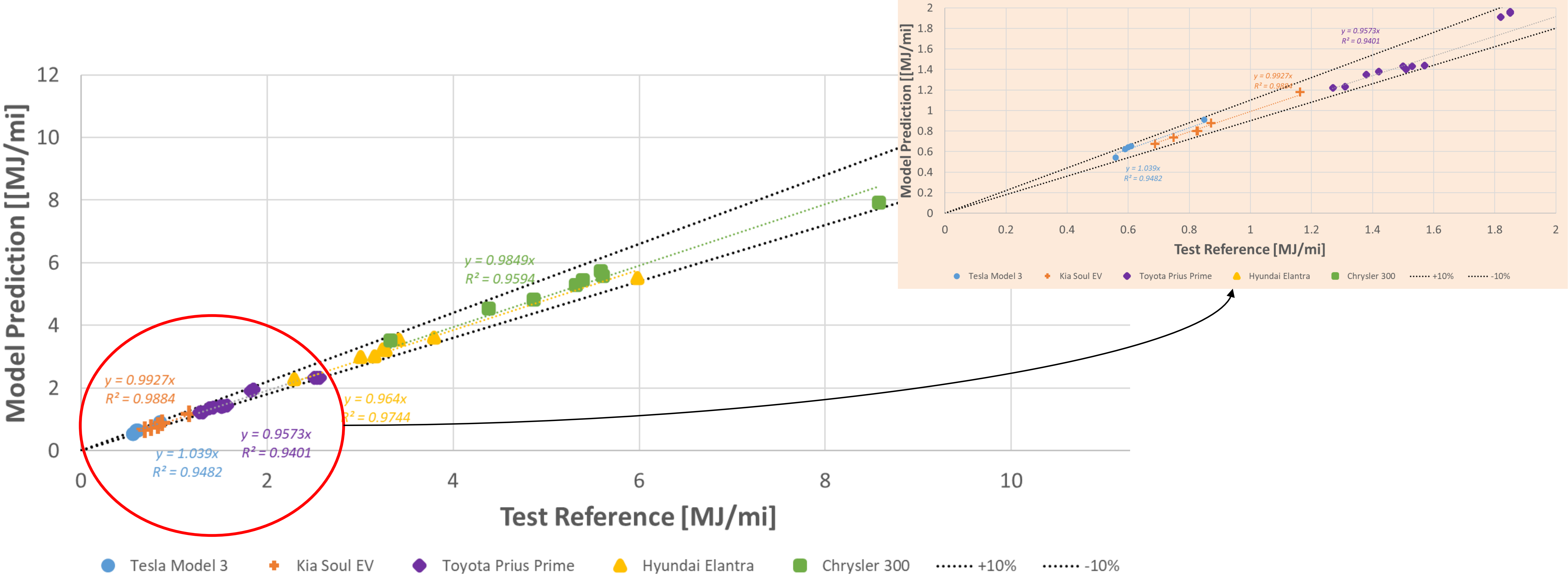
		Automation Levels				
		L0	L1	L2	L2+	L4
Powertrain	ICE	Hyundai Elantra				Chrysler 300
	HEV					
	PHEV			Toyota Prius Prime		
	EV			Kia Soul	Tesla Model 3	Easy Mile EZ 10

Test Data Set	Cycle contents	Simulation		CAN Data		Difference	
		$\frac{kWh}{100mi}$ Net	$\frac{kWh}{100mi}$ Positive	$\frac{kWh}{100mi}$ Net	$\frac{kWh}{100mi}$ Positive	% Net	% Positive
1	1st 1200s UDDS	18.8	25.7	19.1	26.2	-1.6	-1.7
2	Part UDDS	20.5	27.2	20.8	27.1	-1.7	0.3
3	1x HwFET +	22.2	24.5	23.0	25.2	-3.5	-2.9
4	1x HwFET +	22.2	24.6	22.9	24.6	-3.0	0.2
5	Part HwFET	24.4	26.3	24.2	25.5	0.7	3.3
6	US06 – 1 Full + 1 Partial	32.8	39.1	32.3	39.4	1.6	-0.7

Example: Kia Soul EV validation

Technical Accomplishments and Progress:

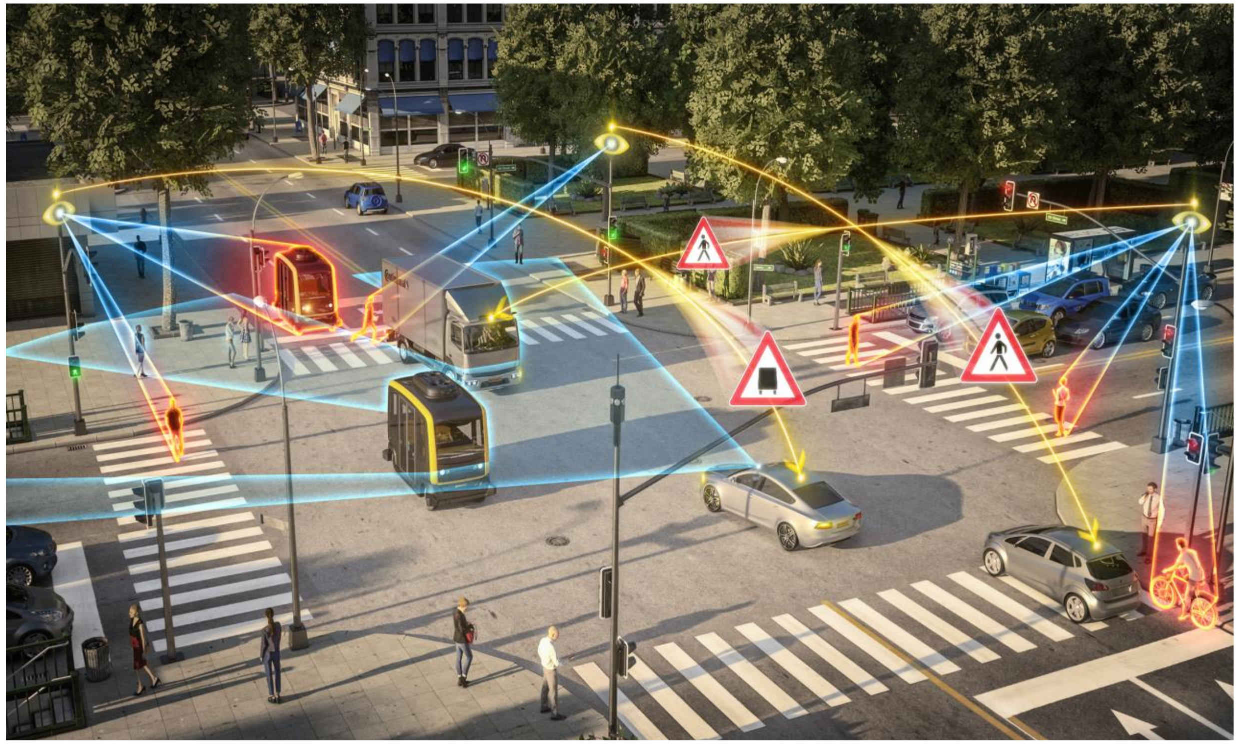
Vehicle Powertrain Models Validation

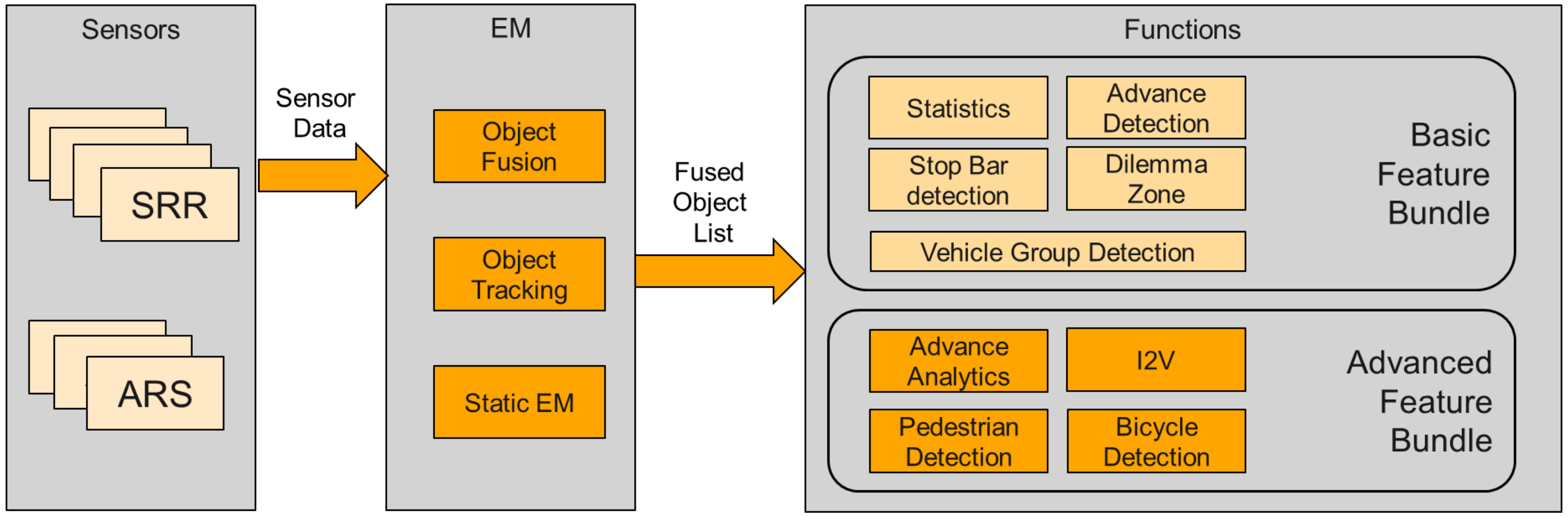


Technical Accomplishments and Progress:

Intersection Stack Validation

- Intersection stack consisting of short/long range radars with cameras in Auburn Hills, MI
- Vehicles equipped with differential GPS (DGPS) for ground truth position, heading and speed
- Data from stack and DGPS equipped vehicle taken over various times of day/traffic conditions in Jan 2021
- All possible intersection maneuvers (left, through, right) on all possible intersection maneuvers





Technical Accomplishments and Progress:

Intersection Stack Validation

- Accuracy requirements defined via large scale simulation studies to avoid most common accidents
- Error averaged out for the whole intersection comparing stack and DGPS data
- Speed error (%) higher at lower vehicle speeds (less than 10 mph)
  - Passed error criteria when speeds less than 10 mph filtered out (~6.7% speed error)
- Future work on improving speed error and pedestrian information

Scenario type	GES frequency
Rear end lead vehicle stopped	681,414
Run red light	221,965
Left turn across path opposite direction at signalized intersection	187,275
Rear end lead vehicle decelerating	134,063
Turning same direction	130,243
Changing lanes	87,949
Read end lead vehicle slower	73,026
Rear end striking maneuver	36,208
Turn right at signalized intersection	34,821
Rear end lead vehicle accelerating	18,328

Automated Mobility Partnership (AMP) Database

	Accuracy Requirement				
Target ->	<1.5 m	< 3m	< 0.75 m	< 5 [deg]	< 7.5%
Maneuvers	Avg Pose error [m]	AVG Longitudinal error [m]	AVG Lateral error [m]	AVG Heading Error [deg]	AVG Speed Error %
2 straight	0.75	0.45	0.47	1.97	6.50
6 straight	0.92	0.92	1.08	2.43	7.95
4 Right	0.85	0.39	0.73	3.80	11.54
6 Right	1.21	0.70	0.29	4.31	24.17
8 Right					
2 Right	0.70	0.40	0.73	3.02	13.03
3 Left	0.85	0.39	0.73	3.80	11.54
1 Left	1.38	1.29	0.50	1.24	7.16
7 Left					
5 left	1.59	0.68	1.30	2.71	29.64
Results	1.03	0.65	0.73	2.91	13.94
	PASS	PASS	PASS	PASS	FAIL

Technical Accomplishments and Progress:

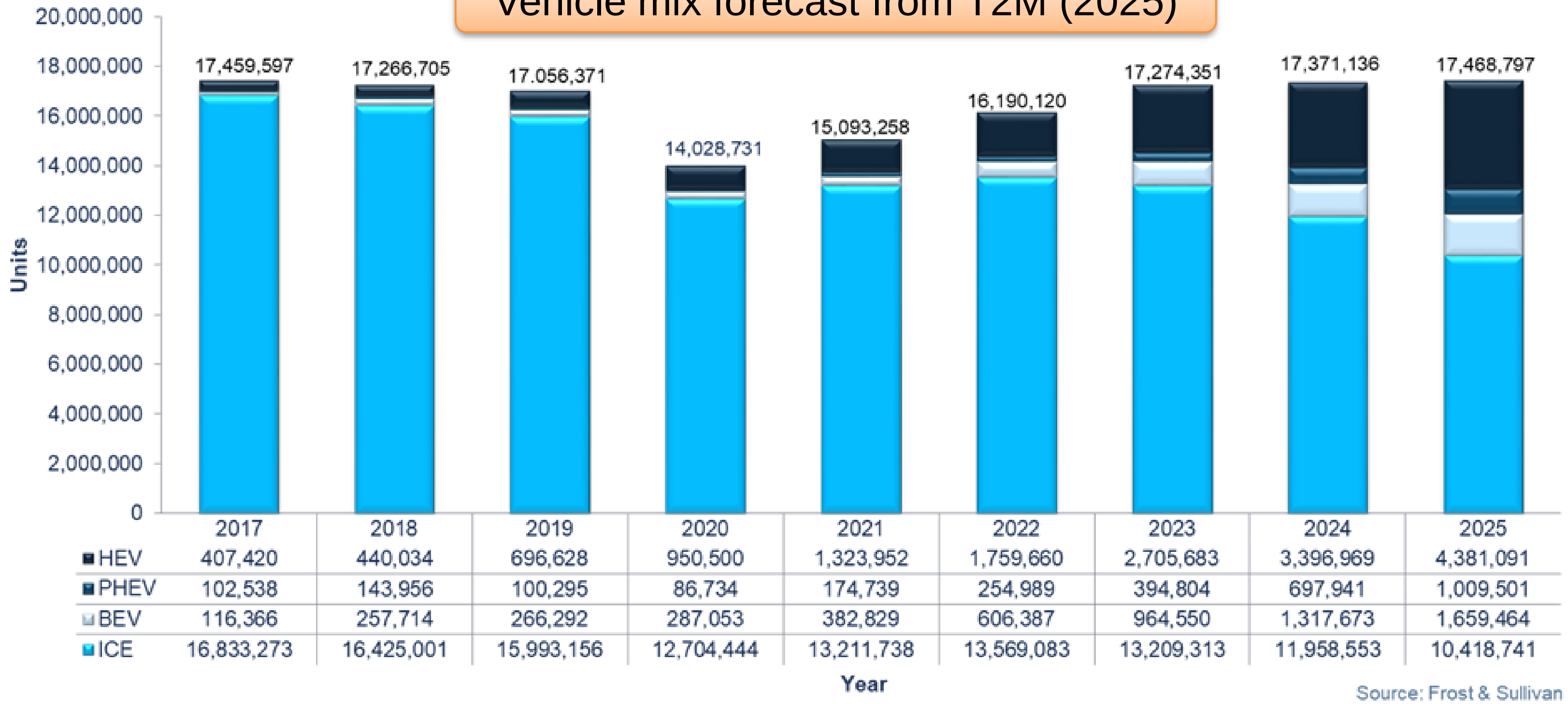
Software-in-the-Loop (SiL) Testing

- Nomenclature
  - *'Smart'* Vehicles: Connected vehicles controlled by SwRI eco-driving technology
  - *Control* corridor: only Vissim controlled baseline vehicles
  - *Eco-*corridor: mix of Vissim controlled baseline and 'smart' vehicles

Traffic Flux (veh/hour)	Smart Vehicles Penetration	Electrification	V2V Penetration
1x	25%	25%	0% (radar + IIS)
2x	50%	50%	100%
3x	75%	100%	
4x			
5x			

Full factorial

Vehicle mix forecast from T2M (2025)

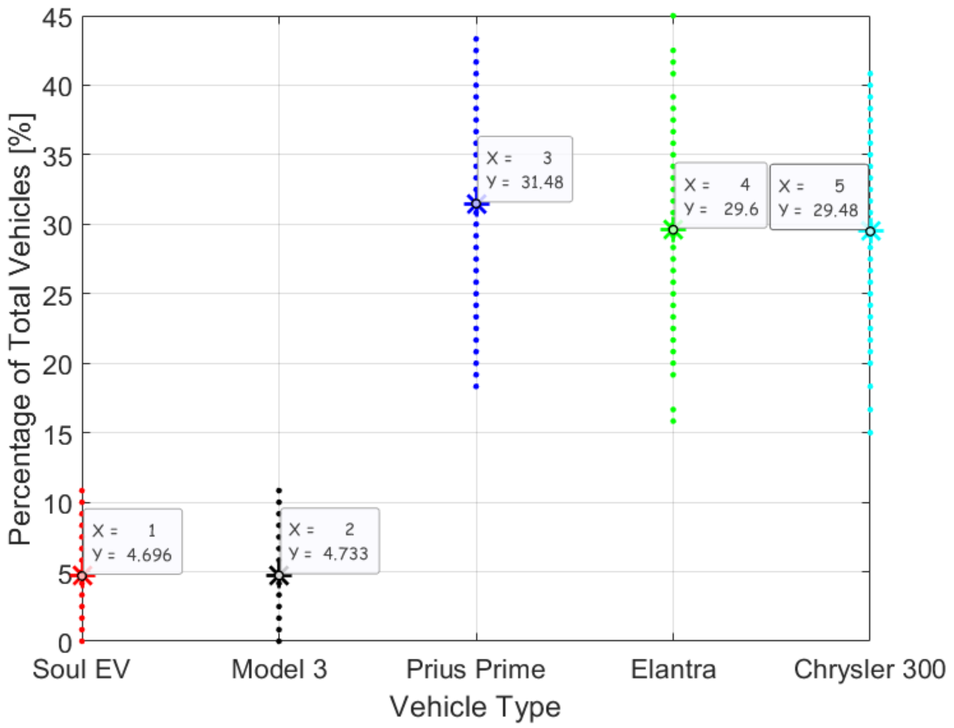


Source: Frost & Sullivan

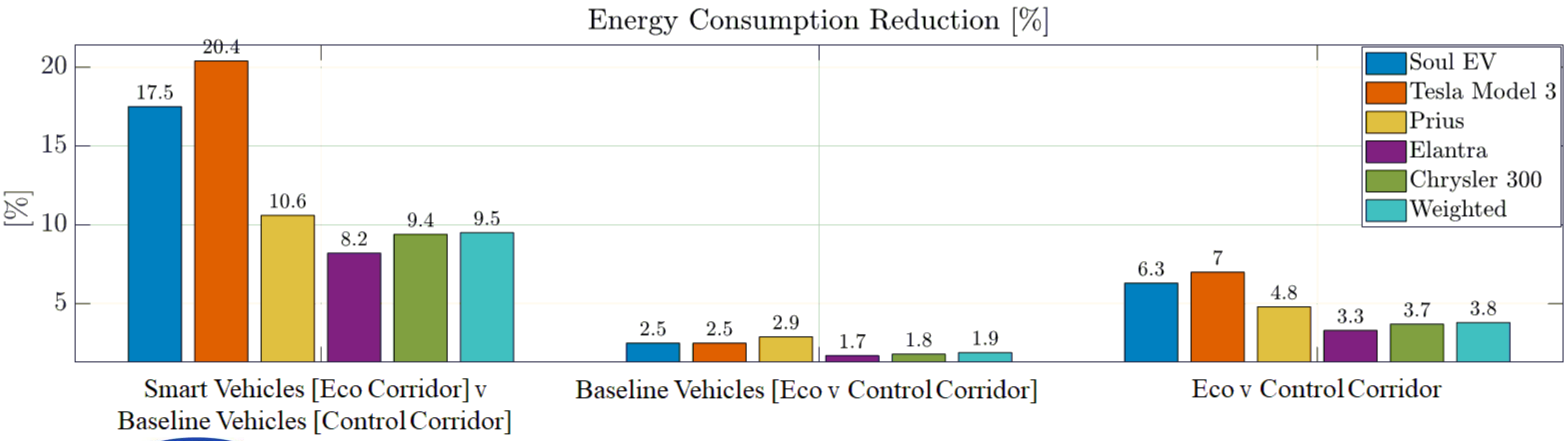
Technical Accomplishments and Progress:

SiL Testing: Base Corridor Observations

- Observed traffic volumes well below road capacity
- Vehicles navigating through the <u>whole corridor</u> for energy analysis
  - Including partial traffic significantly increases complexity of the analysis
  - Team working on setting threshold based on distance traveled in corridor
- 25% penetration of smart vehicles
- Monte Carlo analysis with Hotelling T^2 test for statistical significance



25% Smart Vehicle Penetration

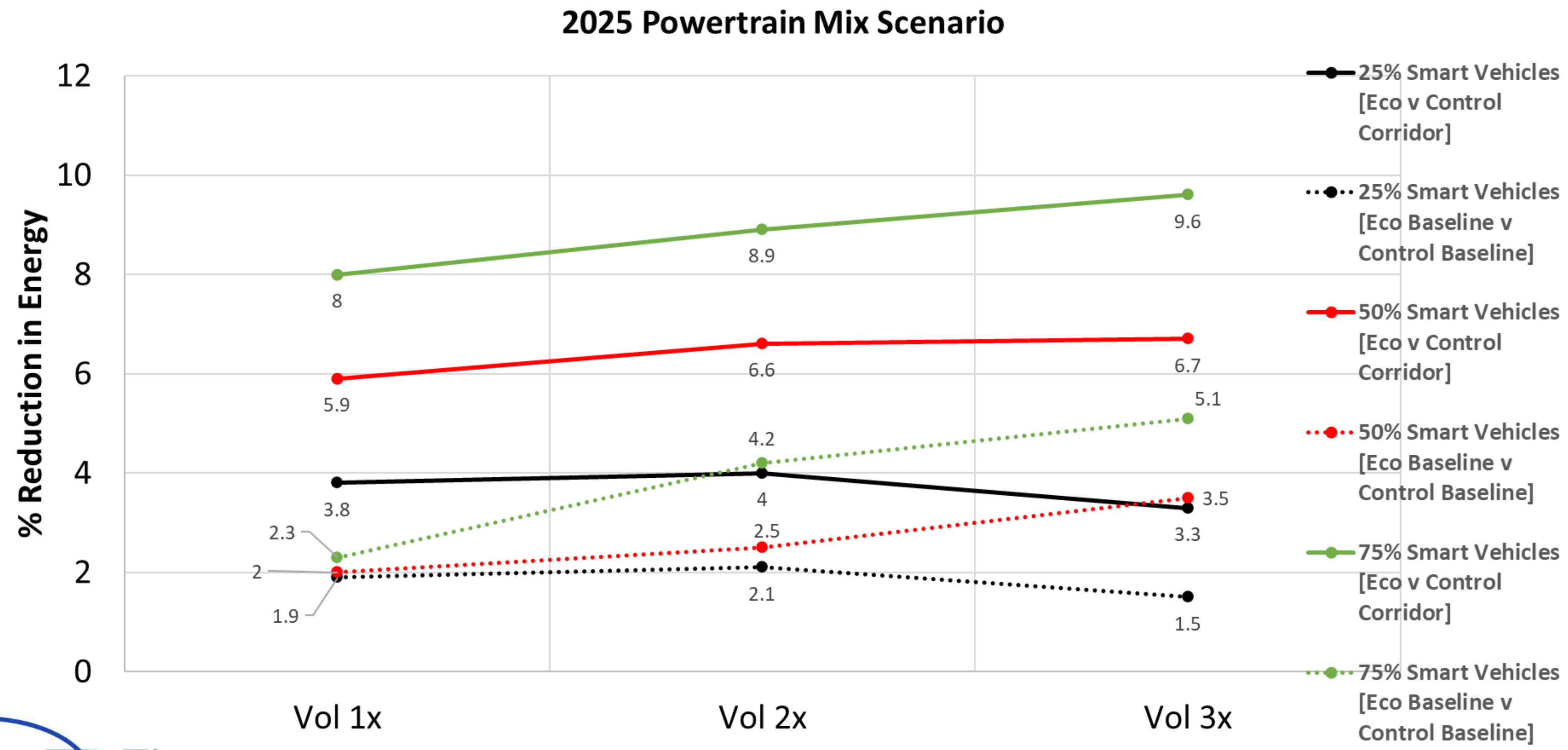


- Each bar represents purely the benefits of smart vehicles in the corridor. For example, the eco-corridor consumed 6.3% less energy compared to the control corridor both consisting of Kia Soul EVs *exclusively*
- Weighted value calculated based on 2025 powertrain mix (above)

Technical Accomplishments and Progress:

SiL Testing: Impact of Flux/Penetration of Smart Vehicles

- Corridor level benefits a strong function of traffic flux
  - Expect benefits to peak and then drop at very high flux
- Higher penetration of smart vehicles do impact baseline vehicles positively at higher flux conditions
  - 75% smart vehicles improve ‘*baseline*’ vehicle energy consumption by 5.1% at 3x flux



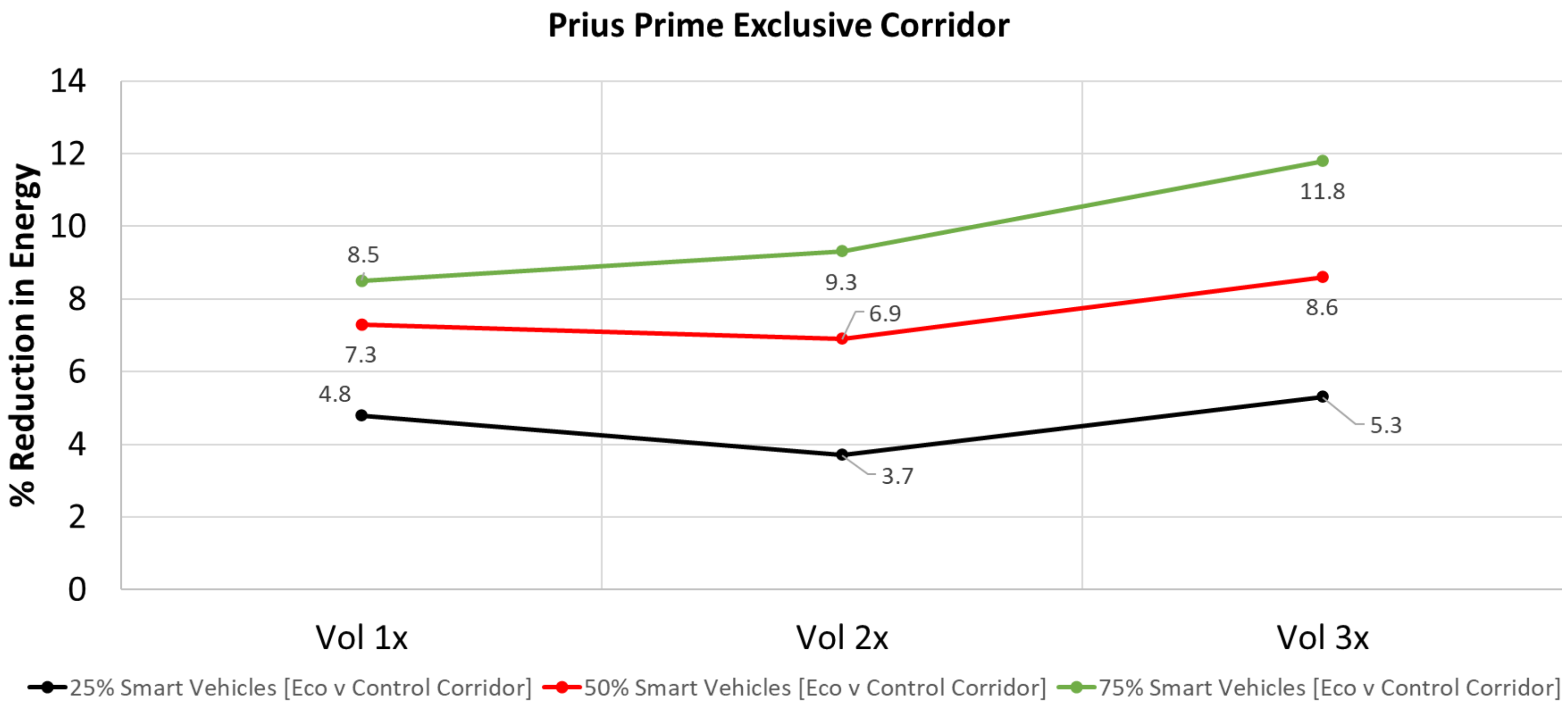
Hypothesis:

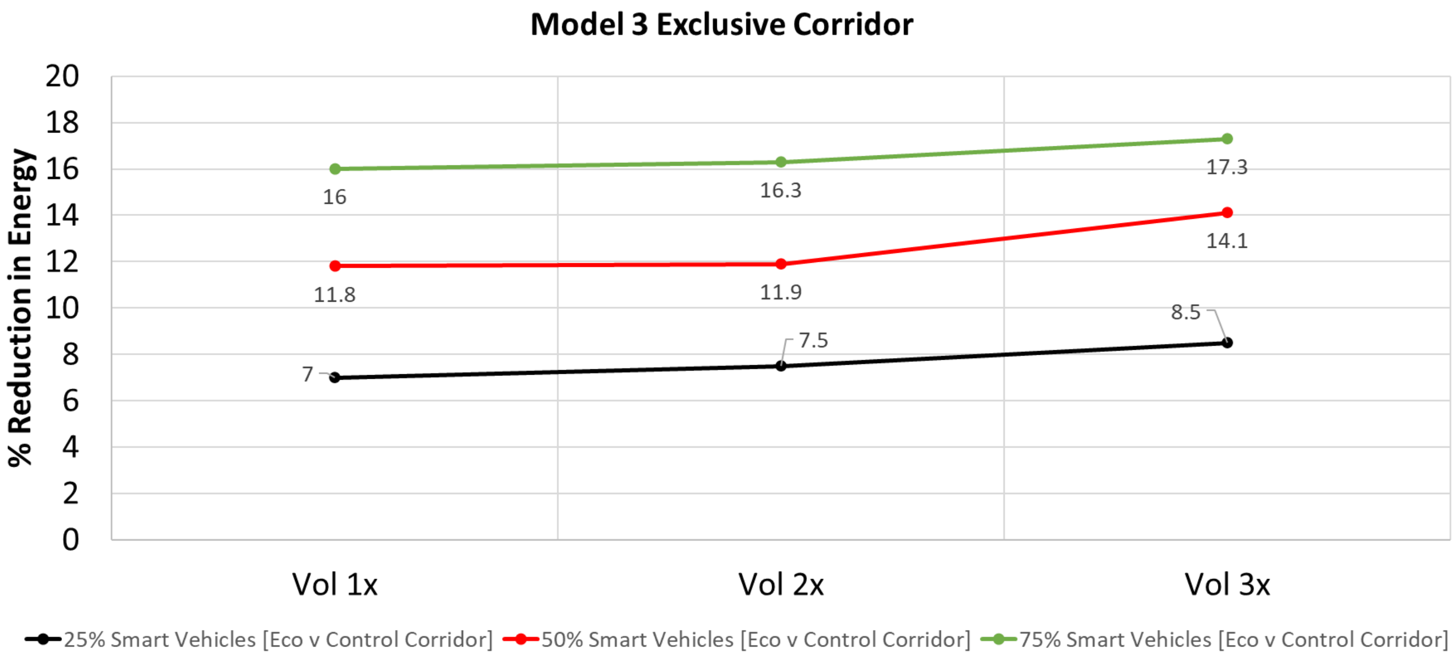
Nonlinearity of an internal combustion engine brake specific fuel consumption map is reflected in benefits ex: transmission in higher gear enables engine down-speeding

Technical Accomplishments and Progress:

SiL Testing: Impact of Electrification

- Significant speed harmonization benefits realized for xEVs
- Even at 25% penetration of smart vehicles, notice 8.5% corridor level improvements at 3x flux on an eco-corridor that is exclusively Tesla Model 3
- Energy benefits monotonically increasing generally with traffic flux (up to 3x) for pure EVs

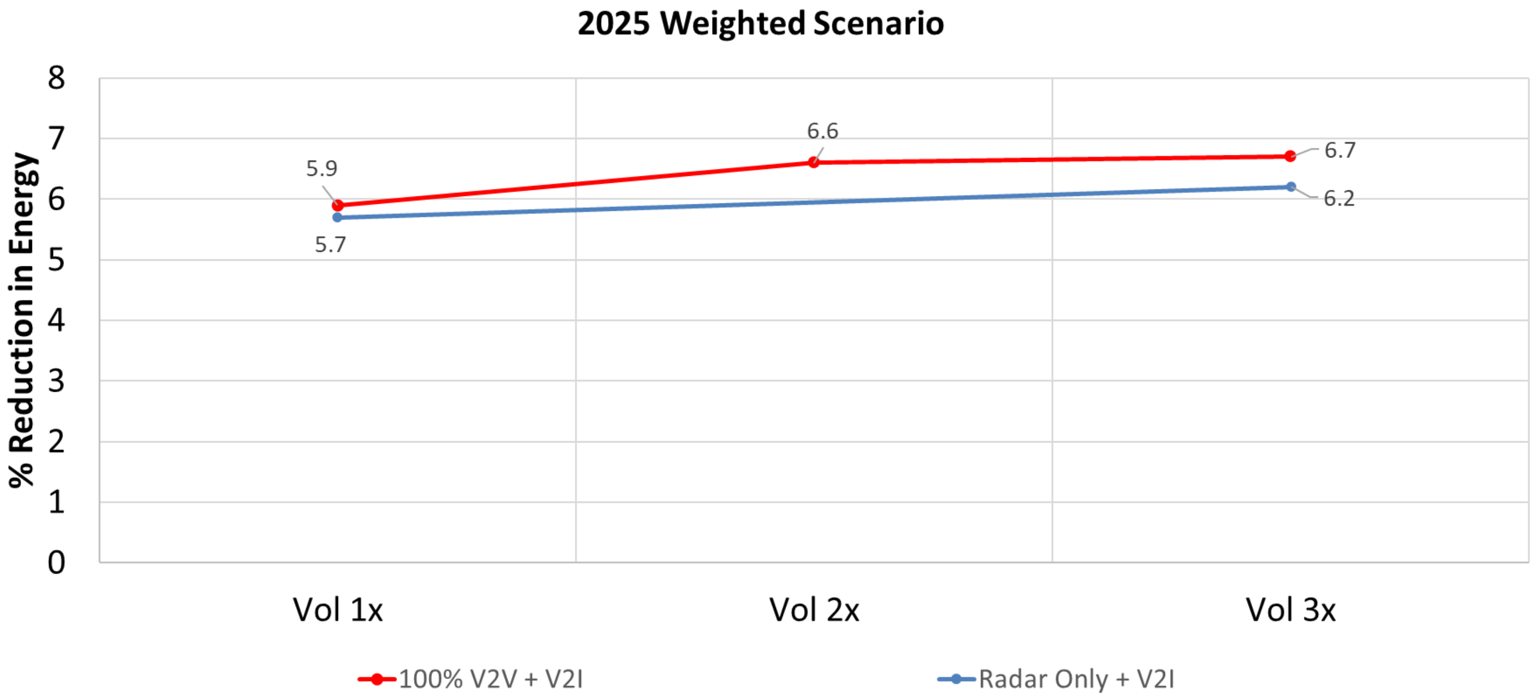


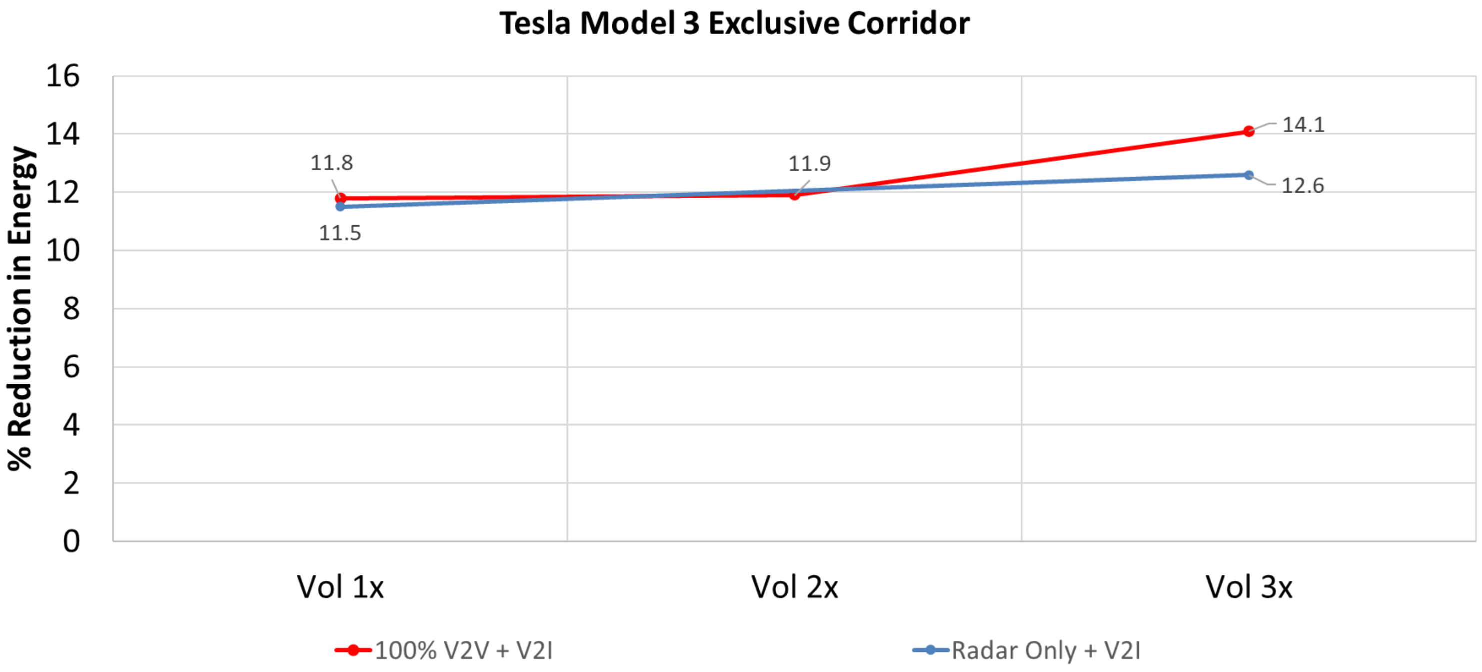


Technical Accomplishments and Progress:

SiL Testing: Impact of V2V Communication

- Significant portion of energy consumption benefits can be realized with just radar and V2I connectivity under 'normal' driving conditions
  - No stalled vehicle or emergency vehicle scenarios etc.
- The benefits do depend on traffic flux
  - At higher traffic flux conditions, V2V penetration does yield increased energy benefits but not significant





Technical Accomplishments and Progress:

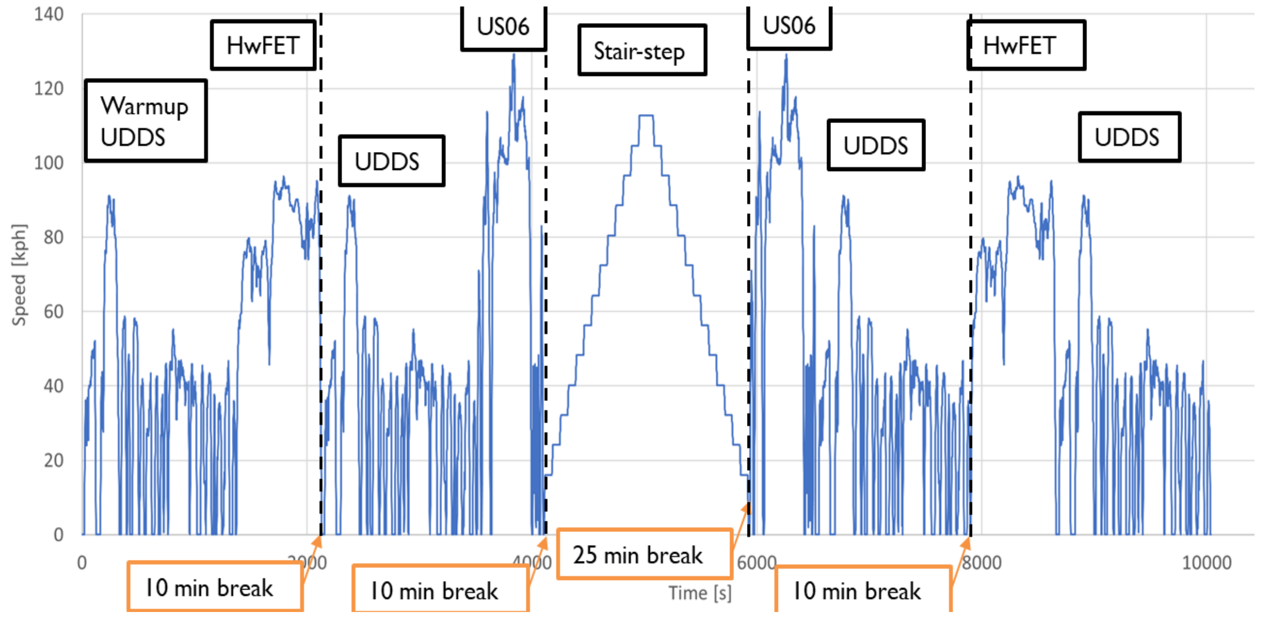
Vehicle Testing on Dynamometer

- Baseline testing complete for 3/5 vehicles
  - Tesla Model 3 (powertrain model check-out complete)
  - Hyundai Elantra (model check-out in progress)
  - Toyota Prius Prime (powertrain model check-out complete)

- Instrumentation and DAQ set up complete for Chrysler 300 and Kia Soul EV

- Couple of challenges with different vehicle model year
  - Hyundai Elantra (CVT as opposed to 6-speed transmission)
  - Kia Soul EV with larger battery pack/motor capacity

- Instrumentation to capture energy consumption for automated driving stack in progress
  - Real world driving in urban and highway environment



Technical Accomplishments and Progress:

Tech-to-Market (T2M) Highlights

- Initial T2M plan complete
- Forecast studies accelerated to feed into simulation studies
  - will be updated semi-annually
- Public sector engagement with City of Austin
  - Strong interest with safety as primary driver; efficiency focus will follow
  - Expect application marketplace like Apple/Google Play store
  - Expect vehicle manufacturers to pay for the services as primary beneficiaries
  - *CAV-as-a-Service* business model: city gets revenue share
- Competitive landscape
  - Discussion with Velodyne
- Further discussions planned with vehicle OEMs, cities, competitors

Plan for FY2021 and FY2022

BSMs

Intelligent Intersection

Sensing	*Perception*	*Processing*	*Comms*

V2V: distance, speed
V2I: distance to light, phase, time remaining in phase

Simulate velocity trajectories for all vehicles

Eco-Driving (x 5)

*Optimal Speed**

Actual Speed

FY2021: Transition from Simulation to CAV Dynamometer

BSMs

Intelligent Intersection

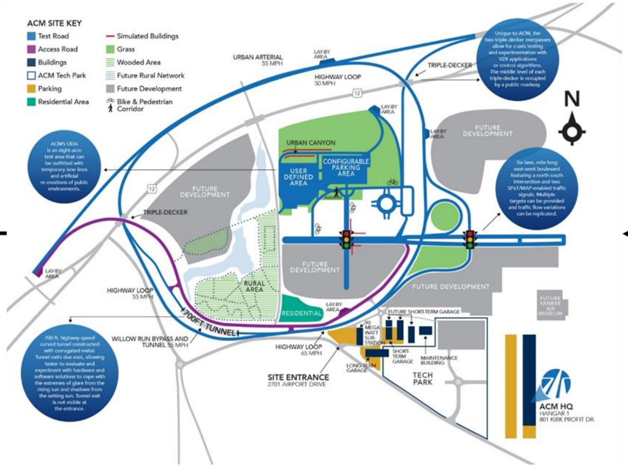
Sensing	*Perception*	*Processing*	*Comms*

V2V: distance, speed
V2I: distance to light, phase, time remaining in phase

Eco-Driving (x 5)

*Optimal Speed**

Actual Speed



FY2022: Transition from dynamometer to track testing

Proposed Future Research

SiL Testing (Budget Period 2)

- Complete remainder of simulations at higher traffic flux conditions
- *Hypothesis*: Energy consumption benefits at corridor level will increase with traffic flux up to a point and then drop (highly constrained condition)
  - Identify inflection point where peak benefits are realized at *corridor level*
  - Simulate beyond 5x flux if needed to verify if the behavior is observed

Full factorial

Traffic Flux (veh/hour)	Smart Vehicles Penetration	Electrification	V2V Penetration
1x	25%	25%	0% (radar + IIS)
2x	50%	50%	100%
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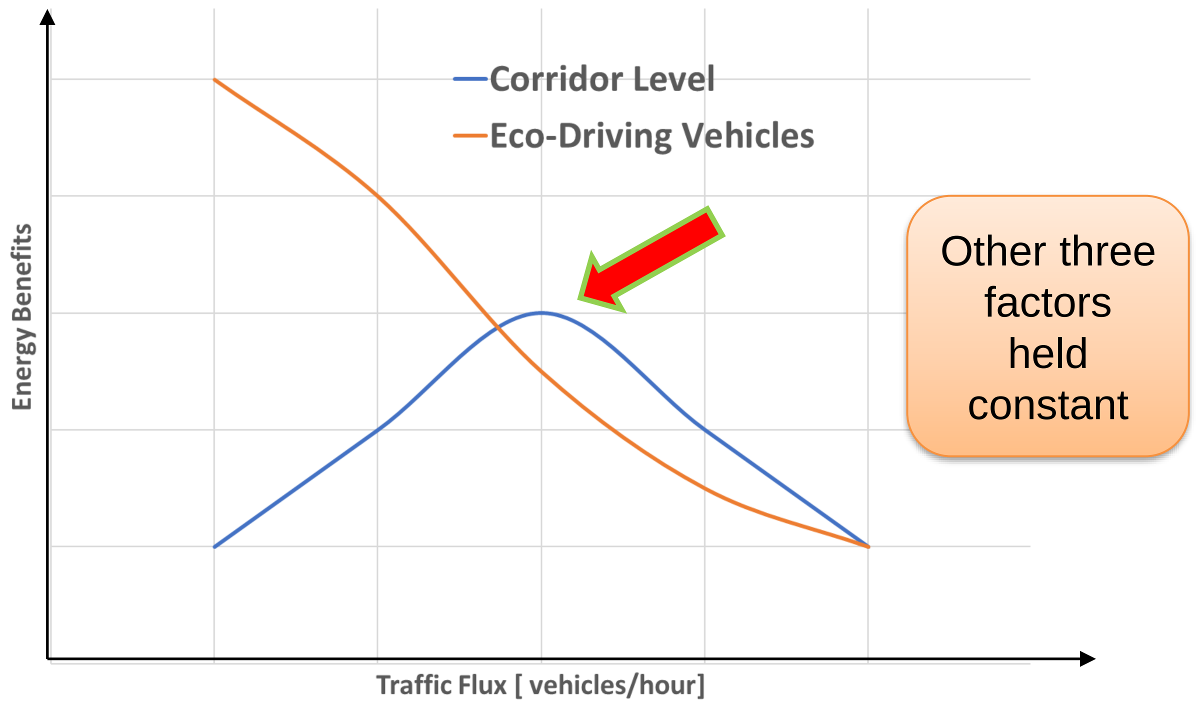


Proposed Future Research

Vehicle Testing

- Chassis dynamometer (Budget Period 2)
  - *Powertrain model verification:* Complete baseline testing for Kia Soul EV and Chrysler 300
  - *SiL Validation:* Conduct vehicle experiments on the dynamometer to quantify and confirm energy consumption numbers from SiL studies
  - *Level 4 protype build up:* Quantify energy consumption of the automation stack for urban driving conditions

- Test Track Technology Demonstration (Budget Period 3)
  - Additional SiL validation as required
  - Driver advisory refinement and integration with DSRC On-Board Unit (OBU)
    - Team currently configuring a Cohda DSRC radio with Android Tablet for V2X parsing
  - Intersection stack installation at American Center for Mobility (ACM)
  - Final demonstration of the overall technology (vehicle and infrastructure)

Response to Previous Year Reviewer's Comments

- The challenge was identified by the project team as "intersection stack validation with real data and long-range conditions (~300 meters from the intersection)." The accuracy of intersection-based detection equipment is significantly reduced at longer distances due to occlusion from other vehicles.
  - SiL testing showcased that radar only plus traffic light information (SPaT/MAP) helps attain most of the benefits enabled via 100% V2V penetration akin to what an intersection stack would enable: *lack of information*
  - Optimal plan from speed optimizer less sensitive to information farther away and the plan is recalculated every 0.5 second based on new information: *uncertain information*
  - At urban speeds (say 35 mph), a 10 second preview is approximately 150 meters which is within good accuracy range of the intersection stack
  - Safety critical information about vehicle in front is provided by radar that ensures robustness

Collaboration & Coordination

Partner	Partnership Type	Role
Continental	Subrecipient	Integral member of technical team working on Level 4 prototypes and intelligent intersection platform.
Frost & Sullivan	Subrecipient	Integral member championing Tech-2-Market milestones along with market research and driver clinic studies. Focus on how public sector can contribute to this area.
Hyundai-Kia America Technical Center, Inc.	Collaborator	OEM partner providing guidance, vehicles and identifying synergies with other connected vehicle programs like smart cities and Crash Avoidance Metrics Partners (CAMP).
Alamo Area Clean Cities Coalition	Industry Partner	Facilitate meetings with public sector entities in Texas and help be an outreach partner for the technology.

Barriers & Challenges

Defining Penetration of Smart Vehicles

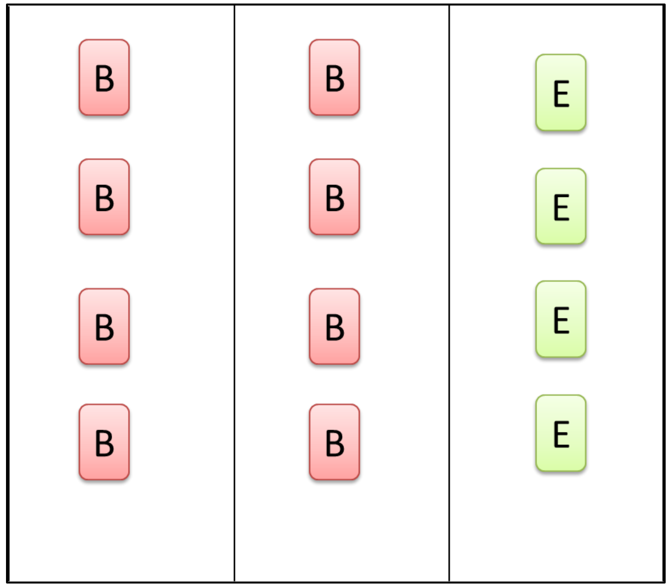


Figure I

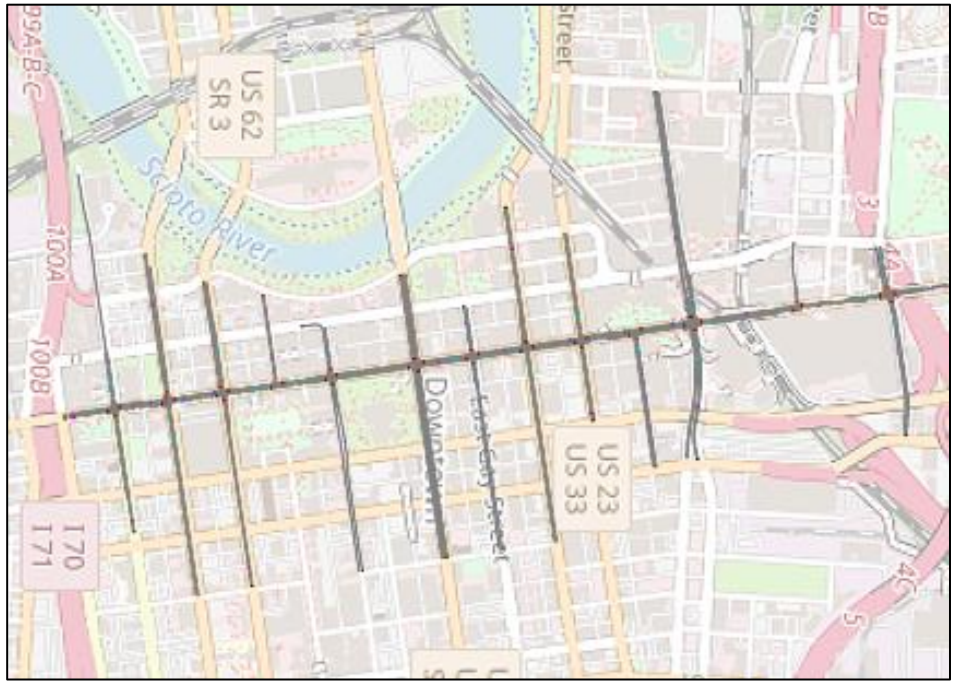


Figure II

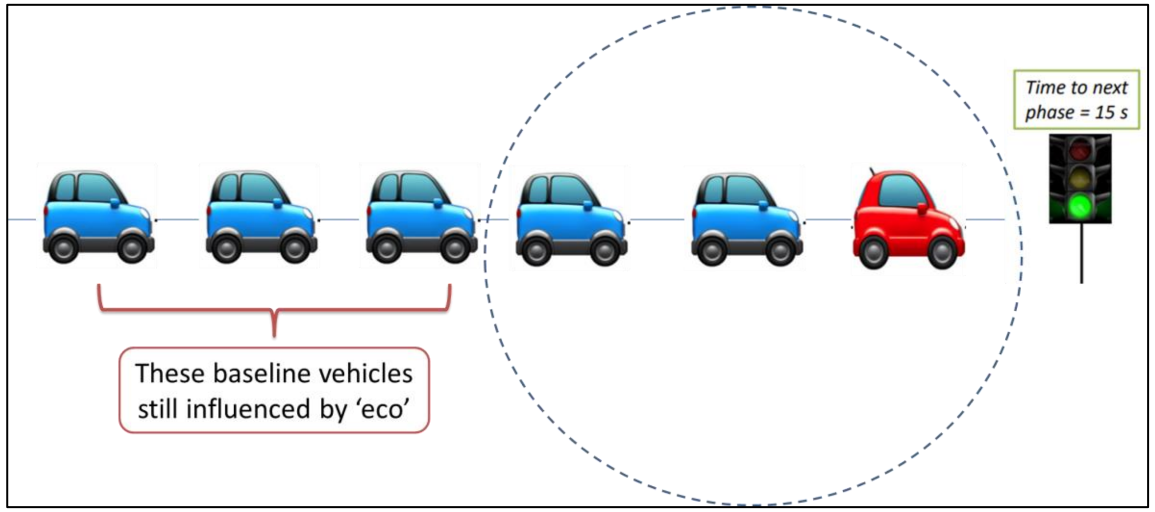
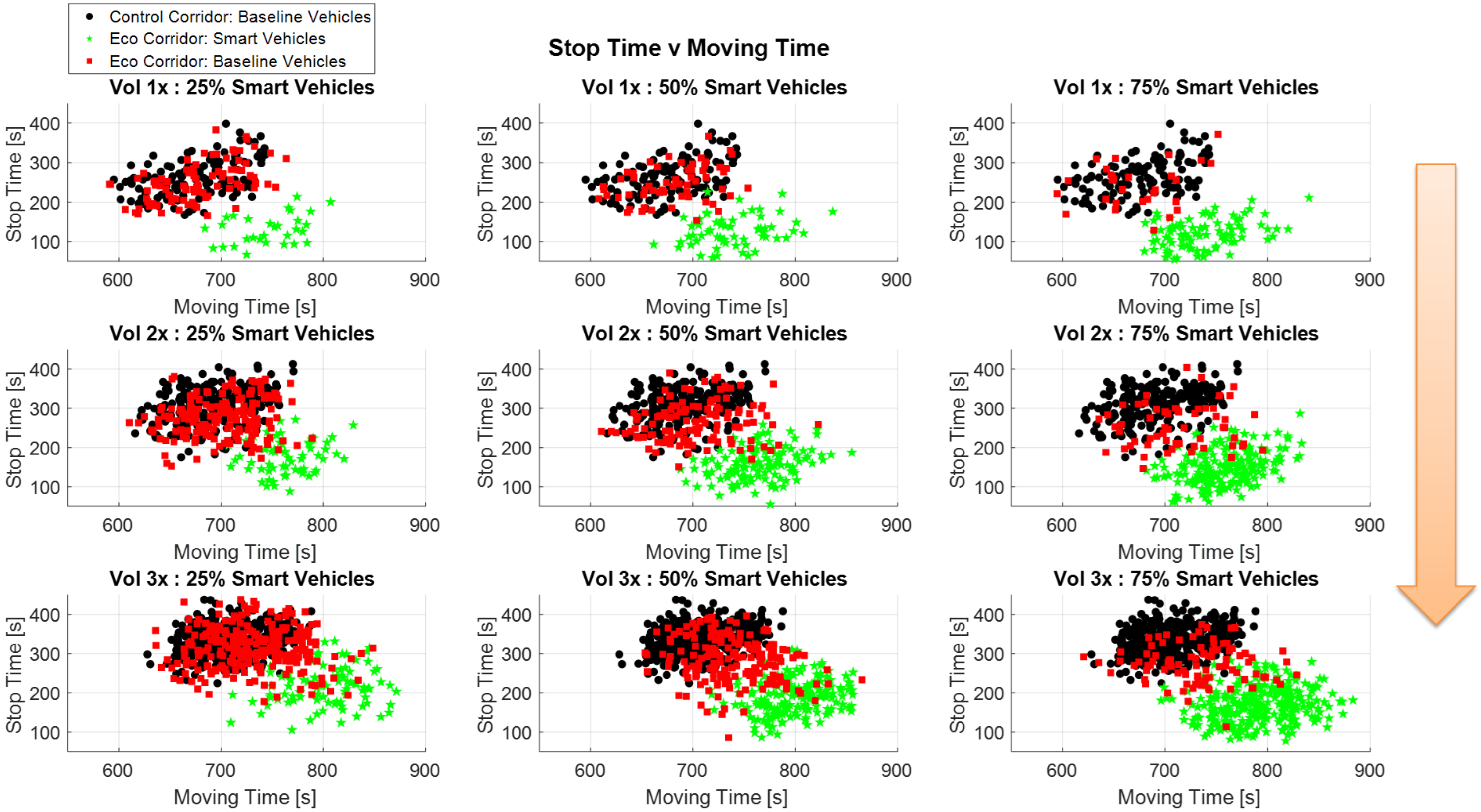


Figure III

- Penetration rate needs to be characterized at lane level
  - In figure I, penetration from volume perspective is 33% but eco-vehicles will have no impact on baseline vehicles
- Urban corridors have multiple entry and exit points (figure II)
  - Penetration rate is continuously varying as a function of location and traffic that travels through corridor partially
- Distance based metric to eco-vehicles possibly not accurate
  - Figure III shows example of vehicles outside a given radius that could be affected akin to shock wave effect

Barriers & Challenges

Influence Factor Analysis



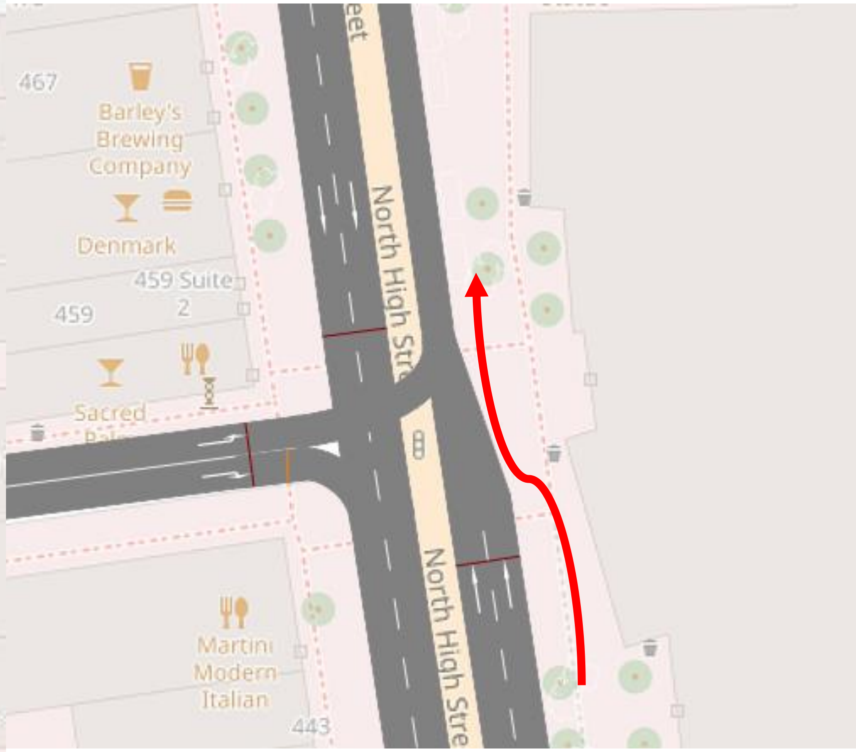
- Smart vehicles tend to spend more time moving compared to baseline vehicles
  - Typical eco-driving strategies strive to minimize braking and encourage cruising
- In the eco-corridor, how many baseline vehicles (red dots) transition into the smart vehicle (green dots) cluster
- Influence factor

$$\frac{\#\ of\ vehicles\ in\ eco\ cluster}{\#\ of\ vehicles\ total}$$

Barriers & Challenges

Increasing Flux

- Testing high flux scenarios introducing new bottlenecks in the corridor
  - Ex: unprotected left turns, two lane to single lane merge
- Certain portions of the corridor with very high-density traffic and free-flowing in other portions
  - Team making realistic modifications to uniformly scale and flow traffic



Summary

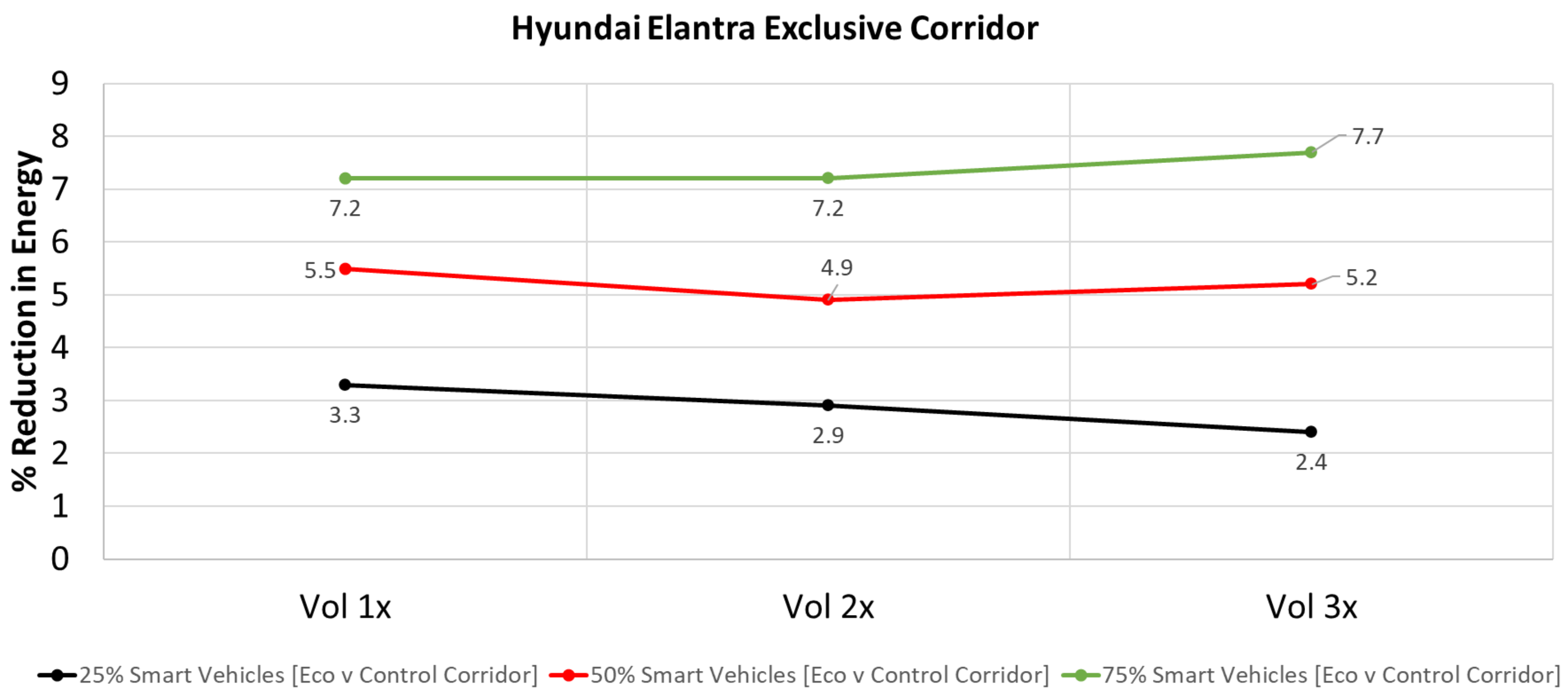
- Traffic and vehicle simulation platforms built with good fidelity to enable realistic corridor level analyses
- SiL studies progressing well with interesting insights on the impact of various factors – traffic flux, powertrain electrification, V2V penetration and penetration of smart vehicles in traffic
- The influence factor analysis is providing a new perspective to characterize speed harmonization effects particularly in urban corridors
- Intersection stack validated with real data with further improvements in pipeline
- Transition to vehicle testing on dynamometer for remainder of budget period 2
- Driver advisory refinement, V2X radio integration and infrastructure stack installation in pipeline for vehicle track testing at ACM in budget period 3
- Tech-to-Market tasks involve more discussions with public sector entities, OEMs followed by driver clinics and cost-performance analysis from a commercialization perspective

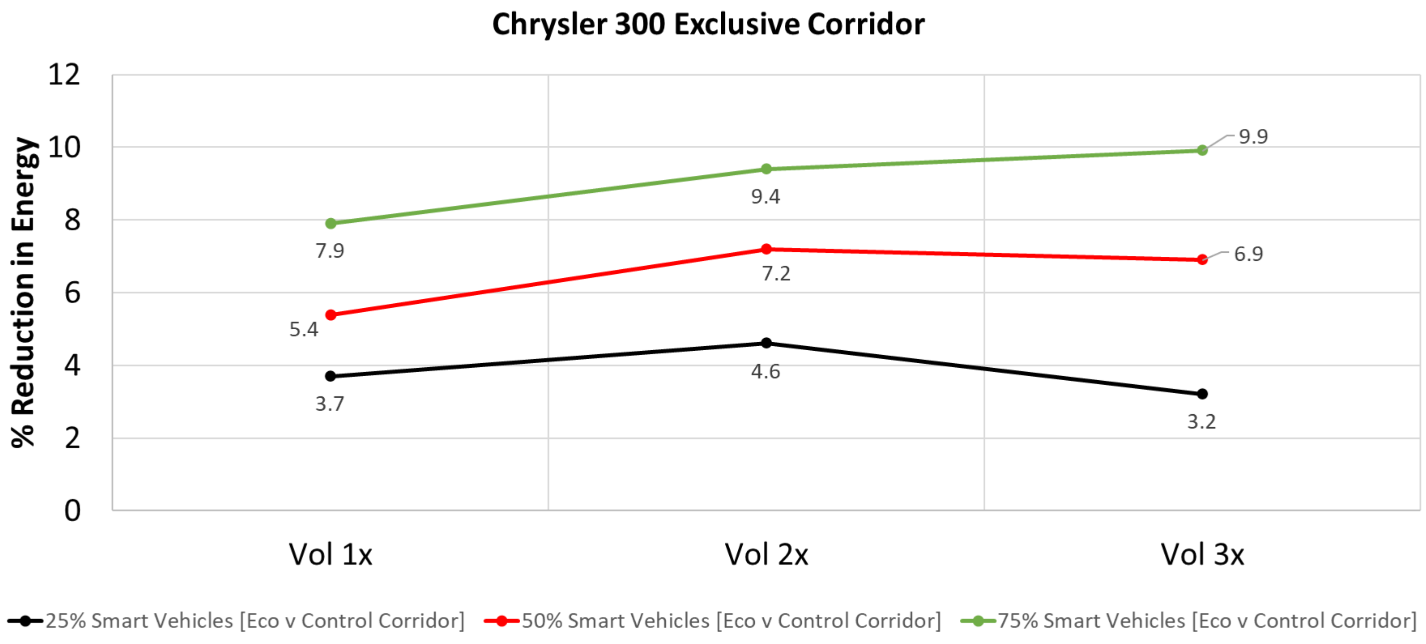
Technical Back-Up

Technical Accomplishments and Progress:

SiL Testing: Impact of Internal Combustion Engine Vehicles

- Nonlinearity of the ICE evident in the plots below
- Need to investigate further at higher flux conditions to see if a trend is observed





Technical Accomplishments and Progress:

SiL Testing: Composition of Vehicles

- Snapshot of vehicle composition in the corridor at 50% penetration of smart vehicles
- Both *smart and baseline vehicles travel the whole corridor*, and the remainder are vehicles that navigate partially through the corridor